Faculty of Science and Technology
Department of Engineering and Safety

Criticality Analysis of Platform Supply Vessel (PSV)

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Marziyeh Bagheri Azad

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UiT The Arctic University of Norway
N-9037 Tromsø
NORWAY
www.uit.no

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Abstract

The oil and gas industry has expanded consistently from land operations to inland waterways and then to offshore. A platform supply vessel (PSV) is an important element and one of the most costly resources of offshore supply logistics. The PSVs are getting more and more advanced to fulfill the requirements of offshore operations during oil and gas exploration, project developing and production. Hence, its acceptable level of availability performance is highly demanded. Identification of critical components provides essential information for improving and optimizing the maintenance management, spare part strategy, estimating competence needs for operation of PSV as well as achieving the acceptable level of availability performance. Critically analysis is a systematic screening process that utilizes a number of risk analysis tools including: Failure Modes, Effects and Criticality Analysis (FMECA), Fault Tree Analysis (FTA) and Risk matrix and mentalities, for developing a list of critical components.

Furthermore, studies show the oil and gas industry is pushing towards new unexplored Arctic region. Lack of experience and historical data related to operations in Arctic increases the uncertainty of analysis. Moreover, the sensitive environment, harsh climate, remote area and poor infrastructure of the Arctic region are unique challenges for oil and gas companies. These challenges can influence on PSVs performance.

The aim of this thesis is to study and review the available methods of criticality analysis of PSV in Troms Offshore. Then, based on reviewing standards, meeting with experts and using the experience of other industries is tried to find weaknesses of these methods, modify and improve such methods.

In this thesis, the theoretical framework chapter covers a brief survey of risk analysis, criticality analysis and some of its method. In this part, it is focused more on the methods used in the company to find the weaknesses and bottleneck of available method. Moreover, the impact of operational condition of Arctic on PSVs performance is discussed. The next step by gathering information and using the expert's opinion is tried to improve these methods. At the end a case study for Dynamic Positioning (DP) system of PSV is presented to demonstrate how the method can be applied.

The results of study show that FMECA is a useful tool for criticality analysis of mechanical and electrical equipment. Moreover, a risk matrix can be used as an effective tool to identify the levels of risks and criticalities. It also can help to risk management in decision-making.

Keywords: Criticality analysis, risk matrix, FMECA, RPN, probability of occurrence, severity, detection, PSV, Arctic

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Notation and Abbreviations

PSV	Platform Supply Vessel
DP system	Dynamic Position system
ISM code	International Safety Management Code
IMO	International Maritime Organization
DNV	Det Norske Veritas
FMEA	Failure Mode Effect Analysis
FMECA	Failure Mode Effect and Criticality Analysis
RPN	Risk Priority Number
HSE	Health, Safety and Environment
LTI	Lost Time Injury

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1 Introduction

1.1 Background

Most of the energy and resources needed to run the society is provided by oil and gas extraction. Demanding for energy increased and in order to meet the increasing energy demand, oil and gas will continue to be the major source of the world's energy. Some studies estimates that usage of oil will be doubled in 2025 (Kloff and Wicks, 2005). Over the last decades the oil and industry has expanded consistently from land operations to inland waterways and then to offshore (Sandrea and Sandrea, 2007). Offshore barges start to be used in 1950 for exploration purpose. In 1956 the first deep-water drill ships was used, and semisubmersible rigs in 1964 start to work. In the early 1940s, offshore oil production began and from a modest 1 million barrels a day (b/d) in the 1960s has grown to nearly 25 million b/d in 2005 (Sandrea and Sandrea, 2007). In the production of oil and gas on the Norwegian continental shelf, the Platform Supply Vessels (PSVs) are an important part of the logistics chain (Antonsen, 2009) Due to the high risk of operations offshore, the PSVs play one of the most important roles during the offshore oil and gas fields' exploration, development and production phases.

A PSV is an important element and one of the most costly resources of offshore supply logistics. PSV can be considered as a courier for the seas and its main role is to transport goods (e.g. food, clothes, drilling pipes, cement, spare parts) and merchandize from shore to rigs and vessels. The PSV will also transport mud, waste, etc. from the rigs and vessels back to shore. Average PSV spot rates for both medium (<900m² deck area) and large (>900m² deck area) vessels were both above £27,000 in July2013 (Aas et al., 2009, OffshoreBulletin, 2013). One Norwegian PSV usually consists of 10–15 seamen crew, working rotating 6 hours watches in a 28-day shift. Approximately three times a week a supply vessel in the Norwegian petroleum industry usually call on port to load new goods and unload return cargo from the installations (Antonsen, 2009). Combining daily rate with the cost of crew without assignment, interest costs, repair costs, penalties, etc. it is obvious that the operator will strive to avoid downtime or off-hire time. Then it is very important to evaluate all the risk related of complex and large scaled system like PSV to increase safety and reliability of system. In order to make best decisions for the performance improvement of a system in both the design and operation phases, it is necessary to know the criticality of subsystems/ components from different points of view (Gao et al., 2010).

An effective method to identify the critical component, and then a practicable maintenance strategy and spare part planning for PSV can minimize the downtime. Moreover, developing effective and efficient method of criticality analysis can create value by improving the safety, reliability, availability, technical integrity, regularity, quality and performance of production facilities. Critical components are such components that their failure could result in high repair/replace cost, reduces the production regularity (production losses) or unacceptable HSE (Health, Safety and Environment) risk. In new approaches of the maintenance strategies like reliability centre maintenance (RCM) or risk based maintenance and inspection the maintenance activities are planned, prioritized and executed based on equipment criticality with respect to HSE and production acceptance criteria (Z008, 2001). In general, the purpose of criticality classification is to establish priority of maintenance activities while developing a maintenance program, to specify a common spare part strategy for equipment of equal importance, to decide the extent and quality of technical documentation as well as to decide the priority of corrective maintenance activities. The basis for criticality classification is consequence analysis if a particular function fails. The equipment is classified into different groups, based on the direct consequences on HSE, direct consequence on production, direct consequence on costs and potential for consequence but not direct on HSE, production, and costs (Sukhvir Singh et al., 2012).

Complex systems in general and PSV's in particular, feature many main- and sub functions and a large amount of equipment. Different equipment, on different levels performing different functions will inherent different criticality towards the vessels ability to perform its main function, and thereby overall task. By using different tools such as FMECA, FTA, Risk matrix, Risk Priority Number (RPN) and etc. a list of critical component can be identified. This will help identify weak links in the chain, without the operator needing to suffer the consequences of the chain breaking at the worst thinkable time.

Moreover moving toward the Arctic and lack of experience and historical data related to operations in the Arctic increases the uncertainty of consequences due to failures of different equipment of production facilities. Preventive maintenance has a key role to control or eliminate the consequences of the failures. Furthermore, effective spare part planning can decrease the downtime. In these areas poor infrastructure and supports can make it difficult to establish an effective maintenance program to retain equipment in which they can perform the required functions. Then criticality analysis can be very beneficial.

1.2 Problem statement

A PSV is specially designed to carry out supply operations. A PSV Compared to multipurpose offshore vessels inherent low complexity, and compared to for example a smaller fishing vessel, is highly complex. To achieve requirements towards HSE and regularity, it is necessary to implement modern technological equipment. These complex systems require extensive analysis to identify criticalities and meet the safety requirements.

Hence, complex systems such as PSV's that feature many main and sub functions on different levels and a large amount of equipment require extensive analysis. Considering a vessel's main function this will often consist of several sub functions on different levels. A functional hierarchy relates equipment to sub functions, sub functions to main functions and main functions to vessel systems is needed for the analysis. A complete maintenance schedule and spare part planning is necessary to keep PSV reliable and maintain and resale value.

Therefore, maintenance supports during operation of such complex system is very important as well as spar part planning and particularly is challenging in harsh, remote and sensitive condition of the Arctic. Hence, its acceptable level of availability performance is highly demanded. Identification of critical components provides essential information for improving and optimizing the maintenance management, spare part strategy, estimating competence needs for operation of PSV as well as achieving the acceptable level of availability performance.

Critically analysis is a systematic screening process that utilizes a number of risk analysis tools (such as risk matrix, FMECA and FTA) and mentalities, for developing a list of critical components. In general, the criticality analysis for PSV is important which can help to identify:

- Which function, sub function or equipment of PSV has the most serious potential consequences on PSV performance, "if it fails"?
- What function, sub function or equipment is most likely to negative impact on PSV performance?

Moreover, estimates which indicate a large share of the world's undiscovered oil and gas resources is to be found in the Arctic areas and the increasing demand for energy are important reasons for the growing interest in the Arctic region.(Burton and Feijo, 2008). The sensitive environment, harsh climate, remote area and poor infrastructure of the Arctic region are unique challenges for oil and gas companies. These challenges can influence on PSV performance. For example, when a PSV moves from the North Sea to the Barents Sea, the failure rate of outdoor equipment may increase due to the low temperature and icing. Moreover the repair time may be increased as well. Considering those repair time and failure rates are two important elements of the criticality analysis the criticality ranking of such equipment may be changed.

Hence, it is important to have a proper method to find the critical components. In order to develop such guideline it is necessary to identify the challenges related to working condition in the Arctic region and the effect of these challenges on PSV performance. Moreover, available standard should be reviewed to check their applicability for PSV in this condition. Thereafter, if required the modification should be applied on available method.

1.3 Research Questions

Regarding to development of offshore oil and gas activities and increasing demand for PSVs operation, the main problem is choose the suitable method of criticality analysis of PSVs in Troms Offshore. Troms Offshore is a private shipping company operating offshore service vessels and other special vessel related to offshore activities. In this study the following research questions need to be answered:

1. What are available methods of criticality analysis in Troms Offshore? And what are weaknesses of these methods?
2. How can one modify and improve the methods of criticality analysis in Troms Offshore? And how the operational condition of the Arctic can impact on the methods?

1.4 Research Purpose and Objectives

The purpose of this research is to study and review the available methods for criticality analysis and more specific for maritime operation. And then review the available methods in Troms Offshore and compare with standards, experience of similar industries and knowledge of experts, and also to determine these methods will meet the regulation, ISM (International Safety Management) Code 10.3 and company goals and criteria. Moreover, due to moving oil and gas industries toward the Arctic, application of these methods in harsh condition will be discussed. This study tries to identify the more applicable method of criticality analysis. More specifically, the sub-objectives of the research are:

- To review and discuss the available methods for criticality analysis of PSV,
- To find weaknesses of existing methods,
- To modify available methods or develop other methods to identify the criticalities in PSV to improve maintenance Schedule, spare part planning and reduce downtime by considering the risks.
- To apply the method of criticality analysis in the Arctic condition

1.5 Limitation of the Research

- In this study for FMECA analysis, particularly focus on Dynamic Positioning system (DP system) because there is more information available for this part of the vessel in available time.
- Due to lack of historical data most part of study is only relied on expert judgment.
- Due to lack of historical data as well as lack of expert knowledge in the Arctic condition, these methods are not developed in this area.

2 Research Approach and Methodology

This chapter provides a brief introduction of the research methodology, approaches, and methods for data collection and data analysis for achieving the research objectives. Research has been defined in a number of different ways. A general definition of research is a process through which questions are asked and answered systematically (Dane, 1990). Martyn Shuttleworth give a broad definition of research which states "*In the broadest sense of the word, the definition of research includes any gathering of data, information and facts for the advancement of knowledge*" (Shuttleworth, 2008). Another definition of research is given by Creswell (2008) which is consist of pose a question, collect data to answer the question, and present an answer to the question, he state "*Research is a process of steps used to collect and analyse information to increase our understanding of a topic or issue*". The link between thinking and evidence is research methodology (Sumser, 2000). To do research, a framework for integration of the different technical, commercial, and managerial aspects of study is essential which is by choosing a clear methodology. The knowledge and skills that are needed to solve the problems can provided by study of research methods (Cooper and Schindler, 2003).

2.1 Research purpose

Information gathering and theory testing are two purposes of survey-based research. The first one can be for exploratory or descriptive purposes, whereas second one could be for explanatory or predictive purposes (Neill, 2008). The purpose of research according Neuman are also be organized into three groups based on what the researcher is trying to carry out. Exploratory method applying to discover, uncover and explore a new topic. Descriptive method can be used to summarizing, gathering information, mapping and describing a phenomenon, and explanatory method such as testing and understanding causal relations and explain why something occurs. Studies may have multiple purposes, but usually one of them is dominant (Neuman, 2003).

The research purpose of this study is to describe the method to identify critical component of PSV to improve maintenance plan, spar part planning and comply the IMO regulations. To fulfil this purpose both descriptive and explanatory approach has been chosen. It will also review the standards and then by gathering historical data and information, putting the experts opinion and using experience of similar industry, improve methodologies of criticality analysis. Furthermore by developing FMECA, calculating RPN number for different system, subsystem and component and comparing this number, the reason of criticalities can be explained.

2.2 Research Approach

Research approach refers to the approach or the methodology that has been adopted to conduct the research (Blurtit.com, 2012). The approach to a research can impact on the result and outcome of a research project (Blurtit.com, 2012). The research approaches and the purpose of the study are often closely related to each other. The research approaches can classify and perform according to induction, deduction or abduction, or in qualitative or quantitative groups.

Induction is a process of reasoning which based on individual cases, examples, specific bits of evidence, and other specific types of premises, infers a general conclusion (Neumann, 2003). Inductive reasoning moves from specific observations toward more generalizations and theories (Blaikie, 2009). Deduction is a process of arguing which base on a general truth, and application of that truth to a specific case, result in a second piece of evidence, and draws a specific conclusion from those two pieces of evidence (Neumann, 2003). Deductive approach starts by constructing a theory and deduce hypotheses and then by testing hypotheses by matching them with data explanation in that context ends (Blaikie, 2009). A weakness here is that the approach establishes the rule, instead of explaining it. Abduction can be explained as a combination of deduction and induction. Abduction is to look for a pattern in a phenomenon and suggest a hypothesis (Yu, 1994). In general, abduction creates, deduction explicates, and induction verifies (Neuman, 2003). Table 2.1 shows the Different type of research approach.

Table 2.1: Different type of research approach (Yu, 1994)

Induction	**Deduction**	**Abduction**
- is inconclusive in infinite time - is indefinable in a single case - generates empirical laws but not theoretical laws - is based on generality and law of large numbers	- cannot lead to new knowledge - does not specify necessary or sufficient condition - relies on true premises	- is not symbolic logic but critical thinking - is not Popperian falsification but hypothesis generations - is not hasty judgment but proper categorizations

In this research, deductive approach has been applied. The research started as a deductive approach with a literature review to gain a deeper understanding about criticality analysis approaches and risk assessment methods. And then continue by collecting historical data, expert judgment, and experience of similar industries and the requirements of company, to apply the methods of criticality analysis on different part of PSV to identify the criticalities.

Research approach can be classified in quantitative, qualitative or mixed. In simple terms, qualitative research adopts questioning and verbal analysis (Given, 2008) whereas quantitative research refers to the systematic empirical investigation of phenomena via statistical, mathematical or computational techniques (Sullivan, 2001). Examples of quantitative methods are including survey methods, laboratory experiments, formal methods (e.g. econometrics) and numerical methods such as mathematical modelling. In qualitative research one is interested in the meaning and understanding of a studied process. Examples of qualitative methods are action research, case study research and ethnography.

Mixed research method, or multi-methodology, is an approach to professional research that combines the collection and analysis of quantitative and qualitative data (Creswell et al., 2004). Mixed research uses both deductive and inductive methods, obtains both quantitative and qualitative data, attempts to corroborate and complement findings, and takes a balanced approach to research i.e. it has complementary strengths and non-overlapping weaknesses (Sagepub, 2012).

Both qualitative and quantitative research methodologies have been used in this study. Quantitative research deals with calculation of RPN number. RPN is a numeric assessment of risk priority in which each failure mode has an assigned severity, probability, and detectability values from 1 to 10. Qualitative analysis deals with a survey of risk matrix methodology which according the consequence and probability of hazards related to people, environment, asset and business reputation identify the criticalities. In this method ratings of the likelihood and consequences of an event determine a risk level and evaluate the level of risk against qualitative criteria.

As the research study tries to improve the best of qualitative and quantitative methods, and uses both deductive and inductive methods, it can be characterized as having a deductive-mixed research approach.

2.3 Research Strategy

A procedure for obtaining a particular intermediary research objective such as sampling, data collection, or data analysis is a research strategy (Creswell, 2008). Yin describes five different research strategies to apply when collecting and analysing empirical evidence including: archival analysis, history, experiment, survey, and case study. Archival analysis and history strategies refer to the past conditions of the case under study. Other strategies (experiments, surveys and case studies) usually refer to the present situation (Yin, 2008). The type of research question, the extent of control the researcher has of behavioural events and the degree of focus on contemporary events, are deigned to apply in order to decide upon which strategy to use (Yin, 2003).

In this study the strategy of research is based on using archival analysis and historical data, and then by using a case study research strategy is tried to develop the defined method of criticality analysis. According Soy (1997), a case study research excels at bringing us to an understanding of a complex issue or object and can extend experience or add strength to what is already known through previous research.

2.4 Data Collection

Data is the facts presented to the researcher from the study's environment (Cooper and Schindler, 2003). There are different methods for data gathering and every researcher collects data using one or more techniques (Straub et al., 2004). Researcher chose the method according its overall appropriateness to the research, along with other practical factors, such as: the expected quality of the collected data, estimated costs, predicted non-response rates, expected level of measurement errors, and length of the data collection period (Lyberg and Kasprzyk, 1991). Surveys, secondary data sources or archival data, objective measures or tests, and interviews are the most popular data collection techniques (Yin, 1984). According to Neuman the techniques of data collecting may be grouped into two categories: quantitative, and qualitative. According the type of questions or topic, some techniques are more effective than others. It takes skill, practice, and creativity to match a research question to an appropriate data collection technique (Neumann, 2003).

Table 2.2: Different types of data (Neumann, 2003)

<table>
<tr><th>Quantitative Data</th><th>Qualitative Data</th></tr>
<tr><td>Experiments</td><td rowspan="2">Field research</td></tr>
<tr><td>Surveys</td></tr>
<tr><td>Content analysis</td><td rowspan="2">Historical-Comparative Research</td></tr>
<tr><td>Existing statistics</td></tr>
</table>

According to Blaikie (2003) data is divided to three categories including:

1. Primary data, which is generated by a researcher who is responsible for the design of the study and the collection, analysis and reporting of the data. To answer specific research questions the new data can be used.
2. Secondary data, which is the raw data that has already been collected by someone else, for some general information purpose
3. Tertiary data, which has been analysed by either the researcher who generated them or an analyst of secondary data. In this case the raw data may not available, and only the results of this analysis is available.

Troms Offshore uses some Asset Management System software to gathering and managing data such as Unisea and PreMaster. PreMaster use for planning and reporting of maintenance of Company managed vessels and Unisea reporting system for any discrepancies.

PreMaster software is the ship management solution that enables company to handle a range of activities such as planned maintenance of equipment, analysing risks, reporting events, procurement processes, crewing, document administration and distribution. Troms Offshore is utilizing Asset Management System (PreMaster) to ensure proper maintenance of the vessels and also to report activities as a base of historical data.

All functionality is available both from the office and from ships, and data is replicated between systems. PreMaster consists of the following key modules include (PreMasterPRO Version 2.08.01. Troms Offshore): Maintenance, Parts, Certificate, Procurement, Budget, HSE, Quality and Risk assessment reporting, ISPS, Crewe, and Reports.

UniSea is another software that Troms Offshore used, which is a fully integrated solution for HSE, Quality Assurance (QA) and operation support for shipping and offshore companies. This software helps company improve its internal workflow processes through tailor-made solutions that meet the specific needs of the industry (UiSea, 2014).

Due to limited historical data, quantitative data is hard to come by, therefore for quantitative analysis is trusted on expert judgment. Most of technical staffs of Troms Offshore office have experience to work in ships for years and also one of them was as an inspector during manufacturing the newest vessel that star to work in January 2014, therefore they have a good knowledge and experience of different aspect and failures of PSV. Then in this study data, which is needed to apply the methods, collected from historical data recorded in software, information in last version of methods and knowledge of experts in office and on the vessels.

2.5 Data Analysis

Analysing the collected data generates information. Data analysis is one of the important steps in the research process. Data analysis usually involves inspecting, transforming, and modelling data with the goal of highlighting useful information, suggesting conclusions, and supporting decision-making (Adèr and Mellenbergh, 2008). According Adèr and Mellenbergh (2008), data analysis can be divided into two parts: exploratory data analysis (EDA), which focuses on discovering new features in the data, and confirmatory data analysis (CDA) focuses on confirming or falsifying existing hypotheses. Blaikie divided quantitative methods of data analysis into four types: univariate descriptive analysis, bivariate descriptive analysis, explanatory analysis and inferential analysis (Blaikie, 2003).

The first two are concerned with descriptive analysis. To put this differently, a univariate descriptive analysis examines one variable at a time, while a bivariate descriptive analysis deals with the association between two variables. Explanatory analysis can be either a special kind of bivariate analysis, in which the concern is with influence of one variable on another, or multivariate analysis, which examines the connection or influences between three or more variables.

In this research study in qualitative analysis, a bivariate descriptive data analysis is used. In this analysis the likelihood and consequences of failure of PSV are arranged in risk matrix according the different classification. The combination of a consequence and likelihood range gives an estimate of risk or a risk ranking, and then help to decision maker to determining the most cost-effective means to reduce risk. In quantitative analysis, FMECA, multivariate analysis according the three variables including: severity, probability of occurrence, and the likelihood of detection are used. By collecting data, scoring these variables according collected data; RPN number can be calculated to determine risk ranking and critical parts of PSV.

3 Theoretical frame of reference

3.1 Introduction

Prior to the world war II, mechanical systems were relatively simple in capability and complexity; and most portions of a system seldom failed and when they did were easily fixed (Utter and Utter, 2005). Due to technological advances, systems became more and more complex. These technological advancement leads to a new and more complex failures that are more difficult to diagnose and harder to predict in advance. In other words, complexity created new problems, namely more capable but more fragile systems (Utter and Utter, 2005). Every day, due to increasing complexity of equipment, companies are faced to various types of risk. Risk usually goes along with every business and with direct influence on result (Kremljak and Kafol, 2014). Companies can be connected to their property and making decision also is hard in facing to hazards. Risk analysis can provides an internationally accepted framework for assessing and managing risk posed by hazards (Moy, 2014) In 1960, C.J. Grayson with introducing risk analysis to the industry is credited (Alexander and Lohr, 1998). Nowadays, formal risk analysis and decision theory principles utilize in daily operational decisions (Patteson, 1994). To ensure that risk analysis results in better decisions, and in order to avoid overestimation, underestimation, misidentifying critical risks, overselling projects and underselling projects, it must be applied consistently and properly (Alexander and Lohr, 1998).

Criticality analysis also can use as a tool that examines potential product or service features against a list of critical factors. It also evaluates feature priorities, and helps determine what organization or internal function is responsible for the critical factors. The criticality of an item is a very important factor to be considered for specifying service levels (Gajpal et al., 1994). Criticality analysis is useful in developing features and goals for products, services, and processes. It can be done in order to increase the reliability, availability as well as decreasing the consequence of the failure.

In the oil and gas industries, especially in the Arctic region, critical system downtime might be extremely costly and the consequences of the critical failures might be intolerable. As a result, the request for effective and reliable methods to criticality analysis increased significantly. In other word, criticality analysis becomes important measure assuring to have the highest overall production performance.

3.2 Risk

Risk and variety of types of risk concurrently increases with its development. Research activities become more complex and interconnected, and then new technologies are introducing new risks (Ouédraogo et al., 2011).

In order to establish a unified and common strategy for assessing risk, it is important to establish a 'common language' concerning this concept. Risk is defined in many ways. In engineering contexts, risk is often linked to the expected loss(Aven, 2010). Here are some examples of common alternative definitions of risk:

a) Risk is the combination of the frequency and the severity of the consequence (IMO, 2007).
b) *"Combination of the probability of occurrence of harm and the severity of that harm*" (Z013, 2010)
c) *"Risk a term in general usage to express the combination of likelihood a specified hazardous event will occur and the severity of the consequence of that event*" (ISO17776, 2000)

Equation 3.1 illustrates the concept of risk.

Risk= probability of occurrence × *Consequence* (3.1)

An initial event can result in different consequences such as financial loss, environment damage and loss of lives. The probability factor and expected factor applies to express risk. (Aven, 2008). Risk can be expressed qualitatively as well as quantitatively (Z013, 2010).

Per Hokstad and Trygve Steiro did study to present a framework of an approach to support planning and priority setting for risk control. In their study a classification for losses categories is defined. In this research identification of risk is including (see Figure 3.1)(Hokstad and Steiro, 2006).

- Identification of hazards/threats (possibly causing unwanted events/conditions),
- Identification of values that are threatened by these hazards, (targets).

Four categories of hazards/threats are listed in the figure:

- Acute accidental events/incidents
- Continuous strains or impacts
- Intended harmful actions (sabotage)
- Violations (within the enterprise) of society's accepted ethical rules/standards

Similarly, they suggested six categories of values that may be threatened by these hazards. A categorization of the losses is used for a unified approach of risk evaluation. A total of 11 loss categories are suggested including (Figure 3.1):

1. Loss of life in major accidents
2. Loss of life in other accidents
3. Acute personal injury
4. Chronic disease
5. Reduced quality of life; reduced functionality
6. Acute pollution on external environment
7. Continuous pollution on external environment

8. Material damage
9. Loss of production, (could include deferred and damaged production)
10. Loss of data/information/knowledge
11. Loss of reputation

These 11 categories should include most of the potential losses related to human, environment, material and production. In addition, loss of data, information, knowledge and reputation are included.

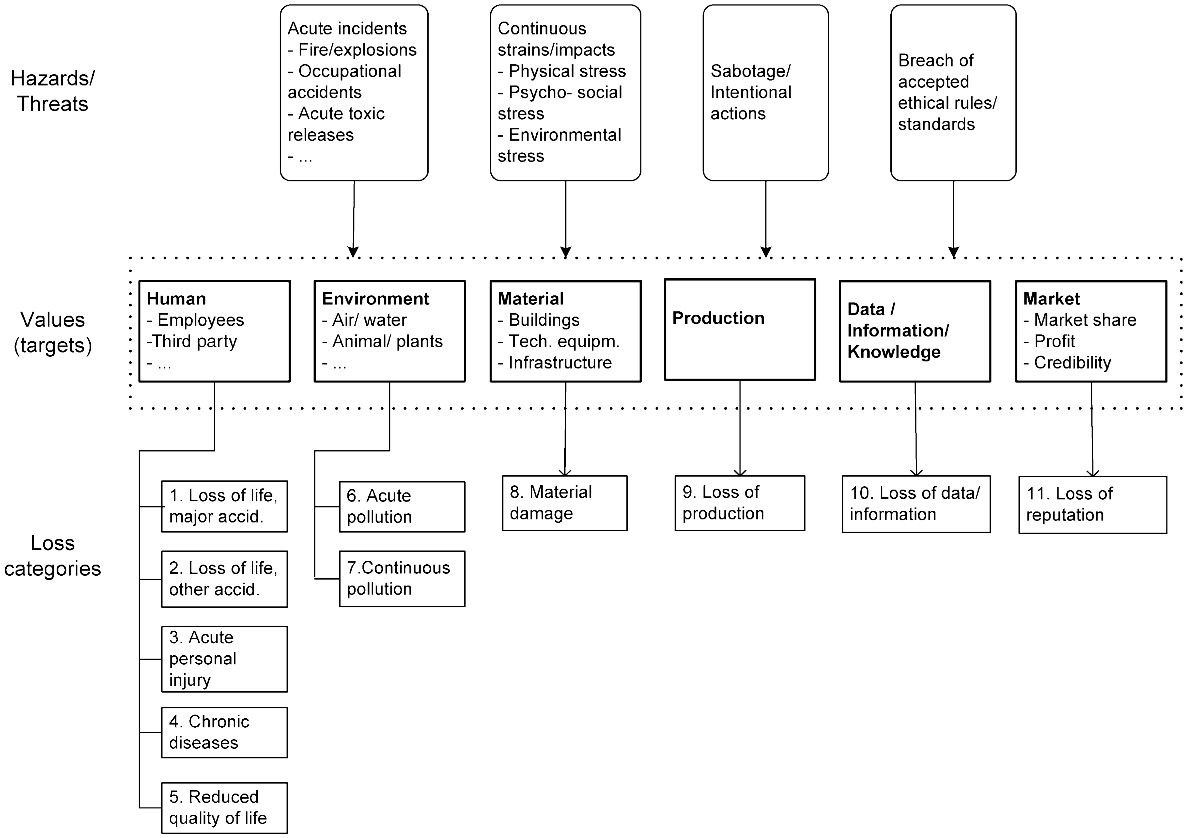

Figure 3.1: Illustration of threats, values and 'loss categories' in risk, and vulnerability management (Hokstad and Steiro, 2006)

The demanding operational conditions of Arctic region increase the risk and limit the effectiveness of any efforts to control such risks. Operating in remote areas might potentially add a vulnerability factor that could increase the risk due to increase in the possible consequences (SINTEF, 2012). It is necessary to understand how risk will depend on various factors related to the Arctic. It is also important to stress that consequence and probability will wary independently. As a result, the risk will not be static. In decision-making, it is precarious to understand the concept of risk with all its contributing factors (Aven, 2007).This understanding will contribute to balance between different considerations when making decisions.

3.3 Elements of risk analysis

Risk analysis process is as a typical activity flow, from problem formulation leading to decision. It can be shown by figure 3.2 (Vose, 2008).

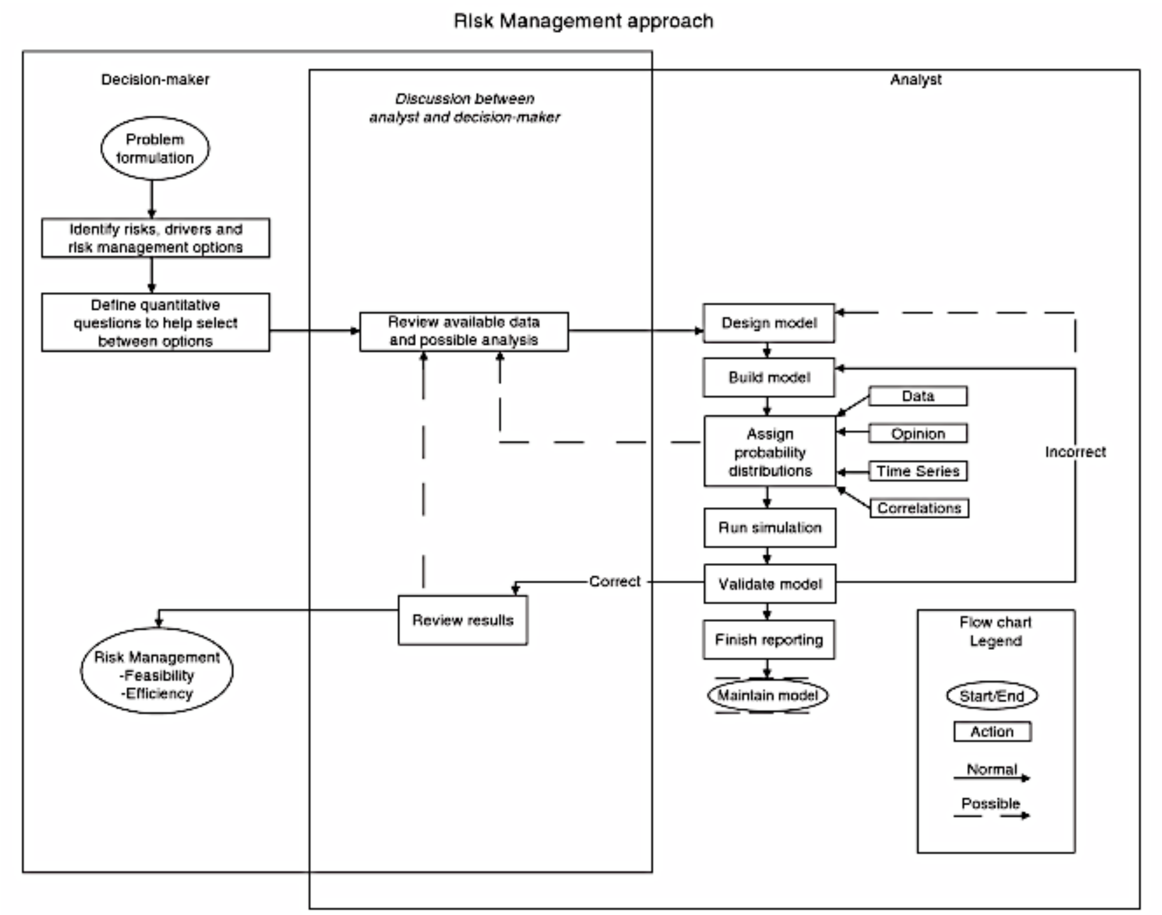

Figure 3.2: risk analysis process (Vose, 2008)

According National Research Council, risk analysis has three core elements of risk assessment, risk management and risk communication (National Research Council, 1983). These elements have overlap and interactions that are shown in figure 3.3 (Modarres, 2006).

Figure 3.3: elements of risk analysis (Modarres, 2006)

3.3.1 Risk assessment

A formal and systematic process to determine or quantify probability and magnitude of losses of different type of hazards such as physical, chemical, or microbial agents, from different type of failure is risk assessment (Modarres, 2006). According Aven and Renn (2010) a methodology to identify and extent of risk is risk assessment, which is including three main steps:

- Identifying of threats, hazards or opportunities
- Analyzing of cause and consequences
- Risk description

In order to reach theses aims three basic questions should be answered (Modarres, 2006):

- What can go wrong?
- How likely is it?
- What are the losses (consequences)?

3.3.2 Risk management

Risk management is an effort to manage uncertainties regarding to losses by identifying, quantifying, and characterizing these uncertainties. In risk management by taking into consideration risk values, economic and technology constraints, legal and political issues, try to coordinate activity to prevent, control and mitigate expected losses. Risk management is the most important part of risk analysis (Modarres, 2006).

According Aven (2008) all measures and activities carried out to manage risk is the risk management. In many enterprises, risk management is divided into three main categorizes which is shown in Table 3.1.

Table 3.1: Risk Categories (Aven, 2008)

Risk Category	Description
Strategic risk	Factors and aspects that is important for the company's plans and long-term risk. Examples can be laws and regulations, technology and competition.
Financial Risk	Factors associated with the company's finances. Examples can be debtor's payment issues, liquidity- and market risk.
Operational Risk	Factors, which interferes with a normal operation. Examples can be unwanted events related to failures, loss of key personnel and sabotage.

The primary focus in risk management involves proactive decision making to (Modarres, 2006):

- Continually assess the risk (what could go wrong?)
- Decide which risk are significant to deal with

- Employ strategies to avert, control, or minimize risk
- Continually assess effectiveness of the strategies and revise them, if needed

The main steps of risk management are (Aven, 2010):

- Identification and generation of Risk Management options
- Assessment of Risk Management option with respect to predefined criteria
- Evaluation of Risk Management options
- Selection of Risk Management options
- Implementation of Risk Management options
- Monitoring of Risk Management options

3.3.3 Risk communication

Information about nature of risk and consequences, result of risk assessment and opinion of risk management are transferred, exchanged or shared between decision makers, analysts and the other stakeholder by Risk Communication process (Modarres, 2006). The aim of risk communication to help all affected parties such as stakeholder and the public to make informed choices about matters of concern to them (Aven, 2010). Studies show that most of people around the world are worried about the risk related to health and environmental quality (Rohrmann and Renn, 2000). But risk communication related to complex health threats and environmental changes are very difficult, because over a long time they are usually affected, and also they may include negative effects, when they combine with the other risk, that hardly cab detected by human (Aven, 2010).

Information depending on what a type is to be communicated and to between which parties is including (Modarres, 2006):

- The nature of the risk
- The nature of benefit
- Uncertainties in risk assessment
- Risk management options

3.4 Criticality analysis

Criticality analysis is *"a procedure by which each potential failure mode is ranked according to the combined influence of severity and probability of occurrence"*(MIL-STD-1629A, 2000). Critical analysis can be done in order to increase the reliability, availability as well as decreasing the consequence of the failure (Ebrahimi, 2010).

As a procedure FMECA can be used by identifying and analysing the individual components of the system and determining their failure modes, and then identify the effects of those failures on the system behaviour (Bowles, 1998). Figure 3.4 shows typical product development cycle and FMECA schedule.

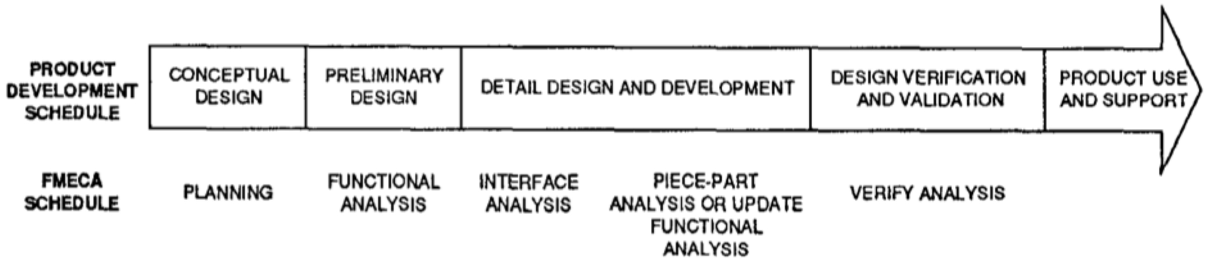

Figure 3.4: typical product development cycle and FMECA schedule (Bowles, 1998)

The critically analysis must be initiated in the early design phase. There is lot of case of malfunction during the operation phase, which is due to the lack of well designing. For example the Howo truck which used as one of the most transportation tools in Iran has a problem in breaking system. This failure made a lot of accident in the road. It is mean the break system is a critical component for this machine. However, it was necessary to find this problem in the design phase. Critical analysis provides such information in design phase. And after use of system and achieve new information the analyses must be updated. .

Criticality analysis is applied in risk and reliability studies to rank decisions on system design and operation. There are a wide variety of methods used to meet the requirements of different organizations. Most methods feature an initial assessment of the consequences of failure and its probability of occurrence; however, other factors may also be applied to provide a more robust analysis applicable to each specific situation. As well as assessing system criticality during the design phase, it is also necessary to continue to evaluate system and equipment criticality during operation so that availability can be maximized(Moss and Woodhouse, 1999).

Many different approaches to express criticality exist, both qualitative and quantitative. Understanding the different methods and their interpretations is essential to choose an approach that fits the information needs.

3.4.1 Qualitative analysis

Qualitative analysis is very simple and quick to perform, probably is the most widely used of ones. This type of analysis uses an interval scale of probability of losses and potential magnitudes of the losses to represent the risk (Modarres, 2006). Each interval is typically represented by non-numerical label (such as the words High, Medium, Low). One of the most effective tools to perform qualitative analyses in order to best decision making is risk matrix.

3.4.1.1 Risk matrix

Risk matrix can be developed qualitative as well as semi-quantitative that in this study the concept of qualitative risk matrix is used. A risk matrix is a table that its rows (or columns) have several classifications of probability, likelihood, or frequency and its columns (or rows) contain several assortments of severity, impact, or consequences respectively. Levels of risk, urgency, priority, or management action recommended with each row-column pair, that is, with each cell (Anthony Tony Cox, 2008). Risk assessment matrix is a classic tool to conduct semi-quantitative risk assessment, which is widely applied in many different situations(Ni et al., 2010). According MIL-STD-882D, severity of the consequences is classified into four categories and frequency into six categories (MIL-STD-882D, 2000).

The first step to produce a risk matrix is standard definition of risk as a combination of severity of the consequences occurring in a certain accident scenario and its probability. In order to construction risk matrix is identify some basic rules: (Markowski and Mannan, 2008)

1. Categorization and scaling of the severity of consequences and frequency,
2. Categorization and scaling of output risk index,
3. Build-up risk-based rules knowledge,
4. Graphical edition of the risk matrix.

- **Probability**

There are many interpretations to use probability concept in risk analysis in practice, but only a few of them are significant. Kaplan (1997) discusses and defines three meanings of probability. The first one is called frequency or fraction because of the statistician's meaning. This meaning refers to the outcome of a repetitive experiment of some kind, like flipping coins. Because this type of probability is in the real world and also is measurable by actually doing the experiment, such a number is called an objective probability. Second meaning does not exist in the real world, and it is degree of confidence or degree of certainty and named Bayesian meaning of probability. It is often called subjective probability, because it exists only in the heads. Third meaning is the mathematician.

Table 3.2: Different meaning of probability (Kaplan, 1997)

Traditional meanings of "probability"			New theories		
Statistician's (frequency, fraction)	Bayesian (probability)	Mathematical (probability	Fuzzy theories (fuzziness)	Possibility theory	Dempster Shafer (relief)
Random Variability "Aleatory" probability "Objective" probability Stochastic ontological "In the world" probability Reliability Chance Risk	Belief "Personal" probability Subjective probability Uncertainty Confidence Epistemic probability Forensic probability Plausibility Credibility "Evidence Based" probability	Formal probability "Axiomatic" probability	Ambiguity Unclarity Vagueness Ill-defined		

According Aven and Reniers a probability in a risk analysis and safety can in general be interpreted as a subjective probability with reference to an uncertainty standard (Aven and Reniers, 2013). There is different classification for probability of occurrence. DNV classify the frequency in 6 categories, Table 3.3 show classification.

Table 3.3: The frequency categories (DNV, 2001)

ACCIDENT FREQUENCY	OCCURRENCE (During operational life considering all instances of the system
Frequent	Likely to be continually experienced
Probable	Likely to occur often
Occasional	Likely to occur several times
Remote	Likely to occur some time
Improbable	Unlikely, but may exceptionally occur
Incredible	Extremely unlikely that the event will occur at all, given the assumptions recorded about the domain and the system

According IMO in order to facilitate the ranking and validation of ranking, it is generally recommended to define probability indices on a logarithmic scale and in 4 classes. Table of logarithmic probability index according IMO is shown in Appendix.

- **Consequence**

Prior to performance of the criticality analysis, the consequences of failures and the degree of functional redundancy, the consequence classes have to be properly defined. The classification of the consequence should be defined according overall company criteria for safety and environment, and reflect the actual plant operation when it comes to economical losses.

In Norsok standard Z008, the consequence classes of the most serious effect of loss of functionality (both loss of main function and sub functions) are defined in three classes (High, Medium and Low) related to HSE, production and cost (Z008, 2001). The Table of this classification can be fined in appendix.

The severity categories for marine risk assessment, which are provided by DNV, are classified in 4 categories and are shown in Table 3.4.

Table 3.4: The severity categories (DNV, 2001)

CATEGORY	DEFINITION
Catastrophic	Multiple deaths
Critical	A single death; and/or multiple severe injuries or severe occupational illnesses
Marginal	A single severe injury or occupational illness; and/or multiple minor injuries or minor occupational illness
Negligible	At most a single minor injury or minor occupational illness

Another example of criteria for categorization of consequences related to maritime risk assessment is shown in Table 3.5.

Table 3.5: Consequence Criteria (ABS, 2000)

Category	Description	Definition
1	Negligible	Passenger inconvenience, minor damage
2	Marginal	Marine injuries treated by first aid, significant damage not affecting seaworthiness, less than 25K
3	Critical	Reportable marine casualty (46 CFR 4.05-1)
4	Catastrophic	Death, loss of vessel, serious marine incident (46 CFR 4.03-2)

IMO for a maritime safety issue defined an example of a logarithmic severity index in 4 classes (Minor, Significant, severe and catastrophic). Consideration of environmental issues or of passenger vessels may require additional or different categories (IMO, 2002). The Table of this classification can be found in Appendix A.

After classification of the severity and frequency according the goals of the company and depends on the type of activity or specifics of the processes, the risk matrix can be defined. Table 3.6 illustrates example of risk matrix for oil and gas industry which done by Germanisc her Lloyd. In this risk matrix risk level is classify in three groups, which is shown by different colours; green, yellow and red. The green means that risk is acceptable, yellow means risk is in the ALARP Zone, and the risk should be reduced As Low As Reasonable Practicable, and the risk in red part is high and unacceptable. In the red zone by proper barrier and risk reduction measures the probability of occurrence or the severity of an unwanted event can be decreased and level of risk can change to yellow or green part.

Table 3.6: HAZID-Worksheet – Risk matrix (Lloyd, 2008)

Severity code		Consequences				Probability				
		Personnel (SP)	Assets (SA)	Environment (SU)	Reputation (SR)	A team does not know of any occurance in industry/ occurance appears unlikely	B has occured in the industry	C has occured within the operating company	D has occured within the operating company	E occurs within the operating company several times a year
minimal	1	negligable injuries /illness	negligable damage	negligable impact	negligable impact					
low	2	minor injuries /illness	minor damage	minor impact	minor impact					
medium	3	major injuries /illness	medium damage	locally limited impact	regional impact					
high	4	1 to 3 fatalities	major damage	major impact	superegional impact					
very high	5	several fatalities	total loss	massive impact	national impact					

According ISO 17776 to compare options and the value of risk reducing measures, in qualitative assessment, it is possible to use a 6×5 risk matrix (ISO17776, 2000). The produced risk matrix by ISO is shown in Table 3.7.

Table 3.7: ISO 17776 Risk Matrix (ISO17776, 2000)

CONSEQUENCE					INCREASING PROBABILITY				
Severity Rating	People	Assets	Environ-ment	Reputation	A	B	C	D	E
					Rarely occurred in E&P industry	Happened several times per year in industry	Has occurred in operating company	Happened several times per year in operating company	Happened several times per year in location
0	Zero injury	Zero damage	Zero effect	Zero impact	Manage for continued improvement				
1	Slight injury	Slight damage	Slight effect	Slight impact					
2	Minor injury	Minor damage	Minor effect	Limited impact					
3	Major injury	Local damage	Local effect	Considerable impact					
4	Single fatality	Major damage	Major effect	Major national impact	Incorporate risk reducing measures				
5	Multiple fatalities	Extensive damage	Massive effect	Major international impact				Intolerable	

According IMO definition a risk index may be established by adding the probability/frequency and consequence indices (IMO, 2002).

$$\text{Risk} = \text{Probability} \times \text{Consequence}$$

$$\text{Log (Risk)} = \log\text{ (Probability)} + \log\text{ (Consequence)}$$

The risk matrix based on IMO can be referred in Appendix A.

DNV also by risk assessment provides a structured basis for offshore operators to identify hazards and to ensure risks have been reduced to appropriate levels in a cost-effective manner. A 6×4 risk matrix is used as a method to apply qualitative risk assessment in DNV and it consist of four decision classes (See in Appendix C) (DNV, 2001).

3.4.2 Quantitative analysis

Quantitative analysis particularly is given for computing the “Failure mode criticality number” with an assumption of a constant failure mode. (MIL-STD-1629A, 2000). FMEA and FMECA can be used as a tool to demonstrate the result of quantitative risk analysis. In the 1960s when demands for improved safety and reliability extended studies of component failures increased, as a formal methodology, and Failure Modes and Effects Analysis was originated (Bowles, 1998). The FMEA analyses different failure modes and their effects on the system.

The FMECA was originally developed by the National Aeronautics and Space Administration (NASA) to improve and verify the reliability of space program hardware. According MIL-STD-785B, FMECA is the procedures for performing on equipment or system. *FMECA shall be performed to the level specified (subsystem, equipment, functional circuit, module, or piece part level). All failure shall be postulated at that level and the effects* *on all higher levels shall be determined(MIL-STD-785B, 1969).* MIL-STD-1629A establishes requirements and procedures for performing a FMECA, to evaluating by failure mode analysis.

Generally the Failure Mode, Effects and Criticality Analysis (FMECA) is consist of two separate analyses, the FMEA and the Criticality Analysis. In the criticality analysis, all failure mode classify or prioritize based on failure rate and severity of the effect of failure (Modes, 2006). Criticality analysis starts up as an integral part of system design and will be improved and updated when the design evolves ((RIAC), 1993). Figure 3.5 illustrates typical flow of FMECA.

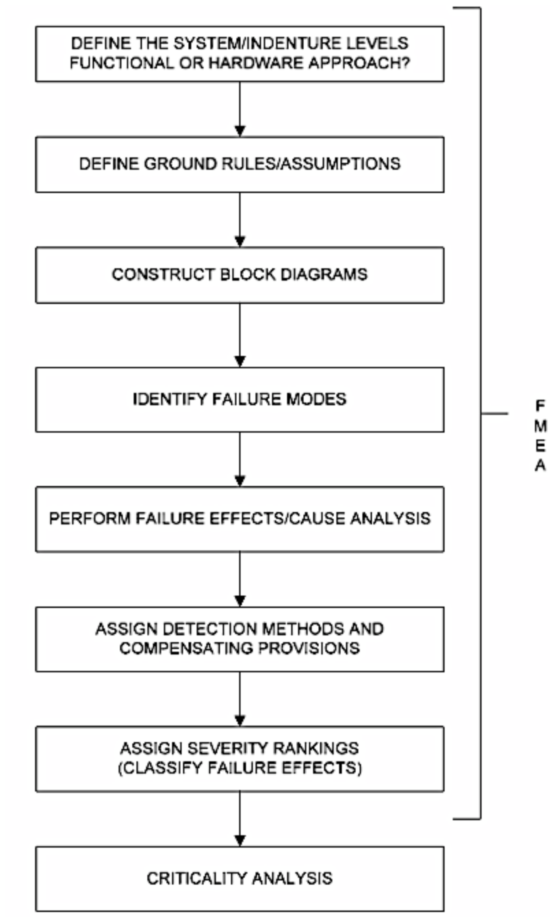

Figure 3.5: Typical FMECA flow (ARMY, 2006)

The FMECA is a tool should be initiated in the first step in design phase when the information is prepared. FMECA is beneficial methodology not only in design phase but also during system use. When the new information from the system is produced the FMECA should be updated in order to provide more benefit. The FMECA is a baseline for failure detection and isolation of subsystem design, maintenance planning, spare part planning, and safety analysis. Application of FMECA may reduce the cost of operate and maintain the facility, although cost is not the main objective of this analysis (Modes, 2006). Some of the strengths of FMECA according DNV (2001) includes:

- It is widely-used and well-understood
- It can be performed by a single analyst
- It is systematic and comprehensive, and should identify hazards with an electrical or mechanical basis
- It identifies safety-critical equipment where a single failure would be critical for the system

Moreover, FMECA has some weaknesses including (DNV, 2001):

- Its benefit depends on the experience of the analyst.
- It requires a hierarchical system drawing as the basis for the analysis, which the analyst usually has to develop before the analysis can start.
- It is optimized for mechanical and electrical equipment, and does not apply to procedures or process equipment.
- It is difficult for it to cover multiple failures and human errors.
- It does not produce a simple list of failure cases.

There are different methods to calculate the criticality of different component/subsystem. Some of these methods are discussed in the following section.

3.4.2.1 Criticality number

According MIL 1629A, when quantitative approach has been specified, calculation of criticality number is defined. Failure mode criticality number C_m, for a failure mode and particular severity classification can be calculated with fallowing formula (MIL-STD-1629A, 2000):

$$C_m = \alpha\beta\lambda_{\mathrm{P}}t \tag{3.2}$$

Where:

C_m: Criticality number for a failure mode
α: Failure mode ration
β: Conditional probability of mission loss
λ_{P}: Part failure rate
t: Duration of application mission phase usually express in hours or number of operating cycles

C_m is a portion of criticality of item under specific severity classification. Criticality number C_r of items is the number of system failures of a specific type expected due to the failure modes of item. The C_r for an item is the sum of the criticality numberC_m, under specific severity classification or can be calculated by formula 3.3. (MIL-STD-1629A, 2000).

$$C_r = \sum_{n-1}^{j} (\alpha\beta\lambda_P t)_n \qquad n = 1,2,\ldots,j \tag{3.3}$$

Where:

C_r: Criticality number for the item
n: The failure modes in the items that fall under a particular criticality classification
j: Last failure mode in the item under criticality analysis

According Bowles there are two problems with the criticality number prioritization. A constant failure rate for all components is considered in this number, which is generally not the case. For example many of electronic devices have constant failure rates over a large part of their life spans. Second problem is that this number in the criticality matrix and a visual perception to identify the most critical components depends on a geometric placement of items (Bowles, 1998).

3.4.2.2 RPN number

Priority Number (RPN) is another method to ranking and assessing the designed risk of potential failure modes. RPN is calculated by devoting potential failure modes respect to the severity (S), probability of occurrence (O), and the likelihood of detection (D). RPN is computed by multiplying of ranking factors (equation 3.4) (Bowles, 2004):

$$RPN = S \times O \times D \tag{3.4}$$

The range of these ranking factors is from 1 to 10 and then ranges of the resulting RPN is from 1 to 1000. Higher RPNs means that risk is higher than those having a lower RPN (Teng and Ho, 1996). The RPN number is used to prioritize failure modes with identical value of RPN, and then define corrective actions(Sellappan and Palanikumar, 2013). Corrective actions can reduce one of the S, O, or D rankings(Bowles, 2004). There is different ranking for severity, probability of occurrence and the likelihood of detection.

Calculating ranking for severity provide a basis to safety, production continuity, scrap loss, etc. Table 3.8 shows an example of severity ranking (SEMATECH, 1992)

Table 3.8: Severity ranking criteria(SEMATECH, 1992)

Rank	Description
1-2	Failure is of such minor nature that the customer (internal or external) will probably not detect the failure.
3-5	Failure will result in slight customer annoyance and/or slight deterioration of part or system performance
6-7	Failure will result in customer dissatisfaction and annoyance and/or deterioration of part or system performance.
8-9	Failure will result in high degree of customer dissatisfaction and cause non-functionality of system.
10	Failure will result in major customer dissatisfaction and cause non- system operation or non-compliance with government regulations.

If the severity ranking is used for safety, severity code that represents the worst-case incident could result from a failure of equipment or process or for lack of a contingency plan for such an incident, will be changed. According SEMATECH, HSE severity definition is shown in Table 3.9 (SEMATECH, 1992). More examples for severity ranking can be found in Appendix D.

Table 3.9: ES&H Severity Level Definitions (SEMATECH, 1992)

Rank	Severity Level	Description
10	Catastrophic I	A failure results in the major injury or death of personnel.
7-9	Critical II	A failure results in minor injury to personnel, personnel exposure to harmful chemicals or radiation, a fire or a release of chemicals in to the environment.
4-6	Major III	A failure results in a low level exposure to personnel, or activates facility alarm system.
1-3	Minor IV	A failure results in minor system damage but does not cause injury to personnel, allow any kind of exposure to operational or service personnel or allow any release of chemicals into environment.

Potential occurrences per unit time define the probability that a failure will occur during the expected life of the system. Probabilities of each failure mode are sorted in different and logical level. Table 3.10 shows example of occurrence ranking criteria (SEMATECH, 1992).

Table 3.10: Occurrence Ranking Criteria(SEMATECH, 1992)

Rank	Description
1	An unlikely probability of occurrence during the item operating time interval. Unlikely is defined as a single failure mode (FM) probability < 0.001 of the overall probability of failure during the item operating time interval.
2-3	A remote probability of occurrence during the item operating time interval (i.e. once every two months). Remote is defined as a single FM probability > 0.001 but < 0.01 of the overall probability of failure during the item operating time interval.
4-6	An occasional probability of occurrence during the item operating time interval (i.e. once a month). Occasional is defined as a single FM probability > 0.01 but < 0.10 of the overall probability of failure during the item operating time interval.
7-9	A moderate probability of occurrence during the item operating time interval (i.e. once every two weeks). Probable is defined as a single FM probability > 0.10 but < 0.20 of the overall probability of failure during the item operating time interval.
10	A high probability of occurrence during the item operating time interval (i.e. once a week). High probability is defined as a single FM probability > 0.20 of the overall probability of failure during the item operating interval.

NOTE: Quantitative data should be used if it is available. For Example:

0.001 = 1 failure in 1,000 hours

0.01 = 1 failure in 100 hours

0.10 = 1 failure in 10 hours

Table 3.11 present the linguistic terms for the occurrence ranking and the corresponding quantitative failure rate provided by the different industry standards.

Table 3.11: Occurrence of failure modes (Kim et al., 2013)

Rank (O_{ij})	Comment	Possible failure rates (λ_{ij})	
		Ford Motor Company [14]	Department of the Army [9]
10	Extremely high	≥1 in 2	≥1/10
9	Very high	1 in 3	1 in 20
8	Repeated failures	1 in 8	1 in 50
7	High	1 in 20	1 in 100
6	Moderately high	1 in 80	1 in 200
5	Moderate	1 in 400	1 in 500
4	Relatively low	1 in 2000	1 in 1000
3	Low	1 in 15000	1 in 2000
2	Remote	1 in 150,000	1 in 5000
1	Nearly impossible	≤1 in 1,500,000	≤1 in 10,000

Ranking for detection can be defined as the probability that the failure mode will be detected under the controls and inspections that are in place. Ranking of the probability of detection is in reverse order which means a very high probability that a failure would be detected before reaching the customer is displayed by "1" and a low probability that the failure will be detected, and therefore the failure would be experienced by the customer, is indicated by "10". Table 3.12 shows ranking of recommended detection criteria (SEMATECH, 1992).

Table 3.12: Detection Ranking Criteria(SEMATECH, 1992)

Rank	Description
1-2	Very high probability that the defect will be detected. Verification and/or controls will almost certainly detect the existence of a deficiency or defect.
3-4	High probability that the defect will be detected. Verification and/or controls have a good chance of detecting the existence of a deficiency or defect.
5-7	Moderate probability that the defect will be detected. Verification and/or controls are likely to detect the existence of a deficiency or defect.
8-9	Low probability that the defect will be detected. Verification and/or controls not likely to detect the existence of a deficiency or defect.
10	Very low (or zero) probability that the defect will be detected. Verification and/or controls will not or cannot detect the existence of a deficiency or defect.

3.5 Issue and challenges of operation in Arctic condition

The oil and gas industry has shown the capability of industry to develop and to apply new innovative technologies, which is growing in the Arctic region, because the increasing demands for energy. Studies show that about 30% of the world's undiscovered gas and 13% of the world's undiscovered oil may be found in the north area of the Arctic Circle (Gautier et al., 2009).

Regarding the moving towards the Arctic, applying the experience will be important, because of facing with new challenges. Then it is important to know how the Arctic factors can affect the ships operation in the environment whit less experience and data. Figure 3.6 displays the boundary of ice-covered water in Arctic that ships may traffic.

Figure 3.6: The guidelines for ships operating in ice covered waters (Jensen, 2007)

Nowadays, most ship traffic is transported through the ice-free part of the Barents Sea. The southern part of Barents Sea water, are ice free and less demanding for ships and personnel, compared to the northern part of the Barents Sea that is ice covered waters. The Figure 3.7 shows Arctic traffic density based on Automatic Identification System (AIS) data from 2011. Frequency of ships per day is displayed with blue dots (INTSOK, 2013).

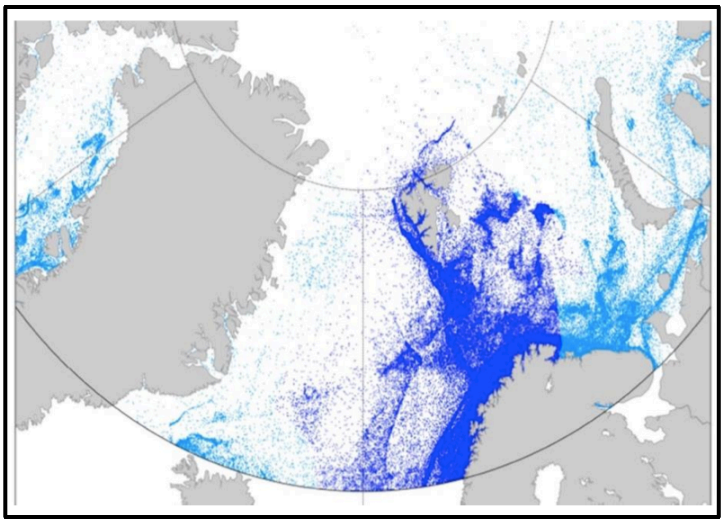

Figure 3.7: Arctic traffic density (INTSOK, 2013)

In the south part of the Barents Sea, ice does not show any effect on risk for maritime operations. But in the northern parts of the Barents Sea, oil and gas activities will be more challenging compared to activities in the Barents Sea South (INTSOK, 2013). These challenges and operational risks include: icing on vessels or installations due to low air temperatures, fog, darkness, polar lows and lack of infrastructure especially related to search and rescue infrastructure capabilities. This challenges will increase the risk level compare to the normal condition (INTSOK, 2013).

Moreover, according Arctic Operations Handbook JIP, due to a lack of reliable long-term measurements, there is uncertainty in weather forecasts in Arctic operation. There are no tools or processes always to identify ice hazards and risks accurately. Locating in remote area can impact on communication and transferring of data. In maritime operation the specific condition of ice and seasonal variations must be considered. Differences between the Arctic with southern regions are visibility, extreme low temperatures, ice accretion, polar lows, variable sea ice and iceberg conditions, and higher waves due to climate change in large area of open water (Ed Wiersema /Heerema Marine Contractors, 2014).

Generally the sensitive environment, harsh climate, remote area and poor infrastructure of the Arctic region are unique challenges for oil and gas companies. These challenges can influence on PSV performance. When a PSV moves from the North Sea to the Barents Sea, probability of failure may increase. The failure rate of outdoor equipment may increase due to the low temperature and icing (Barabadi and Markeset, 2011). Some materials lose their properties in cold climate for example steel become more brittle; plastics and composites causing failures at loads that are routinely imposed without damage in warmer climate. Failures of lubricants increase to perform adequately, thereby resulting in increased wear rates. Increased degradation of seal and filters could result in the increased loss of lubricants and coolants.

The consequence of failures in Arctic region also can be increased. The repair time may be increased when temperature drops (Barabadi and Markeset, 2011). Wind, snow and darkness and low temperature and icing on decks can reduce the effectiveness of maintenance crew to repair a failure. Humans are designed to operate in very narrow temperature range and cold climate can cause to increase human error also possibility of mistakes or being inaccurate increases. Icing and darkness also increase the probability of collision of ships. In this condition the consequences can be very high.

Due to these challenges, the International Maritime Organization (IMO) decided to adopt specific Guidelines for Arctic shipping. The Guidelines, which is an important step towards improved regulatory framework for global shipping in the ice-covered waters, represent the necessity to improve navigation safety and protection of the polar marine environment (Jensen, 2007).

4 Result and Discussion

This chapter discusses and presents the results of the research study (thesis). The areas of discussions focus on the stated research objectives.

4.1 The criticality analysis methods in Troms Offshore

The first objective of this research study is to review the methods and tools, which is used by Troms Offshore for criticality analysis. Based on the requirements in the ISM code 10.3, *The Company should identify equipment and technical systems the sudden operational failure of which may result in hazardous situations. The safety management system should provide for specific measures aimed at promoting the reliability of such equipment or systems. These measures should include the regular testing of stand-by arrangements and equipment or technical systems that are not in continuous use (IMO, 2010).*

In order to identify critical component for electrical and mechanical equipment of PSV, the concept of Failure Mode and Effect Analysis (FMEA) is applied by Troms Offshore. FMEA is applied by EL-DESIGN AS for the dynamic positioning systems of PSV, which is considered as one of the most important system regarding safety. The objective of the FMEA is to provide a complete, systematic and documented investigation of the dynamic positioning systems for the vessel, to reduce the risk to personnel, the vessel, other vessels or structures, subsea installations and the environment while performing operations under dynamic positioning control (EL-DESIGN, 2011). According to the FMEA analysis several single failures may occur in different subsystem of PSV such as thruster unit, main engine, auxiliary engine, switchboard, DP controller, etc. However, all of these subsystem have redundancy and therefore, by a single failure and out of operation, the vessel can still maintain DP operation safely. The effect of single failures are not discussed and covered in the analysis. Then, part of the FMEA is shown in Table 4.1.

Most of failure modes during DP operation for different subsystem and their component tried to identify and discuss in the FMEA. In the worksheet of the FMEA, the function of different component, failure modes and their effect on the component as well as system function are discussed. The last column of Table 4.1 indicates that the component/subsystem has redundancy or not, and because of type of DP system (DYNPOS AUTR), the technical parts of DP system have redundancy.

Table 4.1: FMEA worksheet of M/V Troms Castor

FMEA WORKSHEET OF M/V "Troms Castor" **Hellesøy Verft AS, yard No. 144** **Functional failure analysis of important systems during DP operation (MSB busbar system A and B in open position).**								
Name of analyst:	OH							
Date of analysis:	09.10.2008							
Document No.	E02908							
Revision:	0							
Item No.	***System***	***Component***	***Function***	***Failure***	***Undesirable effect***	***Effects***	***Common causes or interactions***	***Redundancy/ Criticality***
1.	POWER SYSTEM Electrical Main System	690V MSB busbar A1	Electrical power supply, 690V main system A1. Supplying 450V MSB-A and 230V MSB-A through three windings transformers (supply also from A2) Normal supply for 690/230V ESB	Short circuit of busbar A1	Loss of 50% capacity for Bow thruster 1, Loss of 50% capacity for propulsion azimuth thruster PS 50% reduction of Fwd. Azimuth capacity Loss of FW cooling pump No. 1 for PS auxiliaries (standby pump fed from A2) Loss of FW cooling pump No. 1 for PS propulsion (standby pump fed from A2)	Abt. 25% reduction of thruster capacity	Reduction of thruster capacity No loss of position Alarm indication	Redundant
2.	POWER SYSTEM Electrical Main System	690V MSB busbar A2	Electrical power supply, 690V main system A2. Supplying 450V MSB-A and 230V MSB-A through three windings transformers (supply also from A1) Normal supply for 690/230V ESB	Short circuit of busbar A2	Loss of 50% capacity for Bow thruster 1, Loss of 50% capacity for propulsion azimuth thruster PS, Loss of Chilled Water system 1, Loss of FW cooling pump No. 2 for PS auxiliaries (standby pump fed from A1) Loss of FW cooling pump No. 2 for PS propulsion (standby pump fed from A1) Loss of charging for 24V battery system B3	Abt. 25% reduction of thruster capacity	Reduction of thruster capacity. Battery systems have backup for 30 minutes. No loss of position Alarm indication	Redundant

Moreover, in order to identify the criticality of each failure mode, Troms Offshore uses the concept of risk matrix. In the risk matrix probability of occurrence is divided in five categories very low, low, medium, high and very high. Consequences of failure also sorted in five groups, which their definition according different category (people, asset environment and business disruption or reputation) is presented in Table 4.2.

Table 4.2: Risk matrix of Troms Offshore

Potential Severity					Likelihood of Occurrence				
					A	B	C	D	E
	People	Asset	Environment	Business disruption/Reputation	Very low > 10 years	Low Annually	Medium 6Monthly	High Monthly	Very high Daily
1	Insignificant injury (onsite treatment)	Insignificant damage <$1,000 USD	Insignificant spill, contained in drip tray, <1 litre	No disruption to business, no negative media attention					
2	Minor injury (1st aid treatment)	Minor damage<$5,000 USD	Minor spill contained on deck tray, <10 litres	Limit disruption (1 day), slight negative media exposure					
3	Serious injury (Recordable)	Serious damage<$15,000 USD, vessel stability unimpaired	Spill, sea pollution, <10 litres	Short term disruption (3 day), local negative media exposure					
4	Extensive injury (LTI)	Major damage <$50,000 USD, vessel stability impaired	Significant spill, sea pollution, <1000 litres	Medium disruption (1 week), Area significant negative media focus					
5	Fatality	Extensive damage/sinking, vessel total loss	Major spill, sea pollution, >1000litres	Long term business disruption (>1 week), Area significant negative media focus					

The levels of risk are determined with four colours namely: White, Yellow, Green, and Red, and each colour show a different level of risk. Troms Offshore has developed a different strategy, for each risk levels. By these strategies, the company tries to remove or mitigate the consequences of different failures. Their strategies includes (Troms Offshore risk matrix, 2014):

- **White:** Investigation carried out on board the vessel by the Master with assistance from the officers and crew as appropriate. Incident report in UniSea will be delegated to vessel's Captain. Result from investigation should be included in UniSea report.

- **Yellow:** Further investigation carried out by Troms Offshore onshore management. Incident report in UniSea will be delegated to person most suited to lead the investigation. The attached level 2 templates should be used as guidance, but result from investigation may be included in the UniSea report.

- **Green:** Full investigation carried out by investigation team, normally lead by the Tidewater Regional HSES Manager, Troms Offshore QHSE Manager/ Operation Manager or equivalent. The team selected will depend upon the accident or incident and will be such that the necessary competence and technical skills are available to fully determine what happened during incident and to make effective recommendation to prevent a recurrence. The attached level 3 templates shall be used and attached to the incident report in UniSea.

- **Red:** Full investigation Tidewater corporate level carried out by an investigation, normally lead by the Director of HSES, Regional HSES Manager or equivalent senior manager. The team selected will depend upon the accident and will be such that necessary to prevent a recurrence and to ensure that any additional resources that may be deemed necessary to mitigate further loss, damage or risk are effectively applied.

Finding the weaknesses of the available method is another objective of this research. With respect to the available Risk Matrix, currently used by Troms Offshore, the following points can be considered for improvement:

1. Classification of probability is not well defined, in the available Risk Matrix. For example, in the classification very low is defined for failures occur daily. In this situation other measures such as the cost of property, the cost of maintenance crew and etc. of failure should be considered in design phase, and redesign if it is needed. And also daily covers a very short period of time compare to expected lifetime of PSV that should be covered in study. If it is necessary to define the probability classes in short intervals like daily, it is important to use the same concept for other classes, which can be weekly, monthly and etc.
2. Definition of different classes of consequences categories can be improved. For example, in the consequences classification of failure related to people difference

between number 3 and 4 is not clear. Number 4 is defined extensive injury or Lost Time Injury (LTI), and according Australian standard a LTI is defined as an occurrence that resulted in a fatality, permanent disability or time lost from work of one day/shift or more (Standard, 1990). It is defined also LTI is recordable, which is exactly the same definition in class 3 (serious injury/recordable). This classification is better to define more clearly and a distinct way. Moreover, the consequences category related to the environmental impact, is only defined as per the amount of leakage in different place. However, the categorisation has not considered how easily the impact of leakage can be removed. For instance, the scenario to remove the leakage could be completely different when there is 5-liters leakage occurs locally on the deck than 3-liters leakage in the vast dimension or severe operational condition on the deck. In the second scenario, the removal process could be demanding and costly. Furthermore, these generic definitions can also be improved in proper classes.

3. Risk is defined as a combination of probability of unwanted event and consequences of such unwanted event. However, the classification of risk matrix to different colours is not in accordance to the definition. For example, if the consequence of an unwanted event is very high, it will be located in red zone (row 5) and the probability has no effect on the decision. Even if Troms Offshore applies their strategy, still the risk will be in the red area. Furthermore, it should be considered that although probability of some hazards can be decreased to very low, by using proper barriers but removing the probability of occurrence completely is not possible. For example, there is always a very low probability that people will die by some accident during PSV operation. It does not mean that PSV operation have to be halted. However, it means that all aspects of the risk related to the failure should be analysed and the proper risk reduction measure (to decrease the probability of occurrence or consequences) must be considered.

With respect to the criticality analysis using FMEA of Troms Offshore, the following points can be considered for improvement:

1. In FMEA worksheet of Troms Offshore, only one of the operational modes (DP mode) is considered and the other operational modes, such as transition mode are not mentioned. In order to do a complete analysis, it is better to cover all operational modes.
2. Mechanism of failure modes is not mentioned in the worksheet. Although identification of failures mechanism could be time consuming and demanding, but it is very important item, which can help the maintenance group to make a better decision regarding to the inspection period. It can also help to prepare preventive maintenance plans.
3. Available FMEA does not have any suggestion for risk reduction measure. In FMEA not only it is important to identify all failure modes, but also is important to consider

all the risk reduction measure to improve the system performance. Then, this measure can use as a guideline for maintenance and spare part planning groups.

4. The existing worksheet of FMEA only covers failures mode and its effects and does not include the criticality analysis in proper way. The aim of criticality analysis is to identify which component has the most serious potential consequences on system performance and also Health, Safety and Environment (HSE), if it fails. In order to identify the critical component it is better to use some quantitative method such as RPN number. In RPN method, the concept of detection is used beside the severity and probability of occurrence.

4.2 Improvement of criticality analysis methods of Troms Offshore

One of the objectives of the thesis is to suggest how the method of criticality analysis of Troms Offshore can be improved. In order to reach this aim, a literature review and the study of the some available standards such as (ISO17776, 2000) has been carried out. In addition, past experiences from other industries such as HAZID worksheet of oil and gas industry (Lloyd, 2008) and International Maritime Organization (IMO, 2002) has been analysed. Moreover, several meeting with experts has been one of the main parts of the weakness analysis of the available systems. The result of discussion will be presented in this section.

With respect to the Risk Matrix, Troms Offshore can consider the following suggestions for improvement:

1. Probability/frequency of occurrence can be defined in intervals, as follow:

	Old definition	Modified definition
Very high:	Daily	$p \leq 1$week
High:	Monthly	1week$<p\leq$1 month
Medium:	6 Monthly	1 month $<p \leq$1 year
Low:	Annually	1 year$<p\leq$15 year
Very low:	> 10 years	> 15 years

The main motivation for new classification is to define the probability of occurrence in proper intervals. Moreover, duration of these intervals could be defined according to type of activity, policy, and risk acceptance criteria of company.

2. Some descriptions of the different category of the potential severity need to be changed. However, the current consequences definition regarding to asset as well as reputation is based on the goals and policy of company; therefore, these definitions are not changed in this study. With respect to the effect of the consequence on the people, the duration of effects need to be considered in an appropriate way. Thus, the definition of the severity classification regarding to the people are modified, and can be referred in Table 4.3 (column 2). The previous definition about the environment assortment, which is only based on the amount of leakage, has been changed. The current suggestion has included

the dimension of leakage in different places and how the impacts can be removed. In this suggestion concept of the amount of leakage also can be added.

3. Levels of risk, which is identified by colours in the risk matrix, has been modified according to the improved definition of the probability and consequences. In the suggested risk matrix, combination of the probability of occurrence and consequences of failure are used to define the risk levels.

Table 4.3 shows the suggested risk matrix for Troms Offshore; where *P* means Probability/frequency of occurrence. Moreover, the strategies regarding to different levels of risk is the same that is currently applied in Troms Offshore.

Table 4.3: improved risk matrix

Potential Severity					Likelihood of Occurrence; p				
					A (Very low)	B (Low)	C (Medium)	D (High)	E (Very high)
	People	Asset	Environment	Business disruption/Reputation	> 15 years	1 year<p≤1 5 year	1 month <p ≤1 year	1week<p≤1 month	p ≤1week
1	Insignificant: very minor injury	Insignificant damage <$1,000 USD	Insignificant: locally limited leak on deck, can be remove easily	No disruption to business, no negative media attention					
2	Minor injury: need treatment and short-term impact on personal ability to work	Minor damage<$5,000 USD	Minor impact: leak on deck, locally but in vast dimension, no permanent impact	Limit disruption (1 day), slight negative media exposure					
3	Serious injury: Long-term impact on personal ability to work	Serious damage<$15,000 USD, vessel stability unimpaired	Moderate: Contamination is large but local, in the immediate surrounding of the facility	Short term disruption (3 day), local negative media exposure					
4	Extensive injury (LTI), Multiple major injuries	Major damage <$50,000 USD, vessel stability impaired	Major: Heavy environmental contamination, extensive measure to return environment to original state, can be contained and recovered in the sea;	Medium disruption (1 week), Area significant negative media focus					
5	Fatality	Extensive damage/sinking, vessel total loss	Permanent, catastrophic environmental contamination over large area, contamination can be only removed with extensive measure	Long term business disruption (>1 week), Area significant negative media focus					

With respect to the criticality analysis for the mechanical parts in Troms Offshore, we suggest replacing FMECA instead of FMEA. Our recommendation is based on literature review of existing methods, and study of available standard worksheet, meeting with experts, and also uses the experience of the similar industry. The worksheet of FMECA will covers all operational modes of PSV. Moreover, the failure mechanism and measures to reduce the risk is added to the worksheet. Furthermore, a quantitative method, RPN, is integrated in the FMECA worksheet, in order to make it clear and understandable for maintenance crew and also for other personnel. Table 4.4 shows the suggested worksheet for FMECA.

Table 4.4: Suggested FMECA worksheet for Troms Offshore

<table>
<tr><td colspan="8" rowspan="4">FMECA WOKSHEET OF “Troms Castor”</td><td colspan="5">Name of analysis:</td><td colspan="2"></td></tr>
<tr><td colspan="5">Date of analysis</td><td colspan="2"></td></tr>
<tr><td colspan="5">Document No.</td><td colspan="2"></td></tr>
<tr><td colspan="5">Revision:</td><td colspan="2"></td></tr>
<tr><td>Item No.</td><td>System</td><td>Component</td><td>Function</td><td>Operational mode</td><td>Failure mode</td><td>Failure Mechanism</td><td>Undesirable effect on system</td><td>Effect on the system function</td><td>S</td><td>O</td><td>D</td><td>RPN</td><td>Redundancy/ Criticality</td><td>Risk reduction measure</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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</table>

As discussed RPN number can be calculated by using equation 3.4. In this method each failure mode will get a score with respect to Severity, likelihood of Occurrence, and likelihood of Detection from 1 to 10. The suggested classification for severity ranking, likelihood of occurrence and ranking are shown in Tables 4.5, 4.6 and 4.7.

Table 4.5: Severity ranking

Severity ranking	**Failure effect**	**Comment**
10	Very high	Potential for fatality, extensive damage/sinking, vessel total loss, Permanent, catastrophic environmental contamination over large area, contamination can be only removed with extensive measure, Long term business disruption (>1 week), Area significant negative media focus
8-9	High	Extensive injury (LTI), Multiple major injuries, Major damage <$50,000 USD, vessel stability impaired, Major: Heavy environmental contamination, extensive measure to return environment to original state, can be contained and recovered in the sea, Medium disruption (1 week), Area significant negative media focus
5-7	Medium	Serious injury: Long-term impact on personal ability to work, Serious damage<$15,000 USD, vessel stability unimpaired, Moderate: Contamination is large but local, in the immediate surroundings of the facility, Short term disruption (3 day), local negative media exposure
3-4	Low	Minor injury: need treatment and short-term impact on personal ability to work, Minor damage<$5,000 USD, Minor impact: leak on deck, locally but in vast dimension, no permanent impact, Limit disruption (1 day), slight negative media
1-2	Very low	Insignificant: very minor injury, Insignificant damage <$1,000 USD, Insignificant: locally limited leak on deck, can be remove easily, No disruption to business, no negative media attention

Table 4.6: Ranking of likelihood of occurrence

Occurrence Ranking	**Failure effect**	**Comment**
10	Very high	$p \le 1$week
8-9	High	1week$< p \le 1$ month
5-7	Medium	1 month $< p \le 1$ year
3-4	Low	1 year$< p \le 15$ year
1-2	Very low	> 15 years

Table 4.7: Ranking of detection

Detection ranking	Comment
10	Very low (or zero) probability that the defect will be detected. Verification and/or controls will not or cannot detect the existence of a deficiency or defect.
8-9	Low probability that the defect will be detected. Verification and/or controls not likely to detect the existence of a deficiency or defect.
5-7	Moderate probability that the defect will be detected. Verification and/or controls are likely to detect the existence of a deficiency or defect.
3-4	High probability that the defect will be detected. Verification and/or controls have a good chance of detecting the existence of a deficiency or defect.
1-2	Very high probability that the defect will be detected. Verification and/or controls will almost certainly detect the existence of a deficiency or defect.

4.3 Case study

This study is carried out with cooperation of Troms Offshore. Troms Offshore Supply AS owns Troms Offshore Management AS that is a supplier of offshore services and is located in Tromsø, Norway. Troms Offshore Supply AS is owned by Tidewater Inc. The company operates the six Troms Offshore Supply owned PSVs and in addition five offshore services vessels on management contracts. The vessel featured in this study is the Troms Castor, a VS485 PSV shown in Figure 4.1. Troms Castor is designed with common industry standards for modern platform supply vessels by Istanbul Tersanecilik ve Denizcilik and outfitted by Hellesøy Verft AS in 2009.

Figure 4.1: One of VS485′s managed by Troms Offshore: Troms Castor © Troms offshore

The Troms Castor has the following particulars:

Class	DNV
DP Notation	DYNPOS AUTR
Class Notation	1A1 ICE-C OILREC SF LFL* COMF-VC E0 NAUT-OSV (A) CLEAN DESIGN DK (+) HL (2.8)
Length overall	85.0m
Breadth moulded	20.0m
Maximum draft	7.1m

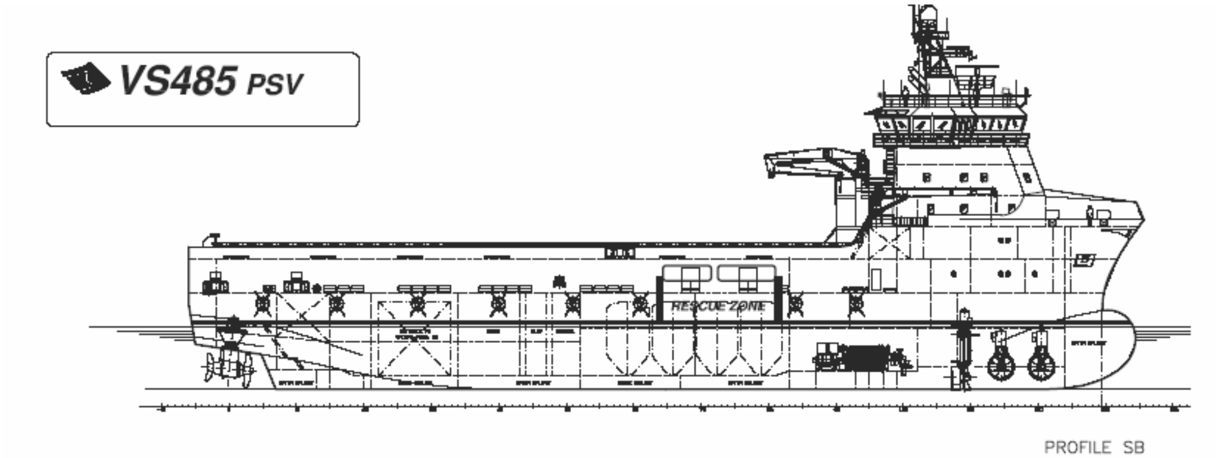

Figure 4.2: Vessel layout © Troms offshore

When the FMECA worksheet and classification for the rankings was finalized, we held another meeting in office of Troms Offshore to discuss and fill the worksheet for part of PSV as a sample, and also to see if there is any ambiguous in definitions or worksheet for users. This study was decided to focus on Dynamic Positioning system (DP system) in available time, because the FMEA was done for DP system of Troms Castor and most of failure modes were defined before. A dynamic positioning system is the complete installation necessary for dynamically positioning of a vessel and comprises the following sub-systems, control panels, and back-up systems (AS, 2011):

- Power system
- Thruster system
- DP-control system.

Type of DP Notation of Troms Castor is DYNPOS AUTR, which means DP system has redundancy in technical design and an independent joystick system back up (DNV, 2011)

In order to fill the worksheet the Pre Master software is used as basis of information, there is one part for maintenance in the software that all the failures, date of failure and the action to remove the failure is submitted by maintenance crews. Most of the Vessels owned by Troms Offshore are almost new; therefore, there is a lack of historical data. Thus, in this study the analysis has been relied on the expert judgment to fill the worksheet.

During criticality analysis when RPN number come to same number for different failure modes, it is decided that any failure mode that has an effect resulting in a higher severity would have top priority. In this assessment the most weight is given to the severity, and in the next step combination of Severity and Occurrence (S x O) is considered.

In the next step, a letter was prepared that definition of criticality analysis, the aim of criticality analysis, explanation of different part of the worksheet, concept of RPN number and equation for calculating RPN number was clarified. The letter was sent to captains of three vessels, and tables of severity ranking, ranking of likelihood of occurrence and detection ranking along with worksheet were attached to the letter. Captains, vessels crew and technicians may have more information compare to experts in office. This is due to their practical experience with dealing of the failure on board. After communication with experts in office and on the vessels the FMECA was finalized. An example of the result of analysis, FMECA, is shown in the Table 4.8. More detail can be found in Appendix E.

Table 4.8: FMECA worksheet for DP system of Troms Castor

FMECA WOKSHEET OF "VS 485"	**Name of analysis:**	
	Date of analysis	
	Document No.	
	Revision:	

Item No.	System	Component	Function	Operational mode	Failure mode	Failure Mechanism	Undesirable effect on system	Effect on the system function	S	O	D	RPN	Redundancy/ Criticality	Risk reduction measure
1	POWER SYSTEM - ELECTRICAL MAIN system	690V MSB busbar A1	Electrical power supply, 690V main system A1. Supplying 450V MSB-A and 230V MSB-A through three winding transformers (supply also from A2) Normal supply for 690/230V ESB	Transit	Short circuit of busbar A1	Breaker malfunction	Black out	Loss of all system function	10	1	5	50		Routine inspections.
2	POWER SYSTEM - ELECTRICAL MAIN system	690V MSB busbar A2	Electrical power supply, 690V main system A2. Supplying 450V MSB-A and 230V MSB-A through three winding transformers (supply also from A1) Normal supply for 690/230V ESB	Transit	Short circuit of busbar A2	Breaker malfunction	Black out	Loss of all system function	10	1	5	50		Routine inspections.

All the method of criticality analysis, which is applied for PSV in Troms Offshore, is applicable in Arctic condition. However, the unique challenges of the Arctic region, harsh climate, sensitive environment, remote location and poor infrastructure, can have an impact on the PSV performance in such condition. The failure rate of outdoor equipment may increase due to the low temperature and icing. Moreover, the repair time can be significantly increased. Considering those repair time and failure rates are two important elements of the criticality analysis, the criticality ranking of such equipment may be changed in the risk matrix. Furthermore, in case of collision the rescue operation can be demanding due to the long distance (remoteness) and the consequences can be catastrophic. In addition, a generation of static electricity can be a challenge, especially for DP operating near the rigs in Arctic region. This is due to the fact that the generation of the static electricity can destroy computers and control circuitry, which significantly impact the DP operation in the cold region.

The other challenge related to the Arctic operation is the difficulty with detection of failure. The likelihood of detection failure, which is an item of criticality analysis, can be decreased. Consequently, the RPN number, which is combination of detectability, severity, and probability of occurrence, may be changed in Arctic region.

In this study due to lack of expert experience in Arctic as well as lack of data, we could not apply the FMECA in Arctic. However, determination of the risk levels when PSV operates in the Arctic condition could be necessary.

5 Conclusions and Suggestions for Further Research

The aim of this chapter is to presents the main conclusion and suggestions for further research of this research study.

5.1 Conclusions

Based on the discussions of the previous chapters, it can be concluded that the research produced the following results:

- Component criticality analysis can be considered in the process of improving and optimizing the preventive maintenance schedule and spare part strategy. And the optimizing when a PSV operates in remote area or Arctic condition can be more important.
- Developing efficient method of criticality analysis can create value by improving reliability, availability, technical integrity, safety, regularity, quality and performance of PSVs parts.
- FMECA is useful for safety-critical analysis of mechanical and electrical equipment. In this study we suggest to replace FMECA instead of FMEA, and apply RPN number as an effective method to determine critical components.
- Risk matrix uses as an efficient method to identify the risk levels and decision-making in the company. In the available risk matrix of Troms Offshore, we changed definition of probability classification to proper intervals. Furthermore, definition of some consequence assortment regard to people and environment is modified in a clear and distinct way. Based on this changes the risk levels are shifted as a combination of probability and occurrence.
- The operational factors of the Arctic condition may influence on the probability of occurrence, severity level and the likelihood of detection of PSV failures, and then the risk level may change in the Arctic region.

5.2 Suggestions for Further Research

Based on the research presented in this thesis, the following points for future research are suggested:

- Application of Fault Tree Analysis (FTA) in the criticality analysis:

In order to consider the effect of redundancy in more proper and effective way the method of FTA can be used in combination with FMECA. It will also make it easy to study the human error in the analysis.

- Study the effect of operational factors of Arctic condition on risk analysis methods.
- To develop a framework for data collection in order to be applicable to different situation.

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Appendixes

Appendix A: Risk matrix, probability and consequences classification (IMO)

Table A.1: Risk matrix based on logarithmic probability/frequency index (IMO, 2002)

Risk Index (RI)					
		SEVERITY (SI)			
		1	2	3	4
FI	FREQUENCY	Minor	Significant	Severe	Catastrophic
7	Frequent	**8**	**9**	**10**	**11**
6		**7**	**8**	**9**	**10**
5	Reasonably probable	**6**	**7**	**8**	**9**
4		**5**	**6**	**7**	**8**
3	Remote	**4**	**5**	**6**	**7**
2		**3**	**4**	**5**	**6**
1	Extremely remote	**2**	**3**	**4**	**5**

Table A.2: logarithmic probability index (IMO, 2002)

Frequency Index			
FI	FREQUENCY	DEFINITION	F (per ship year)
7	Frequent	Likely to occur once per month on one ship	10
5	Reasonably probable	Likely to occur once per year in a fleet of 10 ships, i.e. likely to occur a few times during the ship's life	0.1
3	Remote	Likely to occur once per year in a fleet of 1000 ships, i.e. likely to occur in the total life of several similar ships	10^{-3}
1	Extremely remote	Likely to occur once in the lifetime (20 years) of a world fleet of 5000 ships.	10^{-5}

Table A.3: a logarithmic probability/frequency index (IMO, 2002)

Severity Index				
SI	SEVERITY	EFFECTS ON HUMAN SAFETY	EFFECTS ON SHIP	S (Equivalent fatalities)
1	Minor	Single or minor injuries	Local equipment damage	0.01
2	Significant	Multiple or severe injuries	Non-severe ship damage	0.1
3	Severe	Single fatality or multiple severe injuries	Severe damage	1
4	Catastrophic	Multiple fatalities	Total loss	10

Appendix B: General consequence classification (Norsok Z008)

Table B.1: General consequence classification (Z008, 2001)

Class	Health, safety and environment (HSE)	Production	Cost (exclusive production loss)
High	Potential for serious personnel injuries. Render safety critical systems inoperable. Potential for fire in classified areas. Potential for large pollution.	Stop in production/significant reduced rate of production exceeding X hours (specify duration) within a defined period of time.	Substantial cost - exceeding Y NOK (specify cost limit)
Med.	Potential for injuries requiring medical treatment. Limited effect on safety systems. No potential for fire in classified areas. Potential for moderate pollution.	Brief stop in production/reduced rate of production lasting less than X hours (specify duration) within a defined period of time.	Moderate cost between Z – Y NOK (specify cost limits)
Low	No potential for injuries. No potential for fire or effect on safety systems. No potential for pollution (specify limit)	No effect on production within a defined period of time.	Insignificant cost less than Z NOK (specify cost limit)

Appendix C: Risk Matrix and its decision classes (DNV)

Table C.1: Four decision classes for the risk matrix (DNV, 2001)

RISK CLASS	INTERPRETATION
A	Intolerable
B	Undesirable and shall only be accepted when risk reduction is impracticable
C	Tolerable with the endorsement of the Project Safety Review Committee
D	Tolerable with the endorsement of the normal project reviews

Table C.2: Risk matrix (with the decision classes shown above) (DNV, 2001)

	Catastrophic	Critical	Marginal	Negligible
Frequent	A	A	A	B
Probable	A	A	B	C
Occasional	A	B	C	C
Remote	B	C	C	D
Improbable	C	C	D	D
Incredible	C	D	D	D

Appendix D: Example of severity definition and ranking

Table D.1: Severity definitions for classification of severity (Kim et al., 2013)

Rank (S_{ij})	Failure effect	Comment
10	Hazardous without warning	Potential safety, health, or environmental issue Failure will occur without warning
9	Hazardous with warning	Potential safety, health, or environmental issue Failure will occur with warning
8	Very high	High disruption to facility function All of mission is lost
7	High	High disruption to facility function Some portion of mission is lost
6	Moderate to high	Moderate disruption to facility function Some portion of mission is lost
5	Moderate	Moderate disruption to facility function 100% of process is delayed
4	Low to moderate	Moderate disruption to facility function Some portion of process is delayed
3	Low	Minor disruption to facility function. Repair of failure may be longer than trouble call
2	Very low	Minor disruption to facility function. Repair of failure can be accomplished during trouble call
1	None	No discernible effect on safety, environment, or mission

Appendix E: FMECA worksheet

Table E.1: FMECA worksheet for DP system

FMECA WOKSHEET OF "VS 485"	
Name of analysis:	
Date of analysis	
Document No.	
Revision:	

Item No.	System	Component	Function	Operational mode	Failure mode	Failure Mechanism	Undesirable effect on system	Effect on the system function	S	O	D	RPN	Redundancy /Criticality	Risk reduction measure
1	POWER SYSTEM - ELECTRICAL MAIN system	690V MSB busbar A1	Electrical power supply, 690V main system A1. Supplying 450V MSB-A and 230V MSB-A through three winding transformers (supply also from A2) Normal supply for 690/230V ESB	Transit	Short circuit of busbar A1	Breaker malfunction	Black out	Loss of all system function	10	1	5	50		Routine inspections.
2	POWER SYSTEM - ELECTRICAL MAIN system	690V MSB busbar A2	Electrical power supply, 690V main system A2. Supplying 450V MSB-A and 230V MSB-A through three winding transformers (supply also from A1) Normal supply for 690/230V ESB	Transit	Short circuit of busbar A2	Breaker malfunction	Black out	Loss of all system function	10	1	5	50		Routine inspections.
3	POWER SYSTEM - ELECTRICAL MAIN system	690V MSB busbar A1	Electrical power supply, 690V main system A1. Supplying 450V MSB-A and 230V MSB-A through three winding transformers (supply also from A2) Normal supply for 690/230V	DP operational mode	Short circuit of busbar A1	Breaker malfunction	Loss of 50% capacity for Bow thruster 1, Loss of 50% capacity for propulsion azimuth thruster PS , Loss of Chilled Water system1, Loss of	About 25% reduction of thruster capacity	8	1	5	40		Routine inspections.

			ESB				FW cooling pump No.2 for PS auxiliaries (standby pump fed from A1) Loss of FW cooling pump No.2 for PS propulsion (standby pump fed from A1) Loss of charging for 24V battery system B3							
4	POWER SYSTEM - ELECTRICAL MAIN system	690V MSB busbar A1	Electrical power supply, 690V main system A1. Supplying 450V MSB-A and 230V MSB-A through three winding transformers (supply also from A2) Normal supply for 690/230V ESB	DP operational mode	Short circuit of busbar A1	Breaker malfunction on both sides of MSB	Black out	Loss of system function	8	1	5	50		Routine inspections.
5	POWER SYSTEM - ELECTRICAL MAIN system	690V MSB busbar A1 and A2, 24VDC common control circuit	Electrical power supply, 690V main system A2. Supplying 450V MSB-A and 230V MSB-A through three winding transformers (supply also from A2) Normal supply for 690/230V ESB	Transit	Short circuit of common 24VDC common supply for common functions inside 690V MSB busbar A1/A2	Breaker failure / cable brakeage.	Loss of 2 generators PS and 50% of thruster capacity PS	About 25% reduction of thruster capacity	8	1	5	40		Routine inspections.
6	POWER SYSTEM - ELECTRICAL MAIN system	690V MSB busbar A1 and A2, 24VDC common control circuit	Electrical power supply, 690V main system A2. Supplying 450V MSB-A and 230V MSB-A through three winding transformers (supply also from A2) Normal supply for 690/230V ESB	DP	Short circuit of common 24VDC common supply for common functions inside 690V MSB busbar A1/A2	Breaker failure / cable brakeage.	Loss of 2 generators PS and 50% of thruster capacity PS	About 25% reduction of thruster capacity	5	1	5	25		Regular maintenance according to manufacturer's recommendations
7	POWER SYSTEM - ELECTRICAL MAIN system	690V MSB busbar A1 and A2, 24VDC	Electrical power supply, 690V main system A2. Supplying 450V MSB-A and 230V MSB-A through three winding	DP	Short circuit of common 24VDC common supply for common	Breaker failure / cable brakeage.	Black out	Loss of system function	9	1	1	9		

		common control circuit	transformers (supply also from A2) Normal supply for 690/230V ESB		functions inside 690V MSB busbar A1/A2									
8	POWER SYSTEM - ELECTRICAL MAIN system	690V MSB busbar B1	Electrical power supply, 690V main system A2. Supplying 450V MSB-A and 230V MSB-A through three winding transformers (supply also from A1) Normal supply for 690/230V ESB	Transit	Short circuit of busbar B1	Breaker malfunction	Black out	Loss of all system function	10	1	5	50		Routine inspections.
9	POWER SYSTEM - ELECTRICAL MAIN system	690V MSB busbar B2	Electrical power supply, 690V main system B2. Supplying 450V MSB-B and 230V MSB-B through three winding transformers (supply also from B1)	Transit	Short circuit of busbar B2	Breaker malfunction	Black out	Loss of all system function	10	1	5	50		Routine inspections.
10	POWER SYSTEM - ELECTRICAL MAIN system	690V MSB busbar B1 and B2, 24VDC common control circuit	Electrical supply, 690V main system B1/B2. Supplying 450V MSB-B and 230V MSB-B through three winding transformers (supply also from A1)	Transit	Short circuit of common 24VDC common supply for common functions inside 690V MSB busbar B1/B2	Breaker failure / cable brakeage.	Loss of 2 generators PS and 50% of thruster capacity PS	About 25% reduction of thruster capacity	5	1	5	25		Regular maintenance according to manufacturer's recommendations
11	POWER SYSTEM - ELECTRICAL MAIN system	450 V MSB busbar A	Electrical power supply, 450V main system.	Transit	Short circuit of busbar A	Breaker failure / equipment failure	Loss of 230V MSB busbar A (ships UPS 3, DP UPS 1), Loss of propulsion Azimuth PS (both steering gear pumps), Loss of PS generators	50% reduction of thruster capacity	5	1	5	25		Routine inspections.
12	POWER SYSTEM - ELECTRICAL MAIN system	450 V MSB busbar A	Electrical power supply, 450V main system.	Transit	Short circuit of busbar A	Breaker failure / equipment failure	Black out	Loss of system function	10	1	5	50		Routine inspections.

13	POWER SYSTEM - ELECTRICAL MAIN system	450 V MSB busbar A	Electrical power supply, 450V main system.	DP	Short circuit of busbar A	Breaker failure / equipment failure	Loss of 230V MSB busbar A (ships UPS 3, DP UPS 1), Loss of propulsion Azimuth PS (both steering gear pumps), Loss of PS generators	50% reduction of thruster capacity	5	1	5	25		Routine inspections.
14	POWER SYSTEM - ELECTRICAL MAIN system	450 V MSB busbar A	Electrical power supply, 450V main system.	DP	Short circuit of busbar A	Breaker failure / equipment failure	Black out	Loss of system function	10	1	5	50		Routine inspections.
15	POWER SYSTEM - ELECTRICAL MAIN system	450V MSB busbar B	Electrical power supply, 450V main system.	Transit	Short circuit of busbarB	Breaker failure / equipment failure	Loss of 230V MSB busbar B (ships UPS 2, DP UPS 2), Loss of propulsion Azimuth SB (both steering gear pumps), Loss of SB generators	50% reduction of thruster capacity	5	1	5	25		Routine inspections.
16	POWER SYSTEM - ELECTRICAL MAIN system	450V MSB busbar B	Electrical power supply, 450V main system.	Transit	Short circuit of busbarB	Breaker failure / equipment failure	Black out	Loss of system function	10	1	5	50		Routine inspections.
17	POWER SYSTEM - ELECTRICAL MAIN system	450V MSB busbar B	Electrical power supply, 450V main system.	DP	Short circuit of busbarB	Breaker failure / equipment failure	Loss of 230V MSB busbar A (ships UPS 3, DP UPS 1), Loss of propulsion Azimuth PS (both steering gear pumps), Loss of PS generators	50% reduction of thruster capacity	5	1	5	25		Routine inspections.
18	POWER SYSTEM - ELECTRIC	450V MSB busbar B	Electrical power supply, 450V main system.	DP	Short circuit of busbarB	Breaker failure / equipment	Black out	Loss of system function	10	1	5	50		Routine inspections.

	AL MAIN system					failure							
19	POWER SYSTEM - ELECTRICAL MAIN system	230V MSB busbar A	Electrical power supply, 230V main system.	Transit	Short circuit of busbar A	Breaker failure / equipment failure	Loss of 230V MSB busbar A Loss of ships UPS 3 Loss of DP ups 1, Loss of PS generators	50% reduction of thruster capacity	5	1	5	25		Routine inspections.
20	POWER SYSTEM - ELECTRICAL MAIN system	230V MSB busbar A	Electrical power supply, 230V main system.	Transit	Short circuit of busbar A	Breaker failure / equipment failure	Black out	Loss of system function	10	1	5	50		Routine inspections.
21	POWER SYSTEM - ELECTRICAL MAIN system	230V MSB busbar A	Electrical power supply, 230V main system.	DP	Short circuit of busbar A	Breaker failure / equipment failure	Loss of 230V MSB busbar A (ships UPS 3, DP UPS 1), Loss of propulsion Azimuth PS (both steering gear pumps), Loss of PS generators	50% reduction of thruster capacity	5	1	5	25		Routine inspections.
22	POWER SYSTEM - ELECTRICAL MAIN system	230V MSB busbar A	Electrical power supply, 230V main system.	DP	Short circuit of busbar A	Breaker failure / equipment failure	Black out	Loss of system function	10	1	5	50		Routine inspections.
23	POWER SYSTEM - ELECTRICAL MAIN system	230V MSB busbar B	Electrical power supply, 230V main system.	Transit	Short circuit of busbar B	Breaker failure / equipment failure	Loss of 230V MSB busbar B Loss of ships UPS 2, Loss of DP ups 2, Loss of SB generators	50% reduction of thruster capacity	5	1	5	25		Routine inspections.
24	POWER SYSTEM - ELECTRICAL MAIN system	230V MSB busbar B	Electrical power supply, 230V main system.	Transit	Short circuit of busbar B	Breaker failure / equipment failure	Black out	Loss of system function	10	1	5	50		Routine inspections.
25	POWER SYSTEM -	230V MSB	Electrical power supply, 230V main system.	DP	Short circuit of busbar B	Breaker failure /	Loss of 230V MSB busbar A (ships	50% reduction of thruster	5	1	5	25		Routine inspections.

	ELECTRICAL MAIN system	busbar B				equipment failure	UPS 3, DP UPS 1), Loss of propulsion Azimuth PS (both steering gear pumps), Loss of PS generators	capacity						
26	POWER SYSTEM - ELECTRICAL MAIN system	230V MSB busbar B	Electrical power supply, 230V main system.	DP	Short circuit of busbar B	Breaker failure / equipment failure	Black out	Loss of system function	10	1	5	50		Routine inspections.
27	POWER SYSTEM - ELECTRICAL MAIN system	Ship's UPS system No.1 (PS)	230V uninterrupted clean power supply for ship consumers	Transit, DP	Short circuit in UPS	Malfunction of UPS	Loss of AMCS PC04 bridge, Loss of AC/DC converter bridge	None	3	1	3	9		Regular maintenance according to manufacturer's recommendations
28	POWER SYSTEM - ELECTRICAL MAIN system	Ship's UPS system No.1 and No. 2 (PS)	230V uninterrupted clean power supply for ship consumers	Transit, DP	Short circuit in UPS	Malfunction of UPS	Loss of AMCS PC04 bridge, Loss of AC/DC converter bridge Loss of one CPU for IAS and PMS system, Loss of LLC1 transformer Loss of thruster Bow tunnel thruster 2 and propulsion Azimuth thruster SB	50% reduced thruster capacity	8	1	3	24		Regular maintenance according to manufacturer's recommendations
29	POWER SYSTEM - ELECTRICAL MAIN system	Ship's UPS system No.1, No. 2 and No. 3 (PS)	230V uninterrupted clean power supply for ship consumers	Transit, DP	Short circuit in UPS	Malfunction of UPS	Loss of AMCS PC04 bridge, Loss of AC/DC converter bridge Loss of one CPU for IAS and PMS system, Loss of LLC1 transformer	Loss of thruster capacity	8	1	3	24		Regular maintenance according to manufacturer's recommendations

							Loss of thruster Bow tunnel thruster 2 and propulsion Azimuth thruster SB Loss of one CPU for IAS and PMS system, Loss of LLC2 transformer Loss of thruster Bow tunnel thruster 1, Fwd Azimuth thruster and propulsion Azimuth thruster PS							
30	POWER SYSTEM - ELECTRICAL MAIN system	Ship's UPS system No.2 (SB)	230V uninterrupted clean power supply for ship consumers		Short circuit in UPS	Malfunction of UPS	Loss of one CPU for IAS and PMS system, Loss of LLC1 transformer Loss of thruster Bow tunnel thruster 2 and propulsion Azimuth thruster SB	50% reduced thruster capacity	8	1	3	24		Regular maintenance according to manufacturer's recommendations
31	POWER SYSTEM - ELECTRICAL MAIN system	Ship's UPS system No.3 (PS)	230V uninterrupted clean power supply for ship consumers		Short circuit in UPS	Malfunction of UPS	Loss of one CPU for IAS and PMS system, Loss of LLC2 transformer Loss of thruster Bow tunnel thruster 1, Fwd Azimuth thruster and propulsion Azimuth thruster PS	50% reduced thruster capacity	8	1	3	24		Regular maintenance according to manufacturer's recommendations
32	POWER SYSTEM -	DP UPS No.1	230V power supply for DP equipment	DP	Short circuit in UPS	Malfunction of	DPC-21 PU1 SDP OS 1	Full thruster capacity	8	1	3	24		Regular maintenance

	ELECTRICAL MAIN system					component	Alarm printer for DP DGPS 1 Fan beam power supply Fan beam monitor Wind display No.1 NDU-A1							according to manufacturer's recommendations
33	POWER SYSTEM - ELECTRICAL MAIN system	DP UPS No.2	230V power supply for DP equipment	DP	Short circuit in UPS	Malfunction of component	DPC-21 PU2 SDP OS 2 DGPS 2 History station Hard copy printer for DP Wind display No.2 NDU-A2	Full thruster capacity	8	1	3	24		Regular maintenance according to manufacturer's recommendations
34	POWER SYSTEM - ELECTRICAL Emergency system	690/230V ESB	Electrical power supply, emergency system	Transit, DP	Short circuit of 690V busbar	Breaker malfunction	Loss of supply for ship UPS No.1 Loss of battery charger for 24V battery system B3	Full thruster capacity	5	1	3	15		Regular maintenance according to manufacturer's recommendations
35	POWER SYSTEM - ELECTRICAL MAIN system	PMS A, 690V Busbar A1/A2	Automatic monitoring and control of power plant	Transit, DP	Wire break for network wires between Node 3 SW8 and PMS A	Possible fire	Loss of communication between PMS A and Node 3 SW8	None, as no breaker will change position	8	4	3	96		Routine inspections. IAS/PMS/VSD course for engineers and electrician. For troubleshooting and maintenance
36	POWER SYSTEM - ELECTRICAL MAIN system	PMS A, 690V Busbar B1/B2	Automatic monitoring and control of power plant	Transit, DP	Wire break for network wires between Node 3 SW12 and Node 3 SW13	Possible fire	Loss of communication between PMS B, Node 3 SW12 and Node 3 SW13	None, as no breaker will change position	8	4	3	96		Routine inspections. IAS/PMS/VSD course for engineers and electrician. For troubleshooting and maintenance
37	POWER	PMS A,	Automatic monitoring	Transit,	Power failure	Possible fire	Loss of PLC A	None, as no	8	4	3	96		Routine

	SYSTEM - ELECTRICAL MAIN system	690V Busbar A1/A2	and control of power plant	DP	for PMS A PLC			breaker will change position						inspections. IAS/PMS/VSD course for engineers and electrician. For troubleshooting and maintenance
38	POWER SYSTEM - ELECTRICAL MAIN system	PMS A, 690V Busbar B1/B2	Automatic monitoring and control of power plant	Transit, DP	Power failure for PMS B PLC	Possible fire	Loss of PLC B	None, as no breaker will change position	8	4	3	96		Routine inspections. IAS/PMS/VSD course for engineers and electrician. For troubleshooting and maintenance
39	POWER SYSTEM – Alarm, monitoring and control system	IAS server 1, located on ECR	Alarm, monitoring and control handling for IAS system with communication to I/O cabinets and operator stations	Transit, DP	Computer failure	Power failure/ malfunction of Computer	Loss of Server 1. Server 2 will perform alarm, monitoring and control handling for IAS	None	8	4	3	96		Routine inspections. IAS/PMS/VSD course for engineers and electrician. For troubleshooting and maintenance
40	POWER SYSTEM – Alarm, monitoring and control system	IAS server 2, located on bridge	Alarm, monitoring and control handling for IAS system with communication to I/O cabinets and operator stations	Transit, DP	Computer failure	Power failure/ malfunction of Computer	Loss of Server 2. Server 1 will perform alarm, monitoring and control handling for IAS	None	8	4	3	96		
41	POWER SYSTEM – Alarm, monitoring and control system	IAS server 1 and 2, located on ECR and Bridge	Alarm, monitoring and control handling for IAS system with communication to I/O cabinets and operator stations	Transit, DP	Computer failure	Power failure/ malfunction of Computer	Loss of Server 1. Server 2 will perform alarm, monitoring and control handling for IAS	Loss of control and monitoring system	8	4	3	96		Routine inspections. IAS/PMS/VSD course for engineers and electrician. For troubleshooting

														and maintenance
42	POWER SYSTEM – Alarm, monitoring and control system	Ring-Network for IAS and PMS	Ring-Network between operator station including I/O servers, distributed I/O cabinets and PLC cabinets	Transit, DP	Wire breakage in ring-network	Power failure/ malfunction of Computer	None	None	5	4	3	60		Routine inspections. IAS/PMS/VSD course for engineers and electrician. For troubleshooting and maintenance
43	POWER SYSTEM – Alarm, monitoring and control system	Ring-Network for IAS and PMS	Ring-Network between operator station including I/O servers, distributed I/O cabinets and PLC cabinets	Transit, DP	Short circuit of wire in ring-network	Power failure/ malfunction of Computer	None	None	5	4	3	60		Routine inspections. IAS/PMS/VSD course for engineers and electrician. For troubleshooting and maintenance
44	POWER SYSTEM – Alarm, monitoring and control system	Ring-Network for IAS and PMS	Ring-Network between operator station including I/O servers, distributed I/O cabinets and PLC cabinets	Transit, DP	Wire breakage in ring-network	Fire / sabotage	None	Loss of control and monitoring system	5	4	3	60		Routine inspections. IAS/PMS/VSD course for engineers and electrician. For troubleshooting and maintenance
46	POWER SYSTEM – Electrical 24V System	B1	24V Power supply for various DP consumers		Short circuit of busbar		Loss of serial splitter wind sensor, Loss of serial splitter Fanbeam, Loss of gyro 1 and 2.	Full thruster capacity	5	1	3	15		Regular maintenance according to manufacturer's recommendations
47	POWER SYSTEM – Electrical 24V System	B2	24V Power supply for various DP consumers		Short circuit of busbar		Loss of 24V for gyro 3.	Full thruster capacity	5	1	3	15		Regular maintenance according to manufacturer's

														recommendations
48	POWER SYSTEM – Electrical 24V System	B3	24V Power supply for various diesel generators		Short circuit of busbar		Loss of DG 1 and DG 2	50% reduction of generator capacity	5	1	3	15		Regular maintenance according to manufacturer's recommendations
49	POWER SYSTEM – Electrical 24V System	B4	24V Power supply for various DP consumers		Short circuit of busbar		Loss of DG 3 and DG 4	50% reduction of generator capacity	5	1	3	15		Regular maintenance according to manufacturer's recommendations
50	POWER SYSTEM – Electrical Emergency System	690/230V ESB	Electrical power supply, Emergency System		Short circuit of 690V busbar		Loss of supply for starting air compressor 2 Loss of battery charger for 24V battery system B3	Full thruster capacity	5	1	3	15		Regular maintenance according to manufacturer's recommendations
51	POWER SYSTEM – Emergency stop System	Emergency stop switch E2 for engine room fans	Emergency stop of the two engine room fans. Each fan have separate contact block in switch		Short circuit of 690V busbar		Loss of PS engine room fan. Closure of fire dampers for air supply to PS engine room	Reduce air supply to engine room, the engines	1	1	3	3		Regular maintenance and testing
52	POWER SYSTEM – Emergency stop System	Emergency stop switch E4 for switchboard room cooling machinery	Emergency stop of the two machinery of switchboard room. Each cooling machinery have separate contact block in switch		Short circuit of loop for emergency stop of cooling machinery SB		Loss of SB cooling machinery for switchboard room	Reduce cooling for switchboard room	1	1	3	3		Regular maintenance and testing
53	POWER SYSTEM FW cooling system No. 1	Expansion tank for cooling system for DG1	Cooling of diesel engine for gen set No. 1		Leakage causing loss of FW for cooling ability		Loss of cooling for DG 1	Loss of 25% generator capacity	5	3	3	45		Regular maintenance and control.
54	POWER SYSTEM FW cooling system No.	Expansion tank for cooling system for	Cooling of diesel engine for gen set No. 3		Leakage causing loss of FW for cooling ability		Loss of cooling for DG 3	Loss of 25% generator capacity	5	3	3	45		Regular maintenance and control.

	1	DG3												
55	POWER SYSTEM FW cooling system No. 2	Expansion tank for cooling system for PS propulsion motor	Cooling of PS propulsion motor		Leakage causing loss of FW for cooling purpose		Loss of cooling for PS propulsion motor	Less thruster capacity	5	3	3	45		Regular maintenance and control.
56	POWER SYSTEM FW cooling system No. 3	Expansion tank for cooling system for PS propulsion motor	Cooling of frequency conv. For PS prop. Motor, Fwd. Azim., tunnel thruster 1, LLC transf. PS, motors for fwd. azim., tunnel thr.1 Chilled water unit 1		Leakage causing loss of FW for cooling purpose		Loss of cooling for frequency conv. for PS prop. Motor, Fwd. Azim., tunnel thruster 1, LLC transf. PS, motors for fwd. azim., tunnel thr.1 Chilled water unit 1	Loss of about 50% of thruster capacity after some minutes (depending of loading and ambient temperature)	5	3	3	45		Regular maintenance and control.
57	POWER SYSTEM FW cooling system No. 3	Expansion tank for cooling system for SB propulsion motor	Cooling of frequency conv. for SB prop. Motor, Fwd. Azim., tunnel thruster 21, LLC transf. SB, motors for fwd. azim., tunnel thr.2 Chilled water unit 2		Leakage causing loss of FW for cooling purpose		Loss of cooling for frequency conv. for PS prop. motor, Fwd. Azim., tunnel thruster 1, LLC transf. PS, motors for fwd. azim., tunnel thr.1 Chilled water unit 2	Loss of about 50% of thruster capacity after some minutes (depending of loading and ambient temperature)	5	3	3	45		Regular maintenance and control.
58	POWER SYSTEM Compressed air system	Ball valves for QCV	Air supply to QCV system		Full leakage of valve		Draining starting air systems	None, as all gen sets are running in DP mode	2	3	3	18		Regular maintenance and control.
59	POWER SYSTEM Compressed air system	Ball valves for starting air receiver 1	Air supply to DG1 and DG2		Full leakage of valve		Draining starting air systems for DG1 and DG2	None, as all gen sets are running when in DP mode, Alarm low starting air pressure	2	3	3	18		Regular maintenance and control.
60	POWER SYSTEM Compressed air system	Ball valves for starting air receiver 2	Air supply to DG3 and DG4		Full leakage of valve		Draining starting air systems for DG3 and DG4	None, as all gen sets are running when in DP mode, Alarm low starting air pressure	2	3	3	18		Regular maintenance and control.
61	POWER	PS F.O.	Fuel supply to DG 1/2		Full leakage of		Loss of FO supply	DG 1/2 will	5	3	3	45		Regular

	SYSTEM Fuel oil supply system	service tank			one shut-off valve draining the tank		for DG 1/2	stop						maintenance and control.
62	POWER SYSTEM Fuel oil supply system	PS F.O. service tank	Fuel supply to DG 1/2		Full leakage of one shut-off valve draining the tank		Loss of FO supply for DG 3/4	DG 3/4 will stop	5	3	3	45		Regular maintenance and control.
63	POWER SYSTEM Diesel generators	Over speed protection relay, DG 2	Protect/disconnected a generator, if an over speed of diesel engine should occur		Failure of electronic governor, causing over speed of engine		DG 2 will be disconnected from 690V MSB by the protection system. If protection system is not working (components in protection system not monitored) or fast enough, this can result in unsymmetrical load and cause the other generator to trip on reverse power, before affected generator trips	Loss of 25% generator capacity	5	2	3	30		Regular maintenance according to manufacturer’s recommendations
64	Chilled water system	Expansion tank	Air cooling of switchboard room and wheelhouse		Leakage causing loss of FW for cooling purpose		Loss of air cooling of switchboard room and wheelhouse	switchboard room and wheelhouse will gradually become hot	1	1	1	1		Regular maintenance according to manufacturer’s recommendations
65	CONTROL SYSTEM Thruster control system	TC-1	Thruster control of Bow tunnel thruster 1		Short circuit of power supply inside TC-1		Loss of Bow tunnel thruster 1	Reduced fwd side thrust	5	1	3	15		Regular maintenance according to manufacturer’s recommendations
66	CONTROL SYSTEM Thruster control system	TC-2	Thruster control of Bow tunnel thruster 2		Short circuit of power supply inside TC-2		Loss of Bow tunnel thruster 2	Reduced fwd side thrust	5	1	3	15		Regular maintenance according to manufacturer’s recommendatio

														ns
67	CONTROL SYSTEM Thruster control system	TC-3	Thruster control of Fwd Azimuth thruster		Short circuit of power supply inside TC-3		Loss of Fwd Azimuth thruster	Reduced fwd side/longitudinal thrust	5	1	3	15		Regular maintenance according to manufacturer's recommendations
68	CONTROL SYSTEM Thruster control system	TC-4	Thruster control of PS Propulsion Azimuth thruster		Short circuit of power supply inside TC-4		PS Propulsion Azimuth thruster	Reduced fwd side/longitudinal thrust	5	1	3	15		Regular maintenance according to manufacturer's recommendations
69	CONTROL SYSTEM Thruster control system	TC-5	Thruster control of SB Propulsion Azimuth thruster		Short circuit of power supply inside TC-5		SB Propulsion Azimuth thruster	Reduced fwd side/longitudinal thrust	5	1	3	15		Regular maintenance according to manufacturer's recommendations
70	CONTROL SYSTEM Thruster control system	KThrust TC OS2 Mounting Plate for Operating panel for manual operation of thruster	Operating panel for manual operation of thruster		Short circuit of 230V ships UPS3 power supply for PSU1 for TC OS2 mounting plate		None	None	5	1	3	15		Regular maintenance according to manufacturer's recommendations Spare parts.
71	CONTROL SYSTEM Thruster control system	KThrust TC OS3 Mounting Plate for Operating panel for manual operation of thruster	Operating panel for manual operation of thruster		Short circuit of 230V ships UPS2 power supply for PSU2 for TC OS3 mounting plate		None	None	5	1	3	15		Regular maintenance according to manufacturer's recommendations Spare parts.
72	CONTROL SYSTEM Thruster control system	KThrust TC OS3 Mounting Plate for Operating panel for	Operating panel for manual operation of thruster		Short circuit of RPC 400 No.1 inside TC OS3 Mounting Plate		Will trip both PSU1 and PSU2, and may trip ships UPS 2 and 3 simultaneously, if not proper selectivity is	None	5	1	3	15		Regular maintenance according to manufacturer's recommendations

		manual operation of thruster					arranged							Spare parts.
73	CONTROL SYSTEM DP control	KPOS OS1	Main Operator interface		Power Failure		Loss of KPOS-OS1	None. KPOS-OS2 still operating	5	1	3	15		No longer in DP 2 mode. Regular maintenance according to manufacturer's recommendatio ns Spare parts.
74	CONTROL SYSTEM DP control	KPOS OS2	Main Operator interface		Power Failure		Loss of KPOS-OS2	None. KPOS-OS1 still operating	5	1	3	15		No longer in DP 2 mode. Regular maintenance according to manufacturer's recommendatio ns Spare parts.
75	CONTROL SYSTEM DP control	KPOS DPC-2 A	One of two controller for position keeping		Power Failure		Loss of KPOS DPC-2 RCU A Loss of MRU1 as this is powered from DPS-2 B Alarm indicated in OS2	None. KPOS-DPC-2 controller RCU1 still operating	5	1	3	15		No longer in DP 2 mode. Regular maintenance according to manufacturer's recommendatio ns Spare parts.
76	CONTROL SYSTEM DP control	KPOS DPC-2 B	One of two controller for position keeping		Power Failure		Loss of KPOS DPC-2 RCU B Loss of MRU2 as this is powered from DPS-2 B Alarm indicated in OS2	None. KPOS-DPC-2 controller RCU1 still operating	5	1	3	15		No longer in DP 2 mode. Regular maintenance according to manufacturer's recommendatio ns Spare parts.

77	CONTROL SYSTEM DP control	NDU-A	Network for DP control system		Power Failure		Loss of NDU-A	None. NDU-B still in operation	5	1	3	15		No longer in DP 2 mode. Regular maintenance according to manufacturer's recommendatio ns Spare parts.
78	CONTROL SYSTEM DP control	NDU-A	Network for DP control system		Power Failure		Loss of NDU-A	None. NDU-A still in operation	5	1	3	15		No longer in DP 2 mode. Regular maintenance according to manufacturer's recommendatio ns Spare parts.
79	CONTROL SYSTEM Reference system	DGPS 1	High performance differential position reference system for position input		Signal failure output signal freeze ∗)		The faulty position reference data might be rejected by the DP system, but the DP system might also reject the valid position reference systems	Possible loss of both GPS position reference systems. Fanbeam can be used for position reference (automatic or based on operator interaction, if required)	5	1	3	15		No longer in DP 2 mode. Regular maintenance according to manufacturer's recommendatio ns Spare parts.
80	CONTROL SYSTEM Reference system	DGPS 2	High performance differential position reference system for position input		Signal failure output signal drift ∗∗)		The faulty position reference data might be rejected by the DP system, but the DP system might also reject the valid position reference systems	Possible loss of both GPS position reference systems. Fanbeam can be used for position reference	5	1	3	15		No longer in DP 2 mode. Regular maintenance according to manufacturer's recommendatio ns Spare parts.

								(automatic or based on operator interaction, if required)						
81	CONTROL SYSTEM Reference system	Fanbeam	Position reference system for position input		Sensor failure- Invalid status or telegram		Faulty data not used by DP system	None, as DGPS 1, DGPS 2 and Radius are still available	3	1	3	6		Regular maintenance according to manufacturer's recommendatio ns Spare parts
82	CONTROL SYSTEM Reference system	Serial splitter for DGPS 1 reference system	Sharing single signal from a reference or sensor system to several consumers		Power failure		No Inmarsat correction signal for DGPS systems	DGPS still operating with the remaining correction signal sources						
83	CONTROL SYSTEM Reference system	IALA HF radio beacons	IALA DGPS correction signal		Loss of IALA signals to both DGPS		No IALA correction signal for DGPS systems	DGPS still operating with the remaining correction signal sources						
84	CONTROL SYSTEM Sensors	MRU1	Pitch and roll signal		Sensor failure- Drifting		Loss of MRU1	Operator has to select correct MRU. The DP system uses data from MRU1	5	1	3	15		No longer in DP 2 mode. Regular maintenance according to manufacturer's recommendatio ns Spare parts.
85	CONTROL SYSTEM Sensors	MRU2	Pitch and roll signal		Sensor failure- Drifting		Loss of MRU2	Operator has to select correct MRU. The DP system uses data from MRU1	5	1	3	15		No longer in DP 2 mode. Regular maintenance according to manufacturer's recommendatio ns Spare parts.
86	CONTROL	Gyro	True heading reference		Loss of Gyro		Reduced numbers	None, as gyro 2						

	SYSTEM Sensors	compass No. 1			No.1		of gyros	and 3 are still available						
87	CONTROL SYSTEM Sensors	Gyro compass No. 2	True heading reference		Loss of Gyro No.2		Reduced numbers of gyros	None, as gyro 1 and 3 are still available						
88	CONTROL SYSTEM Sensors	Gyro compass No. 3	True heading reference		Loss of Gyro No.3		Reduced numbers of gyros	None, as gyro 1 and 2 are still available						
89	CONTROL SYSTEM Sensors	Wind sensor 1	Wind, speed and directional signal		Sensor failure-Slow drifting		Failed sensor is rejected	Loss of wind sensor 1 DP system uses data from wind sensor 2						
90	CONTROL SYSTEM Sensors	Wind sensor 2	Wind, speed and directional signal		Sensor failure-Slow drifting		Failed sensor is rejected	Loss of wind sensor 2 DP system uses data from wind sensor 1						
91	CONTROL SYSTEM Sensors	Serial splitter for wind sensor 1	Sharing single signal from a reference or sensor system to several consumers		Power failure		No wind sensor signal from wind sensor 1 for DP controller	Loss of wind sensor 1signal DP system uses data from wind sensor 2						
92	CONTROL SYSTEM Independent Joystick	Joystick controller cC-!	Manual position control of vessel		Power failure		Controller not operating	Loss of manual position keeping	5	1	3	15		maintenance according to manufacturer's recommendatio ns Spare parts.
93	Change-over switch in KThrust OS1	Mechanic al switch for mode selection of thruster control one for each thruster	Selection between thruster control system		Switch stuck between position		No system in control of thrusters ***	Loss of position	5	1	3	15		No longer in DP 2 mode. Regular maintenance according to manufacturer's recommendatio ns Spare parts.

Comments:
∗) Frozen “Time” in the telegram from a GPS receiver is automatically rejected. Frozen position data is a very unlikely single failure,; this will result in an invalid status (failure mode 2)
∗∗) Drift in GPS position data might be common between two or more GPS system (due to failure in GPS satellite or correction data). Use of two or more GPS systems as input to the DP systems increases the risk of faulty actions by DP system.
∗∗∗) A single change-over switch selects between different modes; DP, Independent Joystick and Manual Levers. In case of failure of the switch, it may not be possible to switch between the different modes. The criticality of this failure depends of the operation mode before failure. If none of the modes are functioning, it is possible to operate the thrusters manually. The reliability of the changeover switch should, however, be considered high and probability for critical failure should be low. If fault occurs in one deck/layer, only one thruster will be affected.