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A contribution to reliability qualification of new technical equipment

– with focus on subsea production equipment

Thesis for the degree of Philosophiae Doctor

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“Science never solves a single problem without creating ten more”

George Bernard Shaw, 1856-1950

Preface

This thesis is the result of a PhD project at the Department of Production and Quality Engineering, the Norwegian University of Science and Technology (NTNU). The work was carried out from 2009 to 2013.

The PhD project has been carried out in close collaboration with my main supervisor, Professor Marvin Rausand at Department of Production and Quality Engineering (NTNU), and his contributions are reflected in several articles. The co-supervisor has been Professor Jørn Vatn at Department of Production and Quality Engineering (NTNU).

The PhD project has been a unique opportunity for making contributions to fields in which I take great interest, namely technical safety and reliability, to be used in subsea industry.

Trondheim,
August 2013

Maryam Rahimi

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This PhD could not been carried out without the support and helps of others.

First, I would like to express my sincere gratitude to my main supervisor, Professor Marvin Rausand, for all his support, guidance and encouragement. I was very lucky to have him to be my supervisor. I have learned a lot from him both on scientific and professional levels.

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I would like to thank my colleagues who participated in RAMS group of IPK for sharing their knowledge and discussions on my articles and presentations.

Furthermore, thanks also to my all other friends who put up with me through the whole PhD process and helped me with challenges along the way.

I am, as ever, deeply thankful of my parents for providing indispensable support during these years and also sincere of my parent-in-law's encouragements, all from many miles away Norway.

Finally, I would like to thank my husband, Iman, for his love and patience. It's always easy to start something but it's hard to come to the end properly. Thank you for encouraging and giving me the energy to proceed every day, especially during the final stages of my PhD project.

Summary

This PhD thesis proposes new frameworks and methods which give new insights to qualification and reliability assessments of new subsea systems. The subsea oil and gas industry is an industry with strict requirements to the reliability of their equipment. The provision of new subsea technology with an acceptable level of reliability is a prerequisite to achieve high production availability, low maintenance costs and less consequences such as oil spills to the environment or other types of accidents.

Before a new technology or a new system is accepted for use, the equipment supplier must convince the operator that the reliability of the new technology/system is sufficiently high. This may be accomplished through a technology qualification program (TQP).

The objective of this PhD project has been to develop *systematic approaches* that contribute to the reliability qualification of new subsea equipment and to the following-up of reliability in the operational phase.

The main contributions from this PhD project are:

- A technology qualification framework which is integrated with a product development model, and highlights the key features of commonly used TQP approaches.
- A method for reliability prediction of new subsea equipment based on comparison with similar topside equipment and using the available field data.
- An approach for how to consider and monitor human and organizational factors (HOFs) influencing common cause failures (CCFs) in the operational phase. Along with suggestion of supplementary questions to be added into the IEC 61508 approach for determining CCF factor.
- An approach for failure rate updating during various product's life cycle.
- An approach for reliability prediction of offshore oil and gas equipment operating in arctic environment based on proportional hazard model and the levels of data availability.

- An approach for outlining the reliability improvement process for subsea equipment that can be integrated with the product development process of Murthy et al. [57].

The results of this thesis may academically be used by researchers with interest in the same research field and practically be used by producers, suppliers, end users, decision-makers and other organizations within the field of subsea equipment and oil and gas industry. The generic principles from the proposed frameworks, or methods with minor modifications can also be applied for other new equipments in other industry sector where high reliability is a requirement, such as military, aviation, and so on.

Therefore, it is important to share the contributions and ideas for further work with others. The contributions have been presented in eight articles, where two have been published in international journals, one have been submitted for publication, and five have been presented at conferences and have been published in conference proceedings.

Currently, there are several TQP approaches have been suggested, but only two of these approaches are mainly used in the Norwegian offshore oil and gas industry; one proposed by Det Norske Veritas (DNV) in their recommended practice DNV-RP-A203 and one based on NASA's technology readiness levels (TRLs) approach. Combinations of the two approaches are also used. This PhD thesis presents and discusses the main TQP approaches highlights challenges related to methodological and procedural issues and provides a set of suggestions for improvement. Criteria are established to facilitate comparison and identification of strengths and weaknesses of the TQP approaches. These results, combined with a thorough literature review, have been used to develop a framework that is practical for qualifying new subsea systems.

As part of the TQP, reliability analyses and predictions are performed in the early stages of product development process. Currently, no practical method is available that can be used to extrapolate the available reliability data from similar and known systems and come up to a failure rate prediction for new systems operating in a different environment. This PhD thesis suggests a practical approach on how to predict the failure rate of new subsea systems that has been adapted (i.e., "marinized") from known topside systems.

The reliability assessment should not finish when the equipment enters the operating phase, but should be followed-up during the operational and maintenance phases. Safety-instrumented systems (SISs) are important safety barriers in many technical systems in the subsea industry. CCFs represent a serious threat to the reliability of SISs. For quantitatively incorporating the effects of CCFs, the beta-factor model is often used. During the operational phase of SIS, the hardware architecture and the components will usually remain unchanged. Therefore, any changes in CCF might be as a result of factors including environmental exposure or human and organizational acts. This PhD thesis highlights the importance of HOFs in estimation of β for SISs during the operational phase.In addition this

PhD thesis suggests a set of supplementary questions to the existing methods of beta estimation for SIS such as IEC 61508 approach, for more accurate determination of beta-factor. HOFs are difficult to predict, and susceptible to be changed during the operational phase. Without proper management, changing HOFs may cause the SIS reliability to drift out of its required value. This PhD thesis also proposes a framework to follow the HOFs effects and to manage them such that the reliability requirement can be maintained.

Failure rate prediction provides a quantitative basis for decision-making regarding the adequacy of a design from the early phases in the life cycle. In real-life operation and maintenance, the operating and environmental conditions may change compared to what was assumed by the producer in the design and development phases. Changes in these conditions and unexpected disruptions may make the current predicted failure rate inaccurate and updating is required as a response to such disruptions and changes. This PhD thesis discusses the need for failure rate prediction in the various phases of a product's life cycle and proposes a framework for updating the failure rate prediction to obtain a more realistic prediction.

As the offshore oil and gas industry is currently considers moving into the arctic region. The harsh arctic environment will have an unavoidable influence on the reliability of the equipment operated in it. To understand this influence is of vital importance to ensure the reliability of the equipment and the production availability of the systems. Several types of data, such as data on design, production, usage intensity, and operating environment are required to assess and verify the reliability of the equipment. This PhD thesis proposes a framework for reliability assessment based on proportional hazards modeling and various types of data. It presents important arctic factors influencing the physical performance and discusses how these may influence the reliability of the equipment.

Developing a product with high reliability cannot be achieved overnight and the subsea industry has to adopt a long-term improvement strategy and needs to learn from other industries that are exposed to similar strict reliability requirements, such as the nuclear, aviation, and space industries. This PhD thesis outlines how to integrate continuous reliability improvement into the various phases of the development of new subsea equipment, according to the product development model of Murthy et al. [57].

The areas for further research regarding this PhD project and proposed frameworks and method can be classified into three categories: (1) Development and improvement of proposed frameworks and method, (2) Practical implementation of them into existing industry practices, and (3) Handling of uncertainty.

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Part I

Main report

1

Introduction

This chapter provides the background for this PhD thesis in order to provide a broader context for the work. The articles discuss important issues and results, but the background chapter is meant to put the topics in the articles into a larger context.

Some concepts that are frequently used in the subsea and oil and gas industry, and also used in this thesis and articles, have been described. The thesis objectives are defined at the end of this chapter, along with the delimitations and the research challenges and questions.

1.1 Background

Subsea production equipment range in complexity from one single satellite well with a flow-line linked to a fixed platform, or an onshore installation, to several wells on a template or clustered around a manifold, and transferring to a fixed or floating facility or directly to an onshore installation [6]. The exploration and exploitation of reservoirs in deep/ultra-deep water conditions, and in other new frontiers are usually either technically unfeasible or uneconomical by using traditional surface facilities, such as steel jacket platforms. In this context the development of subsea systems is often inherently dictated by environmental conditions.

The subsea oil and gas industry is moving more and more of the traditional topside fluid processing systems to the seabed. This strategy has the potential to give increased production from low-energy reservoirs and may also lead to significant cost saving. In addition, the oil and gas industry is currently exploring new challenging areas, such as ultra-deep waters and the Arctic region.

To obtain these, several new technical products are required. Such products are being developed at an ever-increasing pace. Many of them are based on new technological solutions and may contain new materials and/or unproven components.

Subsea technology in offshore oil and gas production is a highly specialized field of application with specific demands. The deployment of such systems requires specialized equipment and processes and implies a very high cost. Any requirement to repair or intervene the subsea equipment is normally very expensive and this type of expense may result in economic failure of the subsea technology development.

Reliability is an important factor in the development of subsea oil and gas equipment. But several factors influencing the reliability of an equipment, for instance, the environmental conditions will change significantly as time passes (e.g., reduced pressure, changed gas/oil ratio, more produced water, different chemical content). The equipment must be reliable enough to safeguard the environment, and make the exploitation of the subsea hydrocarbons economically feasible for a rather long period.

Therefore before an operator accepts to install a new subsea system, he must be convinced that the new system has a sufficiently high reliability and a prerequisite is that failures requiring subsea repair interventions must not occur. A subsea intervention requires an intervention vessel and often a long production down-time at a cost of several million US dollars. The time to the first planned intervention may be in five years, and even longer, and it is important that the installed system is able to survive at least this period without failure.

In the subsea oil and gas industry, as for other industries with highly reliable products such as the space industry and the aviation industry, it is required to demonstrate that new products are *fit for purpose* before they are accepted for use. The framework for this demonstration process and the management of its progress is referred to as a *technology qualification program* (TQP). A well-designed TQP is an aid in developing a desired product and reduces the likelihood of ending up with a product that does not fit the purpose [3, 16].

A qualification process must be addressed prior to and in parallel with the product development process. This means that an efficient and practical qualification process needs to be based on an adequate product development model

In 2001, Det Norske Veritas (DNV) developed a recommended practice for qualification of new technology, called DNV-RP-A203. It is intended for the subsea oil and gas industry, but its main principles can also be used in other application areas. More recently, DNV issued a second edition of DNV-RP-A203 [23] based on the experiences gained from the application of the first edition. The main changes include support for the management of the TQP and an outline of the iterative nature of the TQP work-flow. An alternative qualification procedure based on *technology readiness levels* (TRLs) was introduced by NASA. TRL is a metric or measurement system that is used to assess the development status and the maturity of a specified technology or product [91]. The concepts *readiness* and *maturity* are used interchangeably in the literature, and are discussed thoroughly and compared by Tetlay and John [96].

Some other existing TQPs in the literature are Andersen [3], Ardebili and Pecht [8], Engel [26], API-RP-17N [7], NATO AVT-092 [59], SEMATECH [89], which briefly have been described in Section 1.1.4.

As part of the TQP, reliability analyses and predictions need to be conducted from the early stages of the product development at various system levels and degrees of detail, in order to evaluate, determine and improve the dependability measures of an item [27]. Reliability prediction must to be performed in order to:

- Identify potential design weaknesses
- Compare alternative design solutions, materials, etc.
- Determine early estimates of life-cycle costs
- Provide failure rates and other input parameters for system reliability and availability assessments
- Establish requirements and objectives for reliability testing

Successful reliability prediction generally requires developing a reliability model of the system considering its structure. The level of detail of the model will depend on the level of design detail available at the time.

Most of the methods for reliability prediction for electronic equipment are based on the parts count technique (prediction at reference condition) and the part stress technique (prediction at operating condition) presented in MIL-HDBK-217F [56] and similar approaches such as IEC 61709 [41], Telcordia SR332 [95], Siemens SN 29500 [90], FIDES [29].

For mechanical equipment regression-type models can be used. The most commonly used models for reliability analysis fall into two categories [50]. The first category is called *accelerated failure time models*, and the second category includes models from the *proportional hazards* family [48], which Section 1.1.5 briefly describes them.

The reliability assessment will not end when the equipment enters the operating phase, but should be followed-up during the operational and maintenance phases. When entering the operational phase, the conditions may not fully comply with the assumptions made in the design and development phases. The influencing factors need to be identified, monitored, handled and quantified. In addition, the actual values of the predicted measures from the design phase have to be updated accordingly.

The terms product, equipment, and technology are frequently used in this thesis. Technology can be defined as “the scientific study and use of applied sciences, and the application of this to practical tasks in industry” or as “application of knowledge to practical purposes” [23]. Equipment and product therefore denote any physical technical items, components or systems.

This PhD thesis addresses this background and suggests new frameworks, and methods that mainly can be used by researchers, reliability analysts, design engineers, and end users for their joint effort in building and operating new subsea systems.

The next sections briefly describe important concepts regarding technology classification, qualification, its approaches, commonly used qualification processes and prediction methods.

1.1.1 Classification of technology

How detailed and comprehensive the TQP must be, depends on the level of newness of the technology. Several classification systems for the *newness* of technology have been developed to assist in prioritizing TQP activities. Examples are given in this section.

In the aerospace industry [99], new technology is defined as that which (i) has never been previously characterized, (ii) has limited space heritage, or (iii) is commercial off-the-shelf technology (COTS).

In the DNV guideline [23], technology is new when it is not *proven*. Technology is said to be proven when it has a well-documented track record from the actual environment and application. Such documentation must provide confidence in the technology from practical operations, with respect to the ability of the technology to meet the specified requirements [23, 43].

The equipment to be qualified can be classified according to: (i) the *newness* of the technology and (ii) the amount of experience from previous applications of similar technology in the actual operational and environmental context. Based on these factors, the DNV guideline [23] classifies technology (and products) in four categories with three levels for technological maturity and two levels (proven and new) for the application area. The specialized DNV guideline [22] distinguishes between three levels of application as listed in Table 1.1. This gives nine different combinations of maturity level and level of experience. These are again classified in four degrees of newness:

1. *No new technical uncertainties*. This is the least demanding category, where proven (i.e., well known) technology is used in a known application.
2. *New technical uncertainties*. This category has two subcategories:
    a) Technology with a limited field history (i.e., partly known) that is used in a known application.
    b) Proven (i.e., well known) technology that is used in a new application for the company/user.
3. *New technical challenges*. This category has three subcategories:
    a) New or unproven technology that is used in a known application.
    b) Technology with a limited field history (i.e., partly known) that is used in a new application for the company/user.
    c) Proven technology that is used for a new application for the whole industry.

Table 1.1. The degree of newness of technology [22].

	Level of technology maturity		
Experience with the operating condition	Proven	Limited field history or not used by company/user	New or unproven
Previous experience	1	2	3
No experience by company/user	2	3	4
No industry experience	3	4	4

4. *Demanding new technical challenges*. This is the most demanding category where:
    a) New or unproven technology is used in a new application both for the company/user and the industry.
    b) Technology with limited field history that is used in a new application for the industry.

This classification applies to the totality of the applied technology as well as to each of its parts, functions, and subsystems. It is used to highlight where care must be taken due to limited field history. Technology in category 1 is proven technology where proven methods for qualification, tests, calculations, and analysis can be used to document margins. Technology in categories 2 to 4 is defined as new technology, and must be qualified according to a qualification procedure. By distinguishing between 2, 3, and 4, it is possible to focus on the areas of concern.

1.1.2 Qualification

DNV [23] defines qualification as *"confirmation by examination and provision of evidence that the new technology meets the specified requirements for the intended use."* A more goal-oriented definition is given by Hother and Hebert [35] who state that TQP is a systematic process aiming to:

1. Reduce the risk and increase the probability of product success.
2. Ensure that the product is fit for purpose before being put into operation.

The qualification can, according to DNV-RP-A203 [23], be performed by the producer, the customer/operator, or a third party. The TQP sets the scene for the qualification of a new technology and serves the following purposes:

- The producer, who offers the new product/technology to the market, needs to provide a proof of fitness for purpose.
- The system integrator, who integrates the new technology into a larger system, needs to evaluate the effect on the total system reliability and to use as input to the reliability assessment of a larger system.

- The end-user of the new technology must optimize the benefits of her investment through selection between competing products/technologies, and to use as acceptance for implementation/start-up phase.

When we claim that a product is qualified, this should not be misunderstood as a property of the product, rather it implies that according to the provided evidence, our belief is that the product is fit-for-purpose and can start its operational phase.

Performance criteria for the product and/or the technologies must be specified by the producer, regulatory bodies, or by the customer and may be related to various reliability measures based on the time-to-failure probability distribution and/or some defined margins against specified failure modes (e.g., see [23, 38]).

1.1.3 Qualification approaches

Qualification of new technology can be performed from several perspectives as described in the following.

Proactive versus reactive approach

Gerling et al. [32] study electronic products and distinguish between two different approaches for qualification of new technology: a *reactive* and a *proactive* approach. In the reactive approach, the close to final product is examined as a black box by comparing the product's properties with specified requirements as a final inspection at the manufacturing site (or as incoming inspection by the user). The approach is reactive in the sense that it adds an additional phase to the development, and hardly differentiates in giving focus on those issues that really need to be qualified. In this approach, reliability is mainly qualified by means of stress-tests at elevated conditions. The objective is usually to test for the existence of known failure modes that have been observed earlier in similar products.

A proactive approach considers qualification as an integrated part of the design and development with early involvement in this process. In this approach, technology and design properties common to all products or product elements are identified and results gained on similar products are considered.

Qualification by analysis versus qualification by testing

The *analytical* approach is a proactive approach without testing, and has, according to Sunde [94], the following key features:

- Reliability and quality assessments are part of every phase of the product development process.

- Development of reliability models covering degradation is done in parallel or prior to the product development.
- Reliability and development data are used to demonstrate the qualification of the product.
- Qualification plans and their assessment are explicitly based on requirements from customers (this mainly applies for specialized, custom-built products)

The main reason for this type of qualification is the need to reduce the time and cost associated with the design and development of new products as highlighted and exemplified by the NATO report *Qualification by analysis* [59].

Qualification solely by analytical methods may not be appropriate to verify the reliability and safety of products in high-risk industries such as nuclear power plants and offshore oil and gas platforms. For these industries, it may be more relevant to qualify products on the basis of analysis combined with testing, and by using historical data from tests and field service.

IEC 61508 [43], also distinguishes between functional requirements and reliability (i.e., safety integrity) requirements. Both these requirements should met, for the equipment to be qualified, and qualification of the functional aspects, mainly relies on the physical testing (in a relevant environment).

The *experimental* approach typically involves testing under defined conditions on the test site, and sometimes also field testing. Tripsas and Johnson [101] study electronic devices and claim that the most efficient way in qualification for such products is with statistically designed experiments.

While the experimental approach does have certain advantages, such as ease of application and comparable data sets for different products and technologies, the disadvantages are becoming more apparent [72]. Some limitations of the experimental approach are:

- Increasing efforts related to stress-testing of complex products.
- Questionable definition of the resulting internal stress levels for complex products.
- Excessive testing time required for high-reliability products.
- Sample size inconsistent with reliability targets.
- Complicated and time-consuming root cause analysis of products in case of failures.
- Risk to overlook new failure mechanisms.
- Reliability results generated at the end of the development process.

Pecht [70] argues that the TQP should not be based solely on testing and it depends on the risk level, various risk-reducing factors, the ability or inability to test large one-of-a-kind systems, operational environment, and regulatory requirements. Therefore, a combination of analytical methods with experiments is recommended. The main advantages and disadvantages of analytical and experimental qualification are discussed in NATO AVT-092 [59].

Physical versus actuarial approach

In the *physical* approach, the focus is on analyzing the physical phenomena related to the strength of the item and the loads applied to it. It is mainly used for analysis of structural elements. Loads and strengths are modeled as random variables, and failure takes place when the load exceeds the strength [18].

In the *actuarial* approach (also called *statistical* approach), the explicit loads and strengths are of little interest. Instead, it pays attention to the effects of the interaction between the physical variables [83]. Here, the reliability is expressed in terms of a probability distribution for the time-to-failure, which is often selected based on the properties of the failure rate function. For multi-component systems, the actuarial approach is usually the most appropriate approach.

A combination of statistical methods based on physical analysis will be appropriate for many new products or technologies.

1.1.4 Qualification guidelines

Several qualification processes are described in the literature.

NATO AVT-092 [59] presents a qualification process for military aircrafts aiming at reducing the time and cost of their production. This is achieved by increasing the use of analyses, integration of tools, and by finding a balance between analysis and testing, in all design and development phases. It is also claimed that this may improve the quality of the final product.

Blanchard [13] gives a generic description of the qualification process and describes a categorization of tests that are typically performed in the different development stages.

The guideline by Andersen [3] is tailor-made for oil and gas well technology and describes how to perform the qualification as a parallel activity with the product development process. This guideline also describes how qualification activities can be linked to traditional product development activities. The guideline further discusses *operational readiness* and gives requirements for manufacturing and operational planning [19].

SEMATECH [89] provides a qualification guideline intended to be used by producers and users of semiconductor equipment. It is based on a continuous improvement process referred to as the *reliability improvement process*. The guideline has three parts: (1) the equipment lifecycle and the reliability improvement process; (2) the management responsibilities for establishing and implementing the process, including the various activities associated with each step of the reliability improvement process and each phase of the lifecycle; and (3) activities and tools used in applying the reliability improvement process. The reliability activities are classified as engineering, data-related, and testing. Many activities require tools coming from various disciplines, such as probability, statistics, and reliability engineering.

API-RP-17N [7] presents a structured approach which aims to help operators, contractors, and suppliers to gain a better understanding of how to obtain and manage an appropriate level of reliability throughout the lifecycle of subsea oil and gas projects. The approach is based on the same twelve *key reliability processes* that are used in ISO 20815 [45] for production assurance and reliability management. The focus of API-RP-17N is project execution, which is described as a number of integrated reliability and technical risk management activities that are derived from the key reliability processes. These activities are arranged into a cycle of four basic steps: define, plan, implement, and feedback. These are applied during each project stage and also for each reliability assessment.

Ardebili and Pecht [8] divide the qualification process for mass-produced electronic products into three stages: (i) virtual qualification, (ii) product qualification, and (iii) mass production qualification. Virtual qualification, also called design qualification, is the evaluation of the functional and reliability performance of the product design without any physical testing of the product. Product qualification is the evaluation of the product based on physical testing of manufactured prototypes. Product qualification tests are often performed under accelerated stress conditions (known as accelerated testing [24, 62]) and verify whether the product has met or exceeded its intended quality and reliability requirements. After virtual and product qualification, the electronic packages are mass-produced. During and after the manufacturing process, the products are inspected and tested to evaluate their quality and defective parts are screened out. This process is referred to as quality assurance testing or screening.

Engel [26] presents a comprehensive set of verification, validation and testing activities and methods for implementation throughout the entire life cycle of products. The approaches are based on a generic product life cycle model that extends the well-established V-model [55] that portrays project evolution during the development portion of the product life cycle.

Grady [33] presents the steps and procedures needed to implement a quality check of the product being proposed based on the V-model. The approach can be applied to high rate production, low volume - high cost production, and one of a kind production.

The DNV guideline [23] defines a set of activities that should be iterated through the three stages: (a) concept evaluation, (b) pre-engineering, and (c) detailed engineering. Each stage should to be successfully concluded before going on to the next stage. The activities are illustrated in Fig. 1.1.

The qualification basis must, according to Sunde [94], comprise all the steps in the process, with deliverables, methods, responsible people, schedule, man-hours, and cost. It must further take into consideration the qualification limitations, the functional requirements, the product and environmental characteristics, and the product reliability requirements [23].

Qualification methods must be selected to ensure that all potential failure modes are identified and addressed in a satisfactory manner, so that the margins

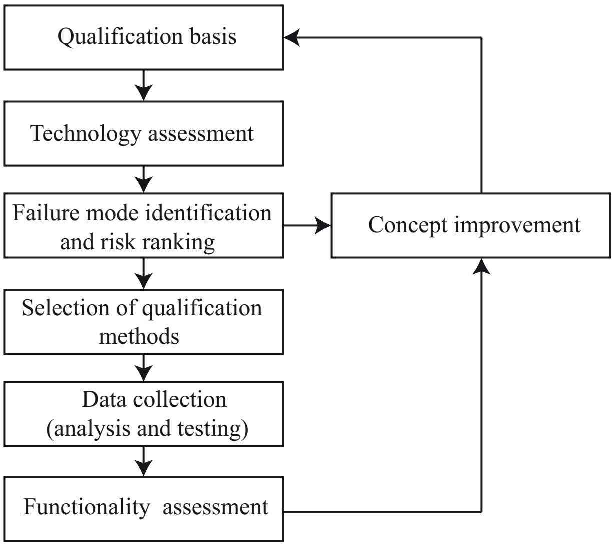

Fig. 1.1. The DNV qualification process.

to failure are documented and the reliability of the product can be proven. The most commonly applied qualitative methods are FMECA [39], HAZOP [42], and fault tree analysis [40]. Other qualitative methods are also available and most of them are presented in Rausand and Hoyland [83].

Some companies in the oil and gas industry, for example, FMC Kongsberg Subsea AS, have developed their own tailor-made TQP based on the DNV-RP-A203. The FMC procedure introduces several improvements concerning both the specification of requirements to which the technology is to be qualified, and a flow diagram to ensure that the process is carried out in a structured way. The main activities of the FMC procedure are described by Sunde [94].

The FMC procedure has the potential for significant cost saving, since the qualification process is more streamlined and efficient with reduced requirements for physical testing—such that tests are only performed when strictly necessary. Potential deficiencies and malfunctions should be revealed during the design and qualification phases, such that the number of in-service failures is reduced. This is particularly important for subsea oil and gas production systems that are not accessible for normal maintenance and repair, other than through high-cost vessel operation.

Another commonly used qualification process is based on the TRL method. The TRL method was introduced in the late 1980s by NASA, and has been used routinely since the early 1990s within the NASA organization [54]. The levels are developed as part of an overall risk assessment process, to support the assessment of a particular product and provide a consistent comparison of maturity between

Table 1.2. Definition of the TRLs.

TRL	Definitions
0	Basic principles observed and reported
1	Technology concept and/or application formulated
2	Analytical and experimental critical function and/or characteristic proof of concept
3	Component and/or breadboard validation in laboratory environment
4	Component and/or breadboard validation in relevant environment
5	System/subsystem model or prototype demonstration in a relevant environment
6	System prototype demonstration in an operational environment
7	Actual system completed and "flight qualified" through test and demonstration
8	Actual system “flight proven” through successful mission operations

Source: U.S. Department of Defense [103]

different products. In 1999, the TRL method was adopted by the U.S. Department of Defense and by the U.S. Air Force Research Laboratory [91].

The TRL method is a systematic metric/measurement system that supports assessment of a particular technology/product and a consistent comparison of maturity between different types of technologies/products.

The Subsea Processing Community (SPC) adopted and modified the TRL method to make it applicable for equipment used in subsea production systems. Since then, the TRL method has been used to determine the qualification status for several new technologies/products. The TRL assessment may be carried out in two different ways:

- As a continuous evaluation of the qualification status of the project.
- As a methodology to assess the qualification status before the project is going to the next phase in the development process.

The TRL method has nine levels (TRLs), ranging from zero to eight. TRL 0 is the lowest level of product maturity, while TRL 8 represents the proven product. These TRLs are determined by tangible evidence identified during the product development. Obviously, the tests at each level have to be successful to claim that a level is reached [12]. A summary of the TRLs is given in Table 1.2.

A more comprehensive readiness assessment should move from an individual technology context to a system context, where interplays between multiple technologies are also involved. The concepts of system readiness level (SRL) and system maturity have been introduced and discussed in [86, 87]. The SRL approach defines nine maturity steps from user requirements to system validation. Each of the SRL steps aligns to key outputs across a set of systems disciplines, such as training, safety and environmental, or reliability and maintainability. SRLs are given scores between 1 and 9, demonstrating the project’s progress against the systems engineering V-diagram [5].

Tetlay and John [96] define “system maturity” as verification within an iterative process of the system development lifecycle and focus on the design maturity of a system. The system is only verified against the system requirements if it is successfully implemented as intended by the design.

Technical performance measurement (TPM) is another concept within this area that determines how well the system or system element is satisfying specified requirements [85].

In some of the qualification procedure such as API-RP-17N [7], Engel [26], IEC 60300-3-15 [37], SEMATECH [89], the qualification tasks and the tasks during the product design and development phases are merged. In other qualification procedures (e.g., DNV-RP-A203 [23], Smith and Simpson [91]) the evaluation tasks are specified and may be carried out independently of the producer's design and development tasks.

1.1.5 Reliability prediction

System reliability requirements can be expressed with quantitative measures, such as the failure rate, the survivor probability, and the mean time to failure (MTTF) [38]. In the oil and gas industry, reliability data are collected and published through the Offshore reliability data (OREDA) handbook [68].

The failure rate of mechanical products is often assumed to be *bathtub*-shaped as illustrated in Fig. 1.2, consisting of three distinct periods [83]:

(i) *Burn-in* period with a decreasing failure rate,
(ii) *Useful life* period with a nearly constant failure rate,
(iii) *Wear-out* period with an increasing failure rate.

Many of the items covered in OREDA are subject to some maintenance or replacement policy. The items will therefore often be replaced or refurbished before they reach the wear-out phase. The main part of the failure events in OREDA database will therefore come from the useful life phase, where the failure rate is close to constant. All the failure rate estimates presented in OREDA are therefore based on the assumption that the failure rate function is constant and independent of time, in which case the failure rates are assumed to be exponential distributed with parameter λ [68].

In this thesis, we also make the same simplification for failure rate for use during the design and development of the subsea system, and denote this by $\lambda^{(S)}$. Burn-in phase and wear-out phase is not considered in the analysis, so the analysis assumes that the failure rate follows the "useful life phase". But the failure rate may in average be somewhat higher, since documented failures in the burn-in phase and wear-out phase is included in the experience data. The corresponding survivor function is $R^{(S)}(t) = \exp(-\lambda^{(S)}t)$ and the mean time to failure is $\mathrm{MTTF}^{(S)} = 1/\lambda^{(S)}$.

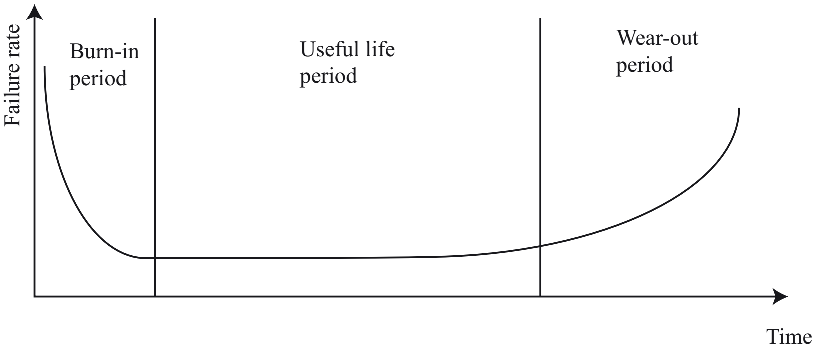

Fig. 1.2. The bathtub curve [83].

Table 1.3. Commonly used reliability prediction guidelines for electronic items.

Reliability prediction guideline	Description
MIL-HDBK-217F [56]	Contains two prediction methods, *parts count* and *parts stress* technique, limited to ambient temperatures between 0°C and 125°C.
Telcordia SR332 [95]	Is based on the principles of MIL-HDBK-217F and reflects Bellcore field experiences, limited to ambient temperatures between 30°C and 65°C
IEC 61709 [41]	Presents stress models and values as a basis for conversion of the failure rate data from reference conditions to the actual operating conditions.
Siemens SN 28500 [90]	Is based on IEC 61709 concept and provides frequently updated failure rate data at reference conditions.
FIDES [29]	Is based on physics of failure and is supported by analysis of test data, field returns, and existing modeling.

Reliability prediction methods

Several models and methods for reliability prediction have been proposed in the literature. For electronic equipment, reliability prediction is well established and is often based on the *parts count* technique (prediction at reference condition) and the *part stress* technique (prediction at operating condition) in MIL-HDBK-217F [56] and similar approaches [41, 95, 90, 29]. Table 1.3 summarizes a number of approaches that have been commonly used for electronic items.

For mechanical and electro-mechanical equipment, there is no generally accepted method for reliability prediction. This may be due to the higher number of, and more complex failure mechanisms. Several studies have shown that the reliability of mechanical equipment is sensitive to loading, operating mode, and utilization rate [63, 31].

Foucher et al. [31] classify the reliability prediction methods into three categories: (1) bottom-up statistical methods, (2) top-down similarity analysis methods based on an external failure database, and (3) bottom-up physics-of-failure methods. The first two categories are based on statistical analysis of failure data, while the last category is based on physics-of-failure models. Foucher et al. [31] compare these methods and conclude that the best prediction is achieved by a combination of different methods, depending on the phase of the system's lifecycle and objectives and assumptions of the manufacturer or the customer.

Most reliability data sources assume that the items have constant failure rates and that failures in a population of identical items occur according to a homogeneous Poisson process (HPP) where the time t is the accumulated time in service. Design variations and operational and environmental conditions may be accounted for by including *covariates* into the model. In some application areas (including the subsea oil and gas industry), the covariates are sometimes referred to as *reliability-influencing factors* (RIFs). A RIF is a relatively stable condition, which by being changed will increase or reduce the failure rate of the item. Ascher & Feingold [9] list 18 RIFs that influence the failure behavior of a repairable system. NSWC-11 [63] considers the effects of the environmental RIFs at the lowest part level of mechanical systems.

To obtain application-specific failure rate estimates, various models have been suggested [4], such as the proportional hazards (PH) model [20] and the accelerated failure time model [28, 51] where the RIFs are included as covariates. A RIF may be a continuous variable, a discrete variable taking several values, or a binary variable.

The most commonly used models for failure rate prediction are; *proportional hazards* (PH) models, and *accelerated failure time* (AFT) models [50]. In a PH-model, the actual, application-specific failure rate is determined by multiplying a baseline failure rate by a positive function of the covariates (RIFs). The approach in MIL-HDBK-217F [56] is a special and simple case of a PH-model, where the predicted failure rate λ is given by $\lambda = \lambda_0 \times \pi_1 \times \pi_2 \cdots$, where λ_0 is the baseline failure rate that is determined for normal (specified) conditions and the factors $\pi_1, \pi_2, \ldots$ are the covariates that are used to adjust the baseline failure rate to the actual temperature, humidity, and so on. The numerical values of $\pi_1, \pi_2, \ldots$ are given in MIL-HDBK-217F.

The covariates do not change the baseline failure rate (or the form of the failure rate function in the more general case), but rather change its scale by multiplying the baseline failure rate with a factor that is determined by the covariates. The most common functional form is the Cox PH-model $\lambda = \lambda_0 \exp\left(\sum_{i=1}^{n} \beta_i x_i\right)$, where $x_1, x_2, \ldots, x_n$ are the covariates (or functions of covariates) and $\beta_1, \beta_2, \ldots, \beta_n$ are parameters that have to be estimated. The Cox PH-model is easy to use since we, by taking logarithms, obtain a linear regression model [20].

The AFT-model assumes that the effect of a covariate is to multiply the time by some constant, such that the time runs faster or slower. The AFT-model can be used together with parametric life models such as the exponential [28, 51], Weibull, log-normal, and extreme value distributions [49]. Under an accelerated failure time model, the covariates are assumed to be constant and multiplicative on the time scale, that is, the covariate impacts on survival by a constant factor (acceleration factor).

The BORA approach [105] and the approach suggested by Brissaud et al. [17] are both based on a PH-model. The BORA project is concerned with reliability assessment of safety barriers on offshore oil and gas installations, and is based on a set of generic RIFs related to human and organizational factors. The RIFs to be used for the specific assessment are selected by expert judgment from the set of generic RIFs. The state of each RIF is classified into one out of six possible states and a scoring and weighing process is used to determine the effect of each RIF.

The approach by Brissaud et al. [17] is based on a set of RIFs that are classified according to life-cycle phases. The estimation of the application-specific failure rate is comparable to the approach in MIL-HDBK-217F [56], but the determination of the multiplicative factors is done in another way by a scoring and weighing procedure.

1.2 Challenges and questions

Based on a thorough literature review of both academical studies and published technical reports by industrial organizations and companies, overall challenges have been divided into three main categories:

1. Challenges regarding *TQPs*: evaluation, key features, challenges, improvements, new developments.
2. Challenges regarding *Reliability/failure rate*: prediction methods, new environment, new system, using available field data, follow-up in operational phase, continuous improvement, new developments.
3. Challenges regarding *CCFs as threat to reliability*: identification of main influencing factors, monitoring and handling the influencing factors, quantification, suggestions, new developments.

More specifically, the following specific challenges related to the qualification and reliability assessments have been identified.

1.2.1 TQP for new subsea systems

For new products, and known products based on new technology with high-reliability requirements, it is necessary to assure that they have the required quality and reliability before they are put into operation. The operator will usually specify strict reliability requirements for the new system and require the supplier to follow an agreed TQP during the design, development, and manufacturing phases of the system. The purpose of such requirement is to reduce the uncertainty and the risk associated with the use of the new equipment.

Several TQP approaches have been proposed, but no approach has yet been generally accepted within the subsea industry.

Currently, some producers in the oil and gas industry who use these approaches encounter difficulties, and they try to overcome them by merging seemingly attractive features from different TQP approaches to their own products, but this has not always given a practical and cost-efficient approach. The main challenges regarding currently used TQPs are required to be highlighted and reduced.

Relevant research questions to address are therefore:

- What are the main features and common challenges of the currently used TQPs?
- How can the identified challenges be considered and rectified?
- What is the most suitable TQP for the subsea industry?
- What criteria should be used to judge the suitability?

1.2.2 Reliability prediction of a new subsea system

As mentioned in Section 1.1, as part of the TQP, reliability analyses and predictions are performed from the early stages of the product development process. There are several approaches for predicting the reliability.

Obtaining a point value for the reliability, is not the single purpose of such an analysis. The analysis should help designers to compare alternative designs, identify potential design weaknesses and give advice on how the design can be improved. Such improvements may be related to physical design changes, establishing requirements and objectives for reliability testing, and so on. An important objective of reliability analysis is therefore to provide a decision basis which is possible to comprehend by design engineers [53].

To predict the reliability of an equipment, the industry usually tries to use the field data as much as possible. For subsea equipment there are not much data available. Most of the new subsea systems are adapted from similar, well known topside (i.e., on the platform) systems. Reliability information for topside systems is available from OREDA [68]. This information cannot be used directly for new subsea systems, because their designs have been modified and there are different environmental stresses, and different maintenance. The reliability information in OREDA [68] is presented as a constant failure rate, together with additional information related to failure modes, failure descriptors/mechanisms, and components that contributed to the system failures.

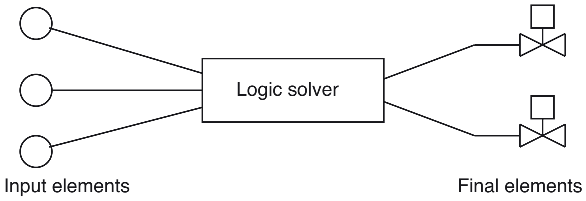

Fig. 1.3. Main parts of a SIS.

Currently, no practical method is available that can be used to extrapolate the available reliability data from similar and known systems and come up with a failure rate prediction for new systems operating in a different environment.

Relevant research questions to address are therefore:

- What kind of reliability modeling and calculation approaches are suitable for complex subsea systems?
- How can a more realistic reliability prediction be achieved for new subsea technologies where no field data are available?
- How can field data from similar topside systems be used to predict the preliminary failure rate of new subsea systems?

1.2.3 HOFs influencing CCFs in the operational phase

Safety-instrumented systems (SISs) are used in the subsea industry and many other industrial sectors to detect hazardous events and prevent such events from developing into accidents. The main parts of a SIS are illustrated in Fig. 1.3. One SIS application is the high integrity pressure protection system (HIPPS) which is installed on a subsea oil/gas pipeline to avoid loss of containment and prevent over-pressure [93].

SISs like other subsea systems have high reliability requirement. Redundancy is often introduced to improve the reliability of SISs, but it is well known that common cause failures (CCFs) may violate the intended reliability gain [92].

During the operational phase of SIS, the hardware architecture and the components will usually remain unchanged unless there is a call for modification (modifications are not quite relevant for subsea system, since interventions are avoided). Therefore, any changes in CCF might be as a result of factors including environmental exposure or human and organizational acts. A number of studies have also shown that CCFs are generally influenced by a range of human and organizational factors (HOFs) [88, 66, 61, 60].

The most commonly used CCF-model for SISs is the *beta-factor* model [30]. This model has also been highlighted and described in IEC 61508 [43]. Due to the lack of data, most of the methods for predicting the beta-factor are based on checklists [36, 46, 43]. In the process industry, the approach described in part 6 of IEC 61508 [43] is dominating and is therefore used in this research.

These checklists, however, mainly focus on technical issues, rather than human-related issues. In the checklist questions in IEC 61508, only about 20% of the questions concern human and organizational factors. Such a low focus on human and organizational factors is not in line with the lessons learnt from the ICDE project [79]. Several studies have shown that HOFs are among the main factors influencing β, but the estimation procedures do have not enough attention to the effects of HOFs.

In the design phase, the beta-factor is predicted (denoted β_{P}) based on several assumptions about the conditions in the operational phase. When entering the operational phase, these conditions may not fully comply with the assumptions made in the design phase. The actual beta-factor in the operational phase (denoted β_{A}) may therefore be different from the predicted β_{P}, and this difference may cause the required reliability to not meet the required SIL.

The events that lead to CCFs may be introduced both during the design and the operational phase. For design, checklists have been developed to ensure that measures are taken to reveal and avoid introducing CCFs. It seems such tools and checklists be missing in the operational phase.

In addition, the SIS end-user needs to have enough awareness about the effects of the HOFs in order to manage them such that the actual beta-factor does not exceed the acceptable limit that are determined by the required SIL.

There are not enough procedures and work practices for monitoring and controlling reliability influencing factors in order to maintain the reliability as predicted. Insufficient attempt regarding monitoring and controlling the HOFs related CCF in the operational phase.

Relevant research questions to address is therefore:

- How to highlight the importance of HOFs influencing CCFs in the operational phase?
- How can HOFs be incorporated into the β-factor model?
- How can HOFs be monitored and handled during the operation and maintenance phases?

1.2.4 Non-constant failure rate of mechanical products

The producer needs to predict the failure rate of new products as input to decision-making related to design options, requirements for testing, and so on. Failure rate predictions will be used to evaluate the need for environmental controls, introducing redundancy, or trading off other reliability enhancing techniques against cost, space or volume, and other resource limitations [84]. The user/operator of the product also needs to predict/update the failure rate to fulfill the requirement and to get a realistic understanding of the performability of the product in the operational phase.

Design weaknesses should be identified and improvements should be made as early as possible in the product life cycle. If flaws are revealed and corrected in the early design phase, their consequences are much less significant than having to redesign after clients discover the problems. The need for failure rate prediction in various phases of product's life cycle should be clarified.

Mechanical products like subsea system may deteriorate with time, due to wear, fatigue, or other stress-related mechanisms, and their reliability can not always be modeled assuming constant failure rates. What constitutes a failure of a mechanical product depends on its application. Lack of a clear definition of a failure delimits the usefulness of the reliability data available [63]. This usually has been neglected by producers and end users.

Most of the failure rate prediction methods are based on analyses of field data, which are used to estimate parameters of life distributions reflecting deterioration characteristics [100]. Failure rate predictions in design and development have to be based on assumptions about the operational and environmental conditions the product will be exposed to in actual operation. In real life applications, however, these conditions are not constant, the product has to adapt to different conditions, and this has a direct impact on its reliability in the operational phase – which is also called the actual reliability. Most of the reliability methods are not well adapted to estimating system reliability under non-uniform and dynamic operation and maintenance conditions. Several reliability prediction methods have been developed for electronic components, but none of these can directly be applied for mechanical products.

The non-constant failure rate of mechanical items like subsea equipment needs to be highlighted and guidances on how to take that into account in the failure rate prediction during the product operational phase should be provided.

Relevant research questions to address are therefore:

- Why is failure rate prediction needed in different phases of product life cycle?
- How can we take the non-constant failure rate into account and what are the challenges in this regards?
- How can failure rate prediction of subsea system in operational phase be more realistic?

1.2.5 Reliability prediction in a new environment (Arctic)

The offshore oil and gas industry is currently exploring new areas in the southern part of the Arctic and is contemplating moving even further to the North. The boundaries of the Arctic region have several definitions [102]. In principle the Arctic is defined as the region north of the Polar Circle. In other words Arctic is a region located at the northern-most part of the Earth (latitude 66 ° 30' north).

Several arctic characteristics influence the reliability of the equipment operated in such an environment. To understand this influence is of vital importance to ensure the reliability of the equipment and the production availability of the systems.

The arctic environment, however, represents a new challenge for much of the equipment and further research is often required before the equipment is qualified for use.

To consider this fact, the producer needs to identify quality problems and potential failures early in the development process to be able to implement improvements in a cost-effective way. Among the reliability prediction methods, the proportional hazard model (e.g. Cox model [20]) is an important supplement to the traditional tools for reliability analysis, as it provides the opportunity for incorporating the effect of factors influencing reliability. However, the industry seems to lack a common approach to how field data can be utilized for reliability prediction.

Relevant research questions to address are therefore:

- What environmental factors influence the reliability of equipment?
- Which methods can be used to address the influencing factors for reliability prediction?
- How the level of data availability influence the reliability prediction?

1.2.6 Reliability improvement during the product life cycle

There is no magical trick that can be used to develop reliable products overnight nor is there a single technique that can optimize the reliability in a short period of time. The success lies in conscious, systematic efforts conducted all over the design and development process of the product.

The reliability improvement process will reveal deficiencies caused by the design, manufacturing process, and/or operation and correct/remove these deficiencies instead of during operation. It is also cost-beneficial over the product life-cycle, since it reduces maintenance and spares [98].

Reliability improvement process takes time and a commitment to change and continuous development seems to be required. It must be an inseparable part of the design and development process strategies. The implementation of a reliability improvement process should start by carefully including reliability into the subsea system requirements. It will influence the design process and the way reliability is managed during the design and manufacturing in the subsea industry. It will also influence the way systems are selected with increased emphasis on a supplier's reliability management capability [14].

Subsea producers and system integrators still seem to lack guidance on what reliability activities and how they have to consider within their current work processes, tools, and procedures.

A relevant research question to address is therefore:

- How can reliability improvement be continuously achieved through a product development model?

1.3 Objectives

The main objective of this PhD Project is:

> "to develop *systematic approaches* that contribute to the reliability qualification of new subsea equipment and to the following-up of reliability in the operational phase"

However, the main focus of the thesis is on the reliability qualification of new subsea equipment in order to assure that the equipment has an *acceptable maturity level*, while the following-up of reliability in the operational phase is treated more briefly.

Based on the main objective and the research challenges, the more specific objectives are:

1. Discuss and review the main approaches regarding technology readiness, verification and validation, and reliability prediction.
2. Propose a qualification framework considering the best features and reducing the challenges within the currently used qualification processes such as DNV guideline [23], technology readiness assessment (TRA) and so on.
3. Identify the key factors that influence the reliability of new subsea equipment in their application area, and determine how the effects of these factors can be included in the calculations.
4. Propose a practical approach for prediction of reliability of new subsea systems by using the available field data from similar, known systems from the topside environment.
5. Consider the non-constant characteristics of the failure rate of subsea systems and propose an updating framework for failure rate prediction for use during the operational phase.
6. Demonstrate how the effects of human and organizational factors on common cause failure factors, and indirectly on reliability measures can seriously lead to drift out of its required reliability value, and improve the awareness, understanding, and controlling of HOFs during the operational phase.

The aim in this thesis is contributing to the research challenges to fulfill the specific objectives and therefore the main objective.

1.4 Delimitations

The main focus of this PhD project is on new technologies developed by the oil and gas industry (subsea and offshore), and therefore more practical examples, terms, and concepts come from this industry sector.

An assumption that is considered in my research and also applies to the most of subsea systems in the oil and gas industry, is that the new subsea systems are developed from similar topside offshore systems, and “marinized” of topside technology.

The production constraints of the oil and gas equipment, makes it impossible to perform operational testing of a complete product prototype in a real environment. Therefore, simulations are used in order to test the virtual product. However, some operational testing may still be performed under similar operational conditions.

Reliability qualification of new technologies does not usually take the sensitivity of the environment in which the technology operates in it, into account. Thus, tasks such as measuring the effects of the technology on the environment, avoidance of creation of polluting substances, and reduction of the risk to the marine environment are not the purposes of reliability qualification and not within the scope of this thesis. However, reliability qualification indirectly considers environmental issues since its purpose is to assure that the technology does not fail and to have least consequences i.e. hydrocarbon leakage to the environment.

The effects of environmental factors such as pressure, temperature, and so on are necessary to be considered and analyzed on the reliability of technology. However tasks such as improving the layout or design of facilities to cope with these factors are not considered in this thesis.

Some conflicting requirements related to the environment, and design of equipment are also relevant to reliability, maintenance and intervention and should be addressed and resolved. It is important that the installed system is able to survive this period without failure.

1.5 Structure of the thesis

The thesis has two main parts; Part I Main report and Part II Articles. A list of abbreviations is provided at the end of the thesis.

Part I gives a brief introduction to the topics covered by the thesis, a presentation of research challenges, objectives, description of the research methods applied, the main results, and ideas for areas of further research. This part combines the main content of the publications found in Part II into a totality that serves to fulfill the objectives of the thesis. Additional details are found in the articles in Part II.

Part II includes the articles that have been submitted, published, or presented during the PhD project, in international journals, in conference proceedings, in conferences. This thesis includes the following publications:

- **Article 1:**
  Rahimi, M. and Rausand, M. (2013), Technology qualification integrated with product development, *Journal of Quality Engineering* (in review)

- **Article 2:**
  Rahimi, M. and Rausand, M. (2013), Prediction of failure rates for new subsea systems: A practical approach and an illustrative example, *Journal of Risk and Reliability*,
  (Available online:http://dx.doi.org/10.1177/1748006X13492954)
- **Article 3:**
  Rahimi, M. and Rausand, M. (2013), Monitoring human and organizational factors influencing common-cause failures of safety-instrumented system during the operational phase, *Reliability Engineering and System Safety*, (Available online:http://dx.doi.org/10.1016/j.ress.2013.03.004)
- **Article 4:**
  Rahimi, M. and Rausand, M. (2012), Failure rate prediction in various life cycle phases: A framework for updating. In *International Conference on Industrial Engineering and Engineering Management: Proceedings of the 2012 IEEE*, IEEE conference proceedings 2012, pp. 762-766.
- **Article 5:**
  Rahimi, M., Rausand, M. and Wu, S. (2011), Reliability prediction of offshore oil and gas equipment for use in an arctic environment. In *Proceedings of 2011 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering*, IEEE Press 2011, pp. 81-86.
- **Article 6:**
  Rahimi, M., Rausand, M. and Lundteigen, M.A. (2011), Management of factors that influence common cause failures of safety instrumented system in the operational phase. In *Advances in Safety, Reliability and Risk Management - proceedings of the European Safety and Reliability Conference*, ESREL 2011. CRC Press 2012, pp. 2036-2044.
- **Article 7:**
  Rahimi, M. and Rausand, M. (2013), Continuous reliability improvement of subsea equipment, In *Proceedings of* 26th *International Congress of Condition Monitoring and Diagnostic Engineering Management*, KP-Media Oy 2013, pp. 426-433.
- **Article 8:**
  Rahimi, M. and Rausand, M. (2013), Qualification of new technology: Approaches, challenges, and improvements, In *Proceedings of* 26th *International Congress of Condition Monitoring and Diagnostic Engineering Management*, KP-Media Oy 2013, pp. 381-388.

2

Research design

This chapter considers the aspects of the research design process that were applied during this research project, including the research method, and the selected research approach.

2.1 Research approach

Different types of research approaches can be found in the literature [106, 65, 47]. However according to OECD [65] we may distinguish between three types of research approach based on the intended use:

a) *Basic research* is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view.
b) *Applied research* is original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific practical aim or objective.
c) *Oriented basic research* is research carried out with the expectation of producing a wide range of knowledge. This form the background to the solution of recognized or expected, current or future problems or possibilities.

While the main purpose of basic and oriented basic research is to acquire new knowledge, the main purpose of applied research is to solve a particular problem.

The research performed in this PhD project can be classified as oriented basic research, since its focus is mainly on the development of new frameworks and methods for fulfilling the current needs, and forming the basis for further research and aiming to meet the needs of the future.

Many of the scientific studies in the field of reliability and safety engineering are related to the development of models, methods, and frameworks for reliability and safety analysis. As this research focuses on oil and gas industry, it aims to develop new frameworks and methods meant for practical applications in this industry. The new models, frameworks, and methods have been developed based on the existing literature within qualification and reliability assessment.

In this context, verification and evaluation can be problematic because performing experiments or empirical verification like classic natural science is not often possible. From a classical point of view, the usefulness of models should be empirically verified, for example, by experiments or by collecting field data. Empirical verification may be impossible in the reliability and safety engineering field, where we deal with analyzing and modeling of unexpected events such as failures, accidents and catastrophes. These events occur infrequently. In addition, the analyzed objects especially in subsea industry are often one-of-a kind or customized and have expensive constructions with a long lifetime. It is very costly and time-consuming to carry out experiments and collect data to confirm the models and modeling results. Thus, the evaluation and verification of the scientific work and the models must be done by approaches other than empirical or experimental methods.

Launching the Model Evaluation Group in 1992 [71] was an attempt to overcome this problem. The group suggested a model evaluation process, consisting of the following three main elements: scientific assessment, verification, and validation. The scientific assessment should include a comprehensive description of the model, an evaluation of the scientific content, limits of applicability, advantages and limitations of the model. Verification was defined as "the process showing that a model has a sound scientific basis, that any assumptions are reasonable, that equations are being solved correctly, and more generally, that the model presented to the user actually does what the document claims" and validation as "the process of assessing a model so that its accuracy and usefulness can be determined". The latter often involves comparison with other models [67].

In regards to taking decisions about the quality of one's research, great care must be given to issues surrounding the validity of the approach taken. The veracity and accuracy of any conclusions will at best be questionable, at worst be indefensible. In other words, a good piece of research meets accepted standards of validity in a range of dimensions. Croom [21] distinguishes six types of validity; (1) internal validity, (2) external validity, (3) construct validity, (4) descriptive validity, (5) interpretive validity, (6) theoretical validity. These types of validity are intended mainly for quantitative type of research, but some general principles can be applied here as well.

This PhD project contributes to the scientific evaluation of the presented work by a detailed description of the model, an assessment of the content, and a description of the limitations and benefits of the model. According to the above mentioned definition, one aspect of validation is to compare with other models. If there are similar models for the same application, a comparison of the results provides proof that the model has a sound scientific basis, the assumptions are reasonable and the equations are solved correctly.

In this PhD project, the development of frameworks and methods is based on reasoning. Such reasoning can be interpreted as the process where formal logic arguments, existing methods, and knowledge are used as building blocks to derive new relationships or insight. Here, the validity of the method is confirmed by assessing the validity of the underlying building blocks. If some of the initial assumptions are incorrect or the formal logic used to support the new method is wrong or incorrectly used, it can be concluded that the method is not valid at all or only valid within a more narrow application area than originally planned. It is also possible to perform case studies where the method can be tested for a specific application. In this case, the results may be validated qualitatively or by expert judgments, or preferably, compare the results with outcomes from other recognized and comparable methods [52].

In this PhD project, I have customized the assumptions used in method development. By peer review, the arguments, and assumptions have been verified. Furthermore, when was possible, I give an example to illustrate how the method can be applied. However, additional case studies should be performed to obtain more insight on how the results may be applied on subsea systems. The formal validation has been performed by reviewers. I have been able to get feedbacks to my ideas and results from other researchers, via e-mails, meetings and at conferences.

Finally, the research resulting to this PhD thesis is not performed in a vacuum, but in cooperation with other researchers and people from the industry. The research quality improves from the interaction between researchers, and between researchers and the industry. New ideas form the basis for new knowledge, and may often occur unexpectedly when a problem or a system is viewed from different angles and perspectives. The fruitful discussions with my main supervisor, who has challenged me on the quality of reasoning and the application of theory along with participating in several related activities, made me able to raise my understanding of reliability and qualification related guidelines and identify new research areas.

2.2 Research design and research method

There is no best research method which is absolutely preferred in every context. High quality research requires a documented and logical design of the research project. A research project is a sequence of activities or work packages that build into each other. It starts with the definition of research basis and research questions and ends up with the research results. Fig. 2.1 illustrates my research design which I have used for completing my PhD research and also related articles. My research process has four main stages (derived from [2]): (1) research plan, (2) literature review, (3) model development, and (4) research results.

1. *Research plan*:

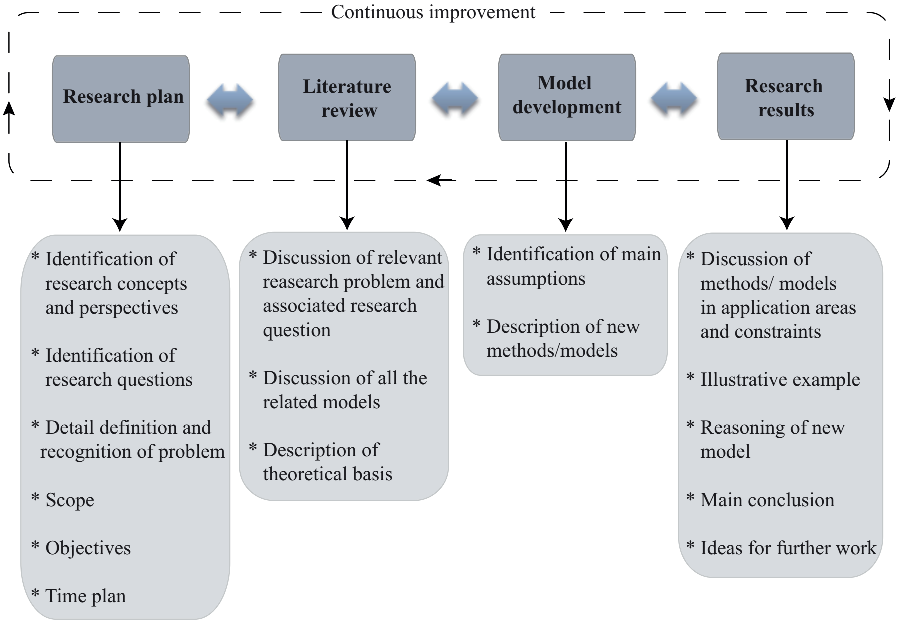

Fig. 2.1. Research design

A research plan development starts early in the PhD research process, in order to define research challenges and to provide a format for further investigation. The research plan describes the principles of research, stating its importance and how it will be conducted.

The research plan should be written to address the following questions [2]:

- What is intended to be done?
- Why is the work important?
- What has already been done?
- How should the work be done?

A typical research plan includes (derived from [2]):

A. Specific aims: The specific aims are statements of the objectives and milestones of a research project. The purpose of this part is to clearly and concisely describe what the proposed research is intended to accomplish.

B. Background: The background section states the research problem including the proposed rationale, current state of knowledge and potential contributions and significance of the research to the field.

C. Research design and methods: The research design and methods are describing how the research will be carried out. This section is critical in order to demonstrate that the study design is developed under a clear, organized and thoughtful scheme.

The PhD research plan resulted in an initial state of the art description, formulation of research questions, and a research execution plan. The research questions have selected from identified or already stated research gaps and partly based on subjects where I would like to increase my skills and knowledge.

2. *Literature review*:
   The initial research activity has briefly reviewed the literature and developed research questions. The literature review spanned the body of journals, abstracts, relevant book sections, published reports and recommended practices by industry, and within the scope of reliability qualification, subsea systems, and other relevant subjects. It is necessary that existing sources of evidence, especially systematic reviews, are considered carefully prior to undertaking research [21].
   Review of literature, ongoing research and development (R&D) reports, and industry practices are carried out in order to obtain enough knowledge about the state of the art both in the scientific and the practical point of view.
   In regards to qualification program, academic studies are scant, and the development of the existing approaches has mainly been done by industry organizations and companies. The results of which have primarily been published as technical reports and industrial guidelines, and they mainly formed the basis for this subject (See articles [77, 78]).
   The general basis for this PhD project and the topics it addresses have been established through literature surveys. These surveys provide a starting point for the research and support all the further activities. In addition, the professional experience from my main supervisor has contributed valuable input in the identification and solution of problems.

3. *Model development*:
   Developing models are a good way to start distilling all the information we have gathered so far. A model can be described as an analyst's attempt to represent a system and only is a simplification of the reality it is designed to represent[1, 69]. The model is therefore strongly dependent on the properties of the system and the analyst's competence. The analyst has to struggle with the trade off between the need to simplify and accuracy. Creating model has iterative process until an appropriate model has been developed.
   The level of detail or suitability of a model is restricted by the time, approximation formulas and software solutions availability. Different models may be used to analyze a system and none of these models is clearly more correct than the others [97].
   Choice of model forces the analyst into a system structure that more or less is in accordance with the real life system. Due to the limitations in including the natural variability in the real life system, a model will at its best only be an approximation [58]. Model uncertainty will therefore, up to a certain

degree, always exist. Standards, guidelines and internal company policies may often require or recommend specific types of models.
By discussing all the models and methods related to this subject and to achieve the objectives of research, a new framework would be developed under specific assumptions, aiming to overcome the shortages and challenges have found in the earlier steps.

4. *Research results*:
   Research results should include the application area of the developed models, methods, or frameworks, discussion about constraints, and also suggestions for new perspectives and ideas for future works.
   Usually the case study or illustrative example will be used for systematic description of the situations regarding how and why events occur and also for demonstration of framework/model usability. The information acquisition is based on open data. But in the context of developing a new subsea system, the industry is highly confidential and therefore presenting any real case is not possible. In addition, subsea systems are complex, and it is difficult to cover all of their components or failure modes and so on in the case study and into the calculations/models.
   The research results are presented to the academia and the industry through publication in international journals and proceedings of the conferences with referees and double blind peer review process. In addition, the reasoning of the models has been confirmed by sharing research ideas and results at international conferences. The purpose of the communication of the research results is both for spreading the results, and for getting comments and feedbacks from others who have the same field interest.
   These principles have contributed to the evaluation and quality assurance of the research results, since the input from the "outside world" has influenced the research work and thus influenced the results presented in this thesis.
   On all the topics that are covered in my articles and their related areas, I have held lectures. Holding lectures lead me to improve my understanding of fundamental issues and methods within reliability assessment. Furthermore, the presented material is subject to a quality check by the participants.

5. *Continuous improvement*:
   The development of this thesis has been an iterative process as new results, ideas and insights have been obtained from the research articles and other related activities, like participation in conferences and seminars.

A research project should provide answers to the initially stated questions, provide new methods, highlight their application areas, and suggest new perspectives and ideas for further work.

The PhD main report (thesis) describes the research basis, research questions, and research approach, and outlines the main results from the research articles. The research articles have been developed following the same research design.

3

Main results

This chapter gives a summary of the main results from the research articles. More specific information about the results are presented in the research articles in part II of the thesis.

Six research challenges were stated in Section 1.2. The purpose of this chapter is to evaluate to what extent these challenges have been considered. The relationships between the articles and the research challenges are summarized in Table 3.1.

Table 3.1. Research challenges and related contributing articles

No.	Research challenges	Article ref.
1	TQP for new subsea systems	1, 8
2	Reliability prediction of a new subsea system	2
3	HOFs influencing CCFs in operational phase	3, 6
4	Non-constant failure rate of mechanical products	4
5	Reliability prediction in a new environment (Arctic)	5
6	Reliability improvement during the product life cycle	7

3.1 Contributions to research challenge 1

The first challenge concerns the strengths and weaknesses of currently used TQPs and addresses the need for producers and system integrators to perform a more practical TQP for new product. The research questions associated with the challenge are discussed in Section 1.2.1 and articles 1 [77] and 8 [78] took them into account.

As mentioned in chapter 2, there are not many academic studies related to TQP approaches. Therefore, technical reports and industrial guidelines published by industrial organizations and companies have been used and they mainly formed the basis of the research in this area.

A thorough literature survey on commonly used TQP approaches has been conducted. The initial focus was on the two mostly used approaches, i.e. the DNV and the TRL approaches. Ambiguities and challenges related to these approaches which were encountered by several companies, were highlighted. Several companies have tried to integrate the two TQP approaches to overcome the challenges, but they are still facing problem. Several suggestions for improving the performance of the merged TQP are proposed. By implementation of suggested principles, some of the identified challenges can be eliminated and the stakeholders will be more confident about the TQP results.

To perform a more systematic evaluation of the TQPs, six main questions (that can also be seen as criteria) are introduced to determine the main characteristics of an efficient TQP. The questions are based on the following issues:

1. Integration of TQP and the product development process
2. Clear definition of TQP approach, steps, and tasks to be performed in each step
3. Criteria definition for each step
4. Uncertainty quantification of the new product
5. Unified language between producers, suppliers, and end-users.
6. Feedback generation and improvement

These six questions have been developed based on a careful literature study and a scrutiny of the existing TQPs. The TQP approaches have been evaluated based on these questions. A brief description of considered TQPs were stated in Section 1.1.4. Answers to each question have been obtained based on a careful scrutiny of approaches. The answers give a clear overview of the strengths and weaknesses of each approach.

From the obtained answers, it can be concluded that none of the existing TQPs fulfill all the six defined criteria and some of them have significant potentials for improvement. A new TQP approach is therefore proposed, aiming to overcome the weaknesses of the existing approaches.

Identifying potential problems and failures at an early stage of the product development process is important for the producers, due to the high cost of making modifications later in the development process. Several authors [3, 8, 13, 26, 33, 54] and guidelines [7, 89] argue that the qualification process must be addressed prior to and in parallel with the product development process. Most producers have developed their own product development model comprising a number of consecutive phases, where the required development tasks and analyses are listed for each phase. The models are generally rather similar, but the number of phases may vary with the complexity of the product. The proposed approach is based on the product development model suggested by Murthy et al. [57].

The new TQP approach consists of six steps as; Concept qualification, System qualification, Design qualification, Component qualification, Product qualification, Production qualification.

A thorough list of methods and tools for qualification of the product has provided in the different development phases. Several qualification tasks are performed in each phase of the model, and before proceeding to the next phase, the output needs to be evaluated to assure that the desired outcome is obtained. If problems are identified, the next phase should not be initiated until the required corrective actions have been taken.

The key features of the proposed approach, related to the six questions, are as follows:

a) The proposed approach is closely linked to the product development process. The steps are aligned with the product development model proposed by Murthy et al. [57], but can easily be adapted to any step-based product development process. The tasks in product development and the tasks for qualification have reciprocating characteristics. The inputs to the proposed approach usually are the results of tasks in the new product development process and the results of the qualification tasks in each step may give feedback to them. This makes the qualification process sufficiently interlinked to the product development process.
b) In order to avoid ambiguities, each step of the new TQP approach is explained and the tasks required in each step are identified and described. The relevant methods and tools for the various tasks are listed and references to recommended literature given.
c) The objective of each step has been clarified and can be attained with a proper implementation of the defined tasks of each step. A set of criteria can be defined, in order to decide whether or not the objectives have been met.
d) The proposed approach can be seen as a unified language between producers, suppliers, and end-users regarding the qualification status of the new product. When the product is complex, this feature of the TQP approach becomes crucial.
e) The proposed approach along with the product development process tries to get feedback from the implementation of tasks in each step and to improve the revealed weaknesses as early as possible in the product life cycle.
f) Finally, the new TQP approach will, through analysis and testing, produce quantitative results related to the uncertainty of the new product; results that can be useful for all stakeholders to the product.

It is not possible to formally verify a TQP program. Its value can only be evaluated based on long-term use where the cost-efficiency of the program is compared with the actual reliability of the products in operation.

3.2 Contributions to research challenge 2

The second challenge addresses the need for a reliability prediction method for new subsea systems which no data is available for them. Currently, no practical method is available that can be used to extrapolate the available reliability data from similar and known systems and come up with a failure rate prediction for new systems operating in a different environment.

The research questions associated with the challenge are discussed in Section 1.2.2 and article 2 [76] took them into account.

Within the related literature survey, the commonly used models and methods for reliability prediction that have been proposed in the literature, have been considered and discussed. The considered approaches are such as;MIL-HDBK-217F [56], proportional hazard models [48], the approach by Brissaud et al. [17] and the BORA project [11]. However, none of them can be used directly for the failure rate prediction of a new subsea system.

Using PH-model requires extensive data for determining covariate values and related parameters. The approach by Brissaud et al. [17] has difficulties to find the influencing functions for the indicators of each influencing factor. The BORA project [11] mainly focuses on human and organizational factors that influence the risk of hydrocarbon releases. To use the available field data from topside systems, this approach needs some extension in different levels, such as scoring and failure analysis. However, the general principles of these approaches have been used for development of a new failure rate prediction method, aiming to overcome some of the shortcomings of the existing approaches.

An approach for predicting the failure rate of new subsea systems has therefore been suggested. The new approach is based on a detailed comparison with a similar topside system, for which reliability data is available. The failure rate is intended to be used in the design phase of the new system as a basis for design and allocation decisions. The failure rate will, in addition, be an important input parameter to the TQP of the new system.

The new approach has eight distinct steps. Each step is described in detail and emphasis has been put on making each step transparent and verifiable, such that it should be easy for the operator/client to check the relevance and realism of each step - an important feature of any qualification program.

The new and the known systems are compared with respect to structural, operational and environmental conditions, and failure modes and failure causes (incl. failure mechanisms) that may contribute to each failure mode; and similarities and differences are recorded. The new and the known system may not have exactly the same failure modes, and differences must be listed and described. A set of RIFs that are relevant for the new subsea system will be selected based on the physical insight combined with expert judgment. The effects of each RIF on the subsea system are then compared with the effects of the same RIF on the topside system and then scored according to the suggested tables. The failure rates for the failure modes of the subsea system are determined by adjusting the corresponding failure rates for the topside system based on the influences of the RIFs.

The approach is illustrated by an example of a subsea pump. The reliability data used in the illustrative example is from the OREDA [68] handbook. Development of new technology for the subsea industry is highly confidential and we were therefore not able to present any real case. The information about the "new" system has therefore to be based on open sources. In addition, subsea systems are complex, and the number of failure modes, failure causes, and RIFs can be so high that we are not able to cover all of them. The purpose of providing an example is to illustrate the approach, not to present a complete and realistic case study, therefore it does not come to a final result which expresses the realistic reliability.

The suggested approach is stepwise and can be easily used and applied. However it is subject on several assumptions and limitations, which are described in [75] in more detail. The approach is a proposal and has not been formally verified. A possible way of verifying the approach would be to use the approach to estimate the failure rate of a subsea system, from which we have an adequate experience basis. This is, however, not a straight forward task, since the judgments of the experts will likely be biased because of the knowledge that have about the subsea system. The suggested approach has been tailor-made for new subsea systems, since this currently is a very relevant challenge for the oil and gas industry. The approach can, however, easily be adapted to estimating the failure rate of other types of new systems.

3.3 Contributions to research challenge 3

The third challenge addresses HOFs influencing CCFs and how they may be catered in the operational phase. The research questions associated with the challenge are discussed in Section 1.2.3 and articles 3 [75] and 6 [79] took them into account.

During the design phase, the manufacturer has to predict the reliability of the SIS and check that the predicted reliability complies with the specified SIL requirements. This prediction is based on a set of assumptions about the operational, maintenance, and environmental conditions that the SIS will experience when it is put into operation. These conditions may not be fully known and the prediction is based on a certain set of conditions, historical data, etc.

In the operational phase, the parameters that were predicted in the design phase can be updated by using data from the actual operating performance of the SIS. In this phase, the SIS hardware architecture and the components will usually remain unchanged unless there is a call for modification. The main changes in the likelihood of CCFs are therefore the result of factors related to HOFs and a changing operational environment. The actual beta-factor in the operational phase may differ from the predicted one and with proper management the beta-factor can be kept below an acceptable upper limit throughout the operational phase.

How HOFs can affect the CCF of SIS during the operational phase has been considered and how those factors can be incorporated into the beta-factor models has been discussed. Awareness of such factors is necessary since their effects during the execution of functional tests and inspections could increase the possibility of doing some prevention actions. In addition awareness and knowledge about these aspects will be beneficial in order to manage the human and organizational factors such that the likelihood of CCFs is reduced.

A literature review on the recently published checklists [36, 43, 46, 15] for the estimation of beta factor showed that their focus is more on technical issues, rather than human related issues. For example, among the 37 questions provided in IEC 61508 [43] for determining β_P only about 20% are related to HOFs, which is very low and not in line with the lessons learnt from the ICDE project. In this regards, a set of suggested questions has been provided in four main categories; dependency and similarity, omission and wrong action, accessibility, and training. It can help the existing methods of beta estimation for SIS such as IEC 61508 approach, for more accurate determination of β factor.

Furthermore, a framework to manage the factors influencing beta-factor of SISs in the operational phase has been proposed to help the SIS users in maintaining the required SIS reliability. The basis for the proposed framework is the simple beta-factor model, and the beta-factor is assumed to be determined based on answers to the questions in IEC 61508, possibly with some additional questions.

The proposed method is based on observed values of indicators that provide information about the changing status of HOFs and at planned times. We continue to monitor and check deviation from the previous measurement and check for trends. It is suggested that the deviations be categorized by expert judgment into three categories: large, medium, and small deviation. These categories are depending on the SIL requirements. The approach is in line with an approach suggested by Øien [66] for follow-up of organizational factor that influence risk on offshore oil and gas installations.

Still, I think the contribution needs further development. The questions and how they can be quantified should be discussed with the industry and in particular with end users. The discussions may lead to new questions, and perhaps modification of the existing ones.

The new framework is not theoretically complicated, but includes small modification to existing practices that may increase the awareness, competence, and treatment of CCFs. By implementing this framework, we are able to follow up the assumptions that were taken during the SIS design phase and to avoid that the attention to CCFs ends when the SIS design has been completed.

Regarding the adoption of the framework in the industry. It seems to me that implementation and follow up of new initiatives may be difficult due to limited resources.

3.4 Contributions to research challenge 4

The fourth challenge concerns the need for clarification of the non constant failure rate of mechanical products like subsea systems during the operational phase, and the need for an updating framework. The research questions associated with the challenge are discussed in Section 1.2.4 and article 4 [73] took them into account.

The literature related to the characteristics of the failure rate of mechanical products has been reviewed and the main failure rate prediction methods have been presented. Further the need for failure rate prediction in the various phases of a product's life cycle has been discussed.

For planning of preventive maintenance and for maintenance optimization, during the operational phase, the predicted failure rate may not be sufficient. However, obtaining the actual failure rate at time *t* seems rather difficult.

A framework for updating the failure rate prediction to obtain a more realistic prediction has proposed. As a prerequisite to the proposed framework, a predicted constant failure rate from the design phase is required. This can be obtained based on the available methods in the literature or the proposed method which contributed to research challenge 2 (also mentioned in Section 1.1.5).

Updating the failure rate will be performed at specified times (milestones). Milestones can be set based on required input to decisions related to required reporting, changes in maintenance plans, and so on. Significant failures or accidents may also trigger an updating of the failure rate. In the operational phase, milestones can be the inspection times, or they can be decided based on the updated failure rate. This evaluation can be done based on a simplified approach as described by [34] or a procedure based on experience data [104].

In each phase, the relevant RIFs from the previous period have to be updated and, if necessary, supplemented. When a milestone has reached, we can update the status of a set of reliability influencing factors (RIFs). The failure rate updating is based on the data acquired during the period since the previous updating and changes of the status of RIFs. We check whether the acquired data are sufficient to predict or update a non-constant failure rate (e.g., Weibull distribution's parameters), or we have to suffice with a constant failure rate. The effects of changes of RIFs' status will be considered and the previous predicted failure rate will be adjusted.

The approach is mainly for use in the operation and maintenance phase, but its generic steps can also be used in other life cycle phases.

The proposed methodology has not yet been evaluated. The main focus of this paper is on mechanical products which can be useful for different industry sectors, such as oil and gas, military, and so on.

3.5 Contributions to research challenge 5

The fifth challenge concerns how to take the new environmental factors into the consideration for reliability prediction. The research questions associated with the challenge are discussed in Section 1.2.5 and article 5 [80] took them into account.

The new operating environment is the region which has arctic conditions. The Arctic region can be defined as the area where the July isotherm is below 10 °C. The infrastructure from oil and gas industry in these areas is limited with low population density. The four categories of the arctic environment challenges have been discussed as: (1) The harshness of the arctic climate, (2) The impact of ice, (3) The sensitivity of the environment, and (4) The remoteness of the location.

Most of the failure rate prediction methods for products (especially electronics) are based on the *parts count* technique (prediction at reference condition) and the *part stress* technique (prediction at operating condition) presented in MIL-HDBK-217F [56].

The main limitation of these methods is that the predictions are limited to temperatures higher than 0 °C, and therefore not directly applicable to the arctic environment. Therefore, other methods that consider the effects of factors influencing the equipment reliability, referred as *reliability-influencing factors* (RIFs) have to be used.

The characteristics and important arctic conditions that influence the reliability of topside offshore oil and gas equipment has outlined. The scope of work was delimited to the physical performance of equipment. Therefore, influences of the environmental factors on the physical performance of the equipment has only considered.

A framework for reliability prediction of equipment operating in an arctic environment is proposed based on the Cox model. It has been discussed how the Cox model can be used for reliability prediction of equipment based on levels of data availability. The development of the framework has been based on theoretical studies and experience from OREDA and the BORA project. To use failure data from non-arctic environments, it is necessary to carefully compare the equipment with the equipment used in another environment. The results of the comparison are classified in three levels: experience from *identical*, *similar*, or *different equipment*. Determination of the covariates and parameters is therefore different in each level. In case where no data is available, several approaches have suggested for estimation of the effects of the RIFs.

The proposed methodology has not yet been evaluated. A limitation to this approach is that human performance has not been considered, even though the Arctic's environmental factors have great influence on human performance and therefore on the reliability of the equipment.

The focus was on offshore oil and gas facilities operated in an arctic environment, but the approach should be applicable also in similar cases in other industry sectors.

3.6 Contributions to research challenge 6

The sixth challenge concerns how reliability improvement can be considered continuously during the product life cycle. The research question associated with the challenge is discussed in Section 1.2.6 and article 7 [74] took it into account.

A framework that integrates the reliability improvement into the product development process proposed by Murthy et al. [57] has been proposed. The framework provides the required reliability related tasks in each phase of the product development process. This will also give insights into some of the tools and techniques that are necessary in achieving the right strategy for highly reliable products such as subsea equipment. All the tools and techniques that are related to the provided tasks in each phase are not explained. However, the relevant tools are listed and references to recommended literature given.

By lessons learned from reliability activities in various phases of a product's life-cycle, the understanding of failures will increase, and therefore the product's reliability can continuously improve.

The improvement of equipment reliability should not finish when the equipment starts operating. The reliability improvement can still continue during the operational and maintenance phases. It requires thorough studies and development of suitable strategies that can be considered as further research areas. Some of the candidates are; maintenance strategy, asset care and failures analysis plans, reliability based spares strategy.

4

Conclusions and further work

This chapter describes the main contributions of the PhD thesis in order to close the research project. Thereafter, several topics for further research are suggested.

4.1 Main conclusions

The main contributions of this thesis with regards to each research challenge are:

a) **Contributions to research challenge 1**
The first challenge is related to practical TQPs for new subsea systems and has been discussed in section 1.2.1 in more detail. The main contribution with regards to this research challenge are:
   - Review of currently used TQP approaches.
   - Identification of challenges regarding the two mostly used TQPs, i.e., DNV guideline and the approach based on TRA.
   - Suggestion of improvements for companies that trying to use an integrated approach of the two mostly used TQPs.
   - Identification of six main criteria for evaluation of TQPs.
   - Evaluation of eight commonly used TQPs based on the identified criteria.
   - Development of a technology qualification framework which is integrated into the product development process and considers identified challenges.
   - Suggestion of the relevant methods and tools for the various tasks of the framework and given references to the recommended literature.

   The more detailed contributions have been discussed in section 3.1.

b) **Contributions to research challenge 2**
The second challenge is related to the reliability prediction of a new subsea system and has been discussed in section 1.2.2 in more detail. The main contributions in terms of this research challenge are:

- Review of currently used reliability prediction methods.
- Development of a practical approach for reliability prediction of new subsea systems based on comparison with similar known topside system. The proposed method can be used for extrapolating the available reliability data from similar and known systems and come up with a failure rate prediction for new systems operating in a different environment.
- Demonstration of how the proposed approach can be performed by giving an illustrative example of subsea pump.

The more detailed contributions have been discussed in section 3.2.

c) Contributions to research challenge 3

The third challenge is related to the HOFs influencing CCFs during the operational phase and has been discussed in section 1.2.3 in more detail. The main contributions in terms of this research challenge are:

- Identification of factors influencing CCFs during the operational phase.
- Identification of main HOFs that contribute to CCFs of SISs.
- Discussion on how insights from HOFs can be used to provide a more realistic estimate of the beta-factor in the operational phase of a SIS.
- Suggestion of several questions and aspects that can be added to the IEC 61508 approach for determining β .
- An approach for monitoring and controlling HOFs influencing CCFs in the operational phase. It is based on monitoring the identified human and organizational indicators and check for trends or deviation from their previous measures.

The more detailed contributions have been discussed in section 3.3.

d) Contributions to research challenge 4

The fourth challenge is related to the non-constant characteristics of mechanical products' failure rates in operational phase and has been discussed in section 1.2.4 in more detail. The main contributions with regard to this research challenge are:

- Clarification of the need for failure rate prediction in the various phases of the product life cycle.
- Clarification of non-constant characteristics of failure rate of subsea systems.
- Review of mainly used failure rate prediction methods.
- Suggestion of a failure rate updating framework during various product's life cycle based on the data we can acquire and the changes in the status of reliability influencing factors (RIFs) at specified times named as milestones.

The more detailed contributions have been discussed in section 3.4.

e) Contributions to research challenge 5

The fifth challenge is related to the reliability prediction of equipment in a new environment (Arctic) and has been discussed in section 1.2.5 in more detail. The main contributions with regard to this research challenge are:

- Outlining the important arctic conditions that influence the reliability of topside offshore oil and gas equipment.
- Suggestion of a procedure for reliability prediction based on Cox model and levels of data availability.

The more detailed contributions have been discussed in section 3.5.

f) Contributions to research challenge 6

The sixth challenge is related to the reliability improvement of subsea systems during their life cycle phases and has been discussed in section 1.2.6 in more detail. The main contribution in terms of this research challenge are:

- Outlining a reliability improvement process for subsea equipment that can be integrated with the product development process of Murthy et al. [57]. The framework will help the subsea equipment producers to focus on reliability needs, forecast and allocate resources, set direction for reliability activities, and consistently deliver improved reliability performance throughout the product development process.

The more detailed contributions have been discussed in section 3.6.

The results of this thesis may practically be used by producers, suppliers, end users, decision-makers and (other types of) organizations within the field of subsea equipment and oil and gas industry. The generic principles from the proposed frameworks, or methods with minor modifications can also be applied for other new equipments in other industry sector where high reliability is a requirement, such as military, aviation, and so on.

Another target group for this thesis are researchers with interest in the same research field to develop new rules and regulations, enforce implementation of more efficient solutions, and implement regular evaluations.

This thesis combines the existing theory and methods in a new way and proposes new solutions. The work is based on established standards for scientific work and research in the disciplines of reliability engineering. Furthermore, the results are useful in solving the concerned problems. Thus, it can be stated that the thesis' main objective: "to develop *systematic approaches* that contribute to the reliability qualification of new subsea equipment and to the following-up of reliability in the operational phase" is fulfilled within contribution to the defined research challenges.

The frameworks and methods that are proposed in this thesis nevertheless need practical examples of their implementations. Further work should concentrate on specific decision situations and evaluate the results from use of the systematic approach suggested in this thesis.

4.2 Further work

In this section, some overall recommendations for further research are given. More specific suggestions for further research are indicated in each of the articles. The areas for further research regarding this PhD project and proposed frameworks and method can be classified into three categories:

a) Development and improvement
b) Practical implementation
c) Uncertainty analysis

Development and improvement of proposed frameworks and methods for qualification and reliability assessments are required to account new technologies and new ways of operating facilities. Methods which consider certain phases of product life cycle, can be extended for other phases of product life cycle.

In regards to the proposed TQP some starting points for extension and improvement are:

- A detailed qualification of manufacturing processes, systems, and environment is required to be linked into the proposed qualification process. A promising activity has here been initiated by the Stevens Institute of Technology Sauser et al. [87] (See also DoD [25]).
- The producer's business processes indirectly affect the quality of the product and a maturity assessment of these processes should therefore be interfaced with the proposed TQP.
- Consideration of time and costs as limitation in the proposed qualification process. However, with rapid analysis and testing capabilities, the qualification process will be significantly reduced. Optimization of the TQP with time and cost constraints should be pursued.

In regards to the proposed reliability prediction method, some topics for improvement are:

- The combination of information of subsystems and maintainable items from different topside systems instead of using the information of a single and generic topside system.
- Incorporation of experiences and data from the items that previously have been used in other subsea systems into the proposed reliability prediction calculation for a new subsea system.
- Development of strategies/ policies for determining the values of parameters or for making decision about the effects of different factors, which in the proposed method this mainly relies on the expert judgments.
- Human and organizational factors are not included within the factors influencing reliability of subsea equipment, since the focus was only on technical factors. Further research is needed in order to consider them into the calculation and find out their effects on the total reliability.

- For new subsea system, which field data is rather rare, the role of expert judgments has increased in providing information into the reliability assessment and safety related decision making. The use and elicitation of expert judgment are also required in the quality assurance of the assessment or the decision. Therefore, improvements or new developments of methods supporting the use of or aggregating the expert judgments in specific decision contexts seem necessary.

Recommendation for further development and improvement regarding HOFs influencing CCFs in operational phase can be:

- Development of a formula for calculating the actual beta-factor during the operational phase. This has to be obtained based on the amount of changes in the states of HOFs and their effects on the beta-factor. It may be necessary to check the relevancy of the answers to the IEC 61508 questions used for estimation of the beta-factor and actual SIS operational conditions.
- How the suggested question related to HOFs can be quantified and be included in the IEC 61508 checklist for β determination requires further study and research. It is better to be done in collaboration with the relevant regulatory organization.

Implementation of new frameworks and method from this PhD project into existing industry practices is another area of further research. This has to be done in collaboration with the industry, since as mentioned earlier, the available information and open data for detail implementation of the method is not sufficient. The implementation should not be necessarily on a large subsea system. There are new subsystems that need to be qualified, and their reliability need to be predicted which the proposed framework and method can be used.

In regards to the proposed frameworks for updating the failure rate in the operational phase and monitoring HOFs related CCFs in operational phase, implementation is difficult. Since they are involved in the operation and maintenance phase, and the operational phase of subsea systems is long, therefore the implementation takes a long time.

Another area of further research is related to the handling of uncertainty. Uncertainty analysis [10, 64, 82] is desired especially for the proposed reliability prediction method. This should include parametric, model construction and calculation approaches. Sensitivity analyses should be used more frequently in reliability predictions, in order to increase the robustness of the calculated results. An area of further research may therefore be to find practical ways to implement such sensitivity analyses.

A good starting point for developing an overall approach to uncertainty and sensitivity analysis can be the guidelines developed by ISA on safety integrity calculation methods [44] that discuss parametric uncertainty and sensitivity analysis.

5

Acronyms

API	American Petroleum Institute
AVT	Applied Vehicle Technology
BORA	Barrier and operational risk analysis
CCF	Common cause failure
COT	Commercial off-the-shelf technology
DNV	Det norske veritas
DoD	Department of Defense
EC	European Commission
E/E/PE	Electrical, electronic, programmable electronic
E/E/PES	Electrical, electronic, programmable electronic system
EN	European Norm
EUC	Equipment under control
FMEA	Failure modes and effects analysis
FMECA	Failure modes, effects, and criticality analysis
FSA	Functional safety assessment
FTA	Fault tree analysis
HAZOP	Hazard and operability study
HIPPS	High integrity pressure protection system
HOF	Human and organizational factor
HPP	Homogeneous Poisson process
HSE	Health and Safety Executive
ICDE	International Common Cause Data Exchange
IEC	International Electrotechnical Committee
IEEE	Institute of Electrical and Electronic Engineers
ISA	Instrumentation, Systems, and Automation Society
ISO	International Organization for Standardization
MIL-HDBK	Military handbook
MTTF	Mean time to failure
MTTR	Mean time to repair

NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NEA	Nuclear Energy Agency
NORSOK	Norsk sokkels konkurranseposisjon (Eng: Competitive position for the Norwegian continental shelf)
NSWC	Naval Surface Warfare Center
NTNU	Norwegian University of Science and Technology
NUREG	US Nuclear Regulatory Commission
OLF	Oljeindustriens landsforening (Eng: The Norwegian Oil Industry Association)
OREDA	Offshore Reliability Data
PFD	Probability of failure on demand
PFH	Probability of a dangerous failure per hour
PH	Proportional hazards
PhD	Doctor of Philosophy
PSA	Petroleum Safety Authority (Norway)
RAMS	Reliability, availability, maintainability, and safety
RBD	Reliability block diagram
RIF	Reliability influencing factor
ROCOF	Rate of occurrence of failures
RP	Recommended practice
R&D	Research and development
SEMATECH	Semiconductor manufacturing technology
SFF	Safe failure fraction
SIF	Safety instrumented function
SIL	Safety integrity level
SINTEF	Foundation of Science and Technology at the Norwegian Institute of Technology
SIS	Safety instrumented system
SPC	Subsea Processing Community
SRL	System Readiness Level
TPM	Technical performance measurement
TQP	Technical qualification program
TRA	Technology readiness assessment
TRL	Technology Readiness Level

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Part II

Articles

Article 1

Technology qualification integrated with product development
Journal of Quality Engineering (in review)

Technology qualification integrated with product development

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Structured abstract

Purpose- For high-reliability applications, it is necessary to assure that new products, and known products based on new technology, have the required quality and reliability before they are put into operation. To provide such assurance, some industries have implemented a technology qualification program (TQP) to reduce the uncertainty during the design and development of new products.

Several TQP approaches have been proposed, but no approach has yet been generally accepted. Some producers have merged seemingly attractive features from different TQP approaches, but this has not always given a practical and cost-efficient approach. The purpose of this paper is to highlight important features of TQPs and to propose an improved approach that will rectify some weaknesses of the existing approaches.

Design/methodology/approach- The new TQP approach is proposed based on a critical evaluation and comparison of the most commonly used TQP approaches, such as NASA’s technology readiness levels (TRLs) and the approach developed by Det Norske Veritas (DNV). Criteria are established to facilitate comparison and identification of strengths and weaknesses of the TQP approaches. These results, combined with a thorough literature review, have been used to develop a framework that is practical for qualifying new high-reliability products.

Findings- The paper shows that most of the existing TQP approaches do not meet all requirements for an efficient TQP and therefore need improvements. Among the important requirements for a TQP is the ability to be integrated into the product development process and also a clear indication of the product’s development status that can be used by producers, suppliers, and clients. These and several other requirements call for the development an improved TQP.

Originality/value- The proposed TQP approach is new in the sense that it combines the best features from several existing approaches and is well structured and easy to implement and integrate into the product development process. The ability of being integrated into the product development process from the very beginning is an important feature of a TQP in order to avoid costly modifications later in the product's life cycle. The new TQP approach is of greatest value to producers of products with strict reliability requirements, such as the space industry, the subsea oil and gas industry, and the aviation industry.

Keywords: Technology qualification program, Product development process, Technology readiness, New product, Reliability

Paper type: Research paper

Introduction

New technical products are being developed at an ever-increasing pace. Many of these products are based on new technological solutions and may contain new materials and/or unproven components. They have the ability to increase the revenue, but can also lead to significant loss, caused by functional mismatch, failures, and malfunctions. Failures may give harmful consequences to humans, the environment, and material and financial assets. In some industries, such as the space industry, the subsea oil and gas industry, and the aviation industry, it is required to demonstrate that new products are *fit for purpose* before they are accepted for use. The framework for the qualification process and the management of its progress is referred to as a *technology qualification program* (TQP). A well-designed TQP is an aid in developing a desired product and reduces the likelihood of ending up with a product that does not fit the purpose (Andersen, 2006; Bratfors, 2005).

In 2001, Det Norske Veritas (DNV) developed a recommended practice for qualification of new technology, called DNV-RP-A203. It is intended for the subsea oil and gas industry, but its main principles can also be used in other application areas. More recently, DNV issued a second edition of DNV-RP-A203 (2011) based on the experiences gained from the application of the first edition. The main changes include support for the management of the TQP and an outline of the iterative nature of the TQP workflow.

An alternative qualification procedure based on *technology readiness levels* (TRLs) was introduced by NASA. TRL is a metric or measurement system that is used to assess the development status and the maturity of a specified technology or product (Smith, 2005). The concepts *readiness* and *maturity* are used interchangeably in the literature, and are discussed thoroughly and compared by Tetlay and John (2009).

Brombacher (1999) proposes a *maturity index on reliability* (MIR) as a tool for quantifying organizational aspects related to products. The MIR index does not consider the reliability of the product as such but, rather, the maturity of the business processes of the organization realizing or operating the product. The focus of the current paper, however, is on assessing the maturity of the products and not the organizational processes.

Identifying potential problems and failures at an early stage of the product development process is important for the producers, due to the high cost of making modifications later in the development process. Several authors (Andersen, 2006; Ardebili and Pecht, 2009; Blanchard, 2004; Engel, 2010; Grady, 2007; Mankins, 1995) and guidelines (API-RP-17N, 2008; SEMATECH, 1995) argue that the qualification process must be addressed prior to and in parallel with the product development process. This means that an efficient and practical qualification process needs to be based on an adequate product development model. Most producers have developed their own product development model comprising a number of consecutive phases, where the required development tasks and analyses are listed for each phase, and the data flow between the phases is illustrated. These models are generally rather similar, but the number of phases may vary with the complexity of the product. This paper is based on the product development model suggested by Murthy *et al.* (2008). This model can also be seen as a framework for decision-making regarding product reliability, and most producer-specific models can easily be translated into the model by Murthy *et al*.

The objective of this paper is to discuss and evaluate existing TQP approaches and highlight their key features based on six defined criteria and to propose a new TQP approach that will rectify the main weaknesses of the existing TQPs. The new approach is seen from the perspective of the producer and will be outlined in accordance with the product development model of Murthy *et al.* (2008).

This paper is based on a thorough literature survey. Academic studies on TQP approaches are scant, and the development of the existing approaches has mainly been done by industrial organizations and companies. The results of which have primarily been published as technical reports and industrial guidelines, and they mainly formed the basis of this paper. Qualification of new technology is a broad subject that is applicable in many different industries and for many categories of products.

The rest of the paper is organized as follows. In Section 2, we describe important concepts regarding qualification. Section 3 describes a product development process. In Section 4, we describe commonly used qualification processes. Section 5 discusses about the main challenges regarding the approaches presented in section 4, and proposes a new qualification framework combined with the product development process, and Section 6 concludes the paper.

Qualification

A. Definition and purpose

DNV-RP-A203 (2011) defines qualification as "*confirmation by examination and provision of evidence that the new technology meets the specified requirements for the intended use.*" A more goal-oriented definition is given by Hother and Hebert (2005) who state that TQP is a systematic process aiming to (i) reduce the risk and increase the probability of product success, and to (ii) ensure that the product is fit for purpose before being put into operation.

A TQP can be performed by different parties with different purposes:

- The *producer*, who offers the new product to the market, needs to prove that the product is fit for the purpose.
- The *system integrator*, who integrates the new product into a larger system, needs to evaluate the effect of the product on the total system reliability.
- The *end-user* of the new product must optimize the benefits of her investment through selection among competing products and technologies.

Performance criteria for the product and/or the technologies must be specified by the producer, regulatory bodies, or by the end-user and may be related to various reliability measures based on the time-to-failure probability distribution and/or some defined margins for specified failure modes (e.g., see IEC 60300-3-4, 2007; DNV-RP-A203, 2011).

B. Verification and validation

The concepts of qualification and verification are sometimes used with the same meaning in the literature, but in this paper, we follow IEC 60300-3-15 (2009) and consider the qualification process to embrace both verification and validation. Several references (Engel, 2010; IEC 60300-3-4, 2007; Maropoulos and Ceglarek, 2010) summarize and discuss different definitions of verification and validation. API-RP-17N (2008) defines validation as the process of ascertaining the appropriateness of data, assumptions, or techniques while verification is the process of determining if a technique or activity has been performed and/or completed, but also the extent to which it conforms to internal or global standards of application or operation.

Verification methods can be classified in different ways (e.g., see IEC 60300-3-15, 2009). Engel (2010) proposes the following classification:

- *Analysis*, which includes mathematical models, simulations, test algorithms, calculations, charts, or graphs.
- *Inspection*, which includes the use of human senses, simple physical tools for manipulation, or mechanical and electrical gauging and measurements.
- *Demonstration*. This is similar to a product testing method but is considered a softer approach to the verification process, for example, by observing the qualitative results of an operation through an exercise performed under a specific condition.
- *Testing*. Naturally, most system requirements will be verified by means of testing. Verification is through the application of established test procedures within specified environmental conditions as well as subsequent compliance confirmation through analysis of the generated test data.
- *Certification*. It is based on a signed certificate of compliance (from the producer) stating that a delivered item is a standard product that meets all the procurement specification, standards, and requirements. It must indicate the standard/procedure to which the testing was conducted and when, where and by which organization and under similar operational conditions.

Several verification methods may be equally appropriate to verify whether or not a requirement has been met and it can sometimes be beneficial to use two or more of these methods. In this case, the criticality, and the time and cost required to complete the verification should be considered.

A product development process

Murthy *et al*. (2008) developed a new life cycle model to assist producers in obtaining the desired product performance. The model consists of three stages (pre-development, development, and post development) and three levels (business, product, and component), and is split into eight phases.

Phase 1, Front-end phase (product definition), involves identifying the need for a new product or the need for modification of an existing product in accordance with business objectives and strategies and the customer needs for the product.

In *phase 2*, *System design phase (product characteristics),* product attributes are translated into product characteristics (engineer's view of the product). The objective is to transform the desired performance from phase 1 into a product design, with subsystems and components that can be used as basis for comparing the predicted performance with the desired reliability, availability, maintainability and safety (RAMS) performance.

The term *front end engineering design* (FEED) is sometimes used in major projects. This activity is carried out after the feasibility studies and the conceptual design of the product and is partly overlapping with our phase 2.

Phase 3, Component design (detail design), involves the detailed design (proceeding from product to component) of the product, placement of orders for components to be purchased, and preparation of initial product construction and testing. All functions identified in phase 2 are transformed into a (product) design specification describing the individual components and their relevant properties. The design specification is used as basis for the specification of components to be purchased. This is the start of product development for subcontractors, and may involve new technology development.

Phases 4, 5, and 6 will be different for products that are developed in high numbers and for one-of-a-kind products.

Phase 4, Component development, deals with product development, from component level to the product prototype. The items are tested in a controlled environment to verify that the desired performance is achieved. For products to be produced in high numbers, the prototype may be a complete product. For a one-of-a-kind product, the prototype may be the construction of some selected subsystems that require further testing before the final construction of the product is started.

Phase 5, System development, consists of operational testing, which means the prototype is released to a limited number of consumers to evaluate the customers' assessment of the product features. This information is used to assess field safety performance and to make design changes, if necessary. Influence from factors such as usage intensity and the operating environment may reveal additional hazards, contributing to a more complete picture of the actual product field performance.

Phase 6, Production, covers the physical production, starting from component and ending with the product for release to customers. This implies large-scale production in the case of standard products, or the final construction of a single product at the target application, in case of custom-built product. The production process must not introduce new failures or have any other negative impact on reliability, safety, operability, or maintainability characteristics of the product. When the production process is fine-tuned, the full-scale production of the product can start.

Phase 7, Installation, commissioning and operation, marks the start of the product life cycle for the customer and is when the product's RAMS performance, that should be integrated from early on in the product development process is challenged and tested in the field.

Phase 8, Business impacts, concludes the product development.

The qualification process is initiated in phase 1 and proceeds through all consecutive phases up to and including phase 6.

Qualification processes

Several qualification processes are described in the literature. NATO AVT-092 (2009) presents a qualification process for military aircrafts aiming at reducing the time and cost of their production. This is achieved by increasing the use of analyses, integration of tools, and by finding a balance between analysis and testing, in all design and development phases.

The guideline by Andersen (2006) is tailor-made for the oil and gas well technology and describes how to perform the qualification as a parallel activity with the product (well) development process. It also describes how qualification activities can be linked to traditional product development activities. The guideline further discusses *operational readiness* and gives requirements for manufacturing and operational planning (Corneliussen, 2006).

SEMATECH (1995) provides a qualification guideline intended to be used by producers and users of semiconductor equipment. It is based on a continuous *reliability improvement* process and is divided into: (1) the equipment life cycle and the reliability improvement process; (2) the management responsibilities for establishing and implementing the process, including the various activities associated with each steps of the reliability improvement process and each phase of the life cycle; and (3) activities and tools used in applying the reliability improvement process. The reliability activities are classified as engineering, data-related, and testing. Many activities require tools coming from various disciplines, such as probability, statistics, and reliability engineering.

API-RP-17N (2008) presents a structured approach aiming to help end-users, contractors, and suppliers to gain a better understanding of how to obtain and manage an appropriate level of reliability throughout the life cycle of subsea oil and gas projects. The approach is based on the same twelve *key reliability processes* that are used in ISO 20815 (2008) for production assurance and reliability management. The focus of API-RP-17N is project execution, which is described as a number of integrated reliability and technical risk management activities that are derived from the key reliability processes. These activities are arranged into a cycle of four basic steps: define, plan, implement, and feedback. These are applied during each project stage and also for each reliability assessment.

Ardebili and Pecht (2009) discuss the qualification process for mass-produced electronic products and divide the process into three stages: (i) virtual qualification, (ii) product qualification, and (iii) mass production qualification. Virtual qualification, also called design qualification, is the evaluation of the functional and reliability performance of the product design without any physical testing of the product. Product qualification is the evaluation of the product based on physical testing of manufactured prototypes. After virtual and product qualification, the electronic packages are mass-produced. During and after the manufacturing process, the products are inspected and tested to evaluate their quality, and defective parts are screened out. This process is referred to as quality assurance testing or screening.

Engel (2010) presents a comprehensive set of verification, validation and testing activities and methods for implementation throughout the entire life cycle of products. The approaches are based on a generic product life cycle model that extends the well-established V-model (Martin and Bahill, 1996) that portrays project evolution during the development portion of the product life cycle.

Grady (2007) presents the steps and procedures needed to implement a quality check of the product being proposed based on the V-model. The approach can be applied to high rate production, low volume - high cost production, and one of a kind production.

DNV-RP-A203 (2011) defines a set of activities that should be iterated through (a) concept evaluation, (b) pre-engineering, and (c) detailed engineering. Each stage should be successfully concluded before going on to the next stage. The activities are illustrated in Fig. 1.

Some companies in the oil and gas industry, such as FMC Kongsberg Subsea AS, have developed their own tailor-made TQP based on DNV-RP-A203. The FMC procedure introduces several improvements concerning the specification of requirements to which the technology is to be qualified, and a flow diagram to ensure that the process is carried out in a structured way. The main activities of the FMC procedure are described by Sunde (2004).

The FMC procedure has the potential for significant cost saving, since the qualification process is more streamlined and efficient with reduced requirements for physical testing, such that tests are only performed when strictly necessary. Potential deficiencies and malfunctions should be revealed during the design and qualification phases, such that the number of in-service failures is reduced. This is particularly important for subsea oil and gas production systems that are not accessible for normal maintenance and repair, other than through high-cost vessel operation.

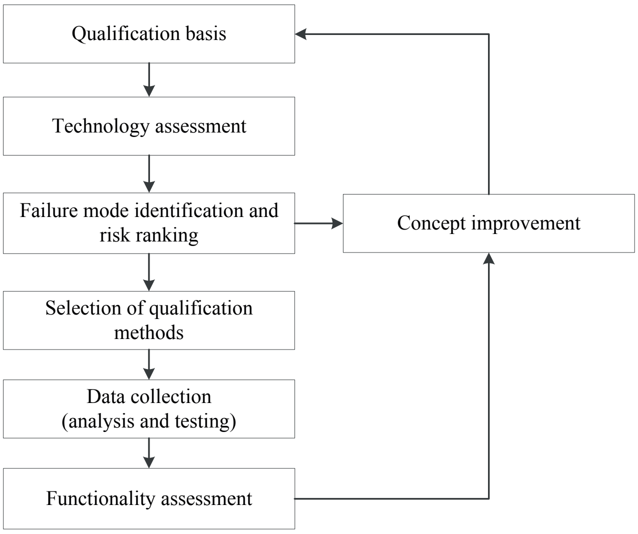


Figure 1: The DNV-RP-A203 (2011) qualification process.

Another commonly used qualification process is based on the TRL method, which is a systematic metric/measurement system that supports assessment of a particular product and a consistent comparison of the maturity between different types of products. The Subsea Processing Community (SPC) adopted and modified the TRL method to make it applicable for equipment used in subsea production systems. Since then, the TRL method has been used to determine the qualification status for several new products.

The TRL method has nine levels (TRLs), ranging from zero to eight, from principles and concepts to the real product (i.e., the lowest level of product maturity to the proven product). These TRLs are determined by tangible evidence identified during the product development. Obviously, the evaluation at each level has to be successful to claim that a level is reached (Berntsen, 2008).

In several references (API-RP-17N, 2008; Engel, 2010; IEC 60300-3-15, 2009; SEMATECH, 1995), the qualification tasks and the tasks during the product design and development phases are merged. Therefore only the producer can perform the qualification and it is not possible to outsource to a third party. In other qualification procedures (DNV-RP-A203, 2011; Smith, 2005), the evaluation tasks are specified and may be carried out independently of the producer's design and development tasks.

Model development

A. Challenges related to the commonly used qualification processes

Several authors (e.g., see Corneliussen, 2006, Graettinger *et al.*, 2002, Sauser *et al.*, 2006, and Mankins, 2009) indicate strengths and weaknesses of some of the TQPs mentioned in the previous section. To perform a more systematic evaluation of the TQPs, we introduce six main questions (that can also be seen as criteria) to determine the main characteristics of an efficient TQP. The six questions have been developed based on a careful literature study and a scrutiny of the existing TQPs. The questions and their reasons of importance are as follows:

Q1. Is the TQP approach well interlinked with the product development process?

- This is important since if a need for modification in the design or development is revealed, the modification can be implemented before it becomes too late and will have too high impact on time, cost, and quality. The better the TQP is integrated into the product development process, the less consequences may occur.

Q2. Are the steps of the TQP approach well defined? Are the tasks that should be performed in each step clear?

- This is important in order not to misinterpret the steps and the tasks that have to be performed, due to ambiguity in definition and description.

Q3. Are the criteria for each step of the TQP approach well defined? Are they attainable?

  - Criteria for each step of the TQP must be defined in order to decide whether or not the objective of the step has been attained.

Q4. Has the uncertainty of the new product been quantified? Is the quantification basis solely analytical – or does it also include physical testing?

  - The quantification of uncertainty of the new product is necessary in order to give confidence to the user of the new product. For some products, such as most of the products in the oil and gas industry, time should not be considered as a limitation; and a qualification based only on analysis may not be sufficient. Some testing may also be required.

Q5. Can producers, suppliers, and end-users use the same approach to verify that their product requirements are met? Can the approach act as a unifying language to indicate the status of the product development?

  - The importance of this issue is obvious for a complex product with several suppliers and subcontractors, and also for a one-of-a kind product where the end-user and the producer are closely interlinked during the development of the product (e.g., during development of new subsea oil and gas equipment).

Q6. Does the process generate feedback that can be used to make improvements?

  - Generation of feedback is an important feature of the TQP. To reveal weaknesses as early as possible will lead to a better product and a more cost-efficient development process.

Table 1: The main weaknesses of existing qualification processes.

Qualification processes	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**
NATO AVT-092 (2009)	P	P	P	P	N	N
Andersen (2006)	P	P	N	N	N	P
SEMATECH (1995)	Y	Y	N	Y	N	Y
API-RP-17N (2008)	Y	P	P	Y	N	Y
Ardebili and Pecht (2009)	P	P	N	P	P	P
Engel (2010)	Y	Y	N	Y	N	P
DNV-RP-A203 (2011)	P	Y	N	Y	P	Y
TRL (Smith, 2005)	P	P	P	P	Y	P

Each of the TQP approaches in the previous section has been subject to a thorough scrutiny based on the six questions. The questions are answerd by “yes” (Y), “no” (N) or “partly” (P). The answer “no” indicates that the TQP approach has a potential weakness and the answer “partly” indicates that the approach has not sufficiently considered the related issue. The answers, presented in Table 1, clearly shows that none of the existing TQPs fulfill all the six criteria and some of them need major improvements in order to fully serve their purpose.

B. A new TQP approach

This section presents a new TQP approach that is integrated into the product development model of Murthy *et al.* (2008), as illustrated in Figure 2. The same ideas can, however, be adapted to any company-specific product development model.

Several qualification tasks are performed in each phase of the model in Figure 2, and before proceeding to the next phase, the output needs to be evaluated to assure that the desired outcome is obtained. This evaluation should be based on a set of defined criteria.

If problems are identified, the next phase should not be initiated until the required corrective actions have been taken, as illustrated in Figure 3. SEMATECH (1995) and API-RP-17N (2008) indicate similar strategies, but from a different perspective and based on different models.

The new TQP approach has six main steps that are numbered according to the six first phases of the product development model of Murthy *et al.* (2008). Each main step is outlined in detail in the following together with the objectives of the step and the tasks that are required to meet the objective. Figure 4 illustrates this framework. Methods and tools that are required for the various tasks are mentioned and references to recommended literature are given.

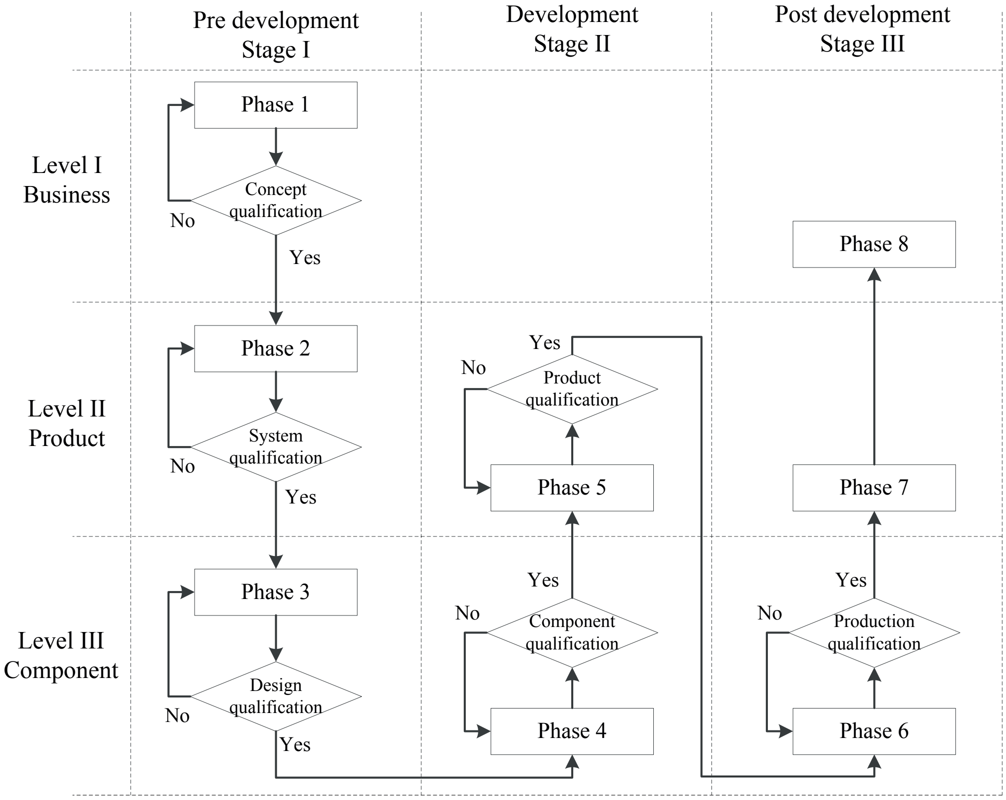


Figure 2: TQP integrated in the product development model of Murthy *et al*. (2008).

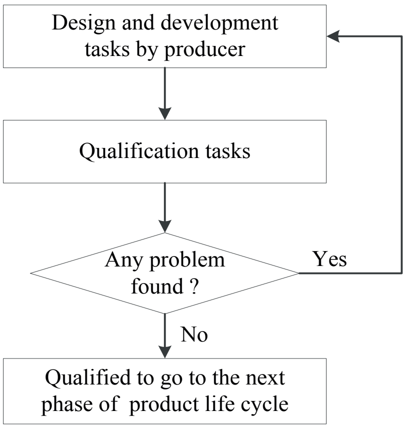
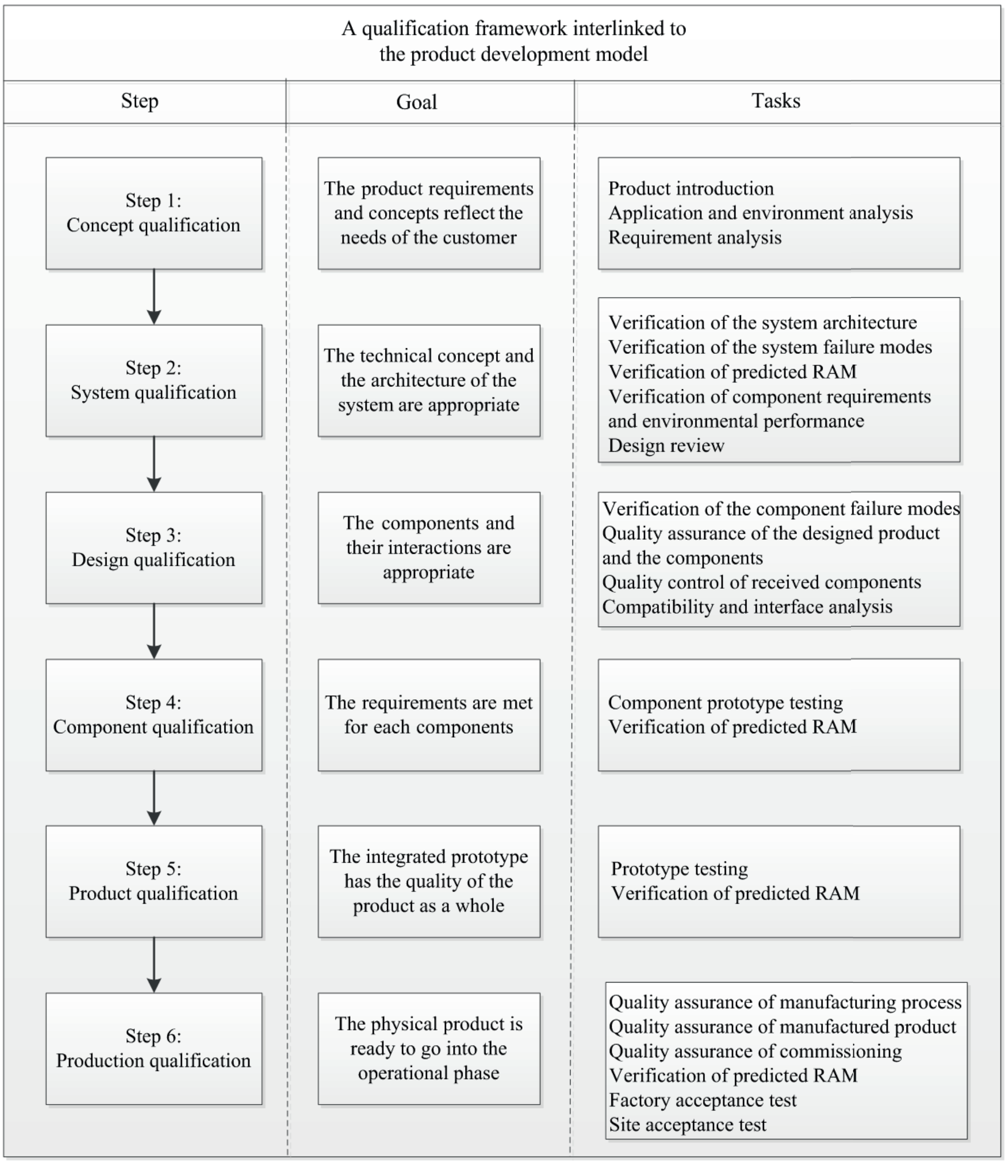


Figure 3: Qualification evaluation in each phase of the product life cycle.



A qualification framework interlinked to the product development model

Step	Goal	Tasks
Step 1: Concept qualification	The product requirements and concepts reflect the needs of the customer	Product introduction Application and environment analysis Requirement analysis
Step 2: System qualification	The technical concept and the architecture of the system are appropriate	Verification of the system architecture Verification of the system failure modes Verification of predicted RAM Verification of component requirements and environmental performance Design review
Step 3: Design qualification	The components and their interactions are appropriate	Verification of the component failure modes Quality assurance of the designed product and the components Quality control of received components Compatibility and interface analysis
Step 4: Component qualification	The requirements are met for each components	Component prototype testing Verification of predicted RAM
Step 5: Product qualification	The integrated prototype has the quality of the product as a whole	Prototype testing Verification of predicted RAM
Step 6: Production qualification	The physical product is ready to go into the operational phase	Quality assurance of manufacturing process Quality assurance of manufactured product Quality assurance of commissioning Verification of predicted RAM Factory acceptance test Site acceptance test

Figure 4: The proposed qualification framework.

Step 1: Concept Qualification

The objective of concept qualification is to ensure that the product requirements and the proposed product concepts accurately reflect the needs of the end-user(s). A complete understanding of the requirements, the concepts, and the operational context is therefore required. The concept qualification comprises the following tasks:

- *Product introduction*. The new product must be described as completely as possible, through drawings, text, data, and other relevant documents. In most cases, only the main functions of the product are known at this stage. Further details will become known as part of the product development process.
- *Application and environment analysis*. The intended application of the product must be clearly defined and the operational and environmental conditions must be specified. Potential and realistic deviations from the intended application must be identified and recorded. DNV-RP-A203 (2011) suggests that this is done by a *critical items* list, specifying key issues, such as dimensioning loads, capacities, and functional requirements. A suggestion of what may be included in the description of the product and the environment is provided in IEC 60300-3-4(2007).
- *Requirement analysis*. This analysis should be done to identify the resources that are necessary to satisfy the product needs (Grady, 2006). Requirements must be actionable, measurable, testable, and related to identified business needs or opportunities. Requirements should be defined prior to any efforts to develop a design for the product.

It is suggested to define the requirements according to NATO AVT-092, (2009) by flowing-down to the basic subsystems needed to build the system. The common flow-down of requirements are: mission requirements, system requirements, and technical requirements. Reliability requirements are important to meet corporate safety and business goals and should be defined in phase 1 and refined during phase 2 (e.g., see BP, 2002).

A *requirement verification matrix* (RVM) is recommended in order to determine (i) the method of verifying the requirements, (ii) when it should be done in the product life cycle, and (iii) the specific procedure according to which the verification should be accomplished (Wasson, 2005).

Step 2: System Qualification

System qualification is carried out to ensure that the technical concept and the architecture of the system are appropriate. The term “product” signifies an existing physical item and we therefore use the term “system” in this and the next step. This step includes the following tasks:

- *Verification of the system architecture*. The relationships between the various entities of the system should be verified in order not to neglect any entities or any relationships between them (Crawley *et al.*, 2004). It is suggested to apply the IEC 60300-3-15 (2009) approach and select a set of criteria for system integration and for new system developments involving interactions of system functions consisting of hardware, software, and human elements.
- *Verification of the system failure modes identification*. An FMECA (IEC 60812, 1985) should be carried out to systematically address all the potential failure modes in the design, including their causes and probability of occurrence. The FMECA does normally not address multiple failures, and it may therefore be necessary to carry out a fault tree analysis (IEC 61025, 2006). For complex systems, a HAZOP study (IEC 61882, 2001) is suggested to identify potential deviations from the design intent, and examine their causes and consequences. If FMECA reports are provided by subcontractors (e.g., component producers), the correctness of these reports should be assessed.

An alternative approach can be *anticipatory failure determination* (AFD) which provides a systematic way of identifying either potential future failures or root causes for already manifested failures. This methodology offers several strategies to identify failure scenarios (Kaplan *et al.*, 1999). The *risk in early design* method can also be used to identify critical failures and hazardous events (Grantham Lough *et al.*, 2009).

- *Verification of predicted reliability, availability, and maintenance (RAM).* To verify the predicted RAM requires evidence of reliability achievement. Such evidence depends on the phase of the product life cycle and generally takes the form of data collection related to prior field performance, reliability analysis, calculation, expert opinion, and tests (BP, 2002). A preliminary reliability prediction is possible by using methods, such as reliability block diagrams, fault tree analysis, or Markov analysis (Rausand and Høyland, 2004).
- *Verification of component requirements and environmental performance.* Component requirement analysis is used to discover, understand, document, validate, and manage the requirements of the components. Its objective is to produce complete, consistent, and relevant requirements that a component should have, as well as the programming language, platform, and interfaces related to the

component. Component requirement analysis can be done according to the approach suggested by Beydeda and Gruhn (2005) that consists of four main steps: requirements gathering and definition, requirement analysis, component modeling, and requirement validation.

- *Design review.* A design review of the proposed design is essential for evaluating the design and providing assurance about how well a new design reflects the desired product performance. The design review should focus on the intended use as well as foreseeable misuse. In general, the results from the design review document justify design decisions (for more detail see Blanchard, 2004; IEC 61160, 2005; SEMATECH, 1995).

Step 3: Design Qualification

The objective of the design qualification is to ensure that the components and their interactions are appropriate. This phase comprises the following tasks:

- *Verification of the component failure modes identification.* Component failure modes identification can be performed in the same way as system failure modes identification.
- *Quality assurance of the designed product and the components.* Quality assurance involves all the planned and systematic activities implemented within the quality system that can demonstrate that a product or service will fulfill the requirements for the desired quality (Yang *et al.*, 2003). For quality assurance, it is necessary to formulate a set of design parameters in order to deliver the product's intended functions. By using axiomatic design terminology (Suh, 2001), product design is a mapping from the function space to the design parameter space. Therefore, the key task for quality in design is to ensure that the designed product is able to deliver the desired product functions over its useful life.

The quality methods used in this stage include robust design (Taguchi, 1986), design of experiment (DOE), response surface methods (RSMs) (Myers and Montgomery, 1995), design for X (Huang, 1996), axiomatic design, theory of inventive problem solving (TRIZ) (Terninko *et al.*, 1998), and specific methods in reliability engineering.

It is sometimes possible to capture the system design weaknesses and strengths and detect the failures by using virtual prototyping. Technological advances make it possible to virtually define system designs in completely integrated and associative parametric representations that are directly suitable for functional verification and accurate sensitivity design studies (Engel, 2010). Accurate system modeling permits identification of how external parametric changes affect not only a single component of the product but also the integration of various components into the final product.

- *Quality control of received components.* Quality assessment is used for evaluating the received materials, parts, and components from suppliers to decide whether or not the items are acceptable with respect to the product's desired performance requirements. The assessment may include continuous checking of the items against workplace standards and specifications for conformance. Understanding how the received items relate to the current operation and how they contribute to the final quality of the product will help to establish a better set of acceptance criteria (Blanchard and Fabrycky, 1998).

Several methods can be used to evaluate purchased items, see, for example, the discussion in SEMATECH (1995). The evaluation may also include a request for reliability information/data from the suppliers, and performing tests on the components, such as life testing and environmental stress screening. Other alternatives are IEC 61508-2 (2010) and IEC 61508-3 (2010) that suggest the following approach; The needed requirements along with the reasoning behind them (to make them more understandable) should be documented. Then a description in the form of "argument/solution" should be provided on how each requirement is met by listing a set of verification activities and test cases relevant to that requirement. For full traceability, each argument and verification/test activity should be linked with the evidence document showing the results of the work.

Another possible approach is based on API-RP-17Q (2010), which recommends that the supplier or original equipment manufacturer (OEM) maintains a failure mode assessment (FMA) and a standard product qualification sheet (PQS) for each component with a unique component identifier. The PQS states the design parameters, size, rating, testing records, and limits of qualification of the component, but does not include end-user-specific data. The end-user should also develop her own PQS for each component to be used. The PQS should cover field-specific service conditions, parameters, and applicable standards and specifications and requirements. To judge the suitability of a supplier's component for deployment in a given project, the end-user can request a PQS from the supplier and compare the information from the supplier-prepared PQS to their actual service conditions as documented in the end-user-prepared PQS.

- *Compatibility and interface analysis.* The ability of two or more subsystems or components to perform their required functions while sharing the same hardware or software environment is referred to as compatibility (Wasson, 2005), and the relations between elements of the system architecture is referred to as interface (Grady, 2006). Compatibility and interface analyses are important to obtain an optimal architecture for the system before commitments are made related to its design. For hardware and software interface testing, see Engel (2010).

Step 4: Component Qualification

Component qualification is carried out to verify that the requirements are met for the components. The step includes the following activities:

- *Component prototype testing.* Here, the components are tested over a wide range of controlled conditions, usually in a laboratory. The tests are useful in order to determine the validity of design and calculation methods. The objective of the tests is to ensure that the best of several alternative designs is chosen, and that the component will perform satisfactorily at other than nominal conditions when integrated into the product. If the component is to be applied to a major part of a product, a more comprehensive test program must be developed. For some components, testing may not be feasible, especially seen in relation to the required time and cost. The components should be prioritized and tested according to the criticality of the components, the criticality of the potential failures, and our uncertainty related to them.

Problems associated with component testing include: simulating realistic equipment environments, and determining the number of tests required to demonstrate reliability.

Several reliability testing methods with different purposes are required. One type of reliability testing is life testing, which is used to estimate and demonstrate the numerical reliability of a part; that is its useful life or reliability. Life testing can also be performed in the further phases of life cycle (Lloyd and Lipow, 1991).

A special type of reliability testing is accelerated testing which is similar to life testing, but can be used to obtain reliability data in a shorter period of time, by exposing the component to high stresses, but nonetheless representative, during normal operation (Nelson, 1990). Another required type of testing is environmental stress screening (ESS), which can be used to stimulate failures by stressing the component, considering environmental inputs such as: thermal, electrical, and so on. ESS is usually performed to detect and remove latent defects and to find defects not found with inspection or electrical testing. The tests performed at component level can have stronger stresses, with no damage to the product and it results in a higher defect detection rate and lower repair cost later in the life cycle, which is desirable (MIL-STD-810G, 2008).

Among standards used for reliability testing are: IEC 61163-1 (2006), IEC 61163-2 (1998), (SEMATECH, 1995), MIL-HDBK-781A (1996), MIL-STD-810G (2008) and many parts of IEC 60068 (1988).

- *Verification of predicted RAM.* The RAM analysis is updated and reviewed based on new information and data from component prototype testing and component failure modes identification. RAM characteristics can be verified by engineering analysis, analogy, laboratory testing, functional mock-ups, or model simulation (U.S. Air Force, 2000).

Step 5: Product Qualification

Product qualification is performed to ensure that components can be combined properly into a complete product and to verify that the prototype has the required quality. This step includes:

- *Prototype testing.* Prototype tests are intended to explore the effects of component interactions under relevant loading and environmental conditions. Tools and standards that can be used for prototype testing are mentioned in step 4. For some products, such as subsea equipment, it is not possible to perform operational testing of a prototype in a real environment. Instead virtual product testing by means of simulation can be performed. However, some operational testing may still be performed under similar operational conditions.

Integration testing is required to prove that the product elements interact properly.

Several integration testing strategies may be used, and the most relevant among these are; (1) top-down integration testing, (2) bottom-up integration testing, (3) sandwich integration testing and (4) big-bang integration testing; see Engel (2010) for details about these strategies.

- *Verification of predicted RAM.* Verification includes reviewing the reliability, maintainability and operability analysis with new information and data from test results. RAM characteristics should be tested by using the approaches of engineering analyses, analogy, reliability test, functional mock-ups, or model simulation.

Step 6: Production Qualification

The last step of the new TQP approach, production qualification takes place when the physical product is ready to be qualified and goes into the operational phase. This step includes:

- *Quality assurance of the manufacturing process*. This is an important task since ensures that the processes are able to produce the real product consistently, economically, and free of defects. A process FMECA, and manufacturing process control are suggested to be performed before the manufacturing development. They can be done according to AFD-100630-068 (2010). A process FMECA is necessary when there is a new process, a modification to an existing process, or when an existing process is used in a new environment or location.

Another quality method that can be used in this stage is statistical process control (SPC) (Wetherill and Brown, 1991) which verifies the processes are running as planned. Manufacturers (e.g., in the aerospace industry) who have low quantities of final products, can use the approach by Bothe (1991) based on SPC method. Even with a single product, there may be processes that are repeated many times, such as drilling, that would lend themselves to SPC. Six-sigma (Gordon, 2002) is another method which aims to improve the quality of process outputs by identifying and removing the causes of defects (errors) and minimizing the variation in manufacturing processes.

Other quality methods that can be used in this stage include, manufacturing troubleshooting and diagnosis, and the Shainin method (for more detail see Yang *et al.*, 2003).

- *Quality assurance of manufactured product.* The purpose of this task is to ensure that the manufactured product is consistent with its design; that is, the product design on paper or computer can be realized in the manufacturing process. It should be done based on the quality policies, the statement of producer commitments, quality manuals (including documentation system), need for registration according quality standards such as ISO, and IEC, and acceptance inspection for suppliers (Yang *et al.*, 2003).
- *Quality assurance of commissioning.* Verification of commissioning is required to avoid commissioning errors. This task along with the following tasks may not be relevant for mass produced products.
- *Verification of predicted RAM.* The final RAM requirements, as specified in the product specification, the requirements documents, and so on, need to be verified by testing for the types of products that testing is possible.
- *Factory acceptance test (FAT).* It is performed to verify the correct operation of the product and to formally approve the product, before the product is moved to its final destination. The level of detail involved varies widely depending on customer requirements, but all aspects of source inspections are normally covered during tests (SEMATECH, 1995). A test conducted to determine and document that the product's hardware and software operate according to the specification, covering functional, fault management, communication, support systems, and interface requirements (Corneliussen, 2006). FAT procedures and guidelines are covered in several references (e.g., Corneliussen, 2006; Hedberg, 2006; IEC 60300-3-4, 2007; Grady, 2007).
- *Site acceptance test (SAT).* This is the final part of qualification, and is performed to make sure the delivered product has not been harmed by the transportation and has been adequately tested at the end user's facility and performs to the end user's expectations. This is mainly relevant for one-of-a-kind products such as most of the equipment in the offshore / subsea oil and gas industry.

This will help to give the end-users confidence that the product is as they desired, and as such is "fit for purpose". Invariably, faults found at this stage of testing are expensive to fix, although if the risk-based testing has been performed successfully, then these faults will have been found early and thus expenses will be kept to a minimum (FAA, 2004).

Conclusion

This paper has discussed and evaluated eight commonly used TQP approaches. Six evaluation criteria, formulated as questions, have been developed and the TQP approaches have been evaluated based on these questions. Answers to each question have been obtained based on a careful scrutiny of the eight approaches. The answers give a clear overview of the strengths and weaknesses of each approach. It is concluded that all the existing approaches have significant potentials for improvement.

A new TQP approach is proposed, aiming to overcome the weaknesses of the existing approaches. The new TQP approach consists of six steps and provides a thorough list of methods and tools for qualification of the product in the different development phases. The key features of the proposed approach, related to the six questions, are as follows:

a) The proposed approach is closely linked to the product development process. The steps are aligned with the product development model proposed by Murthy *et al.* (2008), but can easily be adapted to any step-based product development process. The tasks in product development and the tasks for qualification have reciprocating characteristics. The inputs to the proposed approach usually are the results of tasks in the new product development process and the results of the qualification tasks in each step may give feedback to them. This makes the qualification process sufficiently interlinked to the product development process.

b) In order to avoid ambiguities, each step of the new TQP approach is explained and the tasks required in each step are identified and described. The relevant methods and tools for the various tasks are listed and references to recommended literature given.

c) The objective of each step has been clarified and can be attained with a proper implementation of the defined tasks of each step. A set of criteria can be defined, in order to decide whether or not the objectives have been met.

d) The proposed approach can be seen as a unified language between producers, suppliers, and end-users regarding the qualification status of the new product. When the product is complex, this feature of the TQP approach becomes crucial.

e) The proposed approach along with the product development process tries to get feedback from the implementation of tasks in each step and to improve the revealed weaknesses as early as possible in the product life cycle.

f) Finally, the new TQP approach will, through analysis and testing, produce quantitative results related to the uncertainty of the new product; results that can be useful for all stakeholders to the product.

It is not possible to formally verify a TQP program. Its value can only be evaluated based on long-term use where the cost-efficiency of the program is compared with the actual reliability of the products in operation.

Several parts of the new TQP can be extended and improved. Candidates for improvements are:

- A detailed qualification of manufacturing processes, systems, and environment is required to be linked into the proposed qualification process. A promising activity has here been initiated by the Stevens Institute of Technology (Sauser *et al.* 2006). See also DOD (2010).
- The producer's business processes indirectly affect the quality of the product and a maturity assessment of these processes should therefore be interfaced with the proposed TQP.
- Time and costs are not considered as limitation in the proposed qualification process. However with rapid analysis and testing capabilities, the qualification process will be significantly reduced. Optimization of the TQP with time and cost constraints should be pursued.

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Article 2

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Prediction of failure rates for new subsea systems: a practical approach and an illustrative example

Maryam Rahimi and Marvin Rausand

Abstract

In the subsea oil and gas industry, new systems and new technologies are often met with skepticism, since the operators fear that they may fail and lead to production loss, costly repair interventions, and hydrocarbon leakages to the sea. Before a new system is accepted, the producer has to convince the operator that it is fit-for-use and has a high reliability. This is often done through a technology qualification program. An important part of the technology qualification program is to predict the failure rate of the new system in its future operational context. Identifying potential problems and estimating the failure rate at an early stage in the system development process are important owing to the high cost of design modifications later in the development process. This article presents a practical approach to reliability prediction of new subsea systems based on available operational data from similar, known systems from the topside environment and a comparison between the two systems. The application of the approach is illustrated by an example of a subsea pump.

Keywords

Reliability prediction, failure rate, subsea system, reliability-influencing factor

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Introduction

The subsea oil and gas industry is moving more and more of the traditional topside fluid processing systems to the seabed. This strategy has the potential to give increased production from low-energy reservoirs and may also lead to significant cost saving. A prerequisite is, however, the failures requiring subsea repair interventions will not occur. A subsea intervention requires an intervention vessel and often a long production downtime – at a cost of several million US dollars. The seabed processing systems may be used for: removal and re-injection of produced water, sand removal, boosting of well fluids, gas/liquid separation and liquid boosting, subsea gas compression, and so on. The processing systems require electro-power and hence electrical connectors and power distribution systems.

Before an operator accepts to install a new subsea system, he must be convinced that the new system has a sufficiently high reliability. The time to the first planned intervention may be five years, and even longer, and it is important that the installed system is able to survive this period without failure.

The operator will usually specify strict reliability requirements for the new system and require the supplier to follow an agreed *technology qualification program* (TQP) during the design, development, and manufacturing phases of the system.[1,2] As part of the TQP, reliability analyses and predictions are performed in the early stages in order to:

- identify potential design weaknesses;
- compare alternative designs;
- determine early estimates of life-cycle costs;
- provide failure rates and other input parameters for system reliability and availability assessments;
- establish requirements and objectives for reliability testing.

Reliability requirements may be stated according to IEC 60300-3-4[3] and should be based on (1) the

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application of the system; (2) the failure criteria, i.e. what constitutes a failure of the system with the intended application; (3) the operating conditions; and (4) the environmental conditions.

Most of the new subsea systems are adapted from similar, well known topside (i.e. on the platform) systems and the industry often talks about “marinization” of topside technology. Reliability information for topside systems is available from the OREDA handbook[4] and the OREDA database (for the participating companies). This information cannot be used directly for new subsea systems, because of design modifications, different environmental stresses, and different maintenance. The reliability information in OREDA[4] is presented as a constant failure rate, together with additional information related to failure modes, failure descriptors/mechanisms, and components that contributed to the system failures. Currently, no practical method is available that can be used to extrapolate the available reliability data from similar and known systems and come up to a failure rate prediction for new systems operating in a different environment.

The objective of this article is to suggest a practical approach on how to predict the failure rate of new subsea systems that has been adapted (i.e. “marinized”) from known topside systems. The approach builds on the reliability information in OREDA and similar reliability data sources, but also on a careful failure analysis where the subsea and topside systems are compared. The suggested approach is illustrated by an example of a new subsea pump. The main application of the suggested approach will be during the product’s design and development phases, when there is no actual data available from any equivalent systems.

The approach is developed for a new subsea system, but can also be applied in a slightly modified form in other new product-development projects where high reliability is a requirement.

The approach described in this article and the associated discussions are subject to several delimitations. The new subsea system is, for example, compared with a single and generic type of topside system, and it is assumed that relevant data from other subsea systems is not available.

The article is organized as follows. The next section describes the alternative reliability prediction methods, while the section “Failure rate provision for new system” presents a new stepwise reliability prediction procedure. A case study of a subsea pump illustrates the application of the approach. The final section provides conclusions and some ideas for future work.

Reliability prediction

System reliability requirements can be expressed with quantitative measures, such as the failure rate, the survivor probability, and the mean time to failure (MTTF).[3] Since OREDA[4] only provides constant failure rates, we assume that the subsea system also has constant failure rate, and denote this by $\lambda^{(S)}$. The corresponding survivor function is $R^{(S)}(t) = \exp(-\lambda^{(S)}t)$ and the mean time to failure is $\mathrm{MTTF}^{(S)} = 1/\lambda^{(S)}$.

Reliability prediction methods

Several models and methods for reliability prediction have been proposed in the literature. For electronic equipment, reliability prediction is well established and is often based on the *parts count* technique (prediction at reference condition) and the *part stress* technique (prediction at operating condition) in MIL-HDBK-217F[5] and similar approaches.[6–9]

For mechanical and electro-mechanical equipment, there is no generally accepted method for reliability prediction. This may be owing to the higher number of, and more complex, failure mechanisms. Several studies have shown that the reliability of mechanical equipment is sensitive to loading, operating mode, and utilization rate.[10,11]

Most reliability data sources assume that the items have constant failure rates and that failures in a population of identical items occur according to a homogeneous Poisson process (HPP) where the time t is the accumulated time in service. Design variations and operational and environmental conditions may be accounted for by including *covariates* into the model. In some application areas (including the subsea oil and gas industry), the covariates are sometimes referred to as *reliability-influencing factors* (RIFs). A RIF is a relatively stable condition, which by being changed will increase or reduce the failure rate of the item. Ascher and Feingold[12] list 18 RIFs that influence the failure behavior of a repairable system. NSWC-11[10] considers the effects of the environmental RIFs at the lowest part level of mechanical systems.

To obtain application-specific failure rate estimates, various models have been suggested, such as the proportional hazards (PH) model[13] and the accelerated failure time[14,15] where the RIFs are included as covariates. A RIF may be a continuous variable, a discrete variable taking several values, or a binary variable.

The BORA approach[16] and the approach suggested by Brissaud et al.[17] are both based on a PH model. The BORA project is concerned with reliability assessment of safety barriers on offshore oil and gas installations, and is based on a set of generic RIFs related to human and organizational factors. The RIFs to be used for the specific assessment are selected by expert judgment from the set of generic RIFs. The state of each RIF is classified into one out of six possible states and a scoring and weighing process is used to determine the effect of each RIF.

The approach by Brissaud et al.[17] is based on a set of RIFs that are classified according to life-cycle phases. The estimation of the application-specific failure rate is comparable with the approach in MIL-HDBK-217F,[5] but the determination of the multiplicative factors is done in another way by a scoring and weighing procedure.

None of the approaches mentioned above can be used directly to predict the failure rate of a new subsea system. Using the PH-model requires extensive data for determining covariate values and related parameters. The approach by Brissaud et al.[17] has difficulties in finding the influencing functions for the indicators of each influencing factor. The BORA project mainly focuses on human and organizational factors that influence the risk of hydrocarbon releases. To use the available field data from topside systems, this approach needs some extension in different levels, such as scoring and failure analysis. However, the general principles of these approaches have been used to develop a new failure rate prediction method, aiming to overcome some of the shortcomings of the existing approaches.

Failure rate provision for new systems

Required data

How the subsea environment influences a system's failure rate will generally depend on the application of the system and its internal and external environment. Items that are not directly in contact with the subsea environment are mainly affected by internal stresses, while items that are in direct contact with the subsea environment are also affected by external stresses. Failure rate estimates for topside systems are available from OREDA.[4] Other sources, such as MechRel[10] and the RIAC handbook[18] may also give supplementary information. (A list of reliability data sources with links is provided on http://www.ntnu.edu/ross/info/data.) Our objective is to use the available topside data to predict the failure rate of a similar subsea system. Several categories of data and information are required.

- *Technical data* are usually supplied by system manufacturers and are necessary for understanding the system functions and for developing system models. Based on this type of data, similarities among or between systems can be identified.
- *Environmental data* provide information about the operating conditions for the system and needs to be incorporated into the reliability analyses. Subsea environmental meta-data and ocean data can be used for a better understanding of influencing factors.
- *Operational and maintenance data (field data)* are collected under actual operating conditions by the customers, and are plant/system specific.
- *Expert judgment* plays a central role in the provision of data for new applications. Experts may possess valuable knowledge that can supplement the recorded data and provide important input to decision-makers.
- *Reliability prediction methods* are required to find or develop a suitable method for a more realistic estimation.

Table 1. The steps of the suggested procedure.

Step	Description
1	New system familiarization
2	Identification of failure modes and failure causes
3	Reliability information acquisition for the similar known system; comparison of the new and the known system
4	Selection of relevant RIFs
5	Scoring the effects of the RIFs
6	Weighing the contribution the failure causes to failure modes
7	Determination of failure rate for similar failure modes
8	Determination of failure rates of new failure modes, calculation of new total failure rate

RIF: reliability-influencing factor.

Stepwise procedure

A new approach for failure rate prediction of a new subsea system based on data from a similar topside system is described. This approach can be used early in the product development process, i.e. the design and development phases. During the operational phase, the predicted failure rate from previous phases has to be updated based on the real data that are collected. Table 1 summarizes the steps of the suggested procedure.

Step 1: New system familiarization. The intended application of the new subsea system must be clearly defined and its physical boundaries and operational and environmental conditions must be specified. A suggestion on what may be included in the description of the system and its environment is given in BS 5760-4.[19] (This reference is now obsoleted and replaced by BS EN (IEC) 60300-3-4:2008 IEC60300, but it still includes some helpful issues that can be used.) It is recommended to represent the system as a hierarchical structure of subsystems and maintainable items. A maintainable item is a lowest level item in the system hierarchy at which maintenance is carried out.[4]

DNV-RP-A203[1] suggests that a *critical items list* is prepared, specifying key issues, such as materials, dimensioning loads, capacities, frequency of operation, and so on. The description may be in the form of drawings, text, data, or other relevant formats.

Step 2: Identification of failure modes and failure causes. A failure mode and failure cause analysis of the new subsea system should be carried out. A full failure mode, effect and criticality analysis (FMECA)[20] is not required, but may already have been prepared for other purposes at this stage of the system development process. All potential failure modes must be considered,

Description of unit				Description of failure		
Ref. no.	Maintainable item	Function	Operational mode	Failure mode	Failure cause	Detection of failure

Figure 1. Failure mode and failure cause worksheet.

together with the failure causes and mechanisms that may contribute to each failure mode. The assessment must cover all operational modes. The failure modes and failure cause analysis may be based on a worksheet as shown in Figure 1. Some columns in the worksheet, such as "maintainable item" or "function", are not used specifically in the approach or in the calculations, but they are necessary in order to get insight related to failures, influencing factors, and so on. It is further recommended to establish an influence diagram[21] to illustrate the potential causes, as shown in Figure 2.

It is important that the failure causes are specified to be as disjunct as possible, such that a failure mode is "caused" by a failure cause and not mainly by the combined effects of two or more failure causes. For example, a failure mode is caused by "high flow" and by "high sand content in the fluid" as two separate failure causes, but the main cause lies in the combination of "high flow" and "high sand content". In this case, we should specify "high flow and high sand content" as a single failure cause, and not as two separate causes.

Step 3: Reliability information acquisition for the similar known system; comparison of the new and the known system. It is assumed that data are available from a known topside system that performs similar functions and has a similar design and structure as the new system. As much reliability information about the known system as possible must be acquired from OREDA and other relevant sources. The data available from OREDA include:

- failure modes;
- failure rate estimates for each failure mode, including confidence intervals;
- failure descriptors, i.e. failure mechanisms and other factors contributing to each failure mode (quantified);
- maintainable items contributing to each failure mode (quantified).

Let $\lambda^{(T)}$ denote the constant total failure rate given in OREDA for the topside system. The failure rate for failure mode FM_i is denoted by $\lambda_i^{(T)}$, for $i = 1, 2, \ldots, n$, such that $\lambda^{(T)} = \sum_{i=1}^{n} \lambda_i^{(T)}$, when the failure modes are disjoint. If we introduce α_i, such that $\lambda_i^{(T)} = \alpha_i \lambda^{(T)}$, the vector $\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \ldots, \alpha_n)$ is the distribution of the n failure modes. If a system failure has occurred, α_i is the probability that the failure mode is FM_i. The failure modes may not be completely independent (see Figure 2 or 3), since they can have several failure causes in common.

The new and the known systems are compared with respect to structural, operational, and environmental

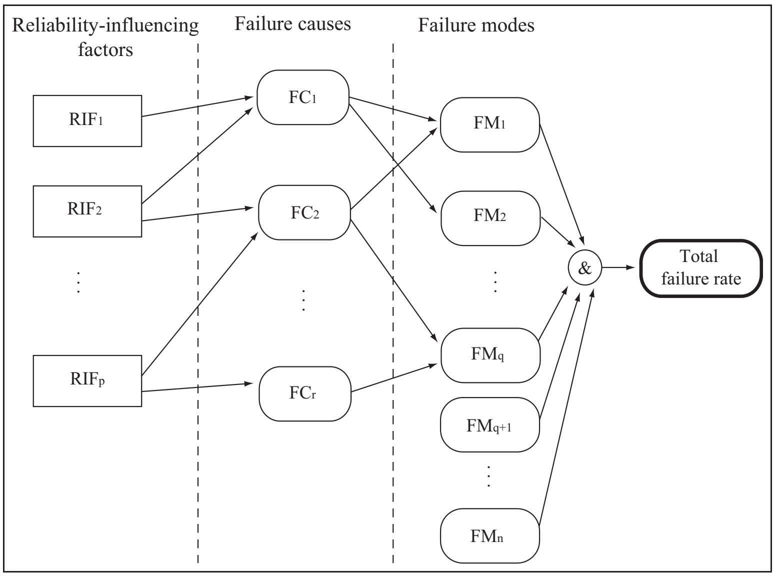

Figure 2. Factors contributing to the total failure rate of the subsea system.

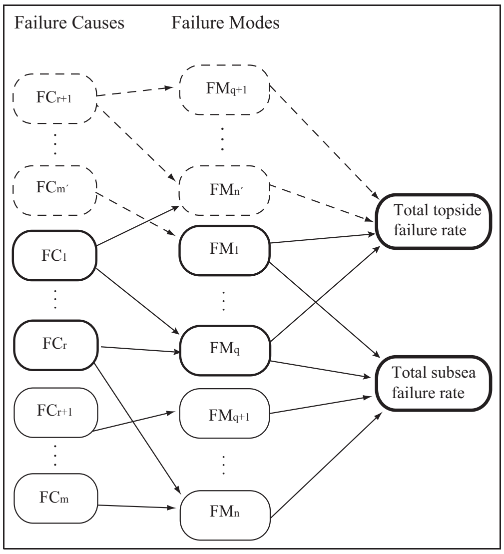

Figure 3. Subsea and topside system comparison.

Table 2. Generic RIFs.

Category		RIFs
Design and manufacturing		System structure
		Materials
		Dimensions
		Loads and capacities
		Quality (manufacturing process, installation, logistics, assembly,...)
Operational and maintenance		Functional requirements
		Time in operation
		Mechanical constraints
		Frequency of maintenance
		Maintenance policy
		Accessibility for maintenance
		Type and quality of maintenance
Environmental	External	Temperature
		Location of operation
		Pressure
		Corrosive environment
		Pollution
	Internal	Pressure
		Sand particles in the fluid
		Chemical content

RIF: reliability-influencing factor.

conditions, and failure modes and failure causes (including failure mechanisms); and similarities and differences are recorded. The new and the known system may not have exactly the same failure modes, and differences must be listed and described. Figure 3 illustrates the comparison of failure modes and failure causes between the new and the known systems. The dashed rounded rectangles and arrows indicate that they belong only to the topside system, the thick rounded rectangles and arrows indicate that they are similar for both the offshore and the subsea systems, and the thin rounded rectangles and arrows indicate that they belong only to the subsea system.

For failure modes that are not relevant for the known system, and consequently not available in OREDA, we may consult other data sources, such as MechRel or RIAC, or rely on expert judgment.

Step 4: Selection of relevant RIFs. The RIFs influence the reliability, and when a RIF is changed, the failure rate of the system may change. Our goal is to determine how much the failure rate changes by evaluating the RIFs' influences on the failure causes. The RIFs that are relevant for the new subsea system are identified based on the physical insight obtained in step 3, combined with expert judgment. It is tacitly assumed that it is possible to measure or evaluate the states of the RIFs.

Table 2 provides a list of generic RIFs, partly based on Ascher and Feingold[12] and Brissaud et al.[17] The generic RIFs in Table 2 are related to; design and manufacturing, operation and maintenance, and environmental factors. The environmental RIFs are classified as internal factors (i.e. mainly affecting the internal parts of the system) and external factors (i.e. affecting the external parts of the system). The effects of the internal factors on a subsea system may be similar to the effects on a topside system, and may sometimes be disregarded in the further evaluation.

The generic RIFs in Table 2 can be used as a checklist to establish a set of specific RIFs for the particular topside and subsea systems. The selection of specific RIFs should be done by experts. In the same way as for failure causes, it is important to try to specify the RIFs as disjunct at possible – so as to guarantee that the influence is more through the individual RIFs than through combinations of several RIFs.

The specific RIFs must next be ranked by experts according to their importance for each failure cause of the new subsea system. This can, for example be done as repeated pairwise ranking, by deciding whether or not RIF_{j,k_1} is more important than RIF_{j,k_2}, for all pairs (k_1, k_2), for failure cause FC_j. The experts should next allocate weights to the various RIFs for failure causes of the subsea system, such that ε_{kj} is the weight of RIF_k for FC_j. The weights should indicate the relative importance of the RIFs and be scaled such that $\sum_{k=1}^{p} \varepsilon_{kj} = 1$ for $j = 1, 2, \ldots, r$.

The selected RIFs are added to the influence diagram, as shown in Figure 2, to illustrate their influences on the failure causes.

Step 5: Scoring the effects of the RIFs. The RIFs selected in Step 4 may be different for the topside and the subsea system. An example is the frequency of maintenance, which for the topside system may involve both preventive and corrective maintenance on a regular basis, while for the subsea system it will only involve corrective maintenance. This should be made clear in order

Table 3. A seven point scale for scoring of RIFs.

−3	−2	−1	0	+1	+2	+3
Much lower effect	Significantly lower effect	Slightly lower effect	No difference	Slightly higher effect	Significantly higher effect	Much higher effect

Table 4. Scoring of RIFs based on comparison with the topside system.

		Failure cause			
Reliability influencing factor		FC_1	FC_2	…	FC_r
RIF_1	Relevance topside	$\nu_{11}^{(T)}$	$\nu_{12}^{(T)}$	…	$\nu_{1r}^{(T)}$
	Relevance subsea	$\nu_{11}^{(S)}$	$\nu_{12}^{(S)}$	…	$\nu_{1r}^{(S)}$
	Scoring topside/subsea	η_{11}	η_{12}	…	η_{1r}
RIF_2	Relevance topside	$\nu_{21}^{(T)}$	$\nu_{22}^{(T)}$	…	$\nu_{2r}^{(T)}$
	Relevance subsea	$\nu_{21}^{(S)}$	$\nu_{22}^{(S)}$	…	$\nu_{2r}^{(S)}$
	Scoring topside/subsea	η_{21}	η_{22}	…	η_{2r}
⋮	⋮	⋮	⋮	⋮	⋮
RIF_p	Relevance topside	$\nu_{p1}^{(T)}$	$\nu_{p2}^{(T)}$	…	$\nu_{pr}^{(T)}$
	Relevance topside	$\nu_{p1}^{(S)}$	$\nu_{p2}^{(S)}$	…	$\nu_{pr}^{(S)}$
	Scoring topside/subsea	η_{p1}	η_{p2}	…	η_{pr}

RIF: reliability-influencing factor.

to help comparing the effects of these RIFs on the failure causes.

Some RIFs may be relevant to only one of the systems. To indicate which of the p selected RIFs that influence the failure causes of the topside and subsea systems, the indicators $\nu_{kj}^{(T)}$ and $\nu_{kj}^{(S)}$ are used, where the topside indicator $\nu_{kj}^{(T)}$ is

$$\nu_{kj}^{(T)} = \begin{cases} 1 & \text{if } \mathrm{RIF}_k \text{ has effecton (topside) failure cause } \mathrm{FC}_j \\ 0 & \text{if } \mathrm{RIF}_k \text{ has no effecton (topside) failure cause } \mathrm{FC}_j \end{cases}$$

and the subsea indicator $\nu_{kj}^{(S)}$ is

$$\nu_{kj}^{(T)} = \begin{cases} 1 & \text{if } \mathrm{RIF}_k \text{ has effecton (subsea) failure cause } \mathrm{FC}_j \\ 0 & \text{if } \mathrm{RIF}_k \text{ has no effecton (subsea) failure cause } \mathrm{FC}_j \end{cases}$$

The effects each RIF has on the subsea system are then compared with the effects the same RIF has on the topside system. For each failure cause FC_j and RIF_k, an *influence score* η_{kj} is used to indicate how much higher/lower influence RIF_k has on failure cause FC_j for the subsea system compared with the topside system. We suggest to use the seven-points scale in Table 3 to assign the score, but other scoring scales may be used if deemed more realistic.

With the scales in Table 3, the score $\eta_{kj} = +3$ indicates, for example, that RIF_k has a much higher influence on failure cause FC_j subsea compared with topside. RIFs that are only relevant for the subsea system and RIFs that have a much higher influence on the subsea system than on the topside system, may be candidates for this score. The score $\eta_{kj} = 0$ means that the influence of RIF_k on FC_j is similar for subsea and topside. Some RIFs may have a high impact on the failure causes of the topside system, but may not be fully relevant for the failure causes of the subsea system. These RIFs must also be considered, and the comparative score $\eta_{kj} = -3$, which indicates much lower effects for subsea system compared with topside system, may be a suitable score.

When $\nu_{kj}^{(T)} = 1$, all the seven points are applicable for scoring, while $\nu_{kj}^{(T)} = 0$, means that only three of the seven points (i.e. only positive points indicating higher influence) have to be considered, since it is meaningless to assign scores indicating a lower effect subsea when there is no effect topside.

The scoring requires detailed physical and operational insight and judgments from experts. Table 4 summarizes the information and parameters introduced above for scoring of the RIFs. The number of RIFs that influence the failure cause FC_j subsea from Table 4 is seen to be $\sum_{k=1}^{p} \nu_{kj}^{(S)}$.

Step 6: Weighing the contribution of the failure causes to failure modes. The failure causes contributing to a failure mode of the subsea system may be different or contribute with different weights compared with the topside system. How much the failure cause FC_j contributes to failure mode FM_i for the topside system is specified as a weight $\omega_{ji}^{(T)}$. The weights can be easily deduced from the data tables in OREDA.[4] In OREDA, it is assumed that the failure causes are disjoint, such that the sum of the weights for each failure mode is equal to 1.

The corresponding weights for the subsea system have to be determined. These weights can be obtained based on expert judgments, technical reports, operational data, feedback knowledge, interview of key staff, and comparison procedure in step 3. In addition, in the previous step, the RIFs have been identified and evaluated. It is therefore very likely that some of our knowledge about the RIFs is incorporated into the values given for $\omega_{ji}^{(S)}$.

The subsea contributing weight of failure cause FC_j for failure mode FM_i is denoted $\omega_{ji}^{(S)}$. If there is no relation between the failure cause FC_j and the failure mode FM_i according to the influencing diagram, then $\omega_{ji}^{(S)} = 0$. The weights should be scaled such that

$$\sum_{j=1}^{r} \omega_{ji}^{(S)} = 1 \quad \text{for} \quad i = 1, 2, \ldots, q \tag{1}$$

where q is the number of failure modes that is similar for both subsea and topside system (see Figure 3).

Step 7: Determination of the failure rate for similar failure modes. The failure rates for the failure modes of the subsea system are determined by adjusting the corresponding failure rates for the topside system based on the influences of the RIFs. Our approach is somewhat similar to the BORA approach.[16] We assume that the failure rate for failure mode FM_i in the subsea environment can be expressed by the failure rate for the corresponding FM_i in the topside environment as

$$\lambda_i^{(S)} = \lambda_i^{(T)} \cdot (1 + \kappa_i) \quad \textit{for} \ \ i = 1, 2, \ldots, q \tag{2}$$

where $\kappa_i > -1$ is a constant scaling factor that needs to be determined.

Since $\lambda_i^{(S)}$ depends on the failure causes of FM_i and their weights, the scaling factor κ_i must depend on the weights $\omega_{ji}^{(S)}$ of the failure causes. The parameter $\omega_{ji}^{(S)}$ can also be interpreted as the conditional probability that if failure mode FM_i has occurred, then failure cause FC_j was one of its causes, that is

$$\omega_{ji}^{(S)} = \Pr(\text{The failure is caused by } \mathrm{FC}_{ji} | \mathrm{FM}_i \text{ has occurred}) \tag{3}$$

The scaling factor κ_i must also depend on how much the various failure causes affect the failure modes of the subsea system compared with the topside system. We suggest that this influence is determined as a weighted average of the scores of the RIFs that influence FC_j, and where the RIFs are weighed according to the relative importance of the RIFs, such that

$$\overline{\eta}_j = \sum_{k=1}^{p} \varepsilon_{kj} \nu_{kj}^{(S)} \frac{\eta_{kj}}{3} \quad \text{for } j = 1, 2, \ldots, r \tag{4}$$

The reason why the weighted average score is divided by 3 is explained below. The factor 3 comes from the highest score in Table 3 and used for normalization. If the scores in Table 3 are changed, this factor must also be changed accordingly.

We now calculate the scaling factor κ_i by

$$\kappa_i = c_i \cdot \sum_{j=1}^{r} \omega_{ji}^{(S)} \cdot \overline{\eta}_j \quad \text{for } i = 1, 2, \ldots, q \tag{5}$$

where c_i is a constant scaling factor whose value is specified later in this step.

We first assume that the failure rate $\lambda_i^{(S)}$ of the subsea system with respect to failure mode FMi can be delimited such that

$$\lambda_i^{(S)} \in \left[\lambda_{Low,i}^{(S)}, \lambda_{High,i}^{(S)}\right]$$

where the boundary values can be determined based on $\lambda_i^{(T)}$. The boundaries are defined by the two factors $\theta_{\min,i}$ and $\theta_{\max,i}$ for each failure mode such that

$$\theta_{\min,i} \cdot \lambda_i^{(T)} \leqslant \lambda_i^{(S)} \leqslant \theta_{\max,i} \cdot \lambda_i^{(T)} \tag{6}$$

The factors $\theta_{\min,i}$ and $\theta_{\max,i}$ have to be determined by expert judgment. From equations (2), (5), and (6), we get

$$\theta_{\min,i} \leqslant 1 + c_i \sum_{j=1}^{r} \omega_{ji}^{(S)} . \overline{\eta}_j \leqslant \theta_{\max,i} \tag{7}$$

Since the values of $\omega_{ji}^{(S)}$ and $\overline{\eta}_j$ were determined in step 6 and earlier in this step, then c_i must be determined as a function of $\theta_{\min,i}$ and $\theta_{\max,i}$.

Considering the extreme case of equation (7) where all the scores of the RIFs, η_{kj}, are given the value $+3$ (maximum case), and also the extreme case when all the scores are given the value -3 (minimum case), the values of $\overline{\eta}_j$ would be 1 and -1, respectively. Along with the fact that the sum of the contributing weights for each failure rate, $\omega_{ji}^{(S)}$ is equal to 1 (see equation (1)), we can infer that in the minimum case $c_i = 1 - \theta_{\min,i}$ and in the maximum case $c_i = \theta_{\max,i} - 1$.

We now suggest that

$$c_i = \begin{cases} 1 - \theta_{\min,i} & \text{when } \sum_{j=1}^{r} \omega_{ji}^{(S)} \cdot \overline{\eta}_j < 0 \\ 0 & \text{when } \sum_{j=1}^{r} \omega_{ji}^{(S)} \cdot \overline{\eta}_j = 0 \\ \theta_{\max,i} - 1 & \text{when } \sum_{j=1}^{r} \omega_{ji}^{(S)} \cdot \overline{\eta}_j > 0 \end{cases} \quad \text{for } i = 1, 2, \ldots, q \tag{8}$$

Then, equation (2) becomes

$$\lambda_i^{(S)} = \lambda_i^{(T)} \cdot \left(1 + c_i \cdot \sum_{j=1}^{r} \omega_{ji}^{(S)} \cdot \overline{\eta}_j\right) \quad \text{for } i = 1, 2, \ldots, q \tag{9}$$

Equation (8) is determined such that:

- If all $\overline{\eta}_j = 0$, then $\kappa_i = 0$, and therefore $\lambda_i^{(S)} = \lambda_i^{(T)}$. This assumption is important to be considered, since it shows that if all the RIFs have the same states as topside, or the negativity and the positivity of the states of RIFs will neutralize each other's effects, the failure rate of the subsea system will be the same as for the topside system.
- If all $\overline{\eta}_j = +1$ (i.e. all $\eta_{kj} = +3$), then $\kappa_i = \theta_{\max,i} - 1$, and therefore $\lambda_i^{(S)} = \theta_{\max,i} \cdot \lambda_i^{(T)}$ (i.e. the right extreme of the interval in equation (6)).
- If all $\overline{\eta}_j = -1$ (i.e. all $\eta_{kj} = -3$), then $\kappa_i = \theta_{\min,i} - 1$, and therefore $\lambda_i^{(S)} = \theta_{\min,i} \cdot \lambda_i^{(T)}$ (i.e. the left extreme of the interval in equation (6)).

Figure 4 shows κ_i as given in equations (5) and (8) and the assumptions mentioned above. It shows how κ_i changes when $\theta_{\min,i}$ and $\theta_{\max,i}$ are changed. The parameter κ_i as determined by $\theta_{\min,i}$, $\theta_{\max,i}$, and η_{kj}.

In Figure 4, we assume a linear relationship between the known points (the three points defined by the three items listed above). We may obviously use other functions depending on how we want to consider the slope; increasing, decreasing, or constant.

Another important aspect of this method is the sensitivity of $\lambda_i^{(S)}$ to the values of $\theta_{\max,i}$ and $\theta_{\min,i}$. If the experts do not determine these factors properly, the values of $\lambda_i^{(S)}$ may differ significantly even with the same scores (see equations (5) and (8)). If the expert judgments could be supported by experience data from generic databases, such as OREDA,oreda09 the result would be more trustworthy.

Step 8: Determination of failure rates of new failure modes, calculation of new total failure rate. The failure rates of failure modes that are only relevant to the subsea system (see Figure 3) cannot be obtained from the available data sources for topside systems. Therefore, the values of $\lambda_{q+1}^{(S)}, \ldots, \lambda_n^{(S)}$ have to be determined based on expert judgments, technical reports, and also limited operational data from other similar systems that are operating in subsea environment .

Finally, the total failure rate for the considered system can be calculated from equation (10). As mentioned earlier, even though the contributing failure modes to the total failure rate are not completely independent, we consider equation (10) to be a sufficiently accurate approximation

$$\lambda_{Total}^{(S)} = \sum_{i=1}^{n} \lambda_i^{(S)} \tag{10}$$

Illustrative example

This section illustrates how the suggested approach can be applied to a new subsea pump that is used to move fluids in a pipeline. The pump is made of components that are normally found in standard topside pumps, but the design and materials are improved and the application is new. Development of new technology for the subsea industry is highly confidential and we are therefore not able to present any real case. The information about our "new" system has therefore to be based on open sources. In addition, subsea systems are complex, and the number of failure modes, failure causes, and RIFs can be so high that we are not able to cover all of them in this article. The purpose of this example is to illustrate the approach, not to present a complete and realistic case study, therefore it does not come to a final result that expresses the realistic reliability.

Step 1: New system familiarization. The pump and the driver (i.e. an electric motor) are integrated in a single pressure-containing cartridge with static seals towards the environment. The pump is a multi-stage pump with several impellers placed in series. This enables a higher pressure increase within a limited area. Critical features for this pump are as follows.

- High reliability is required, which means that all components require special considerations.

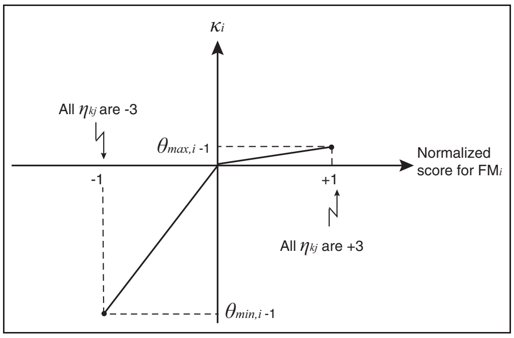

Figure 4. The parameter κ_i as determined by $\theta_{\min,i}$, $\theta_{max,i}$, and η_{kj}.

- The maintenance philosophy is not standard (i.e. not similar to topside application).
- The pumped fluid is only partly conventional, and its properties may change over time.

Step 2: Identification of failure modes and failure causes. All the failure modes and failure causes for the subsea pump have to be identified and listed. In this example, we only consider the most important failure modes, and the failure causes that have a significant contribution to these failure modes. The important failure modes and the failure causes are listed in Table 5. An influence diagram is established in Figure 5, to illustrate relevant relationships.

Step 3: Reliability information acquisition for the similar known system; comparison of the new and the known system. The physical boundary of the known topside pump is specified in OREDA.[4] The subunits of a topside pump are: pump unit, power transmission, control and monitoring, lubricating system, miscellaneous. All the maintainable items related to each subunit are listed in detail in OREDA.

Several reliability data tables for topside pumps are provided in OREDA. [4] For each type of pump, a main data table gives the failure rates for the different failure modes, together with 90% confidence bounds. Another table gives information on which part of the system that failed, and lists the relative contribution from each maintainable item to the total failure rate, and a third table lists the relative contribution from each failure cause to the failure rate.

The subsea pump and the topside pump have to be compared with respect to technological solutions, failure modes, and failure causes. The topside lubrication system is not feasible subsea and a totally different solution may be required, such as magnetic bearings. To assess the effect of this difference will require a detailed analysis and is outside the scope of this article. In this example, we therefore assume that all the important failure modes of the subsea pump are found to be

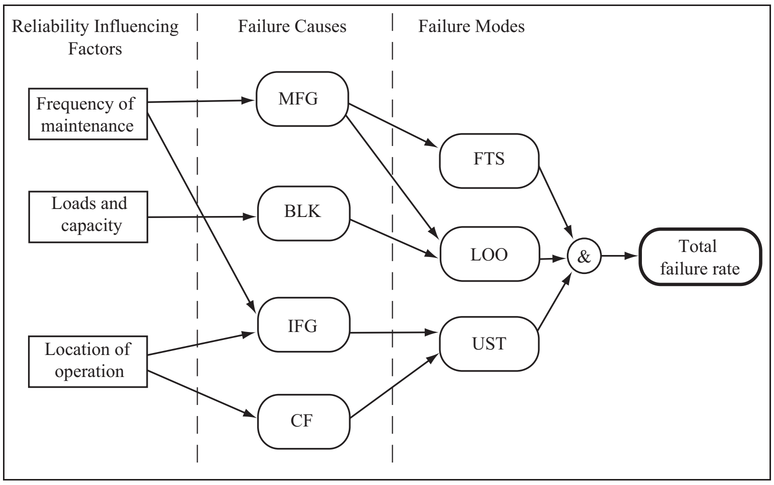

Figure 5. Reliability influencing diagram for a subsea pump
MFG: Mechanical failure-general; BLK: Blockage/plugged; IFG: Instrument failure-general; CF: Control failure; FTS: Fail to start on demand; LOO: Low output; UST: Spurious stop.

similar to the topside pump. The failure causes are also found to be similar, although with different effects.

Step 4: Selection of relevant RIFs. The comparative analysis of the pumps is too comprehensive to be documented completely in this article and we therefore suffice by illustrating the approach for three selected RIFs. These RIFs are selected from the three categories described in step 4 of the stepwise procedure. The selected RIFs are; location of operation, frequency of maintenance, and loads and capacity. Figure 5 illustrates how the selected RIFs affect the failure causes. The weights of RIFs for each related failure cause considered as equal.

Table 5. Important failure modes and failure causes.

Category	Description
Failure modes	Fail to start on demand (FTS) Low output (LOO) Spurious stop (UST)
Failure causes	Mechanical failure-general (MFG) Blockage/plugged (BLK) Instrument failure-general (IFG) Control failure (CF)

Step 5: Scoring the effects of the RIFs. Table 6 summarizes the assessment of the RIFs for the topside and the subsea pump in the format of Table 4. The comparative scores for the subsea pump are given from the seven point scale from Table 3 and indicate how much lower or higher are the effects of RIFs on a subsea pump compared with a topside pump. For example, the RIF "location of operation" effects on the failure cause "IFG" for both subsea pump and topside pump, and therefore they both give the value of 1. In addition the effect of location of operation on IFG for a subsea pump seems to be significantly lower than a topside

Table 6. Scoring of RIFs for subsea pump by comparison with the topside pump.

				Failure causes			
RIFs	Category	Interpretation		MFG	BLK	IFG	CF
Frequency of maintenance	TS	Every year	Relevance	1	0	1	0
	SS	Every 5 years	Relevance	1	0	1	0
			Score	1	0	0	0
Loads and capacity	TS	Normal	Relevance	0	1	0	0
	SS	Up to 2 times more	Relevance	0	1	0	0
			Score	0	0	0	0
Location of operation	TS	Offshore (wind,...)	Relevance	0	0	1	1
	SS	Sea bed (depth,...)	Relevance	0	0	1	1
			Score	0	0	−2	1

RIF: reliability-influencing factor; MFG: mechanical failure-general; BLK: blockage/plugged; IFG: instrument failure-general; CF: control failure; TS: Topside; SS: Subsea.

Table 7. The old and new contribution weights of failure causes of failure modes.

	Failure causes								
	MFG	BLK	IFG	CF	MFG	BLK	IFG	CF	
Failure modes	Old contributing weights ($\omega_{ji}^{(T)}$)				New contributing weights ($\omega_{ji}^{(S)}$)				Sum
FTS	1	–	–	–	1	–	–	–	1
LOO	0.67	0.33	–	–	0.75	0.25	–	–	1
UST	–	–	0.50	0.50	–	–	0.40	0.60	1

MFG: mechanical failure-general; BLK: blockage/plugged; IFG: instrument failure-general; CF: control failure; FTS: fail to start on demand; LOO: low output.

Table 8. Table of the values of $\overline{\eta}_j$ for each failure cause.

Failure causes	MFG	BLK	IFG	CF
$\overline{\eta}_j$	0.33	0	-0.33	0.33

MFG: mechanical failure-general; BLK: blockage/plugged; IFG: instrument failure-general; CF: control failure.

Table 9. Table of the values of θ_{min}, θ_{max}, and κ_i for each failure mode.

θ_{min}	θ_{max}	Failure modes	κ_i
0.3	1.1	FTS	0.033
0.3	1.1	LOO	0.025
0.3	1.1	UST	0.020

FTS: fail to start on demand; LOO: low output; UST: spurious stop.

Table 10. The old and updated failure rates for failure modes.

Failure modes	FTS	LOO	UST
Failure rates for topside pump	40.73	81.46	101.82
Failure rates for subsea pump	42.07	83.50	103.86

FTS: fail to start on demand; LOO: low output; UST: spurious stop.

pump, owing to the design of the subsea pump (i.e. it is located into a capsule), and therefore gives the value of -2.

Step 6: Weighing the contribution of the failure causes to failure modes. The contributing weight of each failure cause to each failure mode for the topside pump are available in OREDA[4] and from step 3. The new contributing weights for the subsea pump have to be determined. These are summarized in Table 7.

Step 7: Adjustment of old failure rate for each failure mode, calculation of total failure rate. It is assumed that $\theta_{\min,i} = 0.3$ and $\theta_{\max,i} = 1.1$ are relevant for all the failure modes. Table 8 shows the values of $\overline{\eta}_j$ calculated based on equation (4). The values of κ_i calculated based on equations (5) and (8) are summarized in Table 9. The failure rate related to each failure mode for topside pump are available from step 3. The updated failure rates for failure modes of the subsea pump are obtained based on equation (9) and are listed in Table 10. The failure rates are given per 10^6 hours.

Step 8: Determination of failure rates of new failure modes, calculation of new total failure rate. Since we have not covered all failure modes, failure causes, and RIFs, we are not able to obtain any failure rate estimate for the subsea pump. In a real case, a subsea pump should be able to survive five years with a probability of at least 95%. This example has only illustrated the stepwise approach. Only three RIFs have been considered, while a complete list of RIFs is very important to be considered owing to the comparative characteristics of the approach. Other important RIFs, such as design and materials, have to be considered.

Discussion

The failure rate that is determined by the suggested approach is not an ontological property of the new subsea system. At this stage the new system is only a concept and does not exist. The failure rate is therefore an epistemological entity that only exists “in our heads”. It has therefore no meaning to discuss whether or not the failure rate estimate is correct. What is important is that the failure rate estimate reflects our best knowledge about the situation and that the estimate has been suggested based on a structured procedure where it is possible to check the relevance of each step.

The suggested failure rate is an important input to the TQP for the new subsea system. The TQP can never guarantee that the new system will survive a time interval of, for example, five years. The role of the TQP is to “provide evidence that the technology will function within specified limits with an acceptable level of confidence”.[1] The evidence must be provided based on a transparent and verifiable procedure. When the operator/client has confidence in the procedure and the results produced by using it, the new system is qualified.

The suggested approach is a proposal and not a “final one” that we claim to be applicable for all new subsea systems. The approach is subject to a number of

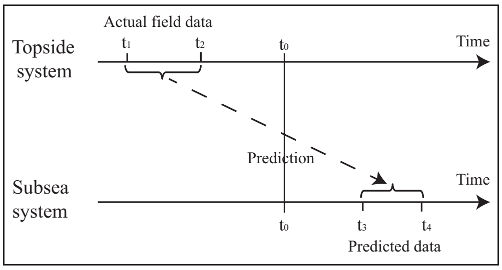

Figure 6. Predicting data for subsea system using topside system's field data.

assumptions and limitations. Some of these are briefly discussed in the following.

- The new subsea system is compared with a single and generic topside system. The new subsea system will, in general, have several subsystems and maintainable items, which may be found in several different topside systems. How to combine information from different systems is not described in the suggested approach.
- The new subsea system may have elements that have previously been used in other subsea systems that are influences by the same RIFs as the new subsea system. How to incorporate experience from the use of these elements is not described in our approach.
- The reliability data used in the illustrative example is from the OREDA handbook.[4] The current edition of the handbook was published in 2009 based on data collected for systems that were in operation in the time period 2000–2003. Some of the systems may have been in use for a long time when the data was collected. This indicates that the reliability estimates in OREDA come from rather old technology that may not represent the current state of the art. The reliability estimates for the new system will apply for future operation, meaning that there may be a time span of more than 15 years. This is illustrated in Figure 6.
- The topside systems are readily available for preventive maintenance and are cleaned and lubricated on a regular basis. When parts of the systems are worn, they are upgraded or replaced. This may be an argument for OREDA to assume a constant failure rate for the topside equipment. The subsea systems are, however, not available for any preventive maintenance, and will normally remain untouched for a long period (e.g. five years). Wear effects will therefore not be removed, and it may be reason to believe that the failure rate of the subsea system is increasing, rather than constant.
- The data in OREDA[4] are generic and average values from several installations, with varying RIFs. In the suggested approach, we compare these inhomogeneous topside RIFs with the specific subsea RIFs. This comparison may give a significant uncertainty.
- The failure rate estimate for the new subsea system is sensitive to the minimum and maximum values ($\theta_{\min}$ and $\theta_{\max}$). To select realistic minimum and maximum values will require extensive experience and knowledge.
- The suggested weighting procedure is a very simple approach and may be improved. Since the approach is transparent, it is, however, easy to introduce new weighting procedures.
- The failure rate estimate for the new system is a single value and we have not discussed how to update this estimate as more information about the new system becomes available (e.g. from detailed analyses and prototype testing).

Scarcity of data lay heavy reliance on the expert's judgments and may significantly affect the results. [22] In the suggested approach, expert judgment has a very important role for deciding the effects of different factors, and determining the parameter's values such as the min–max values.

Conclusions

This article suggests an approach for predicting the failure rate of new subsea systems. The new approach is based on a detailed comparison with a similar topside system, for which reliability data are available. The approach is illustrated by an example of a subsea pump. The failure rate is intended to be used in the design phase of the new system as a basis for design and allocation decisions. The failure rate will, in addition, be an important input parameter to the TQP of the new system.

The new approach has eight distinct steps. Each step is described in detail and emphasis has been put on making each step transparent and verifiable, such that it should be easy for the operator/client to check the relevance and realism of each step – an important feature of any qualification program.

The suggested approach is subject on several assumptions and limitations, some of which are described in the section "Discussions".

The approach is a proposal and has not been formally verified. A possible way of verifying the approach would be to use the approach to estimate the failure rate of a subsea system, from which we have an adequate experience basis. This is, however, not a straightforward task, since the judgments by the experts will likely be biased because of the knowledge that they have about the subsea system.

The suggested approach has been tailor-made for new subsea systems, since this currently is a very relevant challenge for the oil and gas industry. The approach can, however, easily be adapted to estimating the failure rate of other types of new systems.

Declaration of conflicting interest

The author declares that there is no conflict of interest.

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Article 3

Monitoring human and organizational factors influencing common-cause failures of safety-instrumented system during the operational phase

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Monitoring human and organizational factors influencing common-cause failures of safety-instrumented system during the operational phase

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ABSTRACT

Safety-instrumented systems (SISs) are important safety barriers in many technical systems in the process industry. Reliability requirements for SISs are specified as a safety integrity level (SIL) with reference to the standard IEC 61508. The SIS reliability is often threatened by common-cause failures (CCFs), and the beta-factor model is the most commonly used model for incorporating the effects of CCFs. In the design phase, the beta-factor, β, is determined by answering a set of questions that is given in part 6 of IEC 61508. During the operational phase, there are several factors that influence β, such that the actual β differs from what was predicted in the design phase, and therefore the required reliability may not be maintained. Among the factors influencing β in the operational phase are human and organizational factors (HOFs). A number of studies within industries that require highly reliable products have shown that HOFs have significant influence on CCFs and therefore on β in the operational phase, but this has been neglected in the process industry. HOFs are difficult to predict, and susceptible to be changed during the operational phase. Without proper management, changing HOFs may cause the SIS reliability to drift out of its required value. The aim of this article is to highlight the importance of HOFs in estimation of β for SISs, and also to propose a framework to follow the HOFs effects and to manage them such that the reliability requirement can be maintained.

1. Introduction

Safety-instrumented systems (SISs) are used in the process industry and many other industrial sectors to detect hazardous events and prevent such events from developing into accidents. A SIS generally consists of three main subsystems: input elements (e.g., sensors, transmitters), logic solvers (e.g., relay logic systems, programmable logic controllers), and final elements (e.g., safety valves, circuit breakers). The safety functions that are performed by a SIS are referred to as safety-instrumented functions (SIFs). Some failure modes of a SIF are dangerous and may result in severe accidents and cause damage to humans, the environment, and material assets. SIFs are classified according to how often they are demanded, and it is distinguished between low-demand, high-demand, and continuous demanded SIFs [10]. A low-demand SIF is demanded less often than once per year and remains dormant until it is activated. Proof tests are carried out at regular intervals to reveal hidden failures. A SIF is classified as high-demand when it is demanded more often than once per year and is said to operate in continuous mode when demands are always present. The focus of this article is on low-demand SIFs.

The design, construction, implementation, and operation of a SIS are subject to requirements in the generic standard IEC 61508 [10] and in application-specific standards, such as IEC 61511 [11] for the process industry.

Redundancy is often introduced to improve the reliability of SISs, but it is well known that common cause failures (CCFs) may violate the intended reliability gain [30]. The importance of CCFs is documented in a high number of publications, and many of these also discuss how to incorporate CCFs into reliability assessments, e.g., see Lundteigen and Rausand [13] and Hokstad and Rausand [8], and the references therein.

A number of studies have shown that the SIS reliability is generally influenced by a range of HOFs. Schonbeck et al. [29] and Øien [22] discuss the importance of such factors and indicate that a large fraction of CCFs can be explained by human errors and the various factors that influence human performance. For SISs, Carey [4] proposes a framework for addressing HOFs in IEC 61508, and defines the HOFs requirements for a given SIL. HOFs are further pointed out as important contributors to CCFs in NEA [17] and NEA [16], but few publications give any details about this relationship.

A high number of CCF models have been proposed to incorporate the effects of CCFs into quantitative risk and reliability assessments [8]. The most commonly used CCF-model for SISs is the *beta-factor* model [7] and this model has also been highlighted and described in IEC 61508 [10]. The main advantage of the

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beta-factor model is its simplicity, requiring only one additional parameter β that can be easily understood and interpreted as either (i) the fraction of all CCF among all failures of an element, or (ii) the conditional probability that a given element failure really is a CCF affecting several components [27]. Most of the methods for predicting the beta-factor are based on checklists [9,12,10], but in the process industry, the approach described in part 6 of IEC 61508 [10] is dominating and is therefore the basis for this article.

In the design phase, the beta-factor (denoted β_P) is predicted based on several assumptions about the conditions in the operational phase. When entering the operational phase, these conditions may not fully comply with the assumptions made in the design phase. The actual beta-factor in the operational phase (denoted β_A) may therefore be different from the predicted β_P, and this difference may cause the required reliability to not meet the required SIL.

Several studies have shown that HOFs are among the main factors influencing β, but the estimation procedures do have not enough attention to the effects of HOFs. Among the 37 questions provided in IEC 61508 [10] for determining β_P, only about 20% are related to HOFs. This is discussed in more detail by Rahimi et al. [26] who suggest additional questions for incorporation into the β_P determination.

In addition, the SIS end-user needs to have enough awareness about the effects of the HOFs in order to manage them such that the actual beta-factor does not exceed the acceptable limit that are determined by the required SIL.

The objectives of this article are to discuss the main factors influencing the beta-factor for a SIF in the operational phase, β_A and to highlight the importance of the effects of HOFs. A framework for incorporating and managing their effects into the beta-factor model is also suggested.

The structure of the article is as follows. Sections 2 and 3 describe the main attributes of CCFs and discuss about the main factors influencing on beta-factor in operational phase and Section 4 discusses about HOF related CCFs and their effects on beta-factor. Section 5 suggests a framework for incorporating and managing the effects of HOFs into the beta-factor model and Section 6 concludes the article.

2. Common-cause failures in SIS

2.1. Definition

Despite the substantial amount of research, there is still no generally accepted definition of a CCF. Authors of standards, guidelines, textbooks, and scientific articles often make their own interpretation of CCFs, depending on their application area (e.g., see [13,8]). The nuclear industry has put considerable effort into analyzing CCF events through the International Common Cause Data Exchange (ICDE) project. Results from the ICDE project are presented in NEA [18,19]. The CCF definition in IEC 61508 [10] is commonly used in SIS reliability studies, but this definition has some questionable features that are discussed in [26]. This article therefore uses the CCF definition of Lundteigen and Rausand [13], with a minor modification to cover incomplete CCFs: “A CCF is an event that: (i) comprises multiple (complete) failures of two or more redundant components or two or more SIFs due to a shared cause, (ii) occurs within the same inspection or function test interval, and (iii) *may lead to* failure of a single SIF or loss of several SIFs”.

In IEC 61508, SIS failures are classifying as random hardware failures and systematic failures. Random hardware failures are physical failures caused by wear, tear, and stresses (these are dependent since an element that is worn is more vulnerable to tear/stress). These failures are assumed to occur independently of each other. The systematic failures, however, may occur as a result of bad design and decisions and action in all phases of the SIS lifecycle. Such failures are more likely to affect more than one element (in a multi-element system), such that CCFs are likely to be a significant factor when addressing the SIL of such systems. Qualitatively, the standard provides suggestions in order to reduce the occurrence of CCFs:

1. Reduce the number of random hardware and systematic failures overall.
2. Maximize the independence of the components (by separation and diversity).
3. Reveal non-simultaneous CCFs while only one, and before a second, element has been affected, i.e., use diagnostic testing or proof test staggering.

Quantitatively, the standard suggests the use of the beta-factor model.

2.2. Beta-factor model

The beta-factor model is the most commonly used CCF-model, and was originally proposed by Fleming [7]. This model assumes that a certain percentage of all failures are CCFs. When using the beta-factor model, we have to assume that each element of a SIS can fail in two different ways: as an independent failure that only affects the element considered, or as a dependent failure (CCF) where all the elements in the subsystem fail at the same time (or within a short time interval).

The beta-factor model has several weaknesses, the most notable is that it is not possible to distinguish between a common cause event involving all elements of a subsystem and a common cause event involving multiple, but not all, elements. Consider a subsystem that is configured as a 3-out-of-4:G system. This system functions (i.e., is “good” G) when at least three elements are in a failed state and fail when two or more elements fail. When using the beta-factor model, it is not possible to distinguish between a CCF involving all elements and a multiple failure involving two or three elements [8].

2.3. Prediction of application-specific β

Due to lack of data, the beta-factor is often estimated by checklists, such as those given in Humphreys [9], IEC 61508 [10], Johnston [12], and Brand [3].

One of the first methods to determine a beta-factor was suggested by Humphreys [9]. He identifies eight factors that are considered to be important for the actual value of β (grouped in design, operation and environment). The various factors are weighted based on expert judgment and discussions amongst reliability engineers. Some other potential factors are not included because they were found to be too difficult to quantify.

The partial beta-factor method [12] determines β based on partial beta-factors (PBF) obtained by expert opinions of the defenses of the system. The different aspects of the model are broken down into parts (partial β s), and each part is considered separately. All the different defenses are assigned a numerical value, and the product yields the β. This model is not the most rigorous, quantitatively speaking, but it might be helpful if there is no information available regarding CCFs.

The unified partial method (UPM) [3] is developed for the British nuclear power industry. UPM is based on the beta-factor method in the sense that a CCF disables all components in the system. The defenses against CCFs are broken down into eight factors, and five possible levels across each defense, and scores are

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selected from generic tables that have been deduced based on past research.

The approach provided by IEC 61508 [10] part 6 is based on Humphrey' method and provides a “plant specific” beta-factor [8]. Assumptions about the system conditions in the operational phase are combined with engineering judgment to answer 37 different questions. The parameter β is determined based on a weighing and scoring procedure described in IEC 61508. The procedure is an entirely subjective “degree of belief” approach.

The checklists mentioned above are mainly developed for use during the design phase, since most of the questions are related to technical issues in the design phase. In addition these checklists are not properly justified and they lack a scientific basis, have structural ambiguities. Therefore it is not possible to add any operational phase influencing factor or modify parts of them and these methods solely cannot be used for updating of β during the operational phase.

3. β in the operational phase

During the design phase, the manufacturer has to predict the reliability of each SIF and check that the predicted values comply with the specified SIL requirements. These predictions are based on assumptions about the operational, maintenance, and environmental conditions that the SIS will experience when it is put into operation. These assumptions are used to answer the questions listed in IEC 61508. The predicted beta-factor β_P is then determined based on these answers and a simple calculation procedure.

When the SIS is installed, the actual beta-factor, β_A, will be affected by several *influencing factors* and conditions that do not fully comply with the assumptions made in the design phase. The actual value of the beta-factor β_A may be different from the predicted value β_P made in the design phase. This has been illustrated in Fig. 1. The main influencing factors are described later in this section.

An influencing factor is here a relatively stable condition that influences the beta-factor. It may change with time, but does not show rapid fluctuations. Examples of influencing factors are operating conditions, environmental conditions, maintenance policy, staffing level, maintenance competence, and so on.

During the operational phase, the technical properties of the system, such as hardware architecture and component selection, usually remain unchanged unless there is a call for modification. In operation, the SIS reliability will mainly be influenced by: (i) the environmental conditions, (ii) the operational and maintenance/testing procedures, and (iii) the actual human interactions into the systems. By monitoring and managing these influencing factors, it is possible to determine how much they affect the β_A and sometimes prevent β_A from increasing.

With an inadequate management of the operational and maintenance conditions, the beta-factor β_A will have a tendency to increase [5] and, if unattended, the PFD may increase beyond the set SIL requirement as illustrated in Fig. 2. The system's specified SIL provides an upper limit for β, denoted as β_U, and β_A should be kept lower than this limit throughout the operational phase to fulfill the SIL requirements.

For the purpose of monitoring CCFs in the operational phase, it is therefore of interest to split the CCF parameters according to the two main categories of influences, i.e., technical and nontechnical such that

$$\beta_A = \beta_T + \beta_N \tag{1}$$

The two categories of influences are generally not fully independent since a change that influences technical factors may also influence the nontechnical factors. This means that Eq. (1) is only approximately correct. The nontechnical factors have the potential

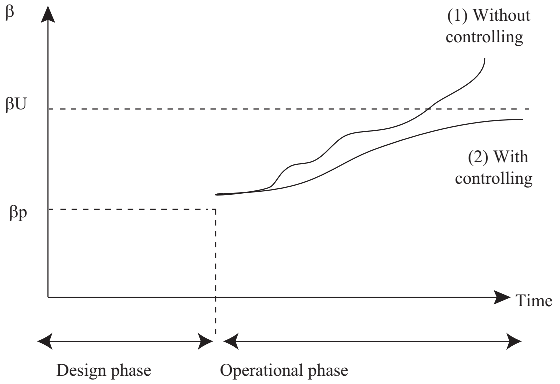

Fig. 2. β in the operational phase.

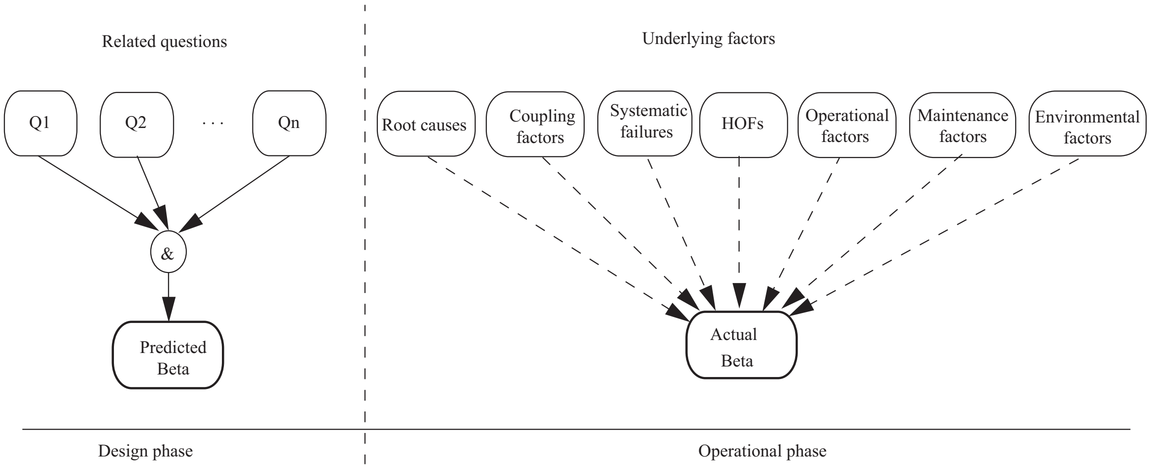

Fig. 1. Determination of the beta-factor in the design and operational phases.

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of being significantly increased during operation, this means that the beta-factor in the operational phase has the potential to be reduced by these factors. In this section we discuss some of the main types of influencing factors.

- *Root causes and coupling factors*: CCFs are often explained based on *root causes* and *coupling factors* [23,24,21].
  A *root cause* is the most basic cause of a failure of an element. Identification of root causes is an iterative process. Root causes may often be shared by many similar types of failures. A corrective action implemented in relation to a particular root cause, may therefore leads to lower failure rates for similar types of elements [2,14,24].
  To identify root causes is a *proactive* strategy aimed at finding the most appropriate corrective actions. Root causes do not always result in CCFs, but many of them have a tendency to result in CCFs. Consequently, management of CCFs requires adequate identification of root causes and the associated corrective actions. A number of methods are available for identification of root causes. Many of them are based on checklists or classifications of potential root causes [8], and may build on lessons learnt from historical CCF events [6,20].
  Coupling factors are properties that make multiple components susceptible to failure from a single shared cause [8] and are identified by searching for similarities in technical design, operating environment, and operation and maintenance practices.
  Identification of coupling factors is, like identification of root causes, often based on classification and checklists. A rather brief classification is proposed by Hokstad and Rausand [8], whereas Mosleh et al. [15] have a more detailed classification of coupling factors.
- *Systematic failures*: Systematic failures are mainly caused by erroneous actions or decisions in all phases of the SIS life-cycle. IEC 61508 requires that a detailed management system be developed to avoid, identify, and remove systematic failures in all life-cycle phases of a SIS. The systematic failures often lead to CCFs.
  In the operational phase, systematic failures mainly stem from improper management of change applied during manufacture, specification, installation, operation and maintenance. For example, the latest version of the embedded software in a transmitter may change according to how the technician configures the device. If the maintenance procedure is not changed, errors may occur during commissioning or maintenance. For this reason, the implementation of a protective management program is required in order to remove and avoid systematic failures.
  The management program to avoid and remove systematic failures is an important issue in the follow-up of beta-factors—and should be discussed thoroughly.
- *Human and organizational factors*: HOFs point at underlying conditions that affect human acts, e.g., policies, procedures, safety culture, supervision, staffing, staff competence, aspects of the working environment when also individual factors (e.g., motivation) are covered by Øien [22].
  Table 1 provides a brief preview on how some authors classify HOFs in their assessments. The HOFs can be classified according to the life-cycle phases, working/managerial levels, underlying factors and so on.
- *Operational factors*: These factors are including the quality of inspection,testing, and bypassing. Any poor, incomplete, and improper actions along with any modifications in frequency of use and loading charge/activation threshold may lead to CCF and therefore affect beta-factor.
- *Maintenance factors*: The quantity/frequency and the quality of preventive and corrective maintenance may lead to CCF and therefore affect beta-factor. For example a SIS element with a low inherent reliability will fail rather often and will require frequent maintenance, which again may cause CCFs.
- *Environmental factors*: It is important that environmental conditions be identified/anticipated accurately at the beginning of the design process. During the operational phase, however these conditions may not remain as anticipated before. Thus the determined criteria from design phase have to be traced and the possible effects of change of environmental conditions on the operational and reliability characteristics of the materials and parts comprising the equipment being designed should be evaluated.

Table 1
Classification of HOFs.

Reference	Category
Øien [22]	Individual Training/competence Procedures, guidelines, instructions Planning, coordination, organization, control Design Preventive maintenance program/inspection
Todinov [31]	Work environment Individuals Management and the organization
NEA [17]	Operational phase Pre-operational phase (design, manufacturing, etc.)
Aven et al. [1]	Personal characteristics Task characteristics Characteristics of the technical system Administrative control Organizational factors/operational philosophy

4. HOFs related to CCF

Several Refs. [17,16,29,22] have pointed out that HOFs are the main contributors to CCFs, but few publications give any details about this relationship.

This fact has not been reflected adequately in the estimation methods for the beta-factor, for example in the checklist questions in IEC 61508 [10].

The IEC 61508 questions that are directly linked to HOFs are listed in Table 2.

Identification of the HOFs that may impact CCFs, starts by identification of the actual or potential, simultaneous or consecutive failures within the redundant, diverse or similar systems, components or barriers, due to a *single or repeated human performance deficiency* [17,25]. All underlying HOFs that lead to this type of human deficiencies (errors) are of interest to us.

During the operational phase, which is the focus of this article, human interaction has a key influencing role, in controlling, processing, and especially in maintenance and testing activities. Many of the ICDE reports also include maintenance and testing activities as a major contributor to experienced CCFs. It is sometimes claimed that manually performed inspections and tests may introduce more failures than what is otherwise expected due to natural degradation. NEA [17,16] indicates that the main HOFs during the operational phase are related to work practice, resource management, communication, managerial methods, documentation, and others.

Many of these factors can be classified as omission error [16,17] in which its origin can be related to both personal factors (e.g., attitude) and organizational factors (e.g., lack of adequate procedures). In many cases, lack of comprehensiveness and ambiguous

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Table 2
HOFs related questions in IEC 61508 [10].

No.	Questions
1	Were the channels designed by different designers with no communication between them during the design activities?
2	Are separate test methods and people used for each channel during commissioning?
3	Is maintenance on each channel carried out by different people at different times?
4	Is all maintenance of printed-circuit boards, etc. carried out off-site at a qualified repair center and have all the repaired items gone through a full pre-installation testing?
5	Have designers been trained to understand the causes and consequences of CCFs?
6	Have maintainers been trained to understand the causes and consequences of CCFs?
7	Is personnel access limited (e.g., locked cabinets, inaccessible position)?

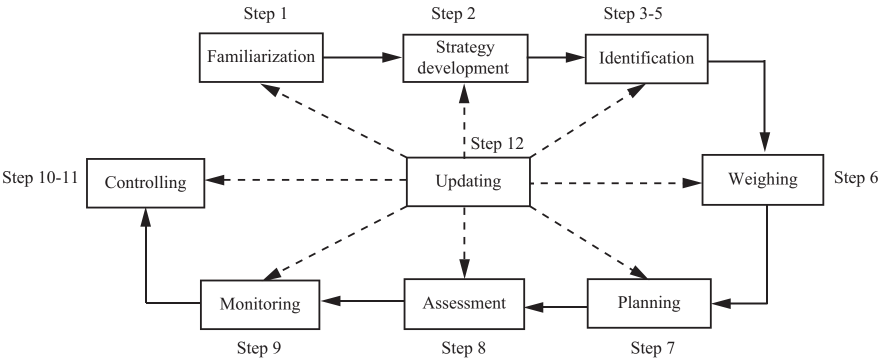

Fig. 3. Framework of managing HOFs influencing β.

statements, and lack of knowledge are mentioned as reasons for omission errors.

The beta-factor for dangerous undetected (DU) failures which lie outside the coverage of the diagnostic tests, is more influenced by HOFs rather than the beta-factor for detected dangerous (DD) failures that lie within the coverage of the diagnostic tests which is mainly influenced by design issues.

5. Management of β_A

5.1. Follow-up based on the questions in IEC 61508

As mentioned in Section 3, the actual β during the operational phase may differ from predicted β, and this difference may result in drifting out of the required value. An option for SIS users can be updating the predicted value of β. An updated prediction may be determined by revising the answers to some operational phase related questions in IEC 61508. Another aspect of this approach is that it is stepwise and therefore always not sensitive to changes of answers to the questions. This means that improving the system to get a “positive” answer will not necessarily be credited with a lower value of the beta-factor.

Another option is to predict a more realistic beta-factor during the design phase. In this order the relevant β influencing factors in operational phase should be taken into the consideration and therefore a set of supplementary questions be defined to IEC 61508 approach. Rahimi et al. [26] suggested a set of supplementary HOFs related questions. The main problem here is how we can consider these questions into the calculation (i.e., their scores) which is not clearly defined in IEC 61508 approach.

5.2. Safety management system for systematic failures

A more practical approach for controlling the β in operational phase can be development of a framework for managing the HOFs and their effects on actual β. A similar approach developed by Øien [22], who assesses the impact of organization factors on the risk. Here we got insight from his approach and tried to develop a framework which is applicable for the beta-factor. The main steps of this framework are summarized in Fig. 3 and described in the following:

1. *Get familiar with the SIS in operation*: Determine the relevant actual operational and environmental conditions. Specify the SIFs and the application of the SIS.
2. *Develop a strategy for identification, analysis, etc.*: Determine the requirements and check how the plan complies with the safety management plan for systematic failures.
3. *Identify related HOFs*: HOFs that may result in changes on the beta-factor (i.e., influence on CCFs) in the operational phase have to be identified. Expert judgment and scientific knowledge are required to determine the influencing factors. Some important HOFs related to operational and maintenance conditions are discussed by [26]. The main categories of HOFs were mentioned in Sections 3 and 4 and more can be found in [1,17,18,26]. Most often, it is difficult to distinguish between human factors and organizational factors, since these two categories are overlapping in some points. An example is “motivation”, which can be both a human factor and an organizational factor. Therefore, we consider these factors as one category (i.e., HOFs) and do not distinguish them any further.
   It is difficult to rank the importance of HOFs in relation to the beta-factor. For instance, we cannot state that the HOF training is more or less important than the HOF accessibility. However an analytical hierarchy process (AHP) [28] might be used in order to weigh them. The weight of HOF i for β is denoted as η_i. These weights can be used, when we want to start some improvements, and we need to start from the important ones.
4. *Identify interconnection between HOFs*: It is important that the HOFs are defined such that they are not interlinked with each

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other. This means that one HOF should not be a subset of, or a cause of other HOFs. It is recommended to establish a Bayesian network to illustrate the potential relationships between the HOFs and the β, as shown in Fig. 4.

5. *Determine status of the various HOFs*: For providing information about the status of HOFs, a set of human and organizational indicators is required to be identified for each HOF. Øien [22] proposes a set of organizational indicators and criteria that may help experts to select suitable indicators. The indicators have to be identified such that: (i) they are not dependent on each other, and (ii) together they cover the status of the HOFs. An example of two dependent indicators are "number of personnel allocated for testing" and "time pressure to perform testing". The same indicator may be used for more than one HOF. An important issue in identifying these factors is the number of indicators. As the number of indicators increases, the complicity of accounting their total state and therefore finding the status of HOFs will increase.
6. *Rate the human and organizational indicators*: A weight is given to each of the selected indicators which represents the importance of the particular indicator among all the selected indicators. The weight of indicator j for HOF$_k$ is denoted ω_{kj}. The weights are such that
$$\sum_{j=1}^{n_k} \omega_{kj} = 1 \qquad (2)$$
for each HOF$_k$. Here, n_k is the number of indicators for HOF$_k$. Fig. 2 shows the human and organizational indicators and their weights.
7. *Make a plan for monitoring the indicators*: Determine how and how often the indicators need to be monitored. For most indicators, it is not possible to measure their values continuously and we have to measure them after specified intervals, for example, every three months [22].
8. *Assess the states of the HOFs using indicators*: Some indicators may be quantitative and have numerical values, and some may be qualitative and have qualitative values. The indicators are not characteristically the same and do not have an identical unit, therefore their values have to be converted such that they are in a uniform format. The measured values of the indicators can be rated according to the five-point scale suggested in Table 3. Other scoring scales (e.g., a seven point scale) can be used if supposed more realistic. If a five point scale is used, the boundaries of these five points have to be defined for each indicator. This requires detailed insight and judgments from experts. If the value of the indicator is between two boundaries, then its value will be converted to the relevant score. Let θ_{jl} denote the upper boundary of point l where $l = 1, 2, \ldots, 5$ for indicator j where $j = 1, 2, \ldots, r$ (see Table 3).
The state of HOF$_k$ is denoted S_k and is obtained by
$$S_k = \sum_{j=1}^{n_k} \omega_{kj} \cdot \nu_{kj} \qquad (3)$$
where ν_{kj} is the value of indicator j related to HOF$_k$.
The HOFs are not completely independent, anyhow we consider (3) as a sufficiently accurate approximation.
Based on the measured states of HOFs, it can be found whether the beta-factor affected by HOFs or not. The beta-factor during the operational phase can be calculated by introducing a scaling factor that is obtained from the states of HOFs and their total effect on β_A. Obtaining this scaling factor is difficult and should be based on expert judgments, since no technical data is available. This is not covered in this article, and instead of finding the total new β_A during the operational phase, we use the effects of changes of HOFs on the beta-factor in order to manage the β_A in the operational phase.
9. *Monitor the indicators and factors according to the plan*: According to the plan from step 8, the state of each human and organizational indicators and also HOFs can be calculated and plotted as illustrated in Fig. 5.
The first measurements should be at the beginning of the operating phase, since we compare the status of each indicator/factor to its previous status. At this stage we cannot say that certain values will meet the predicted β-value (β_P)
10. *Evaluate to find deviation or trend*: We continue to monitor – and check deviation from the previous measurement – and

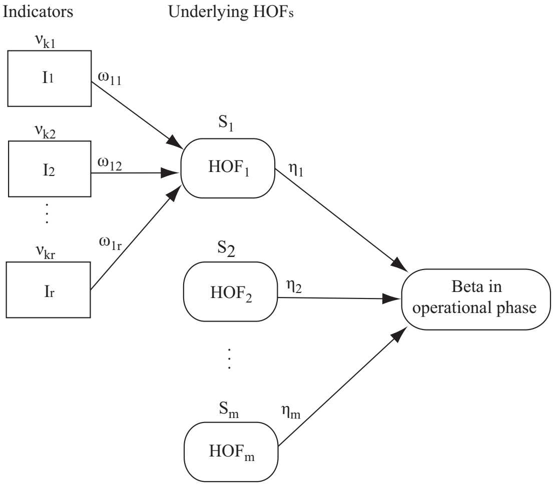

Fig. 4. Influence diagram for β.

Table 3
A five-points scale, converted scores and boundaries for indicators.

Indicators	Converted scores				
	0.2	0.4	0.6	0.8	1
	Very bad	Bad	Average	Good	Very good
I_1	Up to θ_{11}	From θ_{11} to θ_{12}	From θ_{12} to θ_{13}	From θ_{13} to θ_{14}	From θ_{14}
I_2	Up to θ_{21}	From θ_{21} to θ_{22}	From θ_{22} to θ_{23}	From θ_{23} to θ_{24}	From θ_{24}
⋮	⋮	⋮	⋮	⋮	⋮
I_r	Up to θ_{r1}	From θ_{r1} to θ_{r2}	From θ_{r2} to θ_{r3}	From θ_{r3} to θ_{r4}	From θ_{r4}

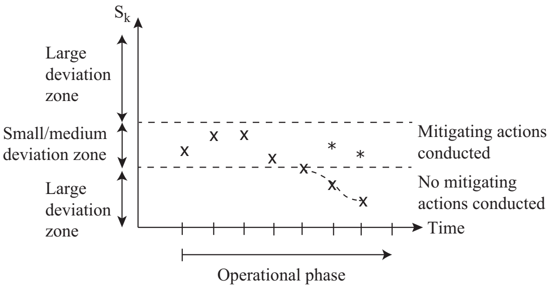

Fig. 5. Monitoring the states of HOF$_k$.

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check for trends. It is suggested that the deviations be categorized by expert judgment into three categories: large, medium, and small deviation. These categories are depending on the SIL requirements.

11. *Conduct the mitigating actions*: If there are significant changes, then mitigating actions need to be identified and implemented (see Fig. 5). A generic list of HOF-related CCF mitigating actions is suggested in the following.

    - Operation, maintenance, and testing:
        - Increase the awareness to CCFs in planning O&M activities
        - Increase the awareness to CCFs in O&M activities
        - Consider CCFs as part of job safety analyses
        - Clarify the complex or difficult O&M and testing activities
        - Monitor the inhibits and bypasses
        - Define the procedures comprehensively
        - Customize the procedures
        - Identify the required preparation tasks and set ups
    - Management:
        - Clarify the responsibilities and roles
        - Develop suitable strategies for adequate staffing
        - Improve interdisciplinary communication skills (with colleagues, supervisors, contractors, and other)
        - Avoid too much individual judgment
        - Make the organizational learning more effective
        - Create enough motivation, morale, and competence in working and in dealing with circumstances
        - Remove time pressure (required times are available)
        - Remove work pressure (productivity vs. safety, or work overload vs. work underload), including stress, fatigue
    - SIS follow-up:
        - Train in CCF awareness
        - Analyses the reported failures
        - Follow-up the identified CCFs
        - Determine the consequences of failures to follow rules/procedures
    - Supporting tools and processes:
        - Label adequately (clarity of signs, signals, instructions and other information)
        - Make additional marking of safety critical components
        - Make adequate access restriction
        - Put security access in place (physical, software)
        - Review the approval process (in relation to planning, restoration, and modification)
        - Define adequate measures to avoid spurious activations (stress level, human machine interface)
        - Provide appropriate tools for task
        - Provide proper working environment (noise, heat, lighting, ventilation, and other)

12. *Updating*: If new HOFs are revealed during the operating phase, they should be added to the initial list of HOFs. The procedure will then have to be updated. In the same way, if initial HOFs are shown to be non-relevant, they should be removed from the list. We may also need to update the weights of the HOFs.

6. Conclusions

This article has proposed a framework to manage the factors influencing beta-factor of SISs in the operational phase to help the SIS users in maintaining the required SIS reliability. In the operational phase, the SIS hardware architecture and the components will usually remain unchanged unless there is a call for modification. The main changes in the likelihood of CCFs are therefore the result of factors related to HOFs and a changing operational environment. The actual beta-factor in the operational phase may differ from the predicted one and the proposed framework is therefore intended as a management tool for keeping the beta-factor below an acceptable upper limit throughout the operational phase.

The basis for the proposed framework is the simple beta-factor model, and the beta-factor is assumed to be determined based on answers to the questions in IEC 61508, possibly with some additional questions.

The proposed method is based on observed values of indicators that provide information about the changing status of HOFs—in line with an approach suggested by Øien [22] for follow-up of organizational factor that influences risk on offshore oil and gas installations.

Further research may be required to find a formula for calculating the actual beta-factor during the operational phase. This has to be obtained based on the amount of changes in the states of HOFs and their effects on the beta-factor. It may be necessary to check the relevancy of the answers to the IEC 61508 questions used for estimation of the beta-factor and actual SIS operational conditions.

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Article 4

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In *International Conference on Industrial Engineering and Engineering Management: Proceedings of the 2012 IEEE*, IEEE conference proceedings 2012, pp. 762-766

Article 5

Reliability prediction of offshore oil and gas equipment for use in an arctic environment
In *Proceedings of 2011 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering*, IEEE Press 2011, pp. 81-86

Article 5

Reliability Prediction of Offshore Oil and Gas Equipment for Use in an Arctic Environment

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***Abstract*—The offshore oil and gas industry is currently moving into the arctic region. The harsh arctic environment will have an unavoidable influence on the reliability of the equipment operated in it. To understand this influence is of vital importance to ensure the reliability of the equipment and the production availability of the systems. Several types of data, such as data on design, production, usage intensity, and operating environment are required to assess and verify the reliability of the equipment. This paper proposes a framework for reliability assessment based on proportional hazards modeling and various types of data. It presents important arctic factors influencing the physical performance and discusses how these may influence the reliability of the equipment.**

Keywords-reliability prediction; proportional hazard model; arctic environment

I. INTRODUCTION

The offshore oil and gas industry is currently exploring new areas in the southern part of the Arctic and is contemplating moving even further to the North. Several arctic characteristics influence the reliability of the equipment operated in such an environment. To understand this influence is of vital importance to ensure the reliability of the equipment and the production availability of the systems.

To identify potential problems and to estimate failure rates at an early stage in the process of product development is important due to the high cost of making design modifications later in the development cycle. Reliability predictions that are updated along with the development process can provide stakeholders with information in their decision-making. Additional objectives of reliability assessments and predictions are:

- to identify potential design weaknesses,
- to compare alternative designs,
- to provide data for system reliability and availability assessments, and
- to establish objectives for reliability tests.

Reliability requirements may be stated according to IEC 60300-3-4 [1] and should be based on (1) the application of the equipment; (2) the failure criteria, i.e., what constitutes a failure of the equipment with the intended application; (3) the operating conditions; (4) the environmental conditions; and (5) the methods intended to be applied for the requirement determination.

Offshore oil and gas installations comprise equipment and structural elements, such as well equipment, X-mas trees, manifolds, pipelines and risers, floating production, storage and offloading (FPSO) vessels, and many more. In some cases, equipment might have previously been used in other environments and is therefore considered as *proven technology*. The arctic environment, however, represents a new challenge for much of the equipment and further research is often required before it is qualified for use.

The influences of the arctic environment on equipment reliability will generally depend on the application of the equipment and where it is located. Topside equipment and connection equipment such as risers and cables might be much more influenced by the harsh environment than well and seabed equipment, although they might experience similar stresses as in southern areas.

The objective of this paper is to outline and discuss important arctic conditions that influence the reliability of topside offshore oil and gas equipment, and to present approaches to reliability prediction based on levels of data availability. The paper focuses on offshore oil and gas facilities operated in an arctic environment, but the approach should be applicable also in similar cases in other industry sectors.

The rest of the paper is organized as follows. Section II describes the characteristics of the arctic environment and its challenges as an operating environment. In Section III, we discuss reliability prediction and current methods, and we describe the proportional hazard (PH) model. Section IV proposes approaches to reliability prediction for different scenarios and identifies a set of arctic factors influencing equipment reliability. Section V concludes the paper.

II. CHARACTERISTICS OF ARCTIC ENVIRONMENT

The Arctic is a region located at the northern-most part of the Earth (latitude 66° 30' north). The infrastructure in these areas is limited with low population density and few industrial establishments to support the petroleum industry.

Until recently, arctic developments have been either onshore or in water depths less than 50m in moderate arctic conditions. The challenges related to exploration and production increase as the activities move to deeper waters, where bottom-founded structures may not be feasible, to areas with iceberg occurrences and regions with multi-year ice, such as the Beaufort Sea, with ice thicknesses up to 8m and ice keel depths that regularly exceed 20m [2].

The Industry Technology Facilitator (ITF) classifies the challenges related to the arctic environment in four categories [3]:

1) *The harshness of the arctic climate:* The arctic climate is characterized by long and cold winters and short and cool summers. The winter temperatures can be lower than -50˚C over large parts of the Arctic and the average summer temperatures can range from about -10 to +10˚C. Additionally, fog is common during the summer.

2) *The impact of ice:* Parts of the Arctic have permafrost such that the ground is frozen throughout the year. A portion of the northern oceans is covered by sea ice for at least a part of the year. For example, the average extent of Arctic sea ice in December 2008 was 12.53 million square kilometers. This was 140,000 square kilometers more than in December 2007, and 830,000 square kilometers less than the December average for the period 1979 to 2000. Sea ice is the dominant surface type throughout the year in the Arctic Basin and covers much of the ocean surface at some point during the year.

3) *The sensitivity of the environment:* The ultimate target is zero discharge and emission to the Arctic. Arctic ecosystems are especially vulnerable to oil pollution as the limited sunlight and cold Arctic climate do not allow for rapid decay of organic pollutants. Hydrocarbons are likely to remain and concentrate in the flat, poorly drained soils and shallow depressions of the Arctic landscape.

   During spring melting, contaminants tend to follow the run-off, ending up in rivers and oceans. Pollution from oil and gas activities can potentially devastate the Arctic marine environment. Associated threats include water dispersal in the drilling phase, and the actual drilling process, which can release oil and chemicals into the water.

4) *The remoteness of the location:* In the Arctic, 24 hours of daylight and 24 hours of night occur at least once a year. The distance from the operational field to relevant resources is often very long.

III. RELIABILITY PREDICTION

Reliability is defined as the ability of an item to perform a required function for a stated period of time and under stated environmental and operational conditions [4]. The reliability of an item can be expressed with quantitative measures such as the *failure rate function*. Some authors prefer to use the term *hazard rate* for the failure rate.

A. Reliability Prediction Methods

Several methods for reliability prediction have been proposed in the literature. Foucher et al. [5] study the reliability of electronic devices and classify the reliability prediction methods into three categories: (1) bottom–up statistical methods, (2) top–down similarity analysis methods based on an external failure database, and (3) bottom–up physics-of-failure methods. The first two categories are based on statistical analysis of failure data, while the last category is based on physics-of-failure models. They compare the methods based on eight specified criteria related to accuracy, ease of data exchange, amount of devoted resources, time to obtain reliability estimate, ease of customization, traceability, repeatability and ability for evolution. They conclude that the best reliability prediction will be achieved by a combination of different methods, depending on the phase of equipment's lifecycle and on the objectives and assumptions of the manufacturer or the customer.

A survey of mean-time-between-failure (MTBF) prediction methods is documented in EPSMA [6] where applications and limitations of the different methods are also discussed. The identified methods provide models for many types of components and assemblies and for different environments. Most of the methods for reliability prediction of electronic equipment are based on the parts count technique (prediction at reference condition) and the part stress technique (prediction at operating condition) presented in MIL-HDBK-217F [7], which provides failure rate estimates for many types of electronic components for temperatures between 0 ˚C and 125˚C.

IEC 61709 [8] presents stress models and values for electronic components as a basis for conversion of the failure rate data from reference (baseline) conditions to the actual operating conditions. The stated stress models are generic for the different component types and contain constants that are averages of typical component values taken from tests or specified by different manufacturers.

The main limitation of these methods is that the predictions are limited to temperatures higher than 0˚C, and therefore not directly applicable to the arctic environment.

Several factors will influence the equipment reliability, and we refer to these as *reliability-influencing factors* (RIFs). A RIF is a relatively stable condition, which by being changed will have a positive or negative effect on the reliability of the equipment. The RIFs should be identified and should, as far as possible, be quantified and monitored. A RIF may be constant (e.g., a design or material feature) or may vary (rather slowly) in time, such as temperature or ice formation [9]. Ascher and Feingold [10] list 18 generic RIFs that influence the failure behavior of a repairable system, but they claim that those RIFs are usually ignored in reliability analysis.

The most commonly used models for times between failures for repairable systems are renewal processes and homogeneous Poisson processes (HPPs). In a renewal process the times between failures are assumed to be independent and identically distributed. An HPP is a special type of a renewal process where it, in addition, is assumed that the times between failures are exponentially distributed, i.e., with a constant failure rate. This means that repairable systems where the observed data indicate any form of trend due to deterioration or improvement of the system, these models are not appropriate. A model with time-dependent failure intensity, such as a non-homogeneous Poisson process (NHPP) may be a better choice [4,11,12].

The models mentioned above consider the time between failures as the sole variable of interest. This may be too restrictive since various RIFs can influence the system reliability. In the past, a rule-of-thumb was either to ignore the presence of RIFs or to split the data sets into two or more subsets based on the major differences in the data sets.

To obtain more realistic estimates of the reliability parameters, various types of regression models have been suggested and the RIFs are included in the models as explanatory variables. Some of the RIFs are qualitative and to include such a RIF into the regression model, it is necessary to define one or more measurable indicators that are correlated with the RIF. This indicator is called a *covariate* or concomitant variable. A covariate may be a continuous variable, a discrete variable taking several values, or a binary variable. The binary variable takes the value 1 when a specific feature is present and the value 0 when the feature is not present.

The most commonly used regression-type models for reliability analysis fall into two categories [13]. The first category is called *accelerated failure time* models, and assumes that the effect of a covariate is to multiply the time to failure by some constant. In this method, the covariates influence how fast the time is running. The accelerated failure time model can be used together with parametric life models such as the exponential [14,15], Weibull, log-normal, and extreme value distributions [16]. The second category includes models from the *proportional hazards* family [17].

B. Proportional Hazards Models

In a *proportional hazards* (PH) model, the actual, application-specific failure rate function, $h_z(t)$, is determined by multiplying a baseline failure rate function, $h_0(t)$, by a positive function, $g(z)$, of covariates such that:

$$h_z(t) = h_0(t)g(z). \qquad (1)$$

Here, $z = (z_1, z_2, ..., z_n)$ is a vector of n covariates (or RIFs). The baseline failure rate function $h_0(t)$ is obtained for some specified normal/known state of the covariates. The covariates will, in the PH model, not change the shape of the failure rate function, but rather change its scale by multiplying the baseline failure rate with a factor that is determined by the covariates.

Cox [18] used the PH model to estimate the effects of different covariates on the times to failures of a system. He suggested a new functional form for the proportionality function $g(z)$ such that

$$h_z(t) = h_0(t)\exp\left(\sum_{j=1}^{n} \alpha_j z_j\right) \qquad (2)$$

where $\alpha_1, \alpha_2, ..., \alpha_n$ are unknown parameters that must be today the most commonly used PH model in life data analyses. By taking the logarithm of (2), a linear expression of the covariates $z_1, z_2, ..., z_n$ is obtained, such that the parameters can be estimated based on linear regression analysis. The regression analysis developed by Cox [18] is based on partial likelihoods and the total approach is usually called Cox regression analysis.

The survivor function corresponding to the failure rate in (2) is given by

$$R_z(t) = R_0(t)^{\left(\sum_{j=1}^{n} \alpha_j z_j\right)} \qquad (3)$$

where $R_0(t)$ is the baseline reliability function for the specified normal states of the covariates and is given by

$$R_0(t) = -\exp\left[\int_0^t h_0(x)dx\right]. \qquad (4)$$

Different functional forms of $g(.)$, however, may also be used other than exponential, for example, a logistic form, $\log(1+\exp(\alpha z))$, an inverse linear form, $1/(1+\alpha z)$, or a linear form, $(1+\alpha z)$. More details on the theory and applications of the proportional hazards model may be found in [18].

In the PH model as presented above, the covariates are constants in time. It is, however, also possible to let the covariates vary with a time τ that may be a time concept that is different from the time to failure, such as the calendar time from production start-up – while the time to failure may be measured as the operational time since the equipment was installed or replaced.

The PH model, and especially the Cox-model, has been applied extensively in medical research [19] and also in reliability applications [17].

IV. MODEL DEVELOPMENT

To apply quantitative reliability techniques we need to have relevant data available. This section presents some categories of data and data sources that are necessary to obtain for realistic reliability estimation. Thereafter a framework for predicting the application-specific reliability of systems operated in an arctic environment is presented.

A. Data and Data Sources

Several categories of data are required to model and analyze the reliability of a system. A survey of *hardware reliability data* sources is given in [20].

- *Technical data* are usually supplied by equipment manufacturers and are necessary for understanding equipment functions and for developing system models. Based on this type of data, similarities among or between equipment can be identified.
- *Operational and maintenance data* are collected under actual operating condition by the customers, and are plant/system specific. A commonly used database is the OREDA handbook [21], which provides data for equipment used in offshore oil and gas production and processing.
- *Environmental data* provide information about the operating conditions for the product and need to be incorporated into the reliability analyses. *Arctic environmental* metadata, Arctic ocean data, arctic environmental data directory, and real-time polar wind data can be used for a better understanding of influencing factors.

- *Regulations and standards* give requirements to the operation of systems and equipment in the arctic environment.

- *Expert judgment* plays a central role in the provision of data for new applications. Experts may possess valuable knowledge that can provide important input to decision-makers.

- *Test data* for parts and components are particularly required for new items for which no historical data are available, but also true for existing items that are to be used in new applications.

- Ideally, test data are obtained from designed experiments conducted under carefully controlled conditions. For complex systems, very extensive testing would be required [22].

B. Framework Development

Fig. 1 shows a proposed framework for prediction of reliability of equipment in an arctic environment. The main steps of the framework are described in the following.

- *Equipment description:* The equipment should be carefully described, including structure, materials and functional requirements. The description may be in the form of drawings, text, data or other relevant documents.

- *Failure modes and failure causes:* All the relevant failure modes for the equipment must be identified and described, for example, in a detailed FMECA [4]. The causes and the RIFs of each failure mode should be identified, with special emphasis on failure causes related to the arctic environment. Some failure causes are linked to various types of events, such as environmental events, construction events, events related to human and organization, and removal and reinstallation events [23]. Some relevant failure causes and RIFs are illustrated in the influence diagram in Fig. 2. The identification and evaluation of arctic RIFs require detailed physical and operational insight, and judgments from experts in several fields. The RIFs identified in Fig. 2 are described briefly in the following.

- *Remoteness of location:* Combined with the harsh climate, the remoteness presents challenges in terms of availability of tools and other resources.

- *High humidity and fog* may result in ice fog, lack of solar radiation, and frosting on windows, visors, and glasses of equipment, and may also cause corrosion and erosion of the equipment.

- *Cold weather* combined with large temperature variations and strong wind, may significantly affect system reliability if the components and subsystems in the system are not properly protected and provisioned. Cold weather may also influence welding processes and lubrication fluids, and cause more failures [24,25]. Materials such as metals, polymers, and concrete may fail more frequently in a cold climate due to their thermoplastic behavior. Ice and snowdrift on the surface of equipment may also increase the weight of the structure, which can easily destroy the structure and lead to a reduction in reliability. Ice and snow, combined with large temperature variation, will cause erosion damage.

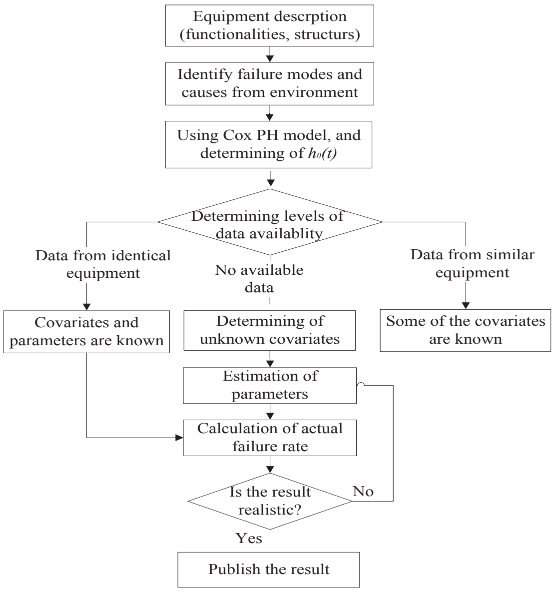

Figure 1. Reliability prediction of equipment in an arctic environment

- *Wind loads* on the structure refer to the forces induced in the part that exerts above the sea level and contains equipments that cause drag from the air motion. It may indirectly affect the equipment connected to them. Arctic has periods of strong wind and with ocean currents cause sea ice to move bringing associated interaction problems with surface and offshore installations.

- *Ice impact:* Floating ice sometimes moves in unpredictable directions, conditions vary and ice fractions change quickly and may impact equipment and result in disorientation and fracture [3].

- *Current* can contribute significantly to the total force applied in the submerged part of the structure. Common categories of current are tidal, circulation and currents generated by storm.

- *Wave* characteristics such as height, period, and directions of loads must be considered to describe the sea state conditions of a selected site.

Having identified all relevant RIFs and quantified them as covariates, we can then use expert judgment and physical insight to delimit the number of covariates and check whether it is relevant to combine two or more covariates or to scale some of the covariates, which is essential a process of selecting covariates z_i. We let $z=\left(z_1,z_2,\ldots,z_n\right)$ denote the set of covariates after having combined and/or scaled the initial covariates.

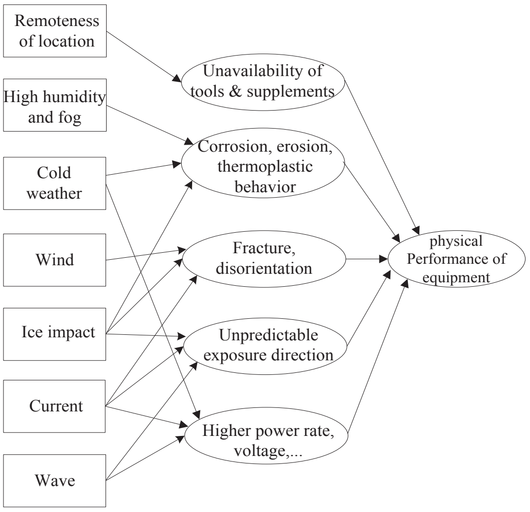

Figure 2. Arctic influencing factors on physical performance of equipment

- *Determining the baseline failure rate function* $h_0(t)$: The Cox model seems suitable for reliability application and inclusion of covariates in the oil and gas industry [9,17]. The baseline failure rate function, $h_0(t)$, should be chosen as the failure rate function for the equipment used in an existing field with covariates as close to the actual covariates as possible; provided that a sufficient amount of operational data are available from this field. In most cases, available data can only be used to estimate a constant failure rate. If the time-depend failure rate function is desired, it may be possible to use knowledge about the deterioration mechanisms to determine the shape of the failure rate curve and then to use the estimate of the constant failure rate to determine the scale parameter of the failure rate function.

- *Determining levels of data availability:* To use failure data from non-arctic environments, it is necessary to carefully compare the actual equipment with the equipment used in the non-arctic environment. The comparison should be conducted based on the characteristics of the considered equipment obtained in the first step, and compared with the characteristics of the equipment used in the non-arctic environments. The results are classified in three levels: experience from *identical*, *similar*, or *different* equipment. For these levels, approaches of reliability prediction are discussed in the following:

a) *Available data from identical equipment*: There might be available data from the same type of equipment, which has been operated in this environment. Uncertainty of determining both covariates $z_1, z_2, ..., z_n$ and parameters $\alpha_1, \alpha_2, ..., \alpha_n$ is in its lowest since they may be known from available data.

b) *Available data from similar equipment*: There might be available data from a similar type of equipment operated in this environment. In this case, the covariates depend on the functions of considered equipment. Some of the covariates $z_1, z_2, ..., z_n$ may be known and then the remaining covariates need to be determined.

c) *No available data for equipment under consideration*: There are neither relevant available data from a type of equipment in the same industry nor with a similar function in this environment.

- *Determining unknown covariates:* The unknown covariates $z_1, z_2, ..., z_n$ need to be quantified for the relevant environment.

- *Estimation of parameters:* The parameters $\alpha_1, \alpha_2, ..., \alpha_n$ need to be estimated by expert judgment supported by the data/covariates from the other fields and possible analyses of these datasets. For each covariate, z_i, the experts should study the comparable covariates and failure rate functions for the other fields and suggest a parameter value α_i that represents an extrapolation of the results from the other fields.

The BORA project [26] is concerned with reliability assessment of safety barriers on offshore oil and gas installations. The approach is based on a set of generic RIFs that are classified into the five categories: human factors, task-related factors, technical factors, administrative factors, and organizational factors. The RIFs to be used for the specific assessment are selected by expert judgment from this set and delimited to maximum six. An influence diagram is then set up linking the RIFs to a defined failure mode. The state of each RIF is classified into one out of six possible states and a scoring and weighing process is used to determine the effects of each RIF. Elements from the BORA approach might also be used as part of the framework outlined in this paper.

An alternative approach based on a PH model is suggested by Brissaud et al. [27]. This approach is also based on a set of RIFs that are classified into five categories: design, manufacture, installation, operation, and maintenance. The estimation of the application-specific failure rate is comparable to the approach in MIL-HDBK-217F [7], but the determination of the multiplicative factors is done in another way by a scoring a weighting procedure. Several elements of their approach might be used as part of the framework in this paper.

Zuashkiani et al. [28] present a methodology for elicitation of expert's beliefs and experience for estimation of the parameters of a PH model with time-dependent covariates which is based on case analyses and case comparisons. Each case describes a combination of a system's working age and covariate values. This method results in a set of inequalities which define a feasible space for the parameter values. The empirical prior distribution can be estimated by sampling from the feasible space. Then, using Bayes formula and statistical data, the posterior distribution can be obtained.

Mazzuchi et al. [29] use a paired-comparison technique for expert judgment to develop a relationship for the probability of failure (using a PH model) as a function of influencing factors in a new environment. A regression model is fit from the failure rate estimates to the environmental variables and is used as an estimate of the failure of new environment.

- *Calculation of the failure rate function:* The actual failure rate for the considered equipment should be calculated based on the Cox model in (2).

- *Checking the result:* As a final step, the experts should review the failure rate function $h_z(t)$ and see if it is realistic. If not, they may have the opportunity to modify some of their α_i estimates.

V. CONCLUSIONS

The producer needs to identify quality problems and potential failures early in the development process to be able to implement improvements in a cost-effective way. Among the reliability prediction methods, the Cox model is an important supplement to the traditional tools for reliability analysis, as it provides the opportunity for incorporating the effect of RIFs. In this paper, a framework for reliability prediction of equipment operating in an arctic environment is proposed based on the Cox model. It has been discussed how the Cox model can be used for reliability prediction of equipment based on levels of data availability. Some important arctic reliability-influencing factors for offshore oil and gas equipment have been identified and their effects have been discussed. The development of the framework has been based on theoretical studies and experience from OREDA and the BORA project. Several approaches to estimate the effects of the RIFs are suggested. But the proposed methodology has not yet been evaluated. This will be done in a follow-up study, and a thorough case study will also be carried out in our future work.

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Article 6

Management of factors that influence common cause failures of safety instrumented system in the operational phase

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Article 6

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Article 7

Continuous reliability improvement of subsea equipment
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Continuous reliability improvement of subsea equipment

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Abstract

Subsea oil and gas production and processing are specialized applications with particular demands. The reliability of subsea equipment is very important due to the extremely high repair and downtime costs, and the potential environmental consequences of oil spills to the sea – especially now when the industry is moving into more sensitive areas, such as the Arctic region. To develop subsea equipment that fulfills the strict reliability requirements requires high competence and analytical skills, and carefully designed procedures. This cannot be achieved overnight and the subsea industry has to adopt a long-term improvement strategy and needs to learn from other industries that are exposed to similar strict reliability requirements, such as the nuclear, aviation, and space industries. This paper outlines how to integrate continuous reliability improvement into the various phases of the development of new subsea equipment, and the paper is structured according to the product development model of Murthy et al. (2008). By lessons learned from reliability activities in various phases of a product's life-cycle, the understanding of failures will increase, and therefore the product's reliability can continuously improve.

1. *Introduction*

The subsea oil and gas industry is an industry with strict requirements to the reliability of their equipment. The provision of new subsea technology with an acceptable level of reliability is a prerequisite to achieve high production availability and low maintenance costs. The time to the first planned intervention may be at least five years, and it is important that the system is able to survive this period without failure. If a critical failure occurs during the operational phase, the associated cost will be extremely high. Therefore, criteria must be prepared with regard to development and testing to fulfill safety and environmental requirements. The suppliers of subsea equipment are required to verify that their equipment is able to meet the end-users' stated requirements regarding functional performance and reliability (Andersen, 2006).

Considering the reliability and reliability improvement from early in the equipment development process is crucial, and inadequate attention can have significant effects on the whole useful life of the equipment (Khan, 2001).

A reliability improvement process aims to identify, correct, and eliminate design and manufacturing deficiencies and failure modes. Reliability improvement techniques can be applied to a new product, to a developed product that the manufacturer wishes to make more competitive, or to an existing product that is not meeting the end-user's expectations of reliability performance. Presumably, the latter case should not occur because the desired level of reliability should be designed into the product before the design is released to production.

The development of highly reliable subsea equipment is not a matter of chance, and a long-term reliability improvement plan must be adhered to during the design and development phases.

The implementation of a reliability improvement process should start by carefully including reliability into the subsea system requirements. It will influence the design process and the way reliability is managed during design and manufacturing in the subsea industry. It will also influence the way systems are selected with increased emphasis on a supplier's reliability management capability (BP, 2002).

The reliability improvement process needs to be followed continuously as equipment moves through its life-cycle phases.

The objective of this paper is to outline a reliability improvement process for subsea equipment that can be integrated with the product development process of Murthy et al. (2008).

The framework will help the subsea equipment producers to focus on reliability needs, forecast and allocate resources, set direction for reliability activities, and consistently deliver improved reliability performance throughout the product development process.

This paper is based on a literature survey of technical reports published by companies and also academic studies.

The paper focuses on subsea equipment for the oil and gas industry, but it is also applicable for other industries that require highly reliable products, such as the aviation and space industry. In addition, the main principles that are proposed based on the product life-cycle model by Murthy et al. (2008), are generic and can also be applied to other product life-cycle models.

The rest of the paper is organized as follows. In Section 2, we get familiar with subsea equipment and their high reliability requirement, and Section 3, briefly presents Murthy et al. (2008) product development process. Section 4, describes reliability improvement, and Section 5 proposes a model for reliability improvement for subsea equipment. Section 6 concludes the paper.

2. *Subsea equipment*

Subsea production systems can range in complexity from a single satellite well with a flowline linked to a fixed platform, to several wells on a template or clustered around a manifold, with roduction to a fixed or floating facility, or directly to an onshore installation (API-RP-17A, 2006).

The exploration and exploitation of reservoirs in deep and ultra-deep waters, and in other challenging environments are usually either technically unfeasible or uneconomical by using traditional surface facilities such as concrete and steel jacket platforms. The development of subsea systems is therefore inherently dictated by environmental conditions.

Subsea technology in offshore oil and gas production is a highly specialized field of application with particular demands. In the development of subsea oil and gas equipment, the reliability is an important factor. The equipment must be reliable enough to safeguard the environment, and make the exploitation of the subsea hydrocarbons economically feasible during a rather long period where the environmental conditions will change significantly (e.g., reduced pressure, changed gas/oil ratio, more produced water, different chemical content).

The deployment of such systems requires specialized and very expensive equipment. Any requirement to repair or intervention into installed subsea equipment will necessarily be very expensive. This type of expense can result in economic failure of the subsea development.

3. *A product development process*

Murthy et al. (2008) develop a new model to assist producers in accomplishing the desired product performance. The model consists of three stages (pre-development, development, and post development) and three levels (business, product, and component). This model has eight phases as listed in Table 1 and briefly described in the following:

Phase	Definition
1	Front-end phase (product definition)
2	System design phase (product characteristics)
3	Component (detail) design
4	Component development
5	System development
6	Physical production
7	Installation, commissioning and operation
8	Business impacts

Table 1 – Phases of product development model by Murthy et al. (2008).

Phase 1, involves identifying the need for a new product or the need for modification of an existing product in accordance with business objectives and strategies and the end-user's needs for the product. The decisions related to the product attributes (end-user's view of the product) are made from an overall business perspective.

Phases 2 and 3 are the most important phases from a producer's perspective. In phase 2, the product attributes are translated into product characteristics (engineer's view of the product) and the desired performance from phase 1 is transformed into a product design, with subsystems and components.

Phase 3 involves detailed design (proceeding from product to component) of the product. All the functions identified in phase 2 are transformed into a (product) design specification describing the individual components and their relevant properties (Murthy et al., 2008). The design specification is used as basis for the specification of components to be purchased. This is the start of product development for subcontractors, and may involve development of new technology.

Phase 4 deals with product development, from component level to the product prototype.

The items are tested in a controlled environment to verify that the desired performance is achieved. For a one-of-a-kind product, the prototype may be the construction of some selected subsystems that require further testing before the final construction of the product is started.

Phase 5 consists of operational testing. Influence from factors such as the usage intensity and the operating environment may reveal additional hazards, contributing to a more complete picture of the actual product field performance.

Phase 6 covers the physical production of the product and deals with the production of products starting from component and ending with the product for release to end-users.

For a one-of-a-kind product, this implies the final construction of a single product at the target application. The production process has to be adapted so that the product achieves the desired performance, and it must not introduce new failures or have any other negative impact on reliability, safety, operability, or maintainability characteristics of the product. When the production process is fine-tuned, the full-scale production of the product can start.

Phase 7 marks the start of the product life-cycle for the end-user and is when the product's reliability, availability, maintainability, and safety (RAMS) performance, that should be integrated from early on in the product development process is challenged and tested in the field.

Phase 8 concludes the product development.

4. *Reliability improvement*

The reliability improvement process provides a means for making advancements when it is applied early in the design stage, or during major design upgrades, or for making evolutionary improvements to existing equipment (SEMATECH, 1995).

The reliability improvement process will reveal deficiencies caused by the design, manufacturing process, and/or operation and correct/remove these deficiencies by testing instead of during operation. It is cost-beneficial over the product life-cycle, since it reduces maintenance and spares (Tomczykowski, 2009).

For implementing a reliability improvement process, it is important to know in which phase of the development process the equipment is. In different phases, different activities should be carried out, and the cost of improvement varies a lot from phase to phase.

The required resources for successful implementation of a reliability improvement process are summarized in the following:

- Equipment/facility resources and physical assets.
- Craft people and equipment/process operator resources.
- Material and part resources and establishing effective materials management processes.
- Information resources, and effective information technology applications.
- Technical knowledge/craft skills resources, and closing the technical knowledge resource gap

Several references (IEC 60300-3-15, 2009; SEMATECH, 1995, Levin & Kalal, 2003) show how to link reliability related tasks into the product design and development process.

Levin and Kalal (2003) consider the reliability improvement process as a proactive process and present different reliability strategies regarding improving product reliability during the product development process, starting from early in the product concept phase.

IEC 60300-3-15 (2009) uses "dependability" as a collective term, for describing the availability performance and its influencing factors such as reliability, maintainability, and maintenance support performance, and provides guidance for system's dependability – and describes a process for realization of system dependability through the system life-cycle to achieve the intended system performance and dependability objectives.

The reliability improvement processes should be mainly based on a simple but practical procedure of test, analysis, and fix (TAAF) in an iterative manner. The term TAAF is often used to describe the sequence of activities by which the failure modes are identified, analyzed, and corrected, and the corrective action finally validated. It should be noted that "fix" refers only to correction through re-design and modification to eliminate the cause of failure and does not imply repair.

In a similar way, SEMATECH (1995) presents an iterative reliability improvement process with five basic steps, which is applied at each phase of the equipment life-cycle:

1. Establish reliability goals and requirements for the equipment
2. Apply reliability engineering or improvement activities, as needed
3. Evaluate the equipment or equipment design
4. Compare the results of the evaluation with the goals and requirements and decide to move either to the next step or the next phase
5. Identify problems and root causes

The process then returns to step 2 and steps 2 through 5 are repeated until goals and requirements are met.

Reliability improvement of an item is through minor design, process, and task changes, which generally classifies as (SEMATECH, 1995):

- *Strengthening the existing design*, by testing and/or modeling to identify optimal design changes to improve reliability.
- *Redesigning part or all of the system*, by considering redundancy, and incorporating error detection techniques.
- *Eliminating known causes of failure,* by using screening and burn-in procedures to eliminate weak components, and using more reliable parts.

5. *Model development*

Activities associated with the reliability improvement process may vary as the equipment moves from one phase of the product development process to the next. This variation results from a change in focus from phase to phase, and from the fact that an activity performed in one phase lays the foundation for activities in subsequent phases. Activities will also vary depending on whether the improvement process is applied continuously as equipment moves through its lifecycle (from the front-end phase to disposal), or whether it is applied for the first time to equipment that is in some advanced (other than concept and feasibility) phase (SEMATECH, 1995).

For continuous reliability improvement in the subsea product development process, we assume the following organizational issues to be available:

- Training, experience, and education in reliability: These are required for effective and systematic involvement of reliability in equipment design.
- Research and development: The research should be carried out in order to develop concepts, tools, and methods to support the reliability strategies.
- Organizational learning: This involves the collection and analysis of data and the generation of lessons learned into a knowledge base, and integrate them to improve system practices.

Fig. 1 shows the proposed framework for continuous reliability improvement within the product development process by Murthy et al. (2008). The main tasks of this framework are described in the following:

Phase 1, Front-end phase

This phase includes the following task:

1) Define reliability requirements: The product reliability requirements should be defined in a realistic way and determined by factors including the targeted application conditions and performance expectations. The product requirements should consider the end-user's needs and the manufacturer's ability to meet those needs. For one-of-a-kind subsea systems, the end-user will usually specify strict reliability requirements, and acceptable outage times.
2) Develop reliability plan: A reliability plan is created to document how the reliability requirements will be achieved. It should mainly consist of; activities to be performed, required resources, schedule, procedures and regulations, required organizations and people for performing the activities. The reliability plan provides a mean of measuring progress and assuring that requirements will be accomplished for both producer and end-user.

Phase 2, System design phase

This phase includes the following tasks:

1) Redefine reliability requirement: The requirements should be redefined as they define the design requirements and form the basis for design specification. They need to be well-defined and understandable by design engineers and manufacturers. Requirements can be both qualitative (e.g., definition of responsibilities and program requirements) and quantitative (e.g., mean time between failures). Redefining the requirements can be done according to the steps provided by IEC 62347 (2006) for system dependability requirements.
2) Create system reliability model: A reliability block diagram (RBD), or a fault tree analysis (FTA) can be used (for more detail see Rausand & Høyland, 2004).
3) Identify the system problems: Identify the potential failure modes, mechanisms, common cause failure by which the product can be expected to fail, and then to prioritize failure mechanisms for efficient product development. Common failure mechanisms for mechanical products are corrosion, binding, and fracture. Specific root causes, including thermal overstress, electrical overstress, contamination, wear out, and mechanical damage must be identified. A precisely completed FMECA will help the analysis process and save valuable time (IEC 60812, 1985).
4) Set up a failure reporting analysis and corrective action system (FRACAS): FRACAS is a closed loop feedback system used to collect and record data, analyze trends, and track problems to root cause. It is ensuring the data integrity and that appropriate data entry fields are in place. For most of the new subsea equipment, historical data from previous applications is not available.
5) Conduct evaluation: Evaluation at this stage comprises a conceptual design review.
6) Corrective actions: If the design requirements are not met, problems and root causes should be identified and corrective actions have to be performed.

Phase 3, Component design

This phase includes the following tasks:

1) Expand reliability model: As the product development process proceeds, it is required to continually change, expand, and improve the

reliability model. This allows the model to be used throughout the development process of the equipment.

2) Data collection: Since the equipment in the design phase has yet not been built, actual failure data may not be available. Therefore, historical failure data from systems that are similar to previous generations of equipment should be collected. For systems where no historical data is available, expert judgment can be used.
3) Reliability prediction: At this stage the prediction can be done based on the previous knowledge of equipment. The main reliability prediction methods are discussed in Rahimi & Rausand (2013).
4) Reliability allocation: This involves allocating or apportioning the equipment reliability into individual subsystems, and components. There are several basic models available such as the equal-apportionment technique, the ARINC apportionment technique and AGREE allocation methods which all are describing in detail in MIL-HDBK-338B (1998).
5) Vendor/supplier selection (for received items): Ensure that the supply-chain participants have the capability to produce the parts (materials) and services necessary to meet the final reliability objectives.
6) Material/part selection: Select the parts (materials) that have sufficient quality and are capable of delivering the expected performance and reliability in the application.
7) Detail design review: A detail design review of the proposed design is carried out to evaluate the design and how well the design reflects the desired performance. The reliability requirements and the predicted reliability values should be compared. If requirements are not met, the problems should be identified.
8) Identify system detail problems: This can be performed in the same way as the previous phase.
9) Set reliability improvement goal: Once the areas of improvement are known with the identified key problem areas, the ways of improving reliability and overcoming the obstacles leading to failure have to be found.
10) Corrective actions: If the design does not comply with the requirements, corrective actions have to be performed. Some of the basic practices according to SEMATECH (1995) are:
    - Adding high-level redundancy. Including more than one method for accomplishing a function by having particular parts or subassemblies in parallel, rather than in series. Redundancy is sometimes the only cost-effective way to design reliable equipment.
    - Using proven high reliability components and parts: To the extent possible, the components that have history of working in the same or similar application areas (i.e., proven) should be used. This will minimize the analyses and testing required for demonstrating the reliability of the equipment.
    - Simplification. Added parts or aspects increase the number of failure modes, therefore simplification of equipment configuration is one of the substantial solutions. A common practice in simplification is *component integration*, which is the use of a single component to perform multiple functions.
    - Derating. Derating is the practice of using components or materials at environmental conditions or loads that are less severe than their limiting condition. Under these conditions, the component or material is expected to be more reliable.

Phase 4, Component development

This phase includes the following tasks:

1) Develop test plan: The aspects that the test plan should consider are; test objectives, parameters, sample size, duration, and environments.
2) Component testing: The component prototypes tests are intended to explore the engineering characteristics of components such as strength, fatigue, fracture, tolerances, corrosion, and aging. The use of physics-of-failure concepts coupled with mechanistic and probabilistic techniques are used to assess the potential problems and trade-offs. The examples of standards that can be used for reliability testing are: IEC 61163-1 (2006), IEC 61163-2 (1998), SEMATECH (1995), MIL-HDBK-781A (1996), MIL-STD-810G (2008).
3) Data collection: The test data should be collected and supplemented by expert judgment. If a FRACAS was initiated earlier, it needs to be updated.
4) Update reliability prediction: The previously predicted reliability should be updated based on the collected data and using a prediction method (Rahimi & Rausand, 2012).
5) Reliability evaluation of received items: Reliability evaluation of received subsystems, components and parts allows the producer to choose those that are the best and that meet the reliability needs of their equipment.
6) Conduct evaluation: An evaluation should be conducted in order to assess the reliability

level of equipment or its design. The reliability of various prototypes is evaluated based on the test data.

7) Corrective actions: In case of problems, corrective actions have to be developed and performed.

Phase 5, System development

This phase includes the following tasks:

1) Product testing: Prototype tests are intended to explore the effects of component interactions under relevant loading and environmental conditions. For subsea equipment, it is not possible to perform operational testing of a prototype in a real environment. Instead virtual product testing by means of simulation can be performed. However, some operational testing may still be performed under similar operational conditions, and some controlling factors may possibly be changed. The standards that can be used for prototype testing are mentioned in phase 4.
2) Data collection: This can be performed in the same way as in the previous phase.
3) Update reliability prediction: This can be performed in the same way as in the previous phase.
4) Conduct evaluation: Reliability of the prototype is evaluated based on the test data. The results of the testing should be compared to the requirements to see if they have been met.
5) Corrective actions: If a FRACAS was initiated, it might identify corrective actions that could be implemented to eliminate failures. Other possibilities include; procedural and process changes.
6) Develop preventive maintenance plan: A preventive maintenance (PM) plan can be developed for subsystems and components that degrade equipment performance. Partnerships established with suppliers are continually nurtured and purchased subsystems and components are continually evaluated.

Phase 6, Physical production

This phase includes the following tasks:

1) Manufacturer selection: The manufacturing and assembly processes must be capable of producing the product as specified in the design. Variability in properties and processes will influence the reliability of the product. Therefore, the characteristics of the process must be identified, assessed, and monitored.
2) Manufacturing process improvement: The defects of manufacturing should be identified and corrected. A process FMECA may be carried out when there is a new process, a modification to an existing process, or when an existing process is used in a new environment or location.
3) Performance tracking and analysis: Tracking the reliability performance of product and analyzing the data is necessary in order to generate useful reliability metrics. The end-user, producer, and suppliers shall collaborate in the development of field performance reporting systems. Data shall be collected on systems, component performance and failures. One of the reliability data collection schemes is OREDA (2002).
4) Variation reduction: Quality improvement requires the never-ending reduction of variation in product and process performance around desired values.
5) Production hazard management: Hazards are required to be identified, assessed and controlled when the production processes are planned, and whenever any changes are made to the system or method of production, substances, and also prior to purchase, hire, lease, or commissioning of plant or substances.
6) Reliability assurance: The contractors, suppliers, and producer are expected to provide documentary evidence to assure the end-user that the required reliability can be and will be achieved. The references to evidence of reliability achievement will generally come from the reliability analysis, calculation, and simulations, along with the documents from testing and expert opinion

Phase 7, Installation, commissioning and operation

This phase includes the following tasks:

1) Installer/commissioner selection: They must be capable of their services within the statistical process window required by the design. This can be done as described for manufacturer selection.
2) Installation/commissioning process improvement: Defects and failures should be tracked, and implementation of corrective actions for improving the processes is required. Likewise the manufacturing processes, a process FMECA can be carried out here.

Phase 8, Business impacts

This phase includes the following task:

1) Realign reliability policies: The key to the success or failure of the whole process depends on management's perception of reliability. Their views should consider competitive advantages, such as reduced down-time, maintenance costs and production losses

	Pre development Stage I	Development Stage II	Post development Stage III
Level I Business	Phase 1		Phase 8
	Define reliability requirements Develop reliability plan		Realign reliability policies
Level II Product	Phase 2	Phase 5	Phase 7
	Redefine reliability requirements Create system reliability model Identify the system problems Set up a FRACAS Conduct evaluation Corrective actions	Product testing Data collection Update reliability prediction Conduct evaluation Corrective actions Develop PM plan	Installer/commissioner selection Installation\commissioning process improvement
Level III Component	Phase 3	Phase 4	Phase 6
	Expand reliability model Data collection Reliability prediction Reliability allocation Vendor selection Material/part selection Detail design review Identify system detail problems Set reliability improvement goal Corrective actions	Develop test plan Component testing Data collection Update reliability prediction Reliability evaluation of received items Conduct evaluation Corrective actions	Manufacturer selection Manufacturing process improvement Performance tracking and analysis Variation reduction Production hazard management Reliability assurance

Figure 1 – Reliability improvement framework within product development model by Murthy et al. (2008).

and therefore make a direct contribution to profitability. The areas that may need reconsideration are such as; end-users' feedback and satisfaction survey, vision and goal, business and resources plans, benchmarking, warranty requirements, and etc.

6. *Concluding remarks*

There is no magical trick that can be used to develop reliable products overnight nor is there a single technique that can optimize the reliability in a short period of time. The success lies in conscious, systematic, and rigorous efforts conducted throughout the entire design and development process of the product.

Reliability improvement takes time and forethought and requires a commitment to change and continuous development. It must be an inseparable part of design and development process strategies.

This paper proposes a framework that integrates the reliability improvement into the product development process proposed by Murthy et al. (2008). The framework provides the required reliability related tasks in each phase of the product development process. This will also give an insight into some of the tools and techniques that are essential in achieving the right strategy for highly reliable products such as subsea equipment.

It is beyond the scope of this paper to explain all the tools and techniques that are related to the provided tasks in each phase. However, the relevant tools are listed and references to recommended literature given.

The improvement of equipment reliability should not finish when the equipment starts operating. The reliability improvement can still continue during the operational and maintenance phases. It requires thorough studies and development of suitable strategies that can be considered as further research areas. Some of the candidates are; maintenance strategy, asset care and failures analysis plans, reliability based spares strategy.

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Article 8

Qualification of new technology: Approaches, challenges, and improvements
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Article 8

Qualification of new technology: Approaches, challenges, and improvements

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Abstract

The oil and gas industry is currently exploring challenging areas, such as ultra-deep waters and the Arctic region. These areas require several new technological solutions and new systems. The oil and gas industry is a conservative industry that is skeptical to solutions and systems that have not been "proven in use," and fear that the new systems may lead to production downtime, oil spills to the environment, and other types of accidents. Before a new technology or a new system is accepted for use, the equipment supplier must convince the operator that the reliability of the new technology/system is sufficiently high. This may be accomplished through a technology qualification program (TQP). Several TQP approaches have been suggested, but only two of these approaches are used in the Norwegian offshore oil and gas industry; one proposed by Det Norske Veritas (DNV) in their recommended practice DNV-RP-A203 and one based on NASA's technology readiness levels (TRLs) approach. Combinations of the two approaches are also used.

The objective of this paper is to present and discuss the main TQP approaches and to highlight challenges related to methodological and procedural issues. This paper surveys the current TQP approaches in the Norwegian oil and gas industry and introduces some potential improvements for integrating the main TQPs.

1. Introduction

New technology includes new products, but also known products used in a new way. They have the potential to create high income, and this is an incentive for their development. On the other hand, product failures may give harmful consequences when the new products are used in operational activities. Criteria must therefore be prepared with regard to development, testing and use in order to fulfil the requirements to health, safety and environment. Various qualification processes assist in developing the wanted product, and reduce the risk of developing a product that is not fit for purpose. In some application areas, such as the offshore oil and gas industry, it has therefore become common to require suppliers of subsea equipment to verify and document that the supplied product is able to meet stated requirements to functional performance and reliability (Andersen, 2006). The demonstration process and the management of the progress are referred to as a *technology qualification program* (TQP).

A TQP can be accomplished by testing and/or analysis. Qualification based on analysis is often the only option for one-of-a-kind products, such as subsea processing systems.

One of the commonly used TQPs is described in the recommended practice DNV-RP-A203 (2001). It is intended for qualification of new technology in the offshore oil and gas industry, but the main principles can also be used in other application areas. A second edition of DNVRP-A203 (2011) was issued based on the experiences gained from using the first edition. In the new edition, an iterative qualification strategy is implemented in the stages of development.

Another commonly used TQP, based on *technology readiness levels* (TRLs), was introduced by the U.S. National Aeronautics and Space Administration (NASA), in the late 1980s. The Subsea Processing Community (SPC) adopted and modified the method to make it applicable for equipment used in subsea production systems. TRL is a metric or measurement system that is used at different stages to assess the development status and maturity of a specified technology or product (Smith, 2005).

Currently, the companies in the oil and gas industry who use these approaches encounter difficulties, and they try to overcome these by combining and adjusting the best features of the two TQPs to their own products.

The objective of this paper is to present and discuss existing approaches of qualification of new technology, and to point out the strengths and weaknesses of each approach. Thereafter, supplementary tasks are suggested for the two commonly used qualification processes.

The paper is based on a thorough literature survey and review of technical reports and papers published by companies, describing their long-term practical experience. Papers from academia are also reviewed.

Qualification of new technology is a broad subject that can range from consumer products to custom-made products. The main focus in this paper is on components, equipment, and assemblies used in the subsea oil and gas industry.

The rest of the paper is organized as follows. In Section 2, we describe important concepts regarding classification of technologies, qualification, and its approaches. In Section 3, we describe two main qualification processes and Section 4 presents some of their ambiguities and challenges. Section 5, introduces some potential improvements for integrating the main TQPs, and section 6 concludes the paper.

2. *Basic concepts*

2.1. Classification of technology

How detailed and comprehensive the TQP must be depends on the level of *newness* of the technology. Several classification systems for the newness of technology have been developed to assist in prioritizing TQP activities.

In the aerospace industry (TOR-8583-5236, 2006), new technology is defined as that which (i) has never been previously characterized, (ii) has limited space heritage, or (iii) is commercial off-the-shelf (COTS) technology.

In DNV-RP-A203 (2011), technology is new when it is not *proven*. Technology is said to be proven when it has a well-documented track record from the same environment and application. Such documentation must provide confidence in the technology from practical operations, with respect to the ability of the technology to meet the specified requirements.

The equipment to be qualified can be classified according to: (i) the newness of the technology and (ii) the amount of experience from previous applications of similar technology in the actual operational and environmental context. Based on these factors, DNV (2008) classifies technology (and products) into four categories with three levels for technological maturity and three levels of operational experience as illustrated in Table 1.

The four degrees of newness listed in Table 1 are:

1. *No new technical uncertainties.* This is the least demanding category, where proven (i.e., well known) technology is used in a known application.

	Level of technology maturity		
Experience with the operating condition	Proven	Limited field history or not used by company/ user	New or unproven
Previous experience	1	2	3
No experience by company/user	2	3	4
No industry experience	3	4	4

Table 1 –The degree of newness of technology (DNV, 2008).

2. *New technical uncertainties.* This category has two subcategories:
   (a) Technology with a limited field history (i.e., partly known) that is used in a known application.
   (b) Proven (i.e., well known) technology that is used in a new application for the company/user.
3. *New technical challenges.* This category has three subcategories:
   (c) New or unproven technology that is used in a known application.
   (d) Technology with a limited field history (i.e., partly known) that is used in a new application for the company/user.
   (e) Proven technology that is used for a new application for the whole industry.
4. *Demanding new technical challenges.* This is the most demanding category where:
   (f) New or unproven technology is used in a new application both for the company/user and the industry.
   (g) Technology with limited field history that is used in a new application for the industry.

This classification applies to the totality of the technology as well as to each of its parts, functions, and subsystems. It is used to highlight where care must be taken due to limited field history. Technology in category 1 is proven technology where proven methods for qualification, tests, calculations, and analysis can be used to document margins. Technology in categories 2 to 4 is defined as new technology, and must be qualified according to a qualification procedure.

2.2. Qualification

Andersen (2006) describes qualification as “activities in addition to development and operational planning activities to ensure that products are functional, safe, and reliable”. Qualification may be understood as “*confirmation by examination and provision of evidence that the new technology meets the specified requirements for the intended use*” (DNV-RP-A203, 2011).

The qualification can be performed by the producer

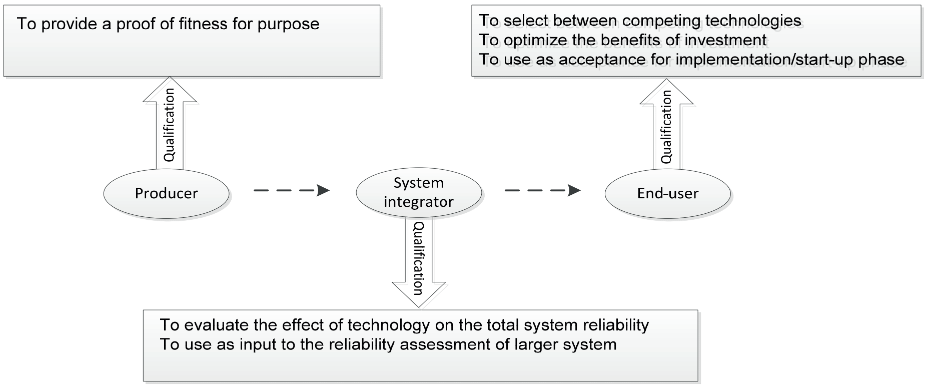

Figure 1 – Qualification purposes.

, the end-user, or an independent third party (DNV-RP-A203, 2011). The producer provides the parts, components, or subsystems for the system integrator and the system integrator provides the final required systems for the end-users, and they all use the qualification process. This summarized in Fig. 1 along with the purposes each may have by performing qualification.

When we claim that a product is qualified, this should not be misunderstood as a property of the product, rather it implies that according to the provided evidence, our belief is that the product is fit-for-purpose and can start its operational phase.

Performance criteria for the product and/or the technologies may be specified by the producer, regulatory bodies, or by the end-user and may be related to various reliability measures based on the time-to-failure probability distribution and/or some defined margins against specified failure modes (e.g., see DNV-RP-A203, 2011 and IEC 60300-3-4, 2007).

2.2.1. Types of qualification

Qualification of new technology can be performed from several perspectives:

(i) Proactive versus reactive approach

In the reactive approach, the close-to-final product is examined as a black box by comparing the product's properties with specified requirements as final inspection at the manufacturing site (or as incoming inspection by the end-user). The approach is reactive in the sense that it adds an additional phase to the development, and hardly differentiates in giving focus on those issues that really need to be qualified (Gerling et al 2002).

The proactive approach considers qualification as an integrated part of design and development with early involvement in this process. In this approach, technology and design properties common to all products or product elements are identified and results gained on similar products are considered.

(ii) Analytical versus experimental qualification

The *analytical* approach is a proactive approach without testing. The main reason for this type of qualification is the need to reduce the time and cost associated with the design and development of new products as highlighted and exemplified in NATO AVT-092 (2009). In the analytical approach, reliability and quality assessments are part of every phase of the product development process. This method is mainly applicable for specialized, custom-built products (Sunde, 2004).

The *experimental* approach typically involves laboratory testing under defined conditions, and sometimes also field-testing. Some advantages of this method are; ease of application and comparable data sets for different products and technologies (Preussger et al, 2003). The disadvantages are more apparent, such as:

- Increasing efforts related to stress-testing of complex products.
- Excessive testing time required for high-reliability products.
- Sample size inconsistent with reliability targets.
- Complicated and time-consuming root cause analysis of products in case of failures.
- Reliability results generated at the end of the development process.

Pecht (1993) argues that the TQP should not be based solely on testing and it depends on the risk level, various risk-reducing factors, the ability or inability to test large one-of-a-kind systems operational environment, and regulatory requirements. On the other hand, qualification solely by analytical methods may not be appropriate to verify the reliability and safety of products in high-risk industries such as nuclear power plants and offshore oil and gas platforms. For these industries it may be more relevant to qualify products on the basis of analysis combined with testing, and by using historical data from tests and field service.

Therefore, a combination of analytical methods with experiments is recommended. A more detail discussion on advantages and disadvantages of analytical and experimental qualification is given in NATO AVT-092 (2009).

(iii) Physical versus actuarial approach
In the *physical* approach, the focus is on analyzing the physical phenomena related to the strength of the item and the loads applied to it. It is mainly used for analysis of structural elements. Loads and strengths are modeled as random variables, and failure takes place when the load exceeds the strength (Choi et al, 2007).
In the actuarial approach (also called *statistical* approach), the explicit loads and strengths are of little interest. Instead, it pays attention to the effects of the interaction between the physical variables (Rausand & Høyland, 2004). Here, the reliability is expressed in terms of a probability distribution for the time-to-failure, which is often selected based on the properties of the failure rate function. The actuarial approach is primarily appropriate for multicomponent systems.
A combination of statistical methods based on physical analysis will be appropriate for many new products or technologies.

3. Qualification processes

Several qualification processes are described in the literature. A summary of these processes including their main application area and a brief description is given in Table 2.
DNV-RP-A203 (2011) and TRL (Smith, 2005) are the most commonly used qualification guidelines and are discussed in more detail in the following. The qualification tasks in these guidelines can be carried out independently from the product development model of the producer, therefore the end-users or a third party can also perform them.

3.1. The DNV qualification process

DNV-RP-A203 (2011) defines a set of activities that should be iterated through the three stages: (a) concept evaluation, (b) pre-engineering, and (c) detailed engineering. Each stage should to be successfully concluded before going on to the next stage. The activities are illustrated in Fig. 2.
Qualification methods must be selected to ensure that all potential failure modes are identified and addressed in a satisfactory manner, so that the margins to failure are documented and the reliability of the product can be proven. (For qualitative methods see Rausand & Høyland, 2004).
Some companies in the oil and gas industry such as FMC Kongsberg Subsea AS, have developed their own tailor-made TQP based on the DNV-RP-A203. The FMC procedure introduces several improvements concerning both the specification of requirements to which the technology is to be qualified, and a flow diagram to ensure that the process is carried out in a structured way. The main activities of the FMC procedure are described by Sunde (2004). The FMC procedure has the potential for significant cost saving, since the qualification process is more streamlined and efficient with reduced requirements for physical testing—such that tests are only performed when strictly necessary. Potential deficiencies and malfunctions should be revealed during the design and qualification phases, such that the number of in-service failures is reduced. This is particularly important for subsea oil and gas production and processing systems that are not accessible for normal maintenance and repair, other than through high-cost vessel operation.

3.2. Technology readiness levels

The TRL method was initially introduced by NASA (Mankins, 1995) and then was adopted by the U.S. Department of Defense, and by the U.S. Air Force Research Laboratory (Smith, 2005). Thereafter SPC modified the TRL method for their products, and used this method to determine the qualification status for several new technologies/products.

Qualification processes	Main application area	Description
NATO AVT-092 (2009)	Military aircraft	Reduces time and cost of production through qualification by analysis
Andersen (2006)	Oil and gas well technology	Performs qualification in parallel with product development process
SEMATECH (1995)	Semiconductor equipment	Includes (1) lifecycle and reliability improvement process; (2) management responsibilities; and (3) activities and tools
API-RP-17N (2008)	Subsea technology	Focuses on project execution, by setting a number of integrated reliability and technical risk management activities which derived from the 12 key reliability processes in (ISO 20815, 2008)
Ardebili and Pecht (2009)	Mass-produced electronic product	Divides the qualification process into (1) virtual, (2) product, and (3) mass production qualification
Engel (2011)	Various manufacturing industries, civilian agencies, or the military	Provides verification, validation and testing activities/ methods through the V-model life cycle of systems.

Table 2 – Qualification processes.

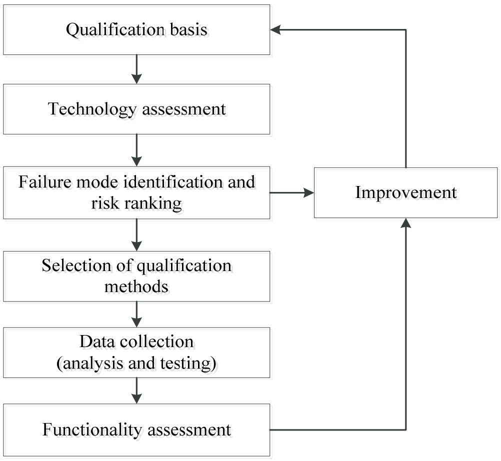

Figure 2 – The DNV qualification process (DNV-RP-A203, 2001).

The levels are developed as part of an overall risk assessment process, to support the assessment of a particular product and provide a consistent comparison of maturity between different products.

The TRL method is a systematic metric or measurement system that supports assessment of a particular technology/product and a consistent comparison of the maturity between different types of technologies/products. The TRL assessment may be carried out in two different ways:

- As a continuous evaluation of the qualification status of the project.
- As a methodology to assess the qualification status before the project is going to the next phase in the development process.

The TRL method has nine levels (TRLs), ranging from zero to eight. TRL 0 is the lowest level of product maturity, while TRL 8 represents the proven product. These TRLs are determined by tangible evidence identified during the product development. Obviously, the tests at each level have to be successful to claim that a level is reached (Berntsen, 2008). A summary of the TRLs is given in Table 3.

A more comprehensive readiness assessment should move from an individual technology context to a system context, where interplays between multiple technologies are also involved. The concepts of system readiness level (SRL) and system maturity have been introduced and discussed in (Sauser et al, 2008 and Sauser et al, 2006).

3.2.1. The TRL calculator

The TRL calculator is developed by the U.S. Air Force Research Laboratory as a tool for applying TRLs in technology development programs.

TRl	Definitions
0	Basic principles observed and reported
1	Technology concept and/or application formulated
2	Analytical and experimental critical function and/or characteristic proof of concept
3	Component and/or breadboard validation in laboratory environment
4	Component and/or breadboard validation in relevant environment
5	System/subsystem model or prototype demonstration in a relevant environment
6	System prototype demonstration in an operational environment
7	Actual system completed and “flight qualified” through test and demonstration
8	Actual system “flight proven” through successful mission operations

Table 3 – Definition of the TRLs (U.S. Department of Defense, 2005).

In its current form, the calculator is a Microsoft Excel spreadsheet application that allows the user to answer a series of questions about a technology project. When the questions have been answered, the calculator displays the achieved level. The calculator provides a formalized and repeatable process for evaluating the readiness of technology/product under development.

The TRL calculator can be a helpful tool in a risk management plan. It can give the manager a significant amount of information about the overall program risk. This is because, in general, the higher the maturity level, the lower will the risk related to implementation of the product be. The calculator’s questions and the percent complete feature can assist the program manager in tracking progress toward accomplishing required tasks (Nolte et al 2003).

4. Ambiguities and challenges related to the DNV and TRL approaches

Several companies are currently using the DNV and TRL approaches, but encounter several difficulties. The challenges related to the TRL approach are partly organizational and partly methodological. Several authors (e.g. Graettinger et al, 2002, Sauser et al, 2006, and Mankins, 1998) have discussed these challenges.

The main challenges related to the TRL approach are:

- **Difficult to use for complex product:** The TRL approach seems more suitable to evaluate the maturity of an individual item. Obtaining the right level of technology maturity levels across multiple subsystems and components is rather difficult.
- **Lack of a figure of merit:** To develop a figure of merit that quantifies the uncertainty of a new product development and especially that allows assessment of anticipated re-

search and development uncertainty. One such figure of merit is the research and development degree of difficulty (R&D^3), which was developed by NASA. The R&D^3 classifies the probability of development success with "normal" R&D effort into five levels, ranging from 20 to 99% (Graettinger et al, 2002).

- **The ambiguities of levels:** It makes it difficult to define when a TRL has been attained.
- **Insufficient attention to the testing inability of some products:** The TRL approach also ignores the possibility that some prototypes and products cannot be tested. For one-of-a-kind products, a full product testing is usually not possible and more analytical approaches should be considered.
- **Limited information about higher levels:** The current TRL does not provide enough information about the development uncertainty; nor does it tell anything about the likelihood of reaching a higher TRL. The TRLs do not evaluate the future uncertainty of TRL maturation.
- **Not enough attention to system and design verification:** They are necessary during the detail design, and have to be performed before component verification in levels 3 and 4, but they are not well considered.
- **A lot of documentation:** The approach leads to more paperwork, reporting, and reviews.

The main challenges related to the DNV approach are:

- **Complexity of quantitative analysis:** The DNV approach is divided into a qualitative and a quantitative analysis loop. The quantitative analysis loop is, by some practitioners, considered to be too complex and also too theoretical.
- **Focuses only on technical qualification:** The DNV approach focuses on reliability and also on reducing uncertainty in developing new technology, but it does not focus on their fit-for-purpose characteristics such as environmental issues, noise, user-friendliness, and human-machine interface (Corneliussen, 2006).
- **Considers a poor product development process:** The process considered in the DNV approach is not precise; it has only three stages, which obviously is not sufficient for complex systems such as subsea equipment. This is important since if a need for modification in the design or development is revealed, the modification can be implemented before it becomes too late. The better the TQP is integrated into the product development process, the less problems may occur.
- **Cannot be considered as a united language:** The DNV approach can be performed by the producer, the end-user, and a third party/supplier, but this approach cannot be seen as a united language between them. The importance of this issue is more obvious for a complex product that has several suppliers and subcontractors, and also for a one-of-a kind product where the end-user and the producer are closely interlinked during the development of the product (e.g., during development of new subsea oil and gas equipment).
- **Similarity of tasks in each product development phase:** The set of defined activities should be iterated through each product development phases (see 3.1.), while the characteristics of each phase are quite different. Each phase requires specific tasks according to its characteristics.

5. Potential improvements

This paper has so far examined the qualification processes and presented some general challenges related to the DNV and the TRL approaches. Several companies have tried to integrate the two TQP approaches to overcome these challenges, but they are still facing problem. In the following, this paper suggests a set of principles for improving the performance of the integrated TQPs:

1) **Stepwise structure:** The integrated approach should structurally rely on the TRL approach, since the TRL approach is interlinked with a more detailed product development process, and also is a stepwise approach that easily can be followed.
2) **Detailed design process:** The integrated approach requires an extra step or level between TRL 2 and TRL 3 focusing on "system/design verification". Additional tasks for this step are: design review, compatibility and interface analysis, and verification of system architecture. To fulfill the requirements of this step, the appropriateness of the system architecture and the components and their interactions need to be verified.
3) **Clarity of steps:** Clarification of the steps is important in order to avoid ambiguities during the project execution. The improved approach has ten steps. The required tasks for the new step are introduced in item 2, and the required tasks for the nine remaining steps can be found in the TRL approach, but needed to be reviewed and combined with DNV's set of activities (see Fig. 2). The relevant methods and tools for the various tasks can be found in recommended literature in section 3.

4) **End-users within the design process:** Many products for the subsea oil and gas industry are one-of-a-kind products, and require a more transparent design process from the end-user's point of view. During the design process, the producer must ensure the end-user that their work has the required quality and that the product will be suitable for the intended purpose.
   The reliability requirement specification for the product is set up in cooperation between the end-user and the producer, and provides a basis for the design. The specification document should be a living document that is further developed and maintained through all the product development phases. At specified stages, it must be verified that the product design is in agreement with the specification document. A reliability analysis report is often developed by the producer, as part of the detailed engineering and development phase, to document compliance with the given requirements.
5) **Third party involvement:** Involvement of a third party in the qualification process should be considered – to perform independent analyses and tests to verify the validity of the qualification evidence and conclusions. The third party should assess and witness the qualification process and also assess analyses and tests performed to confirm compliance with specified standards (DNV-RP-A203, 2011).
   The third party usually performs functional safety assessment (FSA), risk analysis, performance specification, and verification validation through the determined milestones that can be from the initial concept until the product has been fully developed.
6) **Milestone determination:** Milestones are required for involvement of independent third parties, and they have to be decided early in the product development process. When a milestone is reached, the third party performs the required assessment and reports to both producer and end-user. For example for safety instrumented systems (SISs), determining the milestones is based on the Safety Integrity Level (SIL) whether the assessment can be carried out by producer or must be performed by an independent third party (IEC 61508-1, 2010).

6. Conclusion and future work

The paper documents a literature survey and has presented and discussed a number of approaches for technology qualification with focus on the two commonly used approaches, the DNV and the TRL approaches. Ambiguities and challenges related to these approaches, faced by several companies, are highlighted. This paper provides a set of suggestions for improving the performance of the integrated TQPs. By implementation the suggested principles, some of the challenges presented in section 4 may be eliminated and the stakeholders will be more confident about the TQP results.

A main recommendation is to develop a new TQP approach by using a more detail product development process, such as the V-model (Martin & Bahill, 1996) or the model by Murthy et al. (2008). The suggestions in this paper do not address all relevant challenges, but a new approach should take a holistic view and focus on rectifying all the identified challenges.

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