NTNU – Trondheim
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Fleet-Oriented Spare Parts Management

Philosophy, work processes and scientific
methods for spare parts management

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PREFACE

This scientific thesis, "Fleet-oriented spare parts management", is a mandatory part of the Master of Science degree in Marine Technology at the Norwegian University of Science and Technology, NTNU. The course code for the Master of Science thesis in Marine Systems Engineering is TMR 4905, and it counts for 30 credits, equal to a normal semester workload.

The topic for the thesis was decided in collaboration between me and Sigbjørn Stangeland from the DOF Group, based on a need for developing formal work processes and scientific methods for spare parts management in the DOF Group. These necessities were brought to light and described in my project thesis "Maintenance of offshore cranes in a fleet perspective", written in the fall of 2012.

The equipment focus on offshore cranes have been kept for the Master of Science thesis, but the proposed work processes, methods and computer tools for fleet-oriented spare parts management have been developed for usage across all ship types and all types of equipment. The offshore crane on the Skandi Salvador has been used as an example throughout the thesis in order to demonstrate the feasibility of the propositions, and thus also to propose changes in the spare parts policy for this crane, based on the results from using the proposed computer tools.

I am proud to present my thesis, which is a result of hard work during the spring of 2013 and the knowledge gained during 5 years of marine technology studies at NTNU.

Trondheim, 08.06.2013

André Risholm

André Risholm

ACKNOWLEDGEMENTS

I would like to express my very great appreciation to my supervisor at the Norwegian University of Science and Technology, Associate Professor II Trond Michael Andersen, for his valuable and constructive suggestions during the planning and development of this thesis.

I would also like to express my deep gratitude to Mr. Sigbjørn Stangeland, my supervisor at the DOF Group, for his patient guidance, enthusiastic encouragement and useful critiques of my work. My grateful thanks are also extended to Senior Crane Engineer Bernt Ole Brøske from DOF Management AS, for his help in building my understanding of crane systems and for providing useful input data for my calculations.

I wish to thank the DOF Group for enabling me to visit their offices to observe their daily operations, and work on my thesis at their company premises in Bergen. My great thanks are also extended to the staff of DOF Brasil/Norskan Offshore Ltda., where I worked as a technical trainee in 2011-2012. My stay there improved my knowledge of the OSV industry and I had the opportunity to visit many of the ships in the DOF fleet, amongst others the Skandi Salvador which is used as an example for calculations in this thesis.

Finally, my girlfriend Ida, my family and my colleagues at office A2.019 at the Marine Technology Centre in Trondheim deserve my great appreciation for providing moral support and encouragement throughout my studies.

PROJECT DESCRIPTION

<u>Title:</u> Fleet-oriented spare parts management

Description for the Master of Science thesis in operation technology by André Risholm, stud.techn.

<u>Supervisors:</u>

- Trond Michael Andersen, NTNU
- Sigbjørn Stangeland, DOF Group

<u>Problem formulation:</u>

Several areas of improvement for spare parts management in the DOF Group was described in the project thesis that preceded this Master of Science thesis. The candidate shall propose methods and work processes based on best practice standards and relevant theory in order to improve spare parts management in the DOF Group.

Also, recurring issues with the active heave compensated cranes have been a problem in the DOF Group. The DOF Group therefore wants to evaluate the current spare parts policy for these cranes in particular.

<u>Objectives:</u>

The candidate shall present the offshore support vessel industry and the construction support vessel niche, as well as a description of relevant requirements for the operation and maintenance of offshore support vessels and their cranes. A presentation of relevant theory and best practice methods and processes for maintenance and spare parts management, and a description of maintenance practice in the DOF Group, should also be given. In that regard, areas of improvement shall be further evaluated.

Thereafter, the candidate shall propose a fleet-oriented spare parts management philosophy, tailored for the DOF Group, including objectives, work processes and requirements for organization and resources. In addition, the candidate shall develop computer decision tools to be used as a part of the total proposed spare part evaluation method. The computer tools shall be developed for usage by project/vessel managers in the DOF Group, as well as different technical discipline experts.

Furthermore, the candidate shall choose a construction support vessel with an offshore crane as an example throughout the thesis in order to demonstrate the feasibility of the propositions, and also to propose changes in the spare parts policy for this crane, based on the results from using the proposed computer tools.

<u>Scope and limitations:</u>

The candidate is free to set limitations where it is necessary or logical, in order to effectively carry out the objectives set for the thesis.

ABSTRACT

There are 22 construction support vessels in the DOF Group that have active heave compensated cranes with lifting capacity of above 50 tonnes. The Brazilian flagged Skandi Salvador was chosen to represent the fleet in terms of specifications, since she was close to the average numbers for size, age and capacity. She has a NOV crane with SWL of 140 t.

There are two main types of maintenance; preventive maintenance and corrective maintenance. Fault distributions can be used to evaluate which type of maintenance that should be performed, and in which intervals.

Maintenance management should be a process of continuous improvement, with focus on planning, execution, reporting and analysis in order to establish and revise resource needs, goals and requirements, and the maintenance program itself.

Reliability Centered Maintenance (RCM) and Risk Based Inspection (RBI) are useful methods to establish an optimal maintenance and inspection program, based on functional demands, functional faults, and prevention of these functional faults.

The Economic Order Quantity (EOQ) concept and the "Newsboy" model are mathematical decision models that can be used to decide number of spares to be ordered, order point, safety level, and investments in capital spare parts.

Seven areas of improvement for the maintenance practice in the DOF Group were proposed:

1. Informal experience to be made formal.
2. Formalize the maintenance management processes.
3. Introduce scientific methods like Reliability Centered Maintenance and Risk Based Inspection to establish maintenance program.
4. Introduce scientific methods for spare parts management.
5. Introduce a fleet-oriented philosophy for all aspects of the maintenance practice, especially for spare parts management.
6. Bring the users closer to decisions regarding the MMS
7. Increase practical usability of critical equipment classification.

The main objective of spare parts management is to find the optimal numbers, types and locations for spare parts needed to perform the desired tasks with as high uptime as possible. In effect, to have spare parts available when they are needed, but to avoid stocking spare parts that are not needed.

At the heart of the proposed spare parts management philosophy lie fleet orientation, formalization, and scientific methods.

A spare part evaluation work process is proposed, consisting of 6 phases:

1. Basic input. Where the actor responsible collects the data necessary for making the evaluation.

2. Spare part categorization. The spare parts are categorized in three categories, based on given criteria.
3. Risk assessment. A consequence classification is carried out to decide the desired probability of having a spare available during procurement lead time for operational spares and consumables.
4. Decision tools. Two different decision tools are utilized to make optimal decisions for the spare parts considered.
5. Output. The decisions are summarized and carried out. Information related to the capital spare parts decisions are entered into a newly established capital spare parts experience register.
6. MMS. The results from the spare part evaluations are inserted in the maintenance management system.

An important part of the proposed spare parts management philosophy is the ability to make optimal decisions in changing environments. If the evaluation process is not dynamic, the actors responsible will soon revert to the former, subjective methods for making decisions.

So, whenever a change in the operation of a vessel is planned or registered, the project/vessel manager should ask himself how this change might affect the input parameters of the decision tools. This forms the basis for the proposed dynamic spare part evaluation work process.

The decision tool for capital spares is built around the relation between the expected cost of holding a spare part and not needing it, versus the expected cost of not having it when you need it.

When basing the evaluation on significantly lower delivery times than estimated by the manufacturer, the optimal capital spare parts investment decisions for the offshore crane on Skandi Salvador were to purchase all the recommended parts, except the largest crane wire. Using the estimated delivery times from the manufacturer, the optimal decisions were clearly to purchase all the recommended spare parts.

At the delivery time of Skandi Salvador, the DOF Group chose to only purchase four of the items on the list of recommended capital spare parts. The capital spare parts investment decisions taken by the DOF Group at the delivery time of the vessel are therefore considered sub-optimal compared to the findings in this thesis, and the DOF Group is advised to purchase the remaining capital spare parts on the list of recommended spare parts.

The decision tool for operational spares and consumables finds the optimal order quantity, order point and safety stock. An important input parameter is the desired probability of having enough spare during procurement lead time. This parameter is set based on the consequence classification for the part.

The decision tool was used to make decisions for optimal order quantity, order point and safety stock for a list of recommended spare parts for the offshore crane on Skandi Salvador.

SAMMENDRAG

22 construction support vessels i DOF Gruppen har aktivt hiv-kompenserte kraner med løftekapasitet på 50 tonn eller mer. Det brasiliansk-flaggede skipet Skandi Salvador ble valgt til å representere flåten med tanke på spesifikasjoner siden hun er i nærheten av gjennomsnittet for størrelse, alder og kapasitet. Hun har en NOV kran med SWL på 140 tonn.

Det finnes to hovedtyper av vedlikehold; preventivt vedlikehold og korrektivt vedlikehold. Feilfordelinger kan bli brukt til å evaluere hvilken type vedlikehold som bør utføres, og i hvilke intervaller.

Vedlikeholdsledelse bør være en prosess med kontinuerlig forbedring, med fokus på planlegging, utførelse, rapportering og analyse, for å etablere og revidere ressursbehov, mål og krav, samt vedlikeholdsprogrammet i seg selv.

Reliability Centered Maintenance (RCM) og Risk Based Inspection (RBI) er nyttige metoder for å etablere et optimalt vedlikeholds- og inspeksjonsprogram, basert på funksjonelle krav, funksjonsfeil, samt forebygging av feilene.

Konseptet Economic Order Quantity (EOQ) og «Newsboy»-modellen er matematiske beslutningsmodeller som kan brukes til å bestemme antall reservedeler som bør bestilles, når de bør bestilles, lagerets sikkerhetsnivå, og investeringer i «capital spare parts».

Syv forbedringspunkter for vedlikeholdspraksis i DOF Gruppen ble foreslått:

1. Uformell erfaring bør gjøres formell.
2. Formalisere prosessene for vedlikeholdsledelse.
3. Introdusere vitenskapelige metoder som RCM og RBI for etablering av vedlikeholdsprogram.
4. Introdusere vitenskapelige metoder for reservedelsledelse.
5. Introdusere en flåteorientert filosofi for alle aspekter av vedlikeholdspraksis, særlig for reservedelsledelse.
6. Bringe brukerne nærmere beslutninger knyttet til MMS.
7. Øke den praktiske brukbarheten av klassifisering av kritisk utstyr.

Hovedmålet for reservedelsledelse er å finne de optimale antall, typer og lokasjoner for reservedeler som trengs for å utføre de ønskede oppgaver med så høy oppetid som mulig. I praksis, å ha reservedeler tilgjengelig når de trengs, men samtidig unngå å lagre reservedeler som ikke trengs.

I hjertet av den foreslåtte filosofien for reservedelsledelse ligger flåteorientering, formalisering og vitenskapelige metoder.

Den foreslåtte arbeidsprosessen for reservedelsevaluering består av 6 faser:

1. Grunnleggende data. Den ansvarlige aktøren samler inn nødvendig data for å utføre evalueringen.

2. Reservedelskategorisering. Reservedelene blir kategorisert i tre kategorier basert på gitte kriterier.
3. Risikovurdering. En konsekvensklassifisering blir utført for å bestemme den ønskede sannsynligheten for å ha en reservedel tilgjengelig gjennom ledetiden for innkjøp av «operational spare parts» og konsumvarer.
4. Beslutningsverktøy. To forskjellige beslutningsverktøy blir brukt til å gjøre optimale beslutninger for reservedelene under evaluering.
5. Resultat. Beslutningene blir oppsummert og utført. Informasjon knyttet til «capital spare parts» blir ført inn i et erfaringsregister.
6. MMS. Resultatene fra reservedelsevalueringen blir ført inn i vedlikeholdsledelsessystemet (MMS).

En viktig del av den foreslåtte filosofien for reservedelsledelse er muligheten til å ta optimale beslutninger i skiftende miljøer. Hvis ikke evalueringen er dynamisk vil de ansvarlige aktørene fort gå tilbake til de tidligere, subjektive metodene for å ta beslutninger.

Når en endring i operasjonen av et fartøy blir planlagt eller registrert må prosjekt-/fartøyslederen spørre seg selv hvordan denne endringen påvirker parameterne som blir brukt i beslutningsverktøyene. Dette legger grunnlaget for den foreslåtte arbeidsprosessen for dynamisk reservedelsevaluering.

Beslutningsverktøyet for «capital spare parts» er bygget rundt forholdet mellom den forventede kostnad av å ha en reservedel uten at man trenger den, versus den forventede kostnad av å ikke ha en reservedel når man trenger den.

Da evalueringen ble basert på langt lavere leveringstid enn estimert av produsenten ble de optimale beslutningene for offshore kranen på Skandi Salvador å kjøpe inn alle de anbefalte «capital spare parts», utenom den største kranwiren. Da de estimerte leveringstidene fra produsenten ble brukt ble de optimale beslutningene helt klart å kjøpe alle de anbefalte reservedelene.

Da Skandi Salvador ble levert valgte DOF Gruppen kun å kjøpe fire av de anbefalte «capital spare parts». Beslutningene tatt av DOF Gruppen ved leveringstidspunktet blir derfor vurdert som sub-optimale og DOF Gruppen tilrådes å kjøpe inn de resterende anbefalte reservedelene.

Beslutningsverktøyet for «operational spare parts» og konsumvarer finner optimalt ordreantall, ordrepunkt og sikkerhetsnivå for lageret. En viktig parameter er den ønskede sannsynligheten for å ha en reservedel tilgjengelig gjennom ledetiden for innkjøpet.

Beslutningsverktøyet ble brukt til å ta beslutninger for optimale ordreantall, ordrepunkt og sikkerhetsnivå for lageret, for en reservedelsliste for offshore kranen på Skandi Salvador.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AHC	Active Heave compensation
AHTS	Anchor Handling Tug Supply
CSV	Construction Support Vessel
DNV	Det Norske Veritas
DSV	Diving Support Vessel
E&P	Exploration & Production
EOQ	Economic Order Quantity
FMECA	Failre mode, effects and criticality analysis
IMCA	International Marine Contractors Association
IMO	International Maritime Organization
IMR	Inspection, Maintenance, Repair
LOLER	Lifting Operation and Lifting Equipment Regulation
LWI	Light Well Intervention
MMS	Maintenance Management System
MPSV	Multi Purpose Support Vessel
NOV	National Oilwell Varco
OSV	Offshore Support Vessel
PLSV	Pipe Laying Support Vessel
PSV	Platform Supply Vessel
RBI	Risk Based Inspection
RCM	Reliability Centered Maintenance
ROV	Remotely Operated Vehicle
RSV	ROV Support Vessel
SFI	Skipsteknisk Forskningsinstitutt
UN	United Nations

1 – INTRODUCTION

1.1 – PROBLEM DESCRIPTION AND MOTIVATION

There is need to develop a fleet-oriented spare parts management philosophy, tailored for the DOF Group, including objectives, work processes and requirements for organization and resources. Scientific decision tools should be developed and implemented as a part of the proposed philosophy.

Currently, decisions regarding spare parts in the DOF Group are made subjectively, based on the experience and knowledge of the actor responsible. Also, a vessel-oriented viewpoint results in the DOF Group being unable to exploit economies of scale for spare parts management. This is viewed as a weakness, and the motivation for the work conducted in this thesis is to achieve more objective and better decisions.

In order to lay a foundation to achieve this objective, this thesis presents relevant background information and data, as well as a description of relevant requirements for the operation and maintenance of offshore support vessels and their cranes. A presentation of relevant theory and best practice methods and processes for maintenance is also given. A description and assessment of maintenance practice in the DOF Group is included to further investigate weak points in the current practice.

Problems with the active heave compensated offshore cranes are a recurring cause for down time in the operations of the subsea/construction fleet in the DOF Group. It is therefore desired to use the proposed methods and decision tools for spare parts management to evaluate recommended spare parts for an offshore crane.

1.2 – PREVIOUS WORK

(Risholm, 2012) included data collection and presentation of construction support vessels, cranes, relevant maintenance theory, and a description and assessment of maintenance practice in the DOF Group.

A lot of the content in the first chapters of this thesis is similar to the content presented in (Risholm, 2012), but in many cases, especially in the description and assessment of maintenance practice in the DOF Group, the content has been improved and extended.

The proposed philosophy and methods for spare parts management has been built on knowledge gained from higher level courses in operation technology at NTNU, and the scientific methods that inspired the developed decision tools presented in this thesis are based on decision models presented in (Rasmussen, 2004).

1.3 – SCOPE AND LIMITATIONS

The scope of the thesis is set in the project description presented before the abstract, and the following limitations have been set to keep the focus on the main objectives, and to keep the length of the thesis at the desired level.

The cranes in the fleet are very similar, but not identical. In this thesis, one crane is thoroughly presented, to give a representative view of all the cranes. In the same way, one of the CSV vessels in the DOF fleet is presented to give a representative view of the CSV fleet. The chosen vessel is the Brazilian-flagged Skandi Salvador.

There are numerous books and standards for maintenance of ships and lifting equipment, and since the scope of the thesis is limited, and the main effort is put into describing current maintenance practice in the DOF Group and proposing a new philosophy, new work processes and new tools for spare parts management, the presentation of theories and standards will also be limited, but relevant and to the point.

For the proposed decision tool for capital spare parts, presented in chapter 7, there are three points of interest that was chosen to be neglected, that would have changed the decision tool, and might have changed the output from using the tool:

- Other types of fault distributions than the chosen exponential distribution could have been included in order to choose the fault distribution that was most fitting to the part in question, if such data was available. This would have increased the workload for development and the complexity of the decision tool for the user.
- The DOF Group has insurance for loss of dayrate resulting from downtime exceeding two weeks. This was neglected, because over time the price of the insurance can be expected to mirror the downtime costs.
- The DOF Group is currently using condition monitoring for many types of equipment and parts, for example crane wires. It was chosen not to include effects of condition monitoring in the proposed solution, but the user is free to for example adjust delivery times accordingly.

1.4 – THESIS STRUCTURE

In chapter 1, the problem that this thesis proposes solutions for is introduced, along with an overview of relevant previous work, the set scope and limitations for the thesis, as well as the thesis structure and an introduction to the offshore support vessel industry and the construction support vessel niche.

Chapter 2 introduces relevant requirements for operation and maintenance of offshore support vessels and offshore cranes.

Chapter 3 gives a short description of all the construction support vessels with offshore cranes with lifting capacity of 50-400 tonnes. A more in depth description of Skandi Salvador and her 140 t NOV offshore crane, along with contract requirements and economics is then presented.

In chapter 4, relevant maintenance theory is presented, including definitions, maintenance types, best practice routines for maintenance management, reliability centered maintenance and risk based inspection. At last, best practice routines and scientific methods for spare parts management are presented.

Chapter 5 gives a description and assessment of the current maintenance practice in the DOF Group, and along with chapter 4, it lays the foundations for the propositions following in the next chapters.

In chapter 6, the proposed overall philosophy for spare parts management in the DOF Group is described. The proposed work processes are presented in a flow chart, with description of each item in the flow chart.

In chapter 7, the proposed decision tool for capital spare parts is presented, and the tool is used to make optimal capital spare parts decisions for the offshore crane on the Skandi Salvador.

The proposed decision tool for operational spare parts and consumables is presented in chapter 8, and the tool is used to make optimal operational spare parts decisions for the offshore crane on the Skandi Salvador.

Comments to results are presented in each chapter, and the final conclusion of the thesis, including a summary of the most important results and comments are found in chapter 9.

Finally, a summary of ideas for further work is presented in chapter 10.

1.5 – THE OSV INDUSTRY AND THE CSV NICHE

The Offshore Support Vessel (OSV) industry is a loose definition that covers all vessels doing services that are supporting the main operations of offshore oil and gas fields. The industry therefore consists of a number of segments.

The biggest in terms of number of vessels, and most commonly known segments are the platform supply vessels (PSV), and the anchor handling, tug, supply (AHTS) segments. In addition to these there are seismic vessels, construction support vessels (CSV), multi-purpose support vessels (MPSV), diving support vessels (DSV), pipe laying support vessels (PLSV), ROV support vessels (RSV) and various other, smaller segments. Different actors in the industry uses different definitions and abbreviations, and oftentimes the CSV, MPSV, DSV, PLSV and RSV segments are simply bundled together in one segment and referred to as CSVs or subsea vessels.

This bundle definition is used when CSVs are referred to in this thesis, and because of the fleet structure of the DOF Group and the objective of the thesis, it concentrates on CSVs that carry active heave compensated offshore cranes with 50-400 tonnes lifting capacity. They generally have a length over all of 90-200 meters, large working decks, carry ROVs, and spend a large portion of their operational time in DP-operations, performing survey-, maintenance-, and construction tasks.

The largest OSV companies in the world in terms of fleet size are Tidewater, Bourbon Offshore and Edison Chouest Offshore. They all have over 200 vessels in their respective fleets, and focus largely on the PSV- and AHTS-segments. The DOF group has a fleet of 74 vessels, divided on 23 PSVs, 20 AHTSs and 31 CSVs, which puts it in the top 10 of the largest OSV companies in the world, as the largest of the Norwegian companies. Only counting PSV and AHTS makes the DOF Group the second largest Norwegian OSV company, as shown in figure 1.

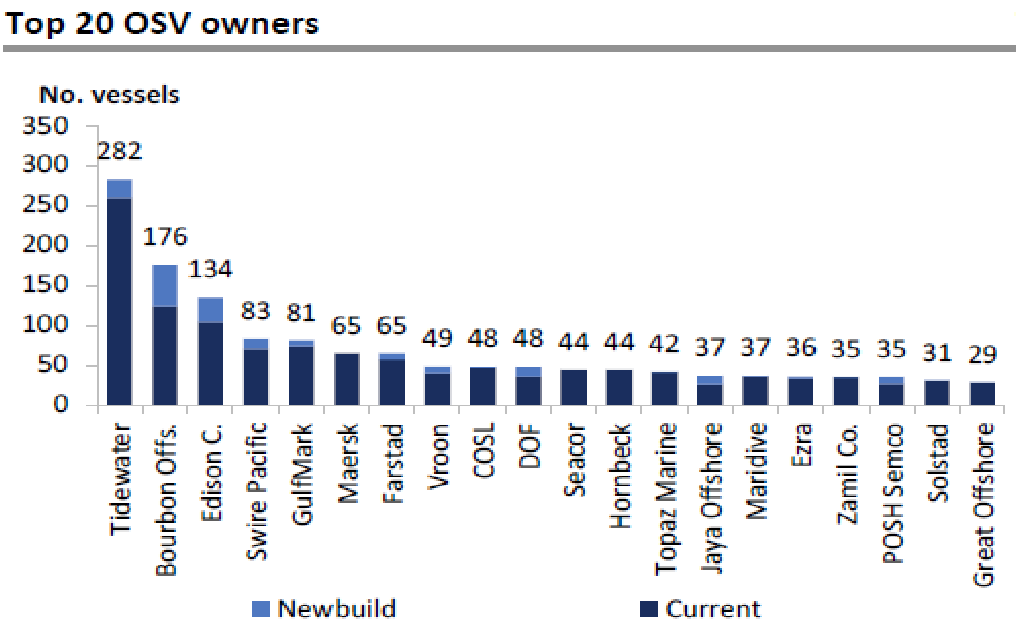

FIGURE 1: TOP 20 OSV OWNERS, ONLY COUNTING PSV AND AHTS (THOMASSEN, 2011).

The largest clients of the OSV industry are the international offshore E&P companies, with the Brazilian government E&P company Petrobras ranking as the largest player in terms of T/C-contracts.

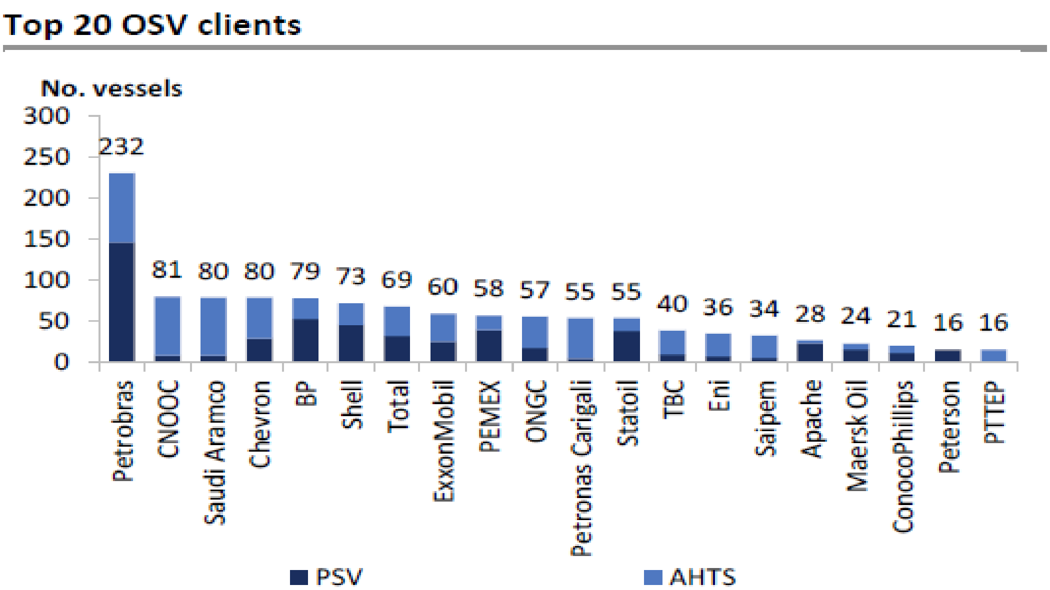

FIGURE 2: TOP 20 OSV CLIENTS, ONLY COUNTING PSV AND AHTS (THOMASSEN, 2011).

For the CSV niche, the OSV companies often charter the vessels out to an engineering based oil service company like Subsea7, Technip or Saipem that use the vessels to provide a part of a larger service to the E&P companies, but less advanced CSVs are also chartered directly to the E&P companies.

2 – REQUIREMENTS FOR OPERATION AND MAINTENANCE

All ships operating from or in countries that are part of the United Nations, have to comply with the rules and regulations set by the International Maritime Organization, IMO, which is a branch of the UN, dealing with maritime issues. The most important regulations, set by the IMO are TMR4260 lecture 3:

- **SOLAS**, Safety Of Life At Sea, mainly concerns vessel design and safety equipment.
- **STCW**, Standards of Training, Certification and Watchkeeping for Seafarers.
- **MARPOL**, International Convention for the Prevention of Pollution from Ships.
- **ISM code**, International Management Code for the Safe Operation of Ships and Pollution Prevention.
- **COLREG**, Convention on the International Regulations for Preventing Collisions at Sea.

All ships must be classed by a classification society. The classification societies have class notations that describe the requirements that the vessel must comply with. Charterer's will often have requirements for which class notations the vessel should have. In chapter 3, I will introduce the multipurpose support vessel, Skandi Salvador. The vessel is classed by DNV, with the notations: 1A1 ICE-C Fire Fighter II SF LFL* COMF-V(3) HELDK E0 DYNPOS-AUTR DK(+) HL(2.8). These are all common notations for construction support vessels, and table 1 summarizes the main requirements of each notation, as given by DNV (Veritas, 2012).

Class notation	Description
1A1	Denotes that the hull, machinery, installations and equipment meet the steel ship rule requirements for the assignment of main class.
Ice-C	The ship can operate in light ice conditions, strengthened hull.
Fire Fighter II	The ship has been built for continuous fire fighting with 2-4 water monitors for at least a period of 96 hours. Capacity of each monitor is 3600 m3/h (2) and 1800 m3/h (4), and length/height of throw is 180/110 m (2), and 150/80 m (4).
SF	Classification of stability and floatation.
LFL*	The vessel is designed for carriage of liquid with flashpoint lower than 43 degrees C. Requirements for fire safety.
COMF-V(3)	Requirements for onboard noise and vibration limits. 3 represents an acceptable level of comfort.
HELDK	Helicopter landing area covering basic strength requirements.
E0	The vessel meets SOLAS requirements for unattended machinery spaces. Requirements for alarm, watch responsibility transfer, safety features, and bridge control system.
DYNPOS-AUTR	Dynamic positioning system complies with IMO equipment class 2 for dynamic positioning systems.
DK(+)	The cargo deck is constructed for heavy cargo loads.
HL(2.8)	The vessel has tanks for heavy liquid, with specific weight of up to 2,8 t/m3.

TABLE 1: DNV CLASS NOTATIONS, EXAMPLES FROM SKANDI SALVADOR.

In addition to requirements from IMO and the class society, each country may have their own requirements. Both the IMO and national requirements are often quite vague, and therefore different agencies have made standards with requirements which secures that you comply with international and national requirements. Such standards include for example Norwegian Standard (NS), European Standard (EN), NORSOK standard developed by the Norwegian petroleum industry, API standards developed by the American Petroleum Institute and adopted by many countries, and ISO standards which are international standards for most business sectors and often mirrors the formerly mentioned standards. Table 2 shows some standards relevant to maintenance in general and to operation and maintenance of cranes that have been used and referred to in this thesis.

Maintenance standards	
NS-EN-13306	Maintenance terminology
NORSOK Z-016	Regularity management and reliability technology
NORSOK Z-008	Risk based maintenance and consequence classification
NORSOK Z-013	Risk and emergency preparedness analysis
Crane standards	
NORSOK R-002	Lifting Equipment
IMCA	Crane specification document
LOLER	Lifting Operations and Lifting Equipment Regulation

TABLE 2: MAINTENANCE AND CRANE STANDARDS.

In addition to complying with international and national requirements, the company must also comply with charterer's requirements and potentially own internal requirements. Charterer's requirements vary with each company. Some companies, like for example Petrobras, have developed their own set of functional, technical and operational requirements. Others require that the DOF Group complies with standardized guidelines for operation and maintenance made by the International Marine Contractors Association, IMCA.

The charterer's requirements are mostly linked to standards and set intervals for testing and inspection of equipment, rather than dictating the type and intervals of preventive maintenance. In some cases, the charterer may also set a minimum requirement for spare parts inventory (Stangeland, 2012).

3 – VESSEL AND CRANE SPECIFICATIONS AND ECONOMICS

As mentioned in chapter 1.2, 22 of the Construction Support Vessels in the DOF Group were chosen, because of their crane capacities. Table 3 shows a summary of the vessels, their cranes, and their operational region.

Vessel name	Built	Type	LOA [m]	Crane [t]		Charterer	Regional area
Geoholm	2006	RSV	85,65	NOV	100	DOF Subsea projects	North Sea
Geosund	2001	RSV	98,5	NOV	100	DOF Subsea projects	North Sea
Ocean Protector	2007	MPSV	105,9	NOV	140	Australian Customs	APAC
Skandi Acergy	2008	CSV	156,9	NOV NOV	400 100	Subsea7	North Sea
Skandi Achiever	2007	DSV	105,9	NOV	140	Technip	North Sea
Skandi Aker	2010	LWI	156,9	NOV NOV	400 100	Aker Oilfield Services	West Africa
Skandi Arctic	2009	DSV	156,9	NOV	400	Technip	North Sea
Skandi Carla	2001	RSV	83,85	NOV	50	Fugro	North Sea
Skandi Constructor	2009	LWI	120	NOV	140	Helix Energy Solutions	North Sea
Skandi Hawk	2012	RSV	88,1	TTS	60	DOF Subsea projects	APAC
Skandi Hercules	2010	CAHTS	108	NOV	140	DOF Subsea projects	APAC
Skandi Inspector	1979	RSV	81,1	NOV	50	Fugro	North Sea
Skandi Neptune	2001	PLSV	108,4	NOV	250	Subsea7	Mexico Gulf
Skandi Niteroi	2011	PLSV	142,2	NOV NOV	250 50	Petrobras	Brazil
Skandi Patagonia	2000	RSV	93,3	NOV	50	Total E&P	Argentina
Skandi Salvador	2009	MPSV	105,9	NOV	140	Chevron	Brazil
Skandi Santos	2009	SESV	120,7	NOV	250	Petrobras	Brazil
Skandi Seven	2008	MPSV	120,7	NOV	250	Subsea7	North Sea
Skandi Singapore	2011	DSV	107,1	NOV	140	DOF Subsea projects	APAC
Skandi Skansen	2011	CAHTS	109,6	NOV	250	Subsea7	North Sea
Skandi Skolten	2010	CAHTS	109,6	NOV	250	DOF Subsea projects	North Sea
Skandi Vitoria	2010	PLSV	142,2	NOV	250	Petrobras	Brazil
Average	2006		114,0		178		

TABLE 3: SPECIFICATION SHEET FOR THE CSV FLEET OF THE DOF GROUP.

Even though the operational assignments of the vessels vary a lot, the basic ship systems and a lot of the equipment are often very similar. The cranes in particular are very similar, almost all are made by the same manufacturer; National Oilwell Varco, NOV, and the main difference between them are the lifting capacities.

In the following sub-chapter the basic technical specifications of Skandi Salvador is presented. She was chosen as an example vessel because her specifications are quite close to the average specifications of the fleet and most of the marine systems and equipment are representative for the rest of the fleet.

Thereafter, some key economical and contractual factors of CSV operations are described.

After that, the main specifications and a list of recommended capital spare parts for the 140 t offshore crane on Skandi Salvador is presented.

3.1 – CSV SPECIFICATION, SKANDI SALVADOR

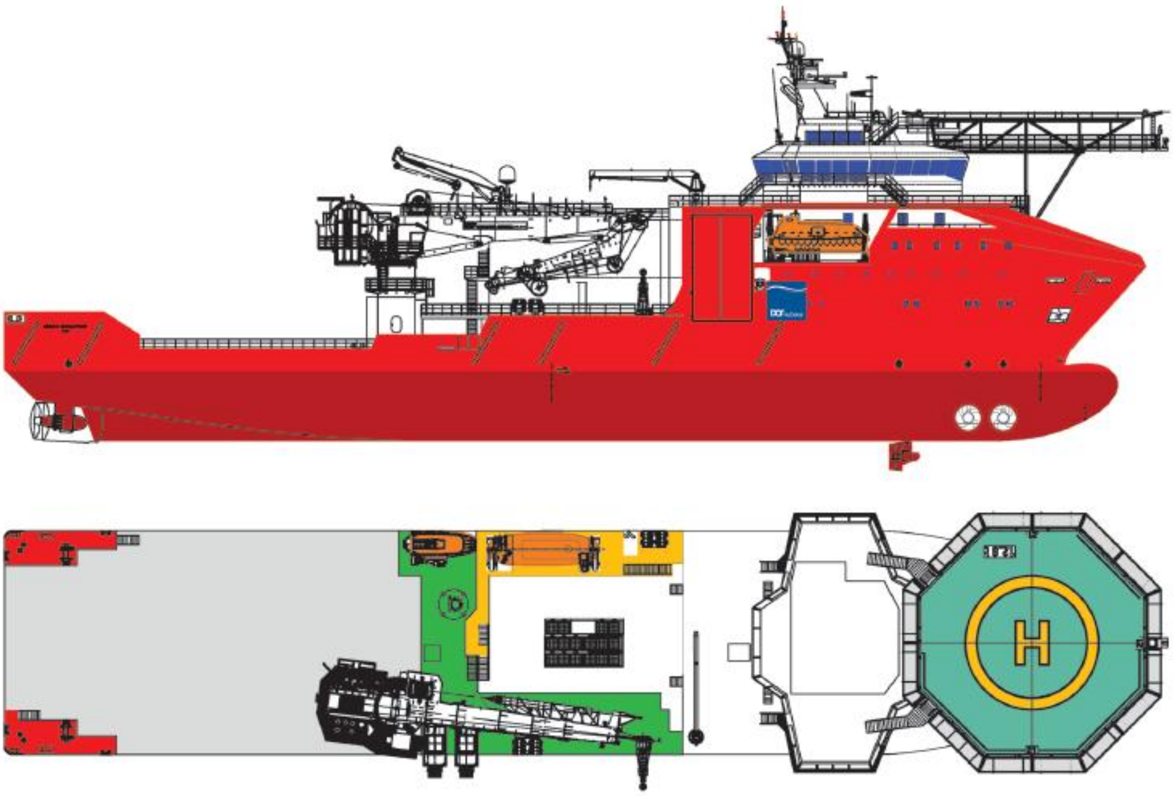

FIGURE 3: SKANDI SALVADOR, PART OF GENERAL ARRANGEMENT DRAWING(DOF, 2012).

General description	
Name	Skandi Salvador
IMO number	9389576
Type	MPSV
Owner	DOF Subsea Brasil Servicos Ltda.
Class	1A1 ICE-C Fire Fighter II SF LFL* COMF-V(3) HELDK E0 DYNPOS-AUTR DK(+) HL(2.8)
Flag	Brazil
Built year/yard	2009/STX Brazil Offshore S.A.
Main dimensions and speed	
Length overall	105,9
Beam	21 m
Depth	8,5 m
Draft	6,6 m

Maximum speed Service speed	15 knots 12 knots
Main deck dimensions and machinery	
Main deck area Main deck material Moonpool Deck machinery	1100 m2 @ 5 t/m2 Timber 7,2 m x 7,2 m Offshore crane: NOV 140 t AHC, 2500 m wire length Subsea winch: NOV 250 t AHC, 2500 m wire length Deck crane: NOV 15 t Deck crane: Palfinger: 10 t tuggers/capstans
Diesel electric Power & Propulsion	
Main generators Main propulsion Thrusters	4 x 2850 kW, 720 rpm, Wärtsilä 2 x RRM contra-rotating azimuth propulsors 2 x RRM bow tunnel thrusters 1 x RRM bow retractable azimuth thruster
Accommodation, capacities and ROV	
Accommodation Marine diesel oil Fresh water Ballast water Helideck ROV ROV LARS	100 persons 1200 m3 1000 m3 2500 m3 21 m diameter, D-rating (Sikorsky 92) 2 x Triton XLX working class ROV 2 x ODIM 50 t AHC (10 m), 3000 m wire length

TABLE 4: SPECIFICATION SHEET FOR SKANDI SALVADOR.

The Skandi Salvador is a multipurpose support vessel, MPSV, and typical tasks include inspection, maintenance and repair, IMR, as well as subsea construction and installation. In order to sustain the operations of the vessel, all systems should be functional, but the most important systems directly involved in the main tasks of the vessel are the 140 t crane and the two ROV systems.

3.2 – CSV CONTRACT REQUIREMENTS AND ECONOMICS

According to (DOF, 2013), the CSV segment total operating income for 2012 was 5873 million NOK with a fleet utilization of about 91%. The downtime was mostly related to planned dockings, vessel transit and contractual downtime on the project fleet. The figures are considering the total DOF CSV fleet, also including some vessels that I have not included in this report due to lower specifications. The total CSV fleet for the most part of 2012 consisted of 31 vessels.

By dividing the total operating income by utilization, number of vessels and the number of days in a year, we get the average CSV contractual dayrate for 2012:

$$\text{Dayrate} = \frac{5873000000000}{0,91 \cdot 31 \cdot 365} = 570380 \text{ NOK}$$

The contract structures are largely based on time-charter agreements where the charterer pays for a functioning vessel with crew, plus fuel consumption. Therefore, all direct costs involved in the running of the vessel, except the fuel cost, are covered by the DOF Group. Any technical downtime on equipment that prevents the vessel from performing its intended duties, like for example the offshore crane, will usually result in a 100% loss of dayrate until the equipment is fixed (Stangeland, 2013).

Considering the capital intensive nature of the business combined with the severe contractual consequences of technical downtime on important equipment, it is needless to say that an optimal maintenance policy is of great importance.

When also noticing the long average delivery times for capital spare parts, presented in table 6, we have to consider very large consequences of breakdown on one or more of these parts.

3.3 – CRANE SPECIFICATION, NOV AHC 140 T, SKANDI SALVADOR

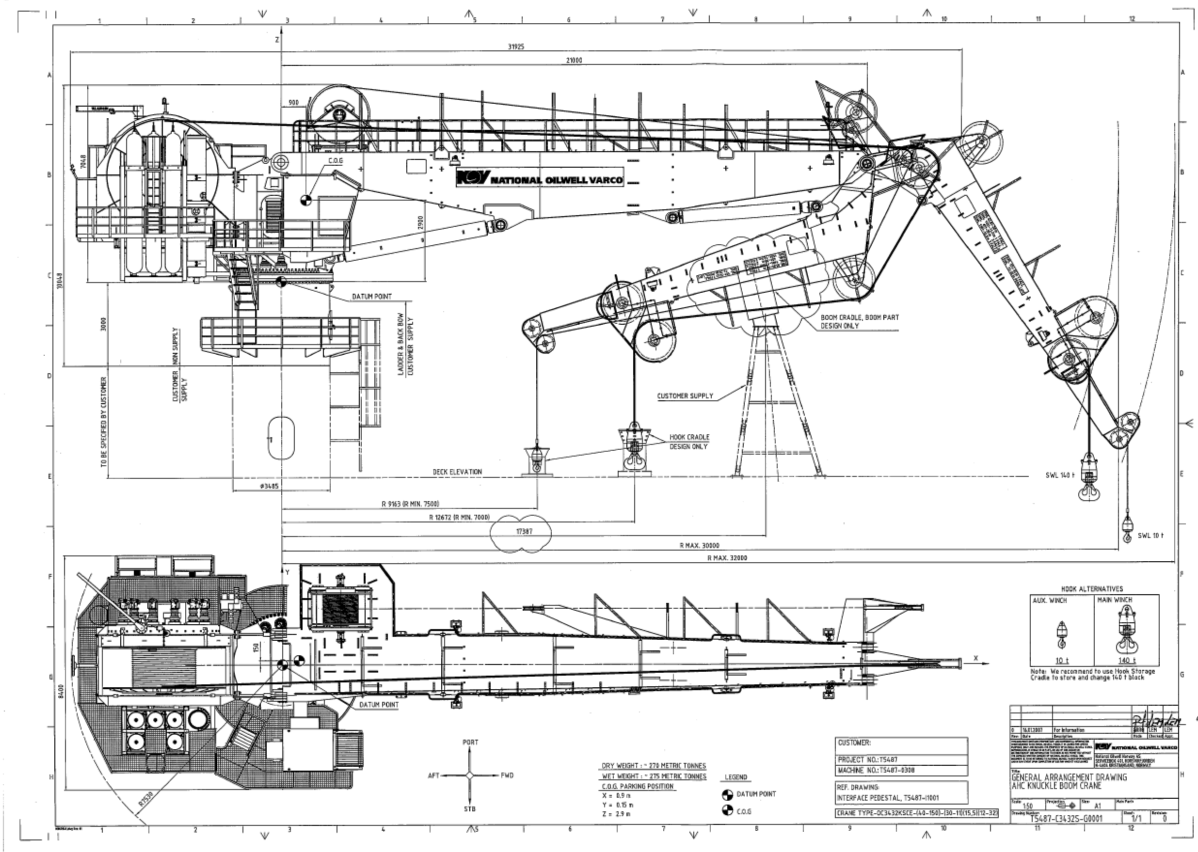

FIGURE 4: GENERAL ARRANGEMENT DRAWING, SKANDI SALVADOR CRANE (VARCO, 2012).

The general arrangement drawing of the active heave compensated 140 t crane, manufactured by National Oilwell Varco and installed on Skandi Salvador is shown in figure 4. A larger version is given in Appendix I.

The crane has one main winch and one auxilliary winch, both with a wire capacity of 2500 meters, and respectively 70 mm and 30 mm wire diameter. The maximum safe working load on the main hoist is 140 t, and 10 t on the auxilliary hoist. The main specifications of the crane are given in table 5, based on information from NOV product data sheet (Varco, 2012).

General description	
Type	AHC Knuckle boom crane, type 3432
Service	Subsea loading, internal and external load handling
Size	OC3432KSCE-(40-150)-(30-11)(21)(10-32)
Third party approval	
Document for certification	DNV Rules for certification of Lifting Appliances, 1994
Third party activities	Design approval, manufacturing survey, witness test and final inspection
Environmental conditions	
Min. ambient temperature	-20 degrees C
Max. Ambient temperature	+45 degrees C
Max. operational wind velocity	15 m/s
Max. stowed wind velocity	45 m/s
Heel/roll angle	5 degrees
Trim/pitch angle	2 degrees
Main dimensions (parked position, from crane datum point)	
Max. Height	7050 mm
Max. Length	31265 mm
Max. Width	8400 mm
Operating weight	275 t
Main capacities	
Main winch, SWL	140 t
Aux. Winch, SWL	10 t
Load radius main winch	7000 mm - 30000 mm
Load radius aux. Winch	7500 mm - 32000 mm
Hoisting speed, main winch, SWL	16 m/min (24 m/min in boost mode)
Hoisting speed, aux. Winch, SWL	100 m/min
Heave compensating speed, SWL	65 m/min
Main winch wire diameter	70 mm
Main winch wire min. breaking load	4430 kN
Aux. Winch wire diameter	30 mm
Aux. Winch wire min. breaking load	823 kN

TABLE 5: SPECIFICATION SHEET, SKANDI SALVADOR CRANE.

As per DOF maintenance procedure, to be further described in chapter 5, NOV has supplied a list of recommended spare parts (Varco, 2012) for the first two years of operation.

Table 6 gives a summary of the recommended capital spare parts. The term capital spare part will be further described in chapter 4.

Item name	Qty.	Unit price [NOK]	Total price [NOK]	Delivery time [weeks]
Slewing gear M22 Z14 X0,5 B210 excentric	1	124 966,00	124 966,00	12
Hydraulic cylinder 420/320	1	952 640,00	952 640,00	20
Hydraulic cylinder 350/250	1	642 980,00	642 980,00	20
Flexible coupling, Spidex	1	12 030,00	12 030,00	6
Winch gear ZHP 4,27 Clockwise	1	442 460,00	442 460,00	30
Winch gear, clockwise	1	175 220,00	175 220,00	30
Loadbolt 2MN w/lub nipple Exi	1	69 493,00	69 493,00	10
Loadbolt 200kN w/lub nipple 1/4" BSP Exi	1	22 750,00	22 750,00	10
Axial piston motor 250 CCM	1	116 462,00	116 462,00	40
Axial piston pump 355 CCM	1	259 916,00	259 916,00	40
Axial piston pump 250 CCM	1	151 068,00	151 068,00	40
Axial piston pump w/el. Motor	1	168 870,00	168 870,00	40
Wire, 70MM - MBL4430	2550	2 252,00	5 742 600,00	10
Wire, 30 MM	2560	355,40	909 824,00	10
Wire, 13 mm	120	94,00	11 280,00	10
Slew gearbox, complete	1	80 957,00	80 957,00	40

TABLE 6: RECOMMENDED CAPITAL SPARE PARTS, SKANDI SALVADOR CRANE.

4 – MAINTENANCE THEORY

The operation of offshore support vessels is a very capital intensive task, and the main goal will always be to maximize the profits of the company, while maintaining safety and environmental standards. Securing the contractual uptime of the vessels and avoiding accidents are therefore the most important goals for the company and the best way to achieve this is through an optimal maintenance program.

This chapter introduces key maintenance theoretical concepts and standards that are used when developing a maintenance strategy. In chapter 5, the internal maintenance systems, processes and methods of the DOF Group are compared to the theory presented in this chapter.

4.1 – IMPORTANT DEFINITIONS

To lay a foundation for understanding the maintenance theory and how it should or could be applied, some definitions of fundamental terms in the theory are presented, as given by the Maintenance Terminology standard from Norsk Standard (Norway, 2010):

MAINTENANCE

Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, state in which it can perform the required function.

MAINTENANCE MANAGEMENT

All activities of the management that determine the maintenance objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics.

MAINTENANCE OBJECTIVE

Target assigned and accepted for the maintenance activities. Note: These targets may include for example availability, cost reduction, product quality, environment preservation, safety, asset value preservation.

MAINTENANCE STRATEGY

Management method used in order to achieve the maintenance objectives.

MAINTENANCE PLAN

Structured and documented set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance.

4.2 – MAINTENANCE TYPES

When choosing a maintenance strategy for a component or a full system we have a number of different methods to choose from. Optimally, we can choose a method based on the predicted fault pattern of the components, but other practical parameters also apply.

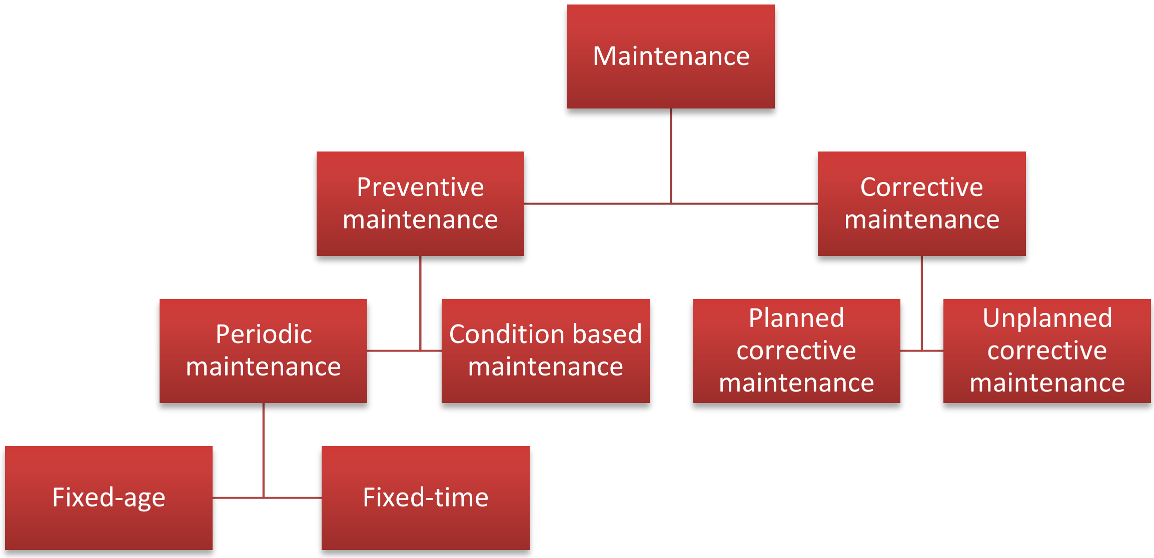

FIGURE 5: MAINTENANCE TYPES.

4.2.1 – PREVENTIVE MAINTENANCE

"Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of an item." (Norway, 2010)

Preventive maintenance is performed when the failure intensity function of the component is increasing over time, in order to restore the component to a previous condition and hence keep the failure probability as low as economically feasible.

PERIODIC MAINTENANCE

Periodic maintenance is performed at predetermined intervals, applying either a fixed-age interval or a fixed-time interval (Rasmussen, 2002). There are also a number of sub-policies to these two main types, but in this report I focus on the two main types.

Fixed-age maintenance is carried out when a component reaches a predetermined number of running hours or total hours since the last maintenance action. It does not matter if the last maintenance action was corrective or preventive.

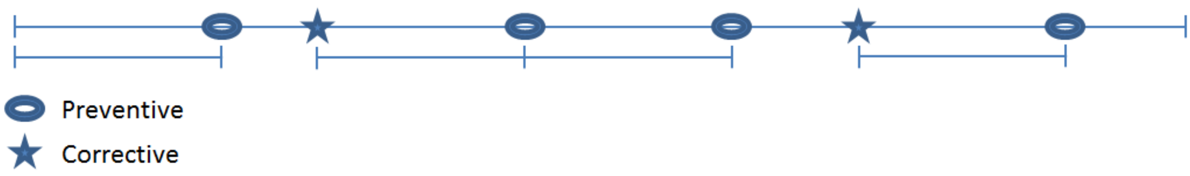

FIGURE 6: FIXED-AGE MAINTENANCE INTERVALS.

Fixed-time maintenance is carried out when a component reaches a predetermined number of running hours or total hours since the last preventive maintenance action. Hence, the maintenance intervals goes from preventive action to preventive action, disregarding any corrective actions.

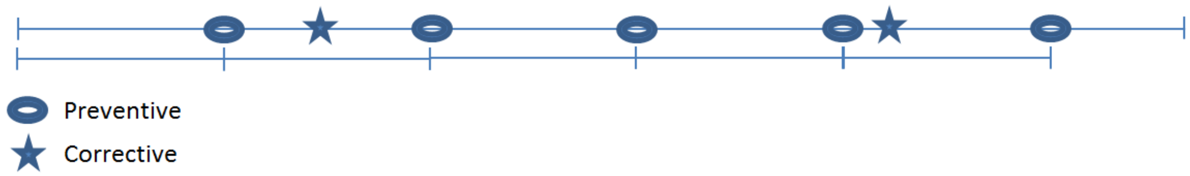

FIGURE 7: FIXED-TIME MAINTENANCE INTERVALS.

CONDITION BASED MAINTENANCE, CBM

For some components, the best way to decide when to perform maintenance is to carry out condition monitoring. When the component reaches a certain predetermined state of degradation, maintenance is performed. There are many methods for conducting tests and inspection of equipment and components, examples including vibration control of rotating machinery, oil samples of lubrication and hydraulic oil, and acoustic or X-ray testing of structural parts and welds.

4.2.2 – CORRECTIVE MAINTENANCE

"Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function." (Norway, 2010)

We divide between two main types of corrective maintenance, planned corrective maintenance, and unplanned corrective maintenance.

Planned corrective maintenance is chosen when the fault pattern of the component is unpredictable. Hence, there is no reason for performing preventive maintenance, since we have no basis to believe that it would work. Therefore we let the component run until failure with a plan for how to fix or replace it when the failure occurs.

Unplanned corrective maintenance is performed when a component fails in between preventive maintenance intervals. It is of course a very undesirable event, since the goal of the preventive maintenance is to prevent this from happening.

4.2.3 – FAULT DISTRIBUTIONS

As mentioned, in order to choose an optimal maintenance strategy for a component or a system, it is important to know the expected fault pattern. Fault patterns have probabilistic fault distributions that can be used in order to determine the type of maintenance to be performed, as well as potential maintenance or inspection intervals. The most important parameters we use are:

- F(t), the failure distribution function of t.
- f(t), the failure probability density function of t.
- R(t)=1-F(t), the reliability function of t.
- z(t), the failure rate function of t, often expressed with λ if the failure rate is constant.
- MTTF=E(x), mean time to failure.

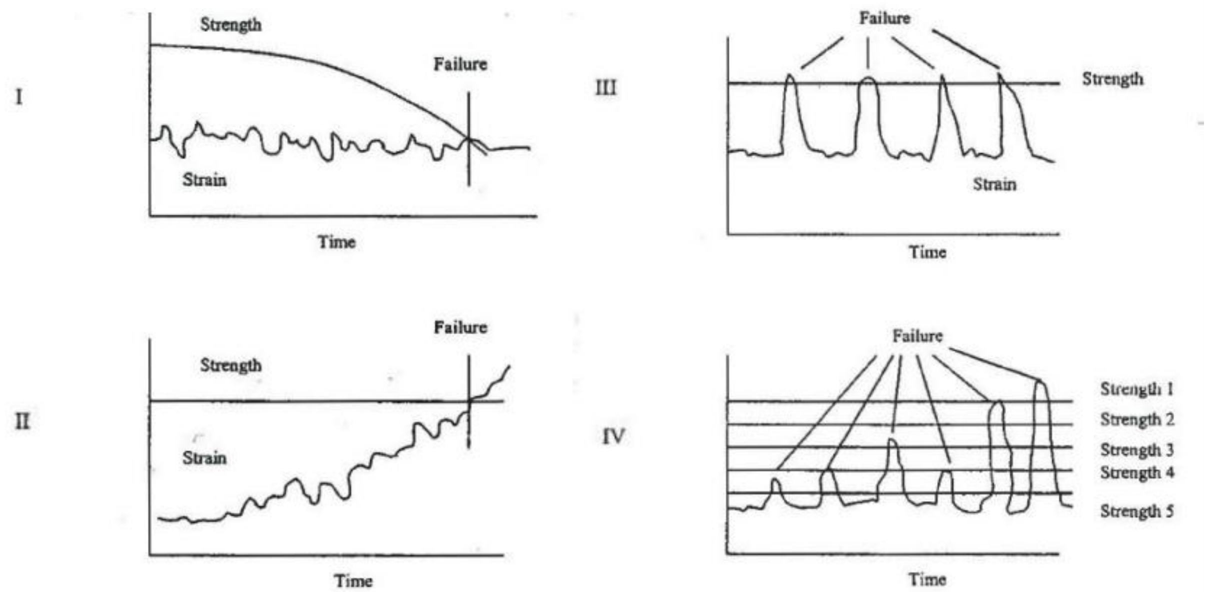

FIGURE 8: COMMON FAULT PATTERNS (RASMUSSEN, 2003).

Any probability model that mirrors the fault pattern of an item can be utilized, but in maintenance theory we often apply the:

- Normal distribution for typical ageing failures, as shown in figure 8, item I and II.
- Exponential distribution for random failures, as shown in figure 8, item III.
- Hyper-exponential distribution for items with high failures rates in the beginning, which falls over time and becomes random, as shown in figure 8, item IV.
- Weibull distribution, which is a semi-empirical distribution model used to analyze operational data in order to identify fault patterns. It is useful since it can be used to represent all the former distributions.

4.2.4 – MAINTENANCE COSTS

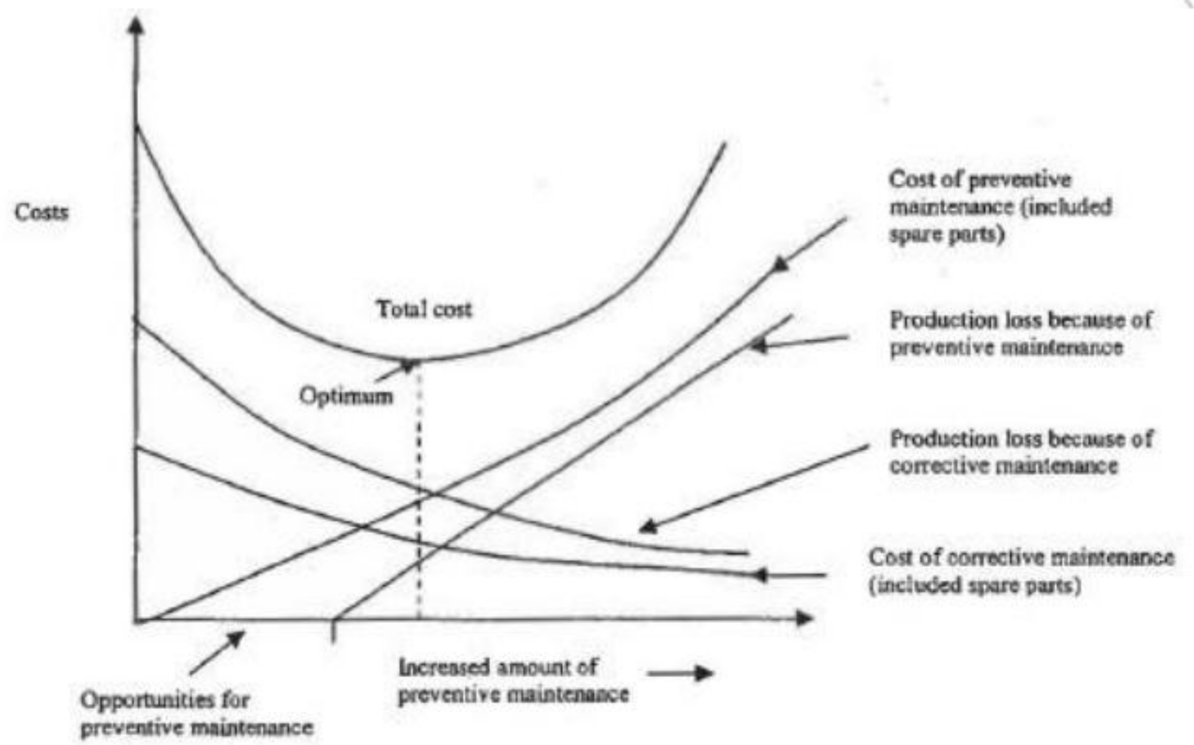

FIGURE 9: GRAPH OF TOTAL COST FUNCTION AND ITS PARAMETERS (RASMUSSEN, 2003).

As shown in figure 9, optimal preventive maintenance intervals can be found when the total cost of maintenance is minimized. If we have a failure probability distribution for the item, and know the different cost parameters involved, we can find the optimum. Of course, different maintenance policies and failure probability distributions give different total cost functions. For the fixed-age policy introduced in sub-chapter 4.2.1, we have according to (Rasmussen, 2002):

$$UEC(t_p) = \frac{c_p R(t_p) + c_c F(t_p)}{\int_0^{t_p} R(t)dt}$$

Where UEC is the expected total cost per unit time, c_p is the cost of preventive maintenance, including production loss due to maintenance and c_c is the cost of corrective maintenance, including production loss due to corrective maintenance. Then the optimal maintenance interval, t_p, can be found by minimizing UEC.

Costs related to procurement and holding of spare parts will be further described in sub-chapter 4.6.

4.3 – MAINTENANCE MANAGEMENT

Chapter 5 in the NORSOK standard for risk based maintenance defines a state of the art maintenance management work process (NORSOK, 2011). Unless otherwise stated, this sub-chapter is based on this standard. Figure 10 from the standard shows a flowchart for the process, and we notice the focus on maintenance management as a process of continuous improvement.

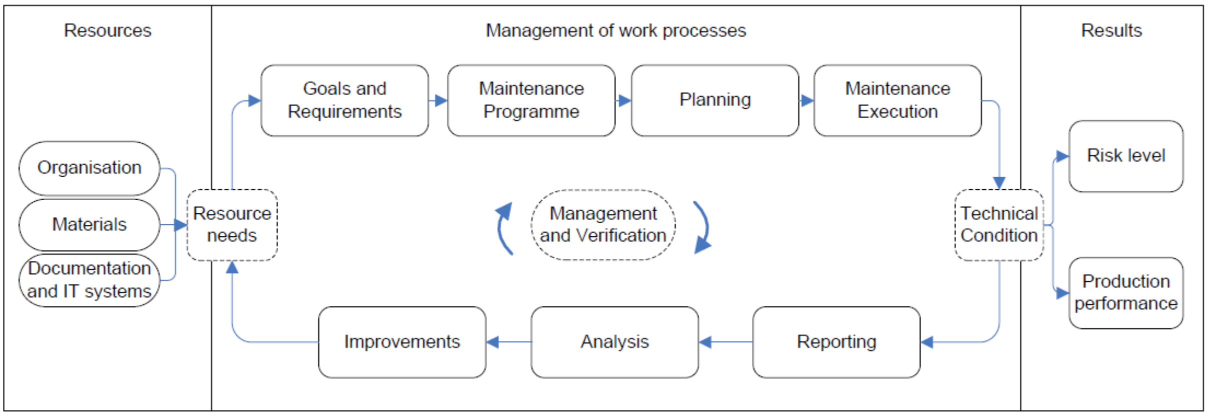

FIGURE 10: MAINTENANCE MANAGEMENT FLOWCHART (NORSOK, 2011).

4.3.1 – RESOURCES

- **Organisation.** *"Consists of the people, their training, competence, job descriptions and work processes."*
- **Materials.** *"Include consumables, spare parts and tools required to carry out maintenance."*
- **Documentation.** *"Includes all documentation required to carry out and manage maintenance in an effective manner. This includes, but are not limited to, equipment/tag register, drawings and design details, historical maintenance data, maintenance task descriptions, spares list."*

4.3.2 – MANAGEMENT OF WORK PROCESSES

- **Goals and requirements.** *"Goals should be established that commit the organisation to a realisable level of performance."* The goals should focus on risk, production and cost, regulatory requirements, technical conditions, improvement of maintenance process.
- **Maintenance program. "***Failure modes, failure mechanisms and failure causes that can have a significant effect on safety and production shall be identified and the risk determined in order to establish a maintenance programme. The maintenance programme includes maintenance interval and written procedures for maintaining, testing, and preparing the various components within the plant."* I will elaborate further on these issues in the chapter 4.4 – Reliability centered maintenance, which is a method to establish a maintenance program.
- **Planning. "***A maintenance plan is a structured set of tasks that include the activities, procedures, resources and the time required to carry out maintenance.*

Planning consists of budgeting, long term planning, day to day planning and prioritising."

- **Execution. "***Execution includes preparations, work permits, carrying out work and reporting mandatory information on the work order. Maintenance and inspection work shall be executed in a safe and a cost-effective manner. System and equipment conditions shall be reported before/after repair for continuous improvement. Risk assessment shall be the basis for operational priorities."*
- **Reporting. "***Reporting involves collection and quality assurance of maintenance data, and presenting these to maintenance departments and management in the form of defined indicators. In particular technical integrity data for safety functions shall be known and reported at appropriate levels to aid decision making."*
- **Analysis and improvements. "***This activity involves carry out analysis of historical maintenance data, and unwanted incidents related to maintenance, e.g. trend analysis, root cause failure analysis. Further the information should be evaluated and implement actions suggested based on the conducted analysis."*
- **Management and verification. "***A key to good maintenance is a well organized management team taking responsibilities in implementing the principles herein and verifying the results. The management team should ensure that the maintenance work processes are followed."*

4.3.3 – RESULTS

- **Risk level (technical condition).** *"The risk level is a result of the operation and maintenance work done to the asset. Risk can be measured as HSE performance, barrier reliability status or related indicators."*
- **Production assurance (technical condition).** *"The plant"s production assurance is a result of the activities implemented to achieve and maintain a performance that is at its optimum in terms of the overall economy and at the same time consistent with applicable framework conditions. An indicator of this would be the achieved production availability."*
- **Cost (technical condition).** *"Cost is here related to man cost for preventive and corrective work, spares and consumables, lost/deferred production that is under the control of the maintenance function."*

4.4 – RELIABILITY CENTERED MAINTENANCE, RCM

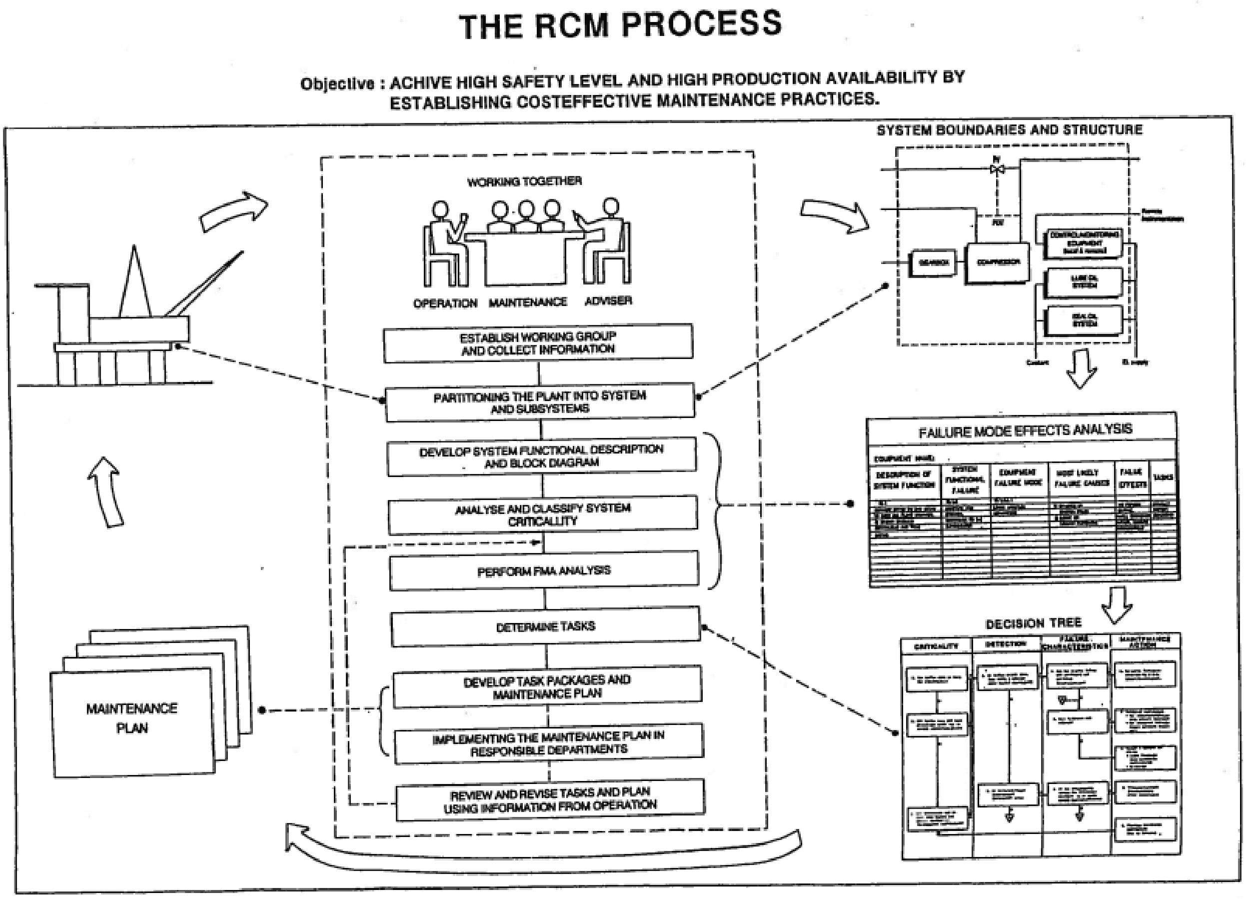

FIGURE 11: RCM FLOWCHART (RASMUSSEN, 2003).

Reliability centered maintenance (RCM) is a set of qualitative methods to develop maintenance strategies, which lays the foundation for the maintenance management system, MMS, of the company. The method can be used in all phases of a technical system, from the design and construction, to operation, and eventually retirement/disposal.

Prof. Magnus Rasmussen defines it as: *"RCM is a method for developing maintenance strategies for all equipment units in a plant, based on internal and external criteria related to safety, environment, operation and economy. RCM views the equipment units in a system perspective, based on functional demands, functional faults, and prevention of these functional faults." (Rasmussen, 2003)*

NORSOK Z-016 summarizes the following steps in a RCM analysis (NORSOK, 1998):

"In a RCM analysis which has the purpose to establish the (preventive) maintenance programme in a systematic way, the following steps are normally covered:

- *Functionality analysis – definition of the main functions of the system/equipment*
- *Criticality analysis – definition of the failure modes of the equipment and their frequency FMECA may be used to a larger or minor degree.*

- *Identification of failure causes and mechanism for the critical fault modes.*
- *Definition of type of maintenance based on criticality of the failure, the failure probability, the maintenance cost, etc.*

The RCM process must be updated throughout the life cycle for necessary revision of the maintenance programme, also using relevant field experience data as well as verifying criticality assessment."

4.4.1 – FUNCTIONALITY ANALYSIS

The purpose of the functionality analysis is to get a structured picture of how the system functions and how the different components work together to deliver the desired function. As a part of the functionality analysis, a functional hierarchy is often established.

The functional hierarchy starts with the main function of the system on top. Below the top function are the direct functions that need to be in place in order to perform the top function, and below those are similar sub-functions for each of these functions.

This is useful to understand how the system functions in itself, but also lays a good foundation for identifying failure modes, effects and failure causes in the FMECA. Also, it is one possible foundation on which to group the system components in the maintenance management system, MMS.

In shipping companies, the components in the systems are often grouped according to the SFI code, when used in the MMS. This is a standardized coding system for grouping systems and components in a ship. The SFI code is loosely based on a functional hierarchy, but does not include how the different components and systems interact.

4.4.2 – FAILURE MODE, EFFECT, AND CRITICALITY ANALYSIS, FMECA

"The primary purpose for the FMECA is to reveal cause-consequence relationships and separate uncritical and critical equipment failures. Critical equipment failures are defined as failures that can cause an unacceptable event, where measures must be implemented to stop such an event from occurring.

The result from an FMECA will therefore be a set of critical and uncritical equipment failures. The critical failures should be avoided, and we therefore make preventive maintenance plans for these components. Uncritical equipment failures can be repaired after failure, and the strategies for these will be planned corrective maintenance." (Rasmussen, 2003)

Hence, we seek to find out if preventive maintenance should be performed, based on criticality criteria. We often operate with four criticality parameters: Safety, Environment, availability and cost.

4.4.3 – DETERMINING MAINTENANCE ACTIONS

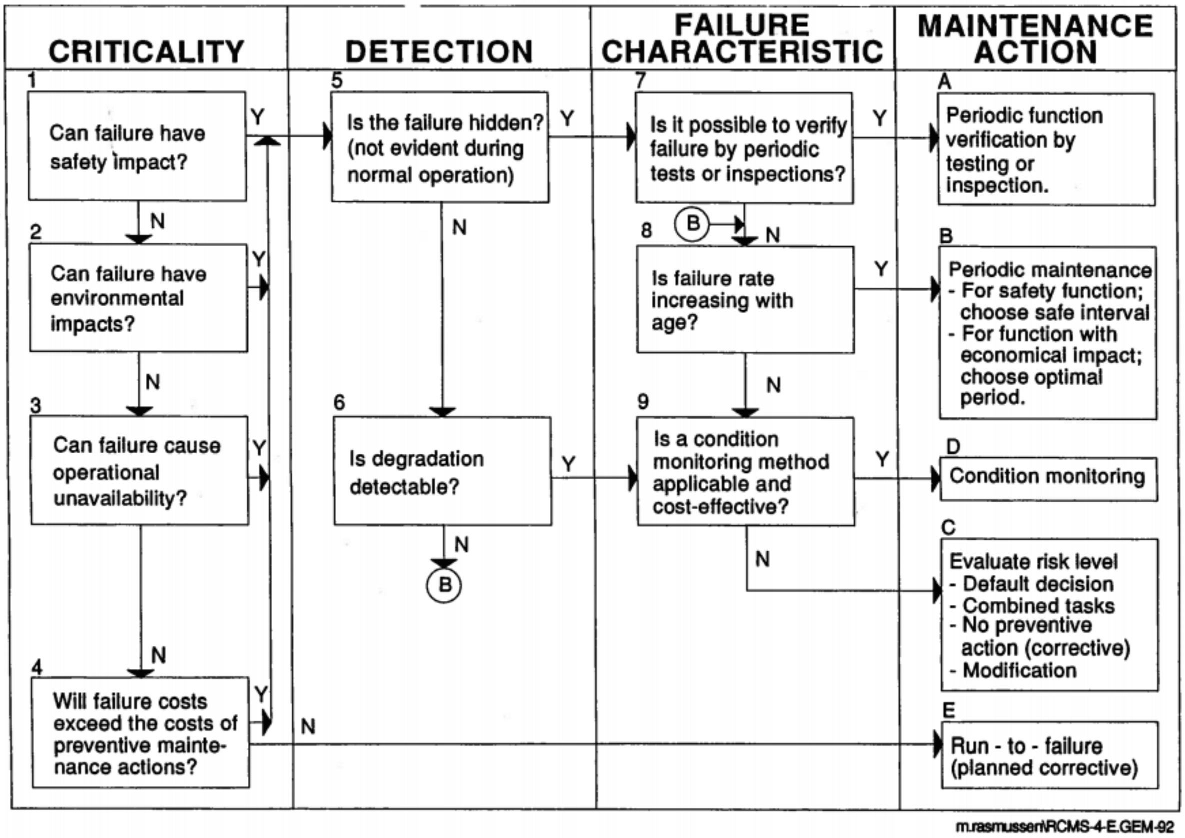

FIGURE 12: MAINTENANCE ACTION DECISION-MODEL (RASMUSSEN, 2003).

After the necessary maintenance actions have been determined, they can be bundled together in maintenance packages with related actions and necessary spare parts and equipment. The maintenance packages together form the maintenance plan.

The NORSOK Z-008 standard (NORSOK, 2011), has a slightly different approach for developing a maintenance programme compared to what Prof. Rasmussen proposes. The step-wise method and decision tree proposed in the standard is given in Appendix II.

4.5 – RISK BASED INSPECTION, RBI

Risk based inspection seeks to establish an optimal inspection program for equipment where the results of an inspection can be used to decide whether or not to perform preventive maintenance or replacement of components. RBI can therefore be a useful tool in relation to condition based maintenance (CBM) defined in chapter 4.2.1 – Preventive maintenance.

"The methodology combines availability and risk analysis work and is typically applied for static process equipment (e.g. piping, pressure vessels and valve bodies). The failure mode of concern is normally loss of containment. The input to a risk analysis is probability of leak and consequence to assets." (NORSOK, 2010)

In other words, the input to RBI is very similar to the input to RCM, since it requires a good picture of the functionality of the system, its failure modes and probability of failures, and the consequences of the failures. Therefore, no further description of RBI will be given here, except explaining the relation between RCM and RBI.

First of all, RCM is a method to establish an optimal maintenance program, which may or may not include inspection, where RBI only tries to establish an optimal inspection program. Secondly, RBI usually only considers failures directly linked to the system or component, for example loss of containment in a pipe, as described in NORSOK Z-013, cited above. With an RCM approach, we would also consider the loss of flow in the pipe, since this is what affects the next system or component in the functional hierarchy.

4.6 – SPARE PARTS MANAGEMENT

NORSOK Z-008 (NORSOK, 2011) states: *"The spare part assessment defining need for spares, (number of, location and lead time) shall be based on results from the consequence classification. Further, the PM programme should state the needed spares for its activity giving estimate of the demand rate for spare parts used for PM."*

The standard proposes the work flow for spare parts management/evaluation, given in figure 13:

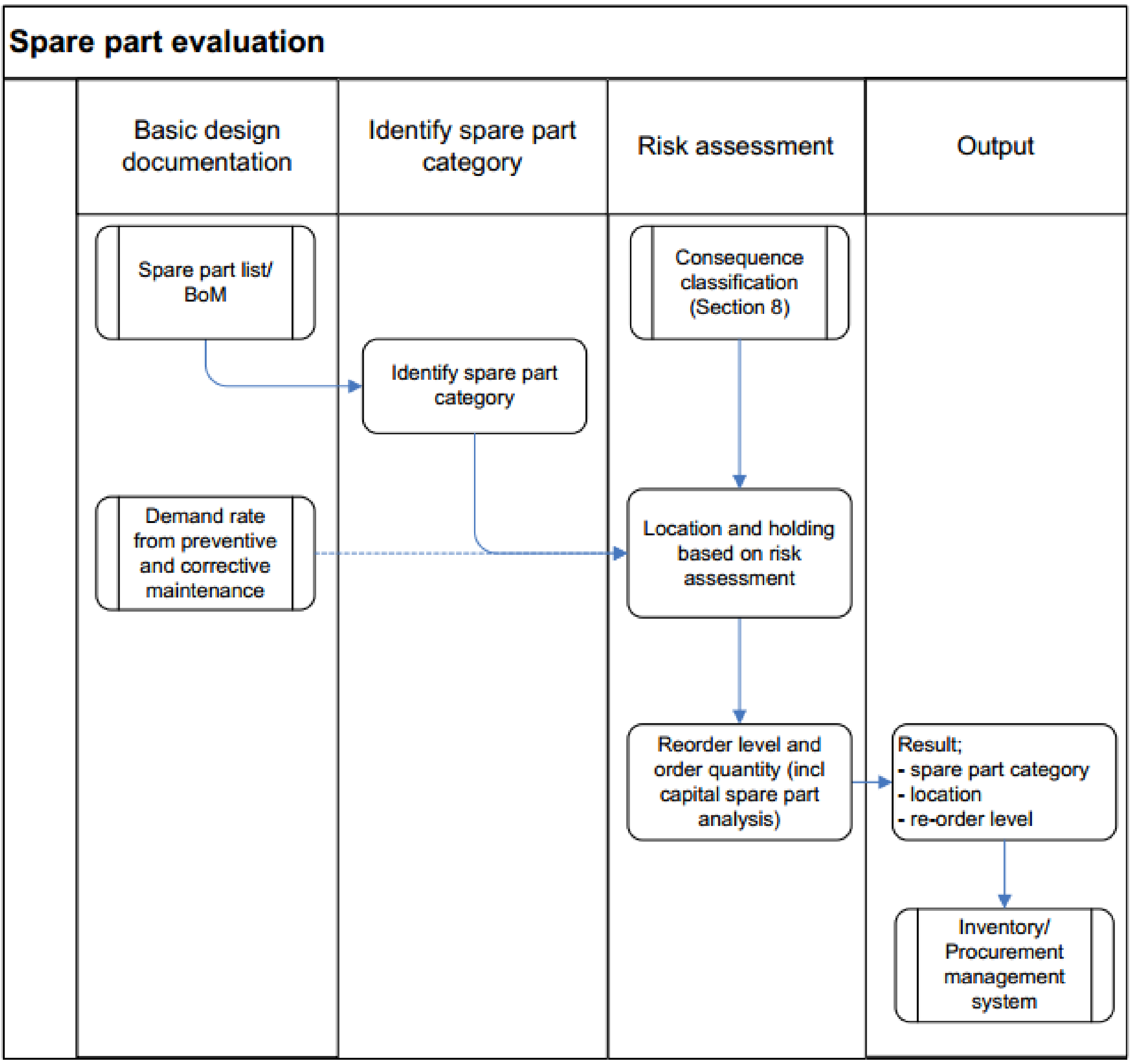

FIGURE 13: SPARE PART EVALUATION FLOWCHART (NORSOK, 2011).

4.6.1 – SPARE PART CATEGORIES

It is useful to categorize the spare parts according to the demand rate, cost, physical characteristics and other component-specific logical parameters. The categories can then lay a foundation for deciding the location and holding of spare parts.

NORSOK Z-008 (NORSOK, 2011) proposes the following categories:

- Capital spare parts – vital, but low probability of failure, long lead time, expensive, lower cost if ordered as a part of the system package.
- Operational spare parts – required to maintain operation and safety.
- Consumables – not item specific and unrepairable.

4.6.2 – LOCATION AND HOLDING OF SPARE PARTS

A risk model using the consequence of not having a spare part in place when needed, together with the spare part categories can be used for deciding on the location and holding of spare parts.

A shipping company will often have a number of spare part locations:

- Onsite on the ship.
- Local storage on the ship.
- Storage space on external land base.
- Storage space on internal land base.
- Central warehouse.

Some spare parts will be deemed unnecessary to hold, either because of low demand rate and high cost, short lead time from the supplier, or a combination of both. These spare parts usually belong in the capital spare parts category.

4.6.3 – REORDER LEVEL AND ORDER QUANTITY

The goal of spare parts management is to make sure that spare parts are always available when needed, without overstocking. When the location and holding for a spare part has been decided, we should calculate when new spare parts should be ordered and the order quantity needed to maintain the average of the holding at the decided level, based on demand rate and lead time.

4.6.4 – DECISION MODELS FOR SPARE PARTS

"The intention with the spare purchasing and stocking process is to optimize the total economy, i.e. spare part cost and mission unavailability cost, in addition to fulfill safety and environmental requirements." (Rasmussen, 2004)

In order to determine types, quantities and order points of spare parts for a system, there are a number of probabilistic and deterministic methods that can be utilized. In this report I will introduce two methods:

1. The deterministic economic order quantity concept, EOQ, which is used to determine order quantity, order point and safety level for operational spare parts and consumables.
2. The probabilistic "Newsboy" model, which is used to determine whether or not to invest in a capital spare part.

ECONOMIC ORDER QUANTITY, EOQ

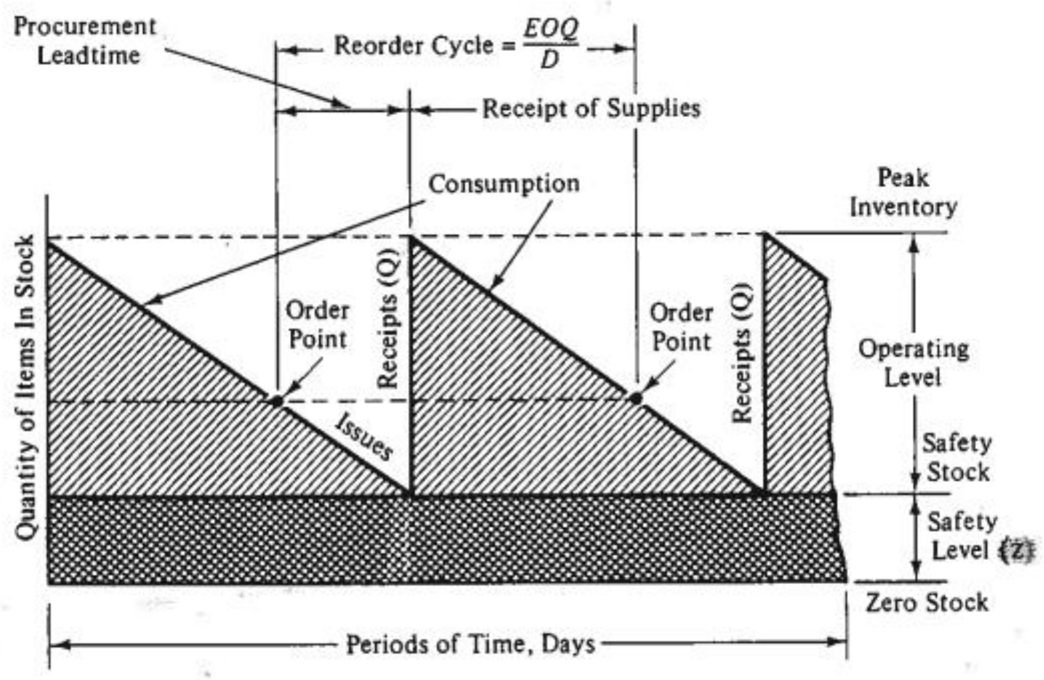

FIGURE 14: SPARE PARTS INVENTORY CYCLES (RASMUSSEN, 2004).

The different elements shown in figure 14 were described by Prof. Rasmussen (Rasmussen, 2004) as:

- *"**Operating level** describes the quantity of items required to support normal system operations in the interval between one receipt of ordered items to the next receipt of ordered items.*
- ***Safety stock** is additional stock required to compensate for unexpected demands and unforeseen delays.*
- ***Reorder cycle** is the interval of time between successive orders.*
- ***Procurement delay time** is the span of time from the date of order to the receipt of the shipment in the inventory.*
- ***Order point** is the point in time when orders are initiated for additional quantities of spares/repair parts. The point is often tied to a given stock level."*

With the help of the EOQ model we wish to determine optimal values for order quantity, order point and safety level.

The order quantity is given by:

$$EOQ = \sqrt{\frac{2C_pD}{C_h}}$$

Where C_p is the average cost of ordering, C_h is the yearly cost of carrying an item in inventory, and D is the yearly item demand, based on failure rate and number of similar items.

The order point is given by:

$$P = \sum_{i=0}^{s} \frac{(n\lambda t)^i e^{-n\lambda t}}{i!}$$

Where s is the number of spares, n is the number of active components of similar type, λ is the component failure rate, and t is the procurement lead time. P gives a probability of having a spare available when required.

The safety level is given by:

$$z = s - d = s - \lambda nt$$

Where s is the number of spares at the order point and d is the average demand during the procurement lead time, t.

THE "NEWSBOY" MODEL

Also described by Prof. Rasmussen (Rasmussen, 2004), is the "Newsboy" model. A short introduction is given here, and the full development of the model as implemented in the proposed decision tool for capital spare parts is given in chapter 7.

Back in the days, newspaper delivery boys, or newsboys, used to buy a number of newspapers in the morning in order to sell them during the day. If they bought fewer newspapers than they could sell, they would make less money, and similarly they would lose money if they bought too many. Alas, they had to consider the cost of not having enough newspapers versus the cost of having too many.

In the same way, we can consider the cost of not having a spare part when it is needed versus the cost of holding spare parts when we do not know whether or not they will be used.

We assume random failure, exponential failure distribution, un-repairable item and zero scrap value.

Then the decision model is given by:

If

$$\frac{C_m}{A} > \left(\frac{r}{\lambda} + \frac{1}{e^{\lambda t} - 1} \right)$$

Then a spare part should be purchased and stocked.

Where C_m is the cost of not having a spare part when needed, A is the purchase price of the spare part, r is the inventory stockholding rent and λ is the component failure rate.

If one spare can be used for n active items, for example one crane wire for n cranes, the decision model becomes:

$$\frac{C_m}{A} > \left(\frac{r}{n\lambda} + \frac{1}{e^{n\lambda t} - 1} \right)$$

5 – MAINTENANCE PRACTICE IN THE DOF GROUP

The daughter company DOF Management AS handles all the vessel management services in the DOF Group, except for the Brazilian operations where Norskan Offshore Ltda. handles their own vessel management. The methods, processes, systems and organization structure are the same for both companies.

5.1 – MAINTENANCE ORGANIZATION STRUCTURE

The full organization chart of DOF Management AS is given in Appendix III. I have simplified it to only include the parts of the organization that are directly involved in the maintenance management. The left side of the organization chart is primarily focused on the execution and revision of the initial maintenance program during the operational lifetime phase of the vessel. The initial maintenance program is set by the right side of the organization chart during the design and construction/re-construction phase. The technical support team consists of experts in all relevant fields of technical vessel operation, for example Crane Superintendent, and the competence of the team is utilized both during the design and construction phase and the operational phase (Stangeland, 2012).

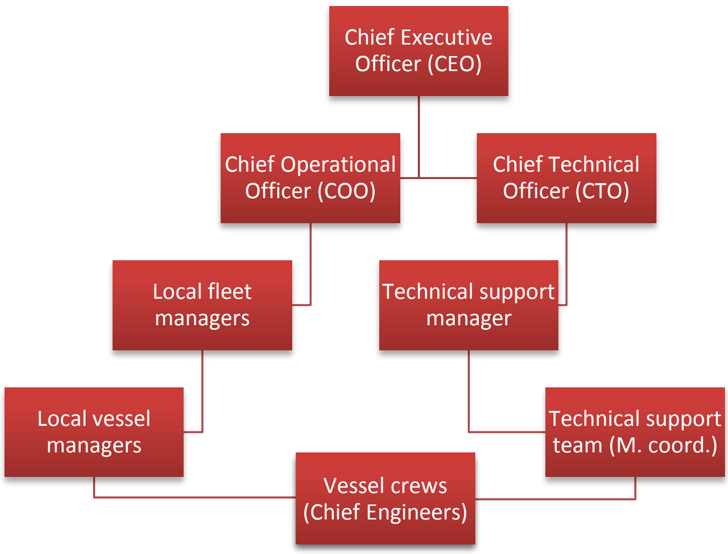

FIGURE 15: MAINTENANCE ORGANIZATION CHART, DOF MANAGEMENT AS.

5.2 – MAINTENANCE PROGRAM DECISIONS

Maintenance program decision making in the DOF Group is primarily divided in two different phases, as mentioned in the previous sub-chapter, the design and construction/re-construction phase and the operational phase.

The initial maintenance program for each vessel is set by the project manager for the construction/re-construction project, based on the discipline expert from the technical support team's revision of maker's recommendation of preventive maintenance intervals, inspection intervals, and holding of spare parts. The initial maintenance program decision making process can be summarized as:

1. Project manager sets initial budget for investments related to maintenance program, based on experience.
2. CEO/Board of Directors approves initial budget.
3. Project manager receives makers recommendation of maintenance for the first two years of operation.
4. Discipline experts from the technical support team revise makers recommendation list to optimize maintenance, while staying close to the initial budget, based on experience.
5. Project manager establishes maintenance program based on advice from all discipline experts, and revises budget for investments related to maintenance program.
6. CEO/Board of Directors approves final budget.

If top management decides not to approve the budget in stage 2 or 6, the decision making process is restarted from step 1 or 3, based on the new conditions.

During the last weeks before delivery of a new or re-constructed vessel, the vessel manager and members of the vessel crew are included in the commissioning of the vessel to get familiarized with the vessel and its systems, as well as the maintenance program. Their input is also included in the final revision of the initial maintenance program and the planned operational procedures of the vessel.

When the operational phase begins, the vessel crew and vessel managers are the primary actors directly involved with the execution and continuous revision of the maintenance program. The maintenance management system (MMS) as described in the next sub-chapter, is used to plan, monitor, and revise the maintenance tasks and spare parts inventory.

Each year, a maintenance budget for each vessel is set by the vessel manager, with input from the vessel crew. The fleet manager approves the budgets for each vessel, and top management approves the total maintenance budget of the fleet.

When system failures or unexpected results from inspections occur, the technical support team is called in to propose corrective actions or further inspections. The proposed actions and potential revision of the vessel budget is then approved by the top management.

The DOF Group has recently implemented an international docking team that plans and executes docking and large maintenance tasks of the vessels during the operational phase. The decision making process for these tasks are similar to those of the design and construction/re-construction phase (Stangeland, 2012).

5.3 – MAINTENANCE MANAGEMENT SYSTEM, MMS

The overall functions, processes and definitions for the maintenance management system are described in the DOF MMS Standard (AS, 2013b). The standard applies to all ships, equipment and warehouses in the DOF Group.

The responsibility of implementation, development and maintenance of the Maintenance Management System lies with the MMS Department, which cooperates closely with MarinIT, a wholly owned IT company responsible for the daily operation and commissioning of the MMS system and the operation of software, hardware and licences necessary to operate smoothly.

The DOF Group has developed a DOF SFI Standard for component hierarchy structure, based on the SFI Group System, and tailored for the types of equipment relevant for the DOF Group.

There are two defined types of critical equipment; Critical To Safety - CRISAF (ISM) & Critical To Operation – CRIOP (ISO 9001). Critical spare parts are marked as critical in the MMS, and extra requirements have been implemented to ensure focus on minimum stock for these spare parts. The company is currently in the middle of a project to define and tag all parts that are CRIOP.

Planned maintenance jobs in the MMS are usually based on the maker's recommendation, and alterations to these recommendations are to be discussed and agreed upon with maker. Maintenance jobs related to class requirements and flag state requirements are marked with a tag that reflects this in the MMS. All maintenance jobs are marked as planned and/or condition based. In the cases where condition monitoring tasks are to take place, they are described based on the maker's recommendations in the same way as for maintenance jobs.

The DOF group uses the fleet management software TM Master v2, delivered from Tero Marine AS for the operation of all the ships in the worldwide fleet. It includes the following modules (TeroMarine, 2012b):

- *"TM Fleet Manager - fleet management solution for the office*
- *TM Maintenance & Inventory - versatile and scalable system for asset maintenance, purchasing and spare part control*
- *TM Procurement - centralized purchasing system*
- *TM Docking - supports and simplifies every type of docking projects*
- *TM Claims - claims management*
- *TM Crew - management of crew and on-board personell*
- *TM Voyage - reduces time spent on manual reporting*
- *TM Exchange - replication of data between ship and office"*

The TM Maintenance & Inventory is a MMS module where the systems and equipment on each ship is grouped together according to the DOF SFI Standard. Within the MMS module there are a number of sub-modules that together lays a good foundation for managing all aspects of maintenance (TeroMarine, 2012a):

- **Maintenance.** *"The Planned Maintenance module is a user friendly and flexible system for planning and managing scheduled, preventive, corrective- and condition based maintenance. The system records, schedules, and manages all data pertaining to maintenance work performed on a vessel."* A screenshot of the history part of the maintenance module for Skandi Salvador is given in Appendix IV.
- **Inventory.** *"The inventory module is a powerful tool to manage components, spare parts and consumables effectively. These are all displayed in user friendly grids, complete with sorting and filtering functions, and provide you with a complete overview. The details window gives you an overview of all information related to each individual component, including jobs, spare parts, history and certificates."* A screenshot of the components part of the inventory module for Skandi Salvador is given in Appendix V.
- **Consumables/Catalogues.**
- **Purchasing.**
- **Safe job analysis.**
- **Risk/consequence analysis.**
- **Work permit.**
- **Trend analysis.**
- **Condition monitoring.**

There are also opportunities to create a lot of different reports for each ship, or for the entire fleet. Reports include work order, maintenance schedule, class related jobs, critical components and spare parts, spare parts below minimum stock, alarm due check list, non-conformance reports, standard claims report, work permit, standard reporting form. You can also generate key performance indicators to get a good view of how the different ships are performing overall and compared to each other.

5.4 – RISK ASSESSMENT

The DOF Risk Management Manual states that (AS, 2013c): *"The purpose of risk management is identify threats to the DOF business and operational activities and establish efficient means of barriers and controls in all phases of the business life cycle."*

There is a risk assessment register for all types of ship equipment and standard operations in the DOF Group. Together with the DOF Risk Management Manual quoted above, it lays the foundation for risk assessment of more specific operations and new projects. In addition to this there is an experience transfer register, where important events related to maintenance and safety are recorded to ensure that the whole company can benefit from experiences gained by individuals.

The DOF Group uses a risk matrix that compares 5 probability categories and 5 consequence categories related to:

- Injury/health
- Environmental (any incident that…)
- Company integrity

- Assets and operations
- Financial

The DOF risk matrix, called the Global Risk Assessment Worksheet is attached in Appendix VII.

The DOF Group operates within a business life cycle which incorporates various phases of activities, and each of these activities requires a level of risk management application appropriate to the phase of the business life cycle. Therefore the group has developed a process sheet for the different stages of risk management from business acquisition until finished project, that describes what tasks are to be done at each stage, what the focus is at each stage, and which department are to be responsible at each stage.

The stages of risk management work process sheet is attached in Appendix VIII.

5.5 – SPARE PARTS MANAGEMENT

As mentioned in the previous sub-chapter, spare parts management is a part of the MMS system of the DOF Group, and as mentioned in chapter 5.2, the average spare parts inventory holding is set based on the discipline experts revision of makers recommendation.

"Spare parts are to be stored in a safe way in their proper location and used parts removed from the ship unless they can re-used or must be kept onboard for other reasons such as examination, reconditioning or return to maker. Parts sent ashore for repair, reconditioning or evaluation for such work, are to be handled in accordance with procedure for landed goods and in agreement with (Senior) Vessel Manager.

Which spares to keep onboard shall be evaluated based on recommendations from supplier, critical spares assessment and experience. It shall be evaluated whether it is cost effective and justifiable to keep the stores onboard, or whether the spares are available from supplier on short notice. " as stated in the DOF Maintenance policy (AS, 2013a).

Generally, the DOF Group does not operate their own onshore bases, and thus all operational spare parts and consumables are stored onboard each vessel. Large and complex maintenance and repair tasks that cannot be performed by the vessel crew are therefore done by sub-suppliers, often the makers of the equipment. Since the vessels operate within large regional areas, this is a logical approach, and also the reason why the company does not buy storage space and services from large onshore bases used by multiple companies (Stangeland, 2012).

An exception to this rule is the DOF base in Macaé, Rio de Janeiro, Brazil, where some capital spare parts are stored and simple repairs are done. This is the only onshore base in the DOF Group, and it is located in Macaé since almost all the vessels in the region are operated out of Macáe or Rio de Janeiro.

To secure access to, and minimize delivery time of critical, capital spare parts that cannot be stored on the vessels, the DOF Group buys parts and storage space from the suppliers of the equipment.

The decision whether or not to invest in capital spare parts to be stored at the makers location is taken by top management, based on advice from the project-responsible person of the technical support team (Stangeland, 2012).

5.6 – ASSESSMENT OF MAINTENANCE PRACTICE IN THE DOF GROUP

With the theory and best practice procedures introduced in chapter 4 as a foundation, four main points of advice for the management of the DOF Group in relation to future revision of internal maintenance routines and procedures were given in the project thesis (Risholm, 2012) that preceded this Master of Science thesis:

1. **Informal experience to be made formal.** In the DOF Group today, maintenance decision-making is to a large degree based on the knowledge and experience of the individual in charge of the process. The total knowledge and experience in the organization should therefore be formalized, and standard procedures for decision-making should be implemented in order to reduce the risk of wrong decisions, and reduce the impact of loss of key employees.
2. **Formalize the maintenance management processes.** In order to secure continuous improvement of maintenance, a maintenance management standard should be implemented, for example based on the method described in chapter 4.3.
3. **Introduce scientific methods like RCM and RBI to establish maintenance program.** In the DOF Group today, the maintenance programs for most of the equipment is based on the maker's recommendation and the experience of the technical support team and vessel manager. In order to optimize the total cost and effect of the maintenance, scientific methods like RCM and RBI should be introduced, at least at the higher levels of the functional hierarchy of each system.
4. **Introduce scientific methods for spare parts management.** Especially for investments in capital spare parts, the DOF Group could probably benefit from this, for example by using a fitting version of the "Newsboy" model, introduced in chapter 4.6.4.

In addition to these areas of improvement described in (Risholm, 2012), further areas of improvement were found during the more thorough assessment of the DOF Group maintenance practice, done in connection with this thesis.

5. **Increase practical usability of critical equipment classification.** When using the definitions for critical equipment introduced in sub-chapter 5.3, the result is often that almost all equipment and components is classified as critical to safety and/or operation. This might be a correct assessment, but if "everything" is critical, the organization loses the possibility to put extra focus on the most critical equipment. In order to still be in compliance with the chosen standards for this classification, the DOF Group could implement additional classifications. For example critical for operation class 1 and class 2, where class 1 constitutes the most critical parts. These classifications should also be used to provide input for planned maintenance in the MMS, and set requirements for spare parts considerations.

6. **Bring the users closer to decisions regarding the MMS.** The maintenance organization chart for DOF Management AS was presented in sub-chapter 5.1, and although that organization structure handles all aspects of the maintenance program from initial planning to exectution, the MMS Department holds the responsibility for implementation, development and maintenance of the MMS, as described in sub-chapter 5.3. In other words, a department that is not directly involved in using the MMS has the full responsibility of its functions. This is considered a weak point, because it creates barriers for user based improvement of the system. Direct, formal influence on the MMS from the maintenance organization is advised.
7. **Introduce a fleet-oriented philosophy for all aspects of the maintenance practice, especially for spare parts management.** Partly described in point 1, the DOF Group is in need of standardizing work processes and experience across all operations throughout the world. Since all planned maintenance is conducted on each vessel, a vessel focus based on common methods for the whole fleet is advised for the planned maintenance part. When it comes to spare parts, and especially capital spare parts, a clear fleet-orientation is advised in order to benefit from economies of scale by having such a large fleet of vessels that the DOF Group has. Instead of evaluating which capital spare parts to invest in for each newbuilding project, the capital spare parts investments should be evaluated by looking at the demand from the number of similar systems in a region. Without a fleet-oriented viewpoint for this, the company will lose opportunities to benefit from economies of scale.

5.7 – PROPOSITIONS FOR SPARE PARTS MANAGEMENT

As stated in the project description it was decided to focus on the areas of improvement related to spare parts management for the proposed new work processes and tools in this thesis. Spare parts management is of course closely related to the rest of the aspects of maintenance, and where the new propositions affects the established general maintenance practice in the DOF Group, this is commented.

In chapter 6, the proposed overall philosophy for spare parts management in the DOF Group is described. The proposed work processes are presented in a flow chart, with description of each item in the flow chart. Emphasis in this chapter is put on the general vision and goals for the proposed spare part management system, classification of spare parts, the roles in the organization involved, and ways to ensure continuous improvement.

In chapter 7, the proposed decision tool for capital spare parts is presented, and the tool is used to make optimal capital spare parts decisions for the offshore crane on the Skandi Salvador.

The proposed decision tool for operational spare parts and consumables is presented in chapter 8, and the tool is used to make optimal operational spare parts decisions for the offshore crane on the Skandi Salvador.

Comments to results are presented in each chapter, and the final conclusion of the thesis, including a summary of the most important results and comments are found in chapter 9.

Finally, a summary of ideas for further work is presented in chapter 10.

6 – PROPOSED SPARE PARTS MANAGEMENT PHILOSOPHY

The main objective of spare parts management is to find the optimal numbers, types and locations for spare parts needed to perform the desired tasks with as high uptime as possible. In effect, to have spare parts available when they are needed, but to avoid stocking spare parts that are not needed.

At the heart of the proposed spare parts management philosophy lie fleet orientation, formalization, and scientific methods.

A fleet-oriented mindset for spare parts management allows you to exploit economies of scale, by looking at the regional fleet demand instead of the demand of each vessel. For example, by investing in one item of a capital spare part to cover three similar systems on three different vessels. A vessel-oriented viewpoint would have resulted in ordering either three or no spare parts of the type in question.

By standardizing the spare parts management to include standard methods and work processes, while also formalizing the experience present in parts of the organization, one can ensure that the same, optimal decisions are taken throughout the different parts of the DOF Group, instead of only being reliant on the experience and knowledge of the individual in charge locally.

When each individual in charge of making decisions for spare parts have access to the same quality input data, mathematical decision tools can be utilized to optimize decisions. Sensitivity analyses can be used to further make sure that informed, optimal decisions are being taken, even when the input data is insecure.

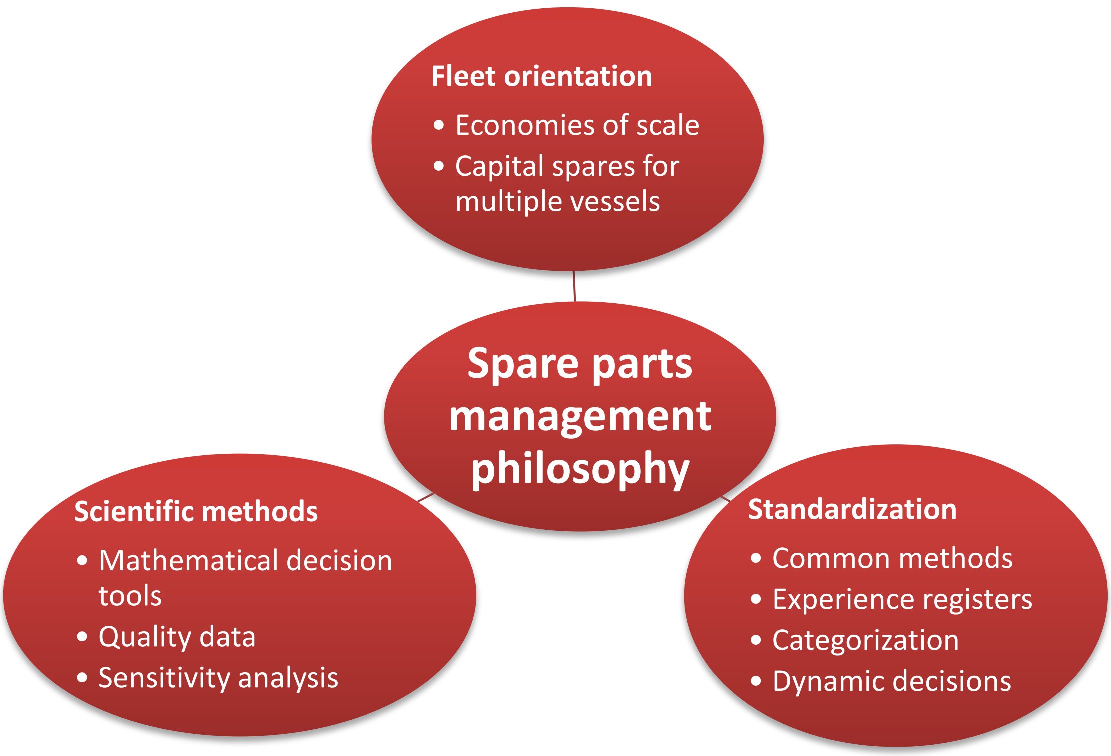

FIGURE 16: PROPOSED SPARE PARTS MANAGEMENT PHILOSOPHY.

6.1 – PROPOSED RESOURCES AND ORGANIZATION

The spare parts management organization structure is proposed to remain the same as it is now, equal to the maintenance organization described in chapter 5.1. Meaning that throughout the whole spare part evaluation work process, the actor in charge is the project manager if the decisions are taken for a newbuilding project, and the vessel manager if the decisions are taken for a vessel in operation, as per the current DOF Group policy described in chapter 5.2.

It is proposed to keep the current maintenance management system and the MMS software described in chapter 5.3. However, the maintenance organization is proposed to have direct closer direct influence over the implementation, development and maintenance of the MMS. The job of the MMS department is proposed to be changed to only carrying out decisions taken by the maintenance organization. All decisions regarding planned maintenance jobs, spare parts stocking and purchasing, and categorization and classification of parts will therefore be the responsibility of the maintenance organization, will the MMS department will have only have the responsibility of maintaining and changing the MMS according to the wishes of the maintenance organization.

The DOF Group is advised to start a capital spare parts experience register, in order to over time increase the quality of the input data for capital spare parts decisions, and to formalize experience present in the organization so that it is available for all individuals in the organization. This is more thoroughly explained in chapter 6.2.

Furthermore, two decision tools are proposed to be implemented as an important part of decision-making regarding spare parts. The decision tools, one for capital spare parts and one for operational spare parts and consumables, are described in chapter 7 and 8.

This means that although the maintenance and spare parts organization is proposed to remain unchanged, they will have to receive training in the overall philosophy, the proposed work process and the proposed decision tools, in order to utilize the proposed methods in the correct way.

6.2 – PROPOSED WORK PROCESS FOR SPARE PARTS EVALUATION

The proposed work process for spare parts evaluation inspired by the work process described in (NORSOK, 2011) and presented in chapter 4.6, is presented in a flowchart in figure 17 below. Thereafter, each proposed sub-process is described phase by phase in the following sub-chapters.

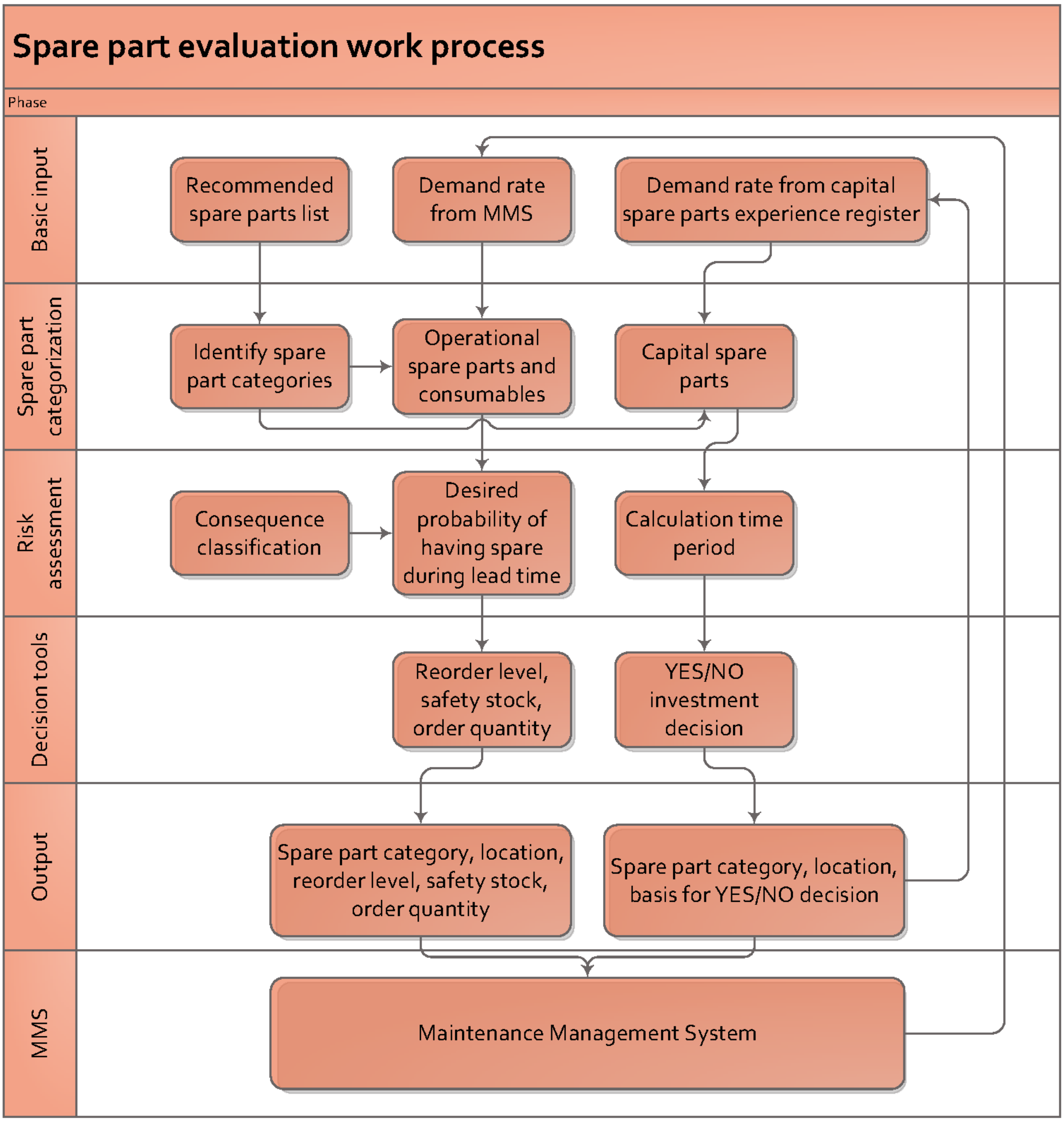

FIGURE 17: PROPOSED SPARE PART EVALUATION WORK PROCESS.

6.2.1 – BASIC INPUT PHASE

In the basic input phase the project/vessel manager receives lists of recommended spare parts for 2 years operation, along with a maintenance manual for all equipment and systems on the vessel in question.

If the vessel is already in operation, the demand rates for operational spare parts and consumables are given by the planned maintenance jobs in the maintenance management system.

If the vessel is a newbuilding project, the initial maintenance program for each type of equipment must be set based on the maintenance manual and input from the relevant expert from the technical support team, along with the vessel crew.

Demand rates for capital spare parts in the form of mean time to failure can be harder to obtain. Therefore, it was decided to start a capital spare parts experience register. In it, all events related to capital spare parts will be recorded. Everything from which investment decisions were taken and the basis on which they were taken, to mean time to failure data and actual delivery times for all capital equipment. In the beginning, the mean time to failure and delivery time data will mostly be based on experience from experts in the technical support team and data received from the equipment manufacturers. Over time, the DOF Group will be able to build its own library of mean time to failure data based on experience across the fleet. This will lead to continuous improvement of the decisions that are taken, because the quality of the input data will gradually increase.

6.2.2 – SPARE PART CATEGORIZATION PHASE

As mentioned in chapter 4.6.1, NORSOK Z-008 (NORSOK, 2011) proposes the following categories:

- Capital spare parts – vital, but low probability of failure, long lead time, expensive, lower cost if ordered as a part of the system package.
- Operational spare parts – required to maintain operation and safety.
- Consumables – not item specific and un-repairable.

It was chosen to use this standard for the proposed spare part categories in the DOF Group.

In absolute terms, a spare part should be considered a capital spare part if one or more of the following statements are true:

- The demand rate is less than 1 item every 2 years.
- The cost per item exceeds NOK 50 000.
- The delivery time is estimated at or above 10 weeks.

If none of these statements are true, the spare part should be categorized as a operational spare part or a consumable, according to the standard.

In the rest of the proposed work process, operational spare parts and consumables are treated as one group, since the same methods and decision tools can be utilized for both.

Generally, operational spare parts and consumables are stored on each vessel, whereas the capital spare parts are stored onshore, either at a DOF warehouse or at the manufacturer's premises.

6.2.3 – RISK ASSESSMENT PHASE

The DOF Group is advised to keep the current classification of parts as Critical To Safety - CRISAF (ISM) & Critical To Operation – CRIOP (ISO 9001). Critical spare parts are marked as critical in the MMS, and the critical parts are tagged as critical in the MMS to ensure focus on minimum stock for these spare parts.

In addition, it is proposed to introduce a new criticality category for parts critical to operation. Critical to Operation class 2 is the same as CRIOP (ISO 9001), and class 1 are parts where there is a high probability (>70%) for a failure of the whole system within 4 weeks after failure of the part.

The class of the category defines the desired probability of having spare parts available during procurement lead time. This is an important input variable for the decision tool for operational spares and consumables.

For parts labeled as critical to safety and critical to operation class 2, the probability is set at 95%. For critical to operation class 1, it is set at 99%.

6.2.4 – DECISION TOOLS AND OUTPUT PHASES

Two decision tools, one for capital spare parts and one for operational spare parts and consumables, were developed. They are thoroughly presented in chapter 7 and 8, respectively.

In short, the project/vessel manager uses the input data gathered in the work processes leading up to the decision tools phase, to make optimized decisions using the decision tools, based on all the variables.

The output from the decision tool for capital spare parts is a YES/NO decision for whether or not to invest in the type of capital spare part in question. Through sensitivity analysis available in the tool, the project/vessel manager is able to assess the strength of the decision made.

The main output from the decision tool for operational spare parts and consumables are reorder level, safety stock and order quantity.

Along with the output for spare part category and location of spare part, the output from the decision tools are entered into the maintenance management system, and the output for the capital spare parts are also entered into the capital spare parts experience register.

6.3 – DYNAMIC SPARE PARTS MANAGEMENT

An important part of the proposed spare parts management philosophy is the ability to make optimal decisions in changing environments. If the evaluation process is not dynamic, the actors responsible will soon revert to the former, subjective methods for making decisions.

Therefore, the project/vessel managers are instructed to make new spare part evaluations whenever any change in the operation of a vessel is planned or registered.

Furthermore, the project/vessel manager should assess how the change affects the input parameters for the decision tools. In some cases, the change of a parameter can be directly evaluated, like for example a change in the contracted dayrate of the vessel. However, in many cases the implications must be assessed further.

So, whenever a change in the operation of a vessel is planned or registered, the project/vessel manager should ask himself how this change might affect the input parameters of the decision tools.

For capital spare parts that means:

- How does the active systems in region change? How many are present now?
- How does the average vessel dayrate change?
- Should the calculation time period be changed?
- How is the mean time to failure affected?
- Is the cost of the spare part still the same?
- How does the storage cost change?
- Is lost dayrate-percentage changed?
- How is the delivery time from manufacturer changed?

For operational spare parts and consumables it means:

- Are there more or less similar parts on the vessel now?
- Is the mean time before maintenance affected?
- Is the cost of the spare part still the same?
- How are the cost of ordering and the cost of holding affected?
- Is the procurement lead time changed?
- Does the part have to be reclassified, and hence change the desired probability of having enough spares during procurement lead time?

Examples of such changes and typical important questions:

- Change of regional area. Operating a vessel in the Persian Gulf is not the same as operating in the Arctic Ocean. How does this affect MTTF? How does it affect delivery time?
- Change of contract. How does it affect the dayrate? How does it affect the percentage of lost dayrate if a breakdown occurs on the equipment in question?
- Demand rate deviation. Why does the demand rate deviate from that collected in the basic input phase? How can a new and more correct demand rate be set?

Hence, the work process for dynamic spare parts evaluation can be summarized in figure 18.

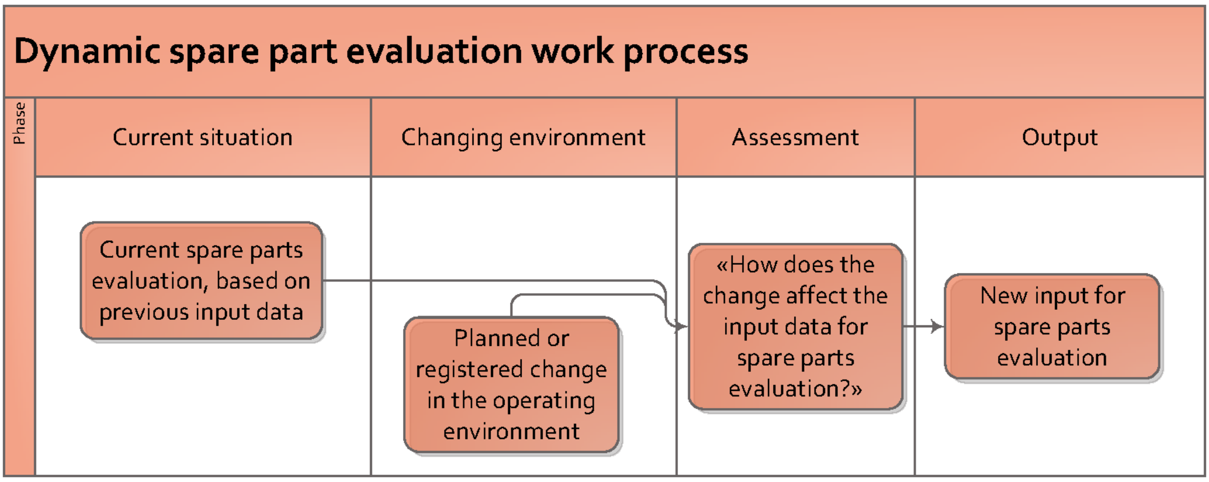

FIGURE 18: PROPOSED DYNAMIC SPARE PART EVALUATION WORK PROCESS.

The exact same procedure can be used to ensure continuous improvement. Whenever something related to the spare parts management functions sub-optimally, the project/vessel manager can use the proposed work process to investigate which parameters are deviating from the values used in the decision tool, and then change those parameters to mirror the reality.

7 – PROPOSED DECISION MODEL FOR CAPITAL SPARES

As shown in chapter 3, the operation of CSVs is a very capital intensive venture, and the ability to make a profit is closely related to keeping the technical uptime of the vessels at an optimal rate. At the same time, as shown in table 6, the delivery time of capital spare parts for the offshore cranes can be up to 40 weeks. The potential economic consequence of breakdown of such a component is therefore very high.

Thus, the decision of whether or not to invest in capital spare parts is not one to be taken lightly. Still, as mentioned in chapter 5, this is a decision that is currently being made based on the experience of the technical support team. In reality this will often be one person, and this will not always be the same person.

Therefore, the need was seen to develop a capital spare parts investment model in order to combine scientific optimization methods with formalized experience, to create a broader, more exact, and common method for spare parts investment decision-making in the DOF Group.

Also, emphasis was put on making a decision model that evaluated the investment decisions from a fleet perspective, taking the possible economies of scale that could be exploited by covering multiple vessels with one spare part into account.

There are three points of interest that was chosen to be neglected, that might have changed the decisions if they were included in the tool.

- Other types of fault distributions than the chosen exponential distribution could have been included in order to choose the fault distribution that was most fitting to the part in question, if such data was available. This would have increased the workload for development and the complexity of the decision tool for the user.
- The DOF Group has insurance for loss of dayrate resulting from downtime exceeding two weeks. This was neglected, because over time the price of the insurance can be expected to mirror the downtime costs.
- The DOF Group is currently using condition monitoring for many types of equipment and parts, for example crane wires. It was chosen not to include effects of condition monitoring in the proposed solution, but the user is free to for example adjust delivery times accordingly.

7.1 – MODEL DEVELOPMENT

In chapter 4.6.4, a general version of the “Newsboy” model was presented, with the resulting equations given.

This model, based on the balance between having a spare part and not needing it and not having a spare part and needing it, lays the foundation for the development of the capital spare parts investment model specifically tailored for OSVs.

Like in the general “Newsboy” model, random failure, exponential failure distribution, un-repairable item and zero scrap value is assumed.

There are four main cost elements in the model to be considered during the time period:

- C_a, expected cost of absence of spare part, if needed.
- C_f, expected stockholding cost of spare part until replacement.
- C_r, expected stockholding cost of spare part, if no replacement is done.
- C_s, expected scrapping cost of spare part, if no replacement is done.

The cost of downtime during replacement of the part is neglected, since it will be part of the cost elements related to both having and not having a spare part in storage. Therefore, the model should not be used to calculate either of the two sides' total cost separately, but rather to see the relation between them in order to make an informed investment decision.

The time period, T, should be chosen based on criteria relevant for each specific investment decision. For example the expected life time of the vessel or equipment, or the length of a specific time charter agreement. The time period should however never exceed the expected life time of the spare part, while kept in storage.

The basic decision model then becomes, if:

$$C_a > C_f + C_r + C_s$$

Then the spare part should be purchased.

Each cost component can then be further evaluated:

$$C_a = D \cdot t_d \cdot p \cdot \left(1 - e^{-\frac{n}{MTTF} \cdot T}\right)$$

Where D is the vessel dayrate, t_d is the delivery time of the spare part, p is the percentage dayrate lost if you have downtime on the equipment, and n is the number of similar, active systems in the region. For example, n, number of similar offshore cranes in a region.

$$C_f = A \cdot r \cdot \left(\int_0^T t \cdot \frac{n}{MTTF} \cdot e^{-\frac{n}{MTBF} \cdot T}\right) = A \cdot r \cdot \left(\frac{MTTF}{n} - \left(\left(T + \frac{MTTF}{n}\right) \cdot e^{-\frac{n}{MTTF} \cdot T}\right)\right)$$

Where A is the purchase price of the spare part, r is the annual stockholding rent for the spare part as a percentage of the purchase price, and the integral is the equation for the calculated mean time to failure within time period T, multiplied with the time to failure distribution, as shown in (Rasmussen, 2004), and then solved by integration to get the final equation.

$$C_r = A \cdot r \cdot T \cdot e^{-\frac{n}{MTTF} \cdot T}$$

Where the last product of the equation is R(T) – the reliability function.

$$C_s = A \cdot e^{-\frac{n}{MTTF} \cdot T}$$

Adding the equations together, we get the full decision model:

If

$$D \cdot t_d \cdot p \cdot \left(1 - e^{-\frac{n}{MTTF} \cdot T}\right) > A \cdot r \cdot \left(\frac{MTTF}{n} - \left(\left(T + \frac{MTTF}{n}\right) \cdot e^{-\frac{n}{MTTF} \cdot T}\right)\right) + A \cdot r \cdot T \cdot e^{-\frac{n}{MTTF} \cdot T} + A \cdot e^{-\frac{n}{MTTF} \cdot T}$$

Then a spare part should be purchased.

7.2 – DECISION TOOL FOR CAPITAL SPARES

After establishing the mathematical model, one can proceed to create a usable tool for investment decisions. In order to maximize the value of the possible users of the tool, usually being the members of the technical support team responsible for the equipment in question, the tool should be made on a familiar platform. Therefore it was chosen to base it on a Microsoft Excel spreadsheet.

The needed input data for the model is:

- Active systems in region [#] – which can use the same spare parts.
- Average vessel dayrate [NOK/day] – for the vessels in the region that can use the same spare parts.
- Calculation time period [years] – To be chosen as explained chapter 6.1.
- Mean time before failure, in operation [years] – for the part in question.
- Cost of spare part [NOK] – for the part in question.
- Storage cost [%/year] - % of the cost of the spare part in question, reflecting the cost of capital tied up, depreciation over the lifetime of the spare part, and direct storage and maintenance cost of the spare part while it is not in operation.
- Lost dayrate if failure on equipment [% of dayrate] – failure as direct function of breakdown of the part in question.
- Delivery time from manufacturer [days] – not including installation time on vessel.

Since almost all the input values have uncertainties, a calculation sheet was also made in order to evaluate how sensitive the decision-making outcome is to changes in the input values.

For added functionality, buttons made with Visual Basic programming were included in the sheet, so that the user can choose which values he wants to evaluate the sensitivities for, by simply pressing the relevant button. The diagram under the sheet will then change into showing the base cases along with sensitivity graphs based on the chosen variable.

The following three variables were chosen for sensitivity analysis:

- Mean time to failure – because the actual time to failure will vary from part to part.
- Delivery time – because actual delivery time can be hard to predict.
- Storage cost – because it might change, and because it is a very important parameter for the stockholding cost.

In addition to the sensitivity analysis buttons mentioned above, a button to reset the input of the diagram was included, in order to easily let the user navigate between the different types of sensitivity analyses.

The decision tool for capital spares has been included as an attachment in the NTNU database for Master of Science theses archiving and deliveries, DAIM. Shown on the next two pages in figure 19 and 20 is the user interface of the tool with and without sensitivity analyses, with example values for demonstration purposes.

Decision tool for capital spares		
Item	**Value**	
Regional data		
Active systems in region	2	[#]
Average vessel dayrate	500 000	[NOK/day]
Calculation time period	4	[years]
Spare part data		
Mean time to failure, in operation	30	[years]
Cost of spare part	5 000 000	[NOK]
Storage cost	20 %	[% of investment cost/year]
Lost dayrate if failure on equipment	100 %	[% of dayrate]
Delivery time from manufacturer	70	[days]
Should the spare part be purchased?	**YES**	

MTTF	Delivery time	Storage cost	RESET INPUT

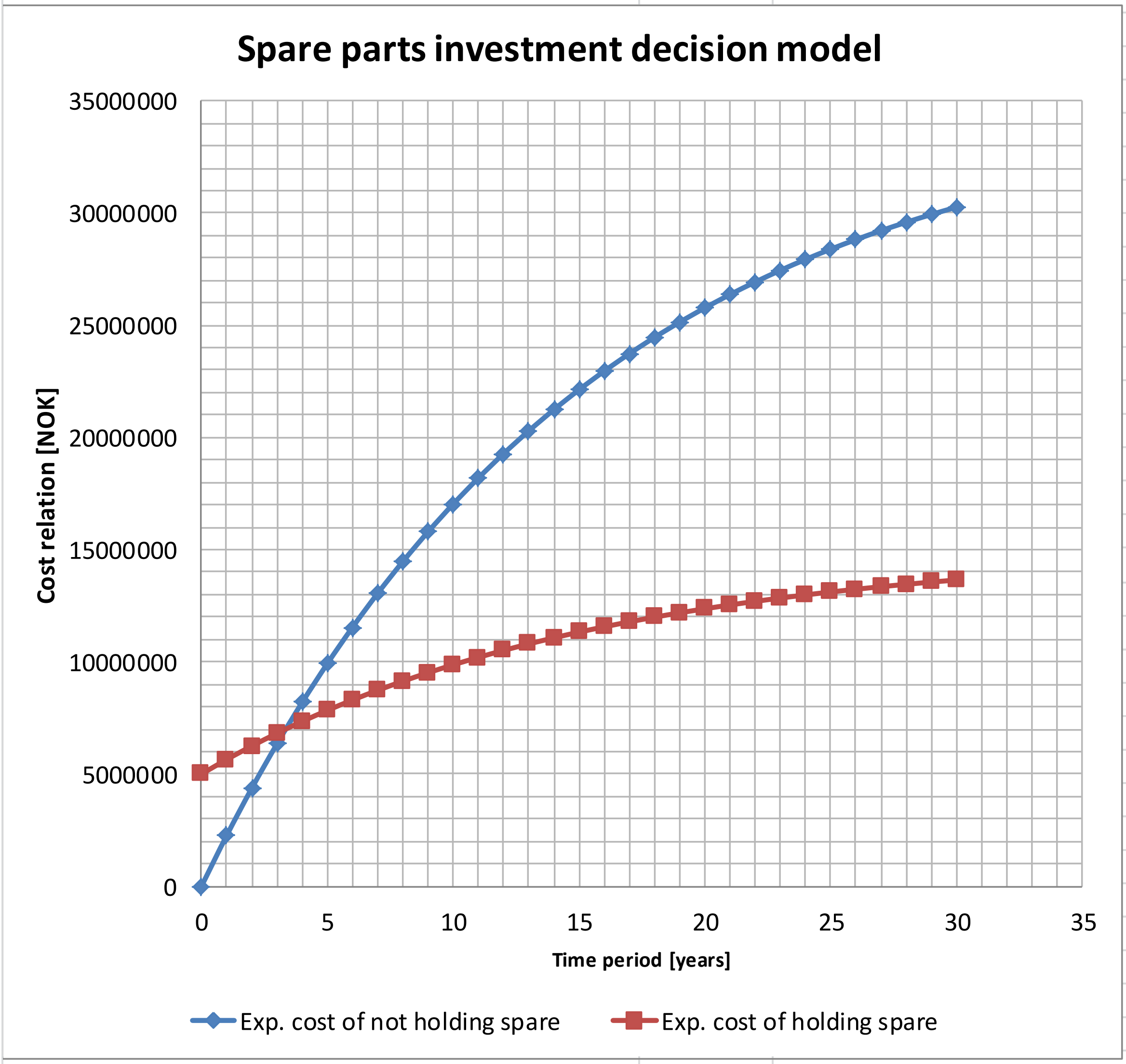

FIGURE 19: DECISION TOOL FOR CAPITAL SPARES, SCREENSHOT W/O SENSITIVITY ANALYSIS.

Decision tool for capital spares		
Item	**Value**	
Regional data		
Active systems in region	2	[#]
Average vessel dayrate	500 000	[NOK/day]
Calculation time period	4	[years]
Spare part data		
Mean time to failure, in operation	30	[years]
Cost of spare part	5 000 000	[NOK]
Storage cost	20 %	[% of investment cost/year]
Lost dayrate if failure on equipment	100 %	[% of dayrate]
Delivery time from manufacturer	70	[days]
Should the spare part be purchased?	**YES**	

MTTF | Delivery time | Storage cost | RESET INPUT

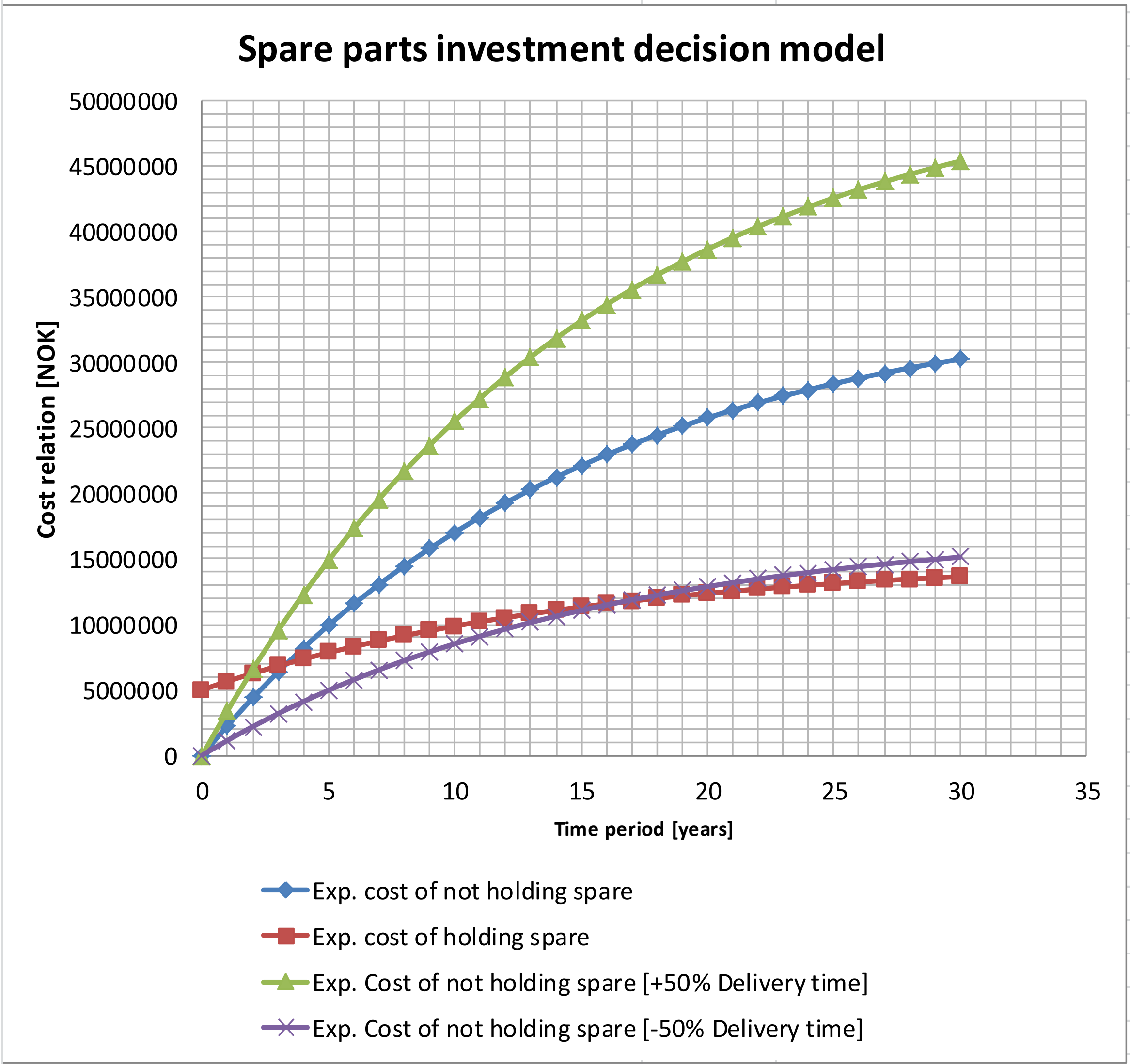

FIGURE 20: DECISION TOOL FOR CAPITAL SPARES, SCREENSHOT WITH SENSITIVITY ANALYSIS.

7.3 – HISTORICAL EQUIPMENT FAILURE CASES

As shown, when using the proposed capital spare parts investment decision tool, the quality of the input data should be as high as possible. High cost and lead time on these parts can drastically increase the economic consequences of the breakdown, but in reality, problems can often be solved faster or cheaper than the worst case scenario. This is of course positive, but it makes decision making using mathematical models more complicated, because it increases the insecurity of the input data, especially for spare part lead time. In order to demonstrate practical consequences of breakdowns needing capital spare parts to be corrected, three examples of breakdowns on vessels in the DOF Group were chosen for presentation.

SKANDI SALVADOR, OFFSHORE CRANE – AXIAL PISTON PUMP ELECTROMOTOR

During the last stages of the building period at the STX Brazil Offshore SA shipyard in Niterói, Rio de Janeiro, Brazil, testing of the offshore crane of Skandi Salvador was conducted. In the middle of a lift, the electromotor on the axial piston pump failed, and thus caused a complete breakdown of the crane.

It had been decided to not invest in this capital spare part, and thus neither the DOF Group, nor the shipyard had a new electromotor available. As shown in table 7, the expected delivery time of this part is 40 weeks. Luckily, the DOF Group had another ship with the same type of crane being built in Norway at the same time. They were able to take that electromotor and fly it to Brazil. The end consequence of the breakdown was therefore limited to only 2 weeks delay. (Stangeland, 2013).

SKANDI BOTAFOGO, HIPAP 500 – TRANSDUCER

The HiPAP 500 is an acoustic ROV positioning system manufactured by Kongsberg Maritime AS. The top transducer is located at the keel in the forward part of the vessel. When being used, the transducer is lowered 1,5-5 meters below the keel level, and when not being used, it should be fully retracted into the keel.

28.03.2010, the crew of Skandi Botafogo discovered that while entering the port of Macaé the previous day, they had forgotten to retract the HiPAP 500 transducer. The transducer had grounded while entering the port, and was irrepairable. A picture of the broken transducer is shown in figure 21. The DOF Group did not have the capital spare part available, nor had the Brazilian division of Kongsberg Maritime AS. Thus, a new transducer had to be ordered from Norway.

11.05.2010, Skandi Botafogo left its operation area in the Campos basin and steamed to the STX Brazil Offshore shipyard in Niterói to install the newly arrived transducer. 15.05.2010, the transducer was tested and accepted, and 16.05.2010 the vessel was back in full operation (S.A, 2010).

The Skandi Botafogo was thus unable to use the ROV for about 45 days. Luckily, Petrobras was able to use the vessel for other tasks, and the breakdown of the transducer was therefore only charged with a 10% reduction in dayrate for 40 days, followed by a 100% reduction for the 5 days of installation and transit. The total cost of the new transducer, including installation was USD 170 000, and the dayrate of the vessel at the time was USD 50 000. Thus, the total economic consequences was USD 620 000, or about NOK 3 600 000. If Petrobras had demanded 100% reduction in the dayrate during the entire downtime of the HiPAP, the total cost would have amounted to USD 2 420 000, or about NOK 14 000 000 (Stangeland, 2013).

FIGURE 21: THE BROKEN HIPAP 500 TRANSDUCER FROM SKANDI BOTAFOGO (S.A, 2010).

SKANDI COPACABANA, MAIN ENGINE 4 – TURBOCHARGER

10.05.2008, Skandi Copacabana was escorting platform “SS-54” from the Campos basin to the coastline when unexpected noises was found coming from the turbocharger on main engine 4. Main engine 4 was immediately shut down, and the vessel was able to complete the task, using the three remaining main engines.

It was found that overheating in the turbocharger had caused changes in the mechanical characteristics of many of the turbocharger components, of whom many had also been severely deformed. 23.05.2008, the turbocharger was removed from main engine 4, and transported to the premises of ABB Rio Ltda., the Brazilian daughter company of ABB, the manufacturer of the turbocharger. ABB Rio Ltda. repaired the turbocharger using parts that had to be imported from Europe, and 15.06.2008 the turbocharger was reinstalled on the vessel (S.A., 2008). Since the vessel was able to operate using 3 of the 4 installed main engines in the downtime period of main engine 4, Petrobras accepted an average 15% reduction of the dayrate during the 35 days of downtime. The cost of spare parts, repairs and installation of the turbocharger amounted to BRL 900 000, or about NOK 2 700 000. The contracted vessel dayrate was USD 37 000, and thus the total cost of the breakdown of the turbocharger was about NOK 3 800 000 (Stangeland, 2013).

Under other contractual agreements, the charterer could have easily demanded 100% lost dayrate, and then the total cost would have amounted to about NOK 10 200 000.

7.4 – USING THE TOOL, SKANDI SALVADOR CRANE CASES

When choosing which capital spare parts to evaluate, the NOV list of recommended spare parts for 2 years operation (Varco, 2012) was used. All spare parts categorized by NOV as capital spare parts were used. In addition, the rest of the list was evaluated in order to find out if any of the other spare parts should be reclassified as capital spare parts according to the procedure outlined in chapter 6. This was considered unnecessary, and the list of capital spare parts shown in table 7 to be evaluated was thus the same as the list presented in chapter 3.

The spare parts are assumed to be unique for the crane, and thus any similar parts on other equipment are neglected in the evaluation. It is highly unlikely that any of these parts can be used elsewhere.

Item name	Qty.	Unit price [NOK]	Total price [NOK]	Delivery time [weeks]
Slewing gear M22 Z14 X0,5 B210 excentric	1	124 966,00	124 966,00	12
Hydraulic cylinder 420/320	1	952 640,00	952 640,00	20
Hydraulic cylinder 350/250	1	642 980,00	642 980,00	20
Flexible coupling, Spidex	1	12 030,00	12 030,00	6
Winch gear ZHP 4,27 Clockwise	1	442 460,00	442 460,00	30
Winch gear, clockwise	1	175 220,00	175 220,00	30
Loadbolt 2MN w/lub nipple Exi	1	69 493,00	69 493,00	10
Loadbolt 200kN w/lub nipple 1/4" BSP Exi	1	22 750,00	22 750,00	10
Axial piston motor 250 CCM	1	116 462,00	116 462,00	40
Axial piston pump 355 CCM	1	259 916,00	259 916,00	40
Axial piston pump 250 CCM	1	151 068,00	151 068,00	40
Axial piston pump w/el. Motor	1	168 870,00	168 870,00	40
Wire, 70MM - MBL4430	2550	2 252,00	5 742 600,00	10
Wire, 30 MM	2560	355,40	909 824,00	10
Wire, 13 mm	120	94,00	11 280,00	10
Slew gearbox, complete	1	80 957,00	80 957,00	40

TABLE 7: LIST OF RECOMMENDED CAPITAL SPARE PARTS FOR 2 YEARS OPERATION.

As shown in table 3 in chapter 3, Skandi Salvador is currently the only CSV in the DOF Group with a 140 t crane that operates in Brazil. Therefore, active systems in region are set to 1. If the 250 t crane had been chosen, the active systems in the same region would have been 3, with Skandi Niteroi, Skandi Vitoria and Skandi Santos.

The contracted vessel dayrate for Skandi Salvador is 120 000 USD/day, or about 700 000 NOK/day. The reader is urged to remember that the whole thesis, but especially this number is classified information.

The DOF Group does not have enough empirical data to be able to set mean time before failure for any of the capital spare parts in the list. The oldest of the 140 t NOV cranes was delivered in 2007, and there are only 6 cranes of this type in the group, so it would have been hard to get trustworthy numbers, even if the cranes were older. Therefore, the data for MTTF is based on indications from NOV, but it should be noted that the numbers are insecure, since the crane design is quite new (Brøske, 2013).

Storage cost was set at 20-30% for all the capital spare parts, and reflects the cost of capital tied up (10% for all spare parts), depreciation over the life time of the spare part (5-15% per year) – linked to the mean time before failure, and storage and maintenance cost (5%).

Lost dayrate if failure on equipment was set to 100%, since failure on all the parts in question will cause direct breakdown of the crane.

The delivery times are set at the level given by NOV, presented in table 7. In reality, delivery time can often be lower than this, and for Brazil, there are special circumstances that can increase delivery time, such as prolonged time in customs once the parts have arrived in the country.

The capital spare parts have been evaluated for investments with calculation time periods of 3, 5, 10 and 15 years. Given the available input data the answer was a clear YES for all the capital spare parts. Therefore, it was decided to only present the decision table with item-specific input and sensitivity analyses for calculation time period 3 years, since the decisions are only more certain with increasing calculation time period. The decisions are presented in table 8.

Since the decisions taken with the decision tool and the input data available were so conclusive, and gave clear answers for all spare parts that were evaluated, it was decided to use the decision tool for significantly lower delivery times as well, and in that way taking account of lessons learned from the practical examples described in chapter 7.3. There it was shown that it was possible to obtain certain capital spare parts for as low delivery time as 2-4 weeks. Therefore, it was chosen to evaluate the recommended capital spare parts list for base case delivery time of three weeks, and sensitivity analysis then calculating for 1.5 and 4.5 weeks. It was chosen to only present the decisions for calculation time period 3 years for these cases as well.

Capital spare parts investment decisions for 3 years calculation time period.					
Input					Decision
Item name	Total price [NOK]	Delivery time [weeks]	MTTF	Storage cost [%]	Base case
Slewing gear M22 Z14 X0,5 B210 excentric	124 966,00	12	10	25 %	YES
Hydraulic cylinder 420/320	952 640,00	20	20	20 %	YES
Hydraulic cylinder 350/250	642 980,00	20	20	20 %	YES
Flexible coupling, Spidex	12 030,00	6	5	30 %	YES
Winch gear ZHP 4,27 Clockwise	442 460,00	30	10	25 %	YES
Winch gear, clockwise	175 220,00	30	10	25 %	YES
Loadbolt 2MN w/lub nipple Exi	69 493,00	10	7	25 %	YES
Loadbolt 200kN w/lub nipple 1/4" BSP Exi	22 750,00	10	7	25 %	YES
Axial piston motor 250 CCM	116 462,00	40	13	20 %	YES
Axial piston pump 355 CCM	259 916,00	40	9	20 %	YES
Axial piston pump 250 CCM	151 068,00	40	9	20 %	YES
Axial piston pump w/el. Motor	168 870,00	40	9	20 %	YES
Wire, 70MM - MBL4430	5 742 600,00	10	7	25 %	YES
Wire, 30 MM	909 824,00	10	7	25 %	YES
Wire, 13 mm	11 280,00	10	7	25 %	YES
Slew gearbox, complete	80 957,00	40	10	25 %	YES

Sensitivity analysis

Item name	MTTF [+50%]	MTTF [-50%]	Delivery time [+50%]	Delivery time [-50%]	Storage cost [+50%]	Storage cost [-50%]
Slewing gear M22 Z14 X0,5 B210 excentric	YES	YES	YES	YES	YES	YES
Hydraulic cylinder 420/320	YES	YES	YES	YES	YES	YES
Hydraulic cylinder 350/250	YES	YES	YES	YES	YES	YES
Flexible coupling, Spidex	YES	YES	YES	YES	YES	YES
Winch gear ZHP 4,27 Clockwise	YES	YES	YES	YES	YES	YES
Winch gear, clockwise	YES	YES	YES	YES	YES	YES
Loadbolt 2MN w/lub nipple Exi	YES	YES	YES	YES	YES	YES
Loadbolt 200kN w/lub nipple 1/4" BSP Exi	YES	YES	YES	YES	YES	YES
Axial piston motor 250 CCM	YES	YES	YES	YES	YES	YES
Axial piston pump 355 CCM	YES	YES	YES	YES	YES	YES
Axial piston pump 250 CCM	YES	YES	YES	YES	YES	YES
Axial piston pump w/el. Motor	YES	YES	YES	YES	YES	YES

Wire, 70MM - MBL4430	YES	YES	YES	YES	YES	YES
Wire, 30 MM	YES	YES	YES	YES	YES	YES
Wire, 13 mm	YES	YES	YES	YES	YES	YES
Slew gearbox, complete	YES	YES	YES	YES	YES	YES

TABLE 8: CAPITAL SPARE PARTS INVESTMENT DECISIONS FOR 3 YEARS CALCULATION TIME PERIOD.

Capital spare parts investment decisions for 3 years calculation time period, lowest delivery time.

Input					Decision
Item name	**Total price [NOK]**	**Delivery time [weeks]**	**MTTF**	**Storage cost [%]**	**Base case**
Slewing gear M22 Z14 X0,5 B210 excentric	124 966,00	3	10	25 %	YES
Hydraulic cylinder 420/320	952 640,00	3	20	20 %	YES
Hydraulic cylinder 350/250	642 980,00	3	20	20 %	YES
Flexible coupling, Spidex	12 030,00	3	5	30 %	YES
Winch gear ZHP 4,27 Clockwise	442 460,00	3	10	25 %	YES
Winch gear, clockwise	175 220,00	3	10	25 %	YES
Loadbolt 2MN w/lub nipple Exi	69 493,00	3	7	25 %	YES
Loadbolt 200kN w/lub nipple 1/4" BSP Exi	22 750,00	3	7	25 %	YES
Axial piston motor 250 CCM	116 462,00	3	13	20 %	YES
Axial piston pump 355 CCM	259 916,00	3	9	20 %	YES
Axial piston pump 250 CCM	151 068,00	3	9	20 %	YES
Axial piston pump w/el. Motor	168 870,00	3	9	20 %	YES
Wire, 70MM - MBL4430	5 742 600,00	3	7	25 %	**NO**
Wire, 30 MM	909 824,00	3	7	25 %	YES
Wire, 13 mm	11 280,00	3	7	25 %	YES
Slew gearbox, complete	80 957,00	3	10	25 %	YES

Sensitivity analysis

Item name	MTTF [+50%]	MTTF [-50%]	Delivery time [+50%]	Delivery time [-50%]	Storage cost [+50%]	Storage cost [-50%]
Slewing gear M22 Z14 X0,5 B210 excentric	YES	YES	YES	YES	YES	YES
Hydraulic cylinder 420/320	YES	YES	YES	**NO**	YES	YES
Hydraulic cylinder 350/250	YES	YES	YES	YES	YES	YES
Flexible coupling, Spidex	YES	YES	YES	YES	YES	YES
Winch gear ZHP 4,27 Clockwise	YES	YES	YES	YES	YES	YES
Winch gear, clockwise	YES	YES	YES	YES	YES	YES

Loadbolt 2MN w/lub nipple Exi	YES	YES	YES	YES	YES	YES
Loadbolt 200kN w/lub nipple 1/4" BSP Exi	YES	YES	YES	YES	YES	YES
Axial piston motor 250 CCM	YES	YES	YES	YES	YES	YES
Axial piston pump 355 CCM	YES	YES	YES	YES	YES	YES
Axial piston pump 250 CCM	YES	YES	YES	YES	YES	YES
Axial piston pump w/el. Motor	YES	YES	YES	YES	YES	YES
Wire, 70MM - MBL4430	NO	**YES**	NO	**YES**	NO	NO
Wire, 30 MM	YES	YES	YES	YES	YES	YES
Wire, 13 mm	YES	YES	YES	YES	YES	YES
Slew gearbox, complete	YES	YES	YES	YES	YES	YES

TABLE 9: CAPITAL SPARE PARTS INVESTMENT DECISIONS FOR 3 YEARS CALCULATION TIME PERIOD, WITH VERY LOW DELIVERY TIMES, SET AT 3 WEEKS.

7.5 – COMMENTS TO THE RESULTS

Given the input data described in the previous sub-chapter, the optimal decisions that were received from the decision tool was for the most part very clear.

For delivery times based on the information received from NOV (Varco, 2012), it was decided to invest in all the capital spare parts in the list, with a calculation time period of 3 years. The quality of those decisions was conclusively confirmed with sensitivity analysis for +/-50% for MTTF, delivery time and storage cost.

For significantly lower delivery times, inspired by the practical examples introduced in chapter 7.3, it was decided to invest in all capital spare parts in the list except the 70 mm wire. For the 70 mm wire, the base case decision was NO, but with -50% MTTF, and +50% delivery time, that decision also became a YES. The base case decision for the largest cylinder was a YES, but with +50% delivery time, that too became a NO.

All in all, the results from using the decision tool on the Skandi Salvador offshore crane are considered very conclusive, and the optimal decision for the DOF Group is to purchase all the recommended capital spare parts.

There are three points of interest that was chosen to be neglected, that might have changed the decisions if they were included in the evaluation:

- Condition monitoring could have allowed the DOF Group to wait until it was necessary to order a new capital spare part, instead of investing in it from the delivery date of the vessel.
- The DOF Group has insurance for loss of day rate resulting from downtime exceeding two weeks. This was neglected, because over time the price of the insurance can be expected to mirror the downtime costs.
- Other types of fault distributions than the chosen exponential distribution could have yielded different results.

7.5.1 – COMPARISON, SKANDI SALVADOR DECISIONS

Skandi Salvador was delivered from the shipyard STX Brasil Offshore SA in 2009. The decisions concerning which capital spare parts for the offshore cranes to invest in were taken as per the DOF Group spare parts management procedure. From the NOV list of recommended capital spare parts for 2 years operation, shown in table 7, the DOF Group decided to invest in the capital spare parts listed in table 10, according to the spare part purchase order for the crane (AS, 2009).

Item name	Qty.	Unit price [NOK]	Total price [NOK]	Delivery time [weeks]
Flexible coupling, Spidex	1	12 030,00	12 030,00	6
Loadbolt 2MN w/lub nipple Exi	1	69 493,00	69 493,00	10
Loadbolt 200kN w/lub nipple 1/4" BSP Exi	1	22 750,00	22 750,00	10
Axial piston motor 250 CCM	1	116 462,00	116 462,00	40

TABLE 10: PURCHASED CAPITAL SPARE PARTS FOR THE SKANDI SALVADOR OFFSHORE CRANE.

The DOF Group thus chose to deviate from the recommendation for the parts listed in table 11, which they chose not to invest in.

Item name	Qty.	Unit price [NOK]	Total price [NOK]	Delivery time [weeks]
Slewing gear M22 Z14 X0,5 B210 excentric	1	124 966,00	124 966,00	12
Hydraulic cylinder 420/320	1	952 640,00	952 640,00	20
Hydraulic cylinder 350/250	1	642 980,00	642 980,00	20
Winch gear ZHP 4,27 Clockwise	1	442 460,00	442 460,00	30
Winch gear, clockwise	1	175 220,00	175 220,00	30
Axial piston pump 355 CCM	1	259 916,00	259 916,00	40
Axial piston pump 250 CCM	1	151 068,00	151 068,00	40
Axial piston pump w/el. Motor	1	168 870,00	168 870,00	40
Wire, 70MM - MBL4430	2550	2 252,00	5 742 600,00	10
Wire, 30 MM	2560	355,40	909 824,00	10
Wire, 13 mm	120	94,00	11 280,00	10
Slew gearbox, complete	1	80 957,00	80 957,00	40

TABLE 11: NOT PURCHASED CAPITAL SPARE PARTS FOR THE SKANDI SALVADOR OFFSHORE CRANE.

Since the DOF Group did not, and does not currently have a fleet-oriented spare part philosophy, it is assumed that they did not plan for the spare parts that they chose not to buy to be covered by spare parts purchased for other vessels.

The capital spare parts investment decisions taken by the DOF Group at the delivery time of the vessel are therefore considered sub-optimal compared to the findings in this thesis, and the DOF Group is advised to purchase the remaining capital spare parts on the list of recommended spare parts for 2 years operation.

7.6 – ALTERNATIVE WAYS TO GAIN ACCESS TO CAPITAL SPARE PARTS

Making the decision that it is optimal to hold a capital spare part does not necessarily mean that it is necessary that the company owns it directly, or that it is stored in a company owned or rented storage space. What it means is that the company should invest in the opportunity to have the spare part delivered and installed in an optimal relation between delivery time and holding cost. Usually this will be as fast, or faster than if the spare part was owned and stored on company premises, and hopefully not as costly.

Five main alternative ways to gain immediate access to capital spare parts were identified:

1. **Owned by the company and located on vessel.** This option should only be used in cases where the spare part is only intended for use on the vessel in question, and where size, weight and storage space on the vessel are not limiting factors. Therefore it is often not a viable solution for capital spare parts.
2. **Owned by the company and located on company controlled storage space.** Since the DOF Group only operates one onshore base worldwide, based in Macáe, Rio de Janeiro, Brazil, this is only a viable option for capital spare parts intended for vessels operating in Brazil. For those vessels however, this is in many cases the best option. Since most of the manufacturers of important equipment, for example the offshore cranes, are based in Norway and does not yet have manufacturing plants and service stations in Brazil, the delivery and installation time will increase compared to storing the parts in the country. Even when you have the possibility for overnight transportation by airplane, the spare parts can often be held by the Brazilian customs for up to a month upon arrival. For other regional areas, the option of operating a company storage space have to be weighted up against the manufacturers ability to secure a swift delivery to that area.
3. **Owned by the company and located on manufacturers storage space.** This is the option that is mostly used for capital spare parts by the DOF Group today, and is considered a good solution for the vessels that mainly operate on the Norwegian continental shelf.
4. **Owned by the manufacturer, and located on manufacturers storage space, with guaranteed immediate delivery.** By paying a fee, it is in some cases possible to get the manufacturer to guarantee immediate delivery by holding the capital spare part in storage, owned by the manufacturer until it is needed. This can probably ensure a lower holding cost for the DOF group, as well limiting the capital tied up in spare parts that does not create a return. This guarantee should however include penalties for the manufacturer, equivalent to the potential lost dayrate of the vessel if the manufacturer is not able to fulfill the guarantee. Therefore, such an agreement should only be entered into with large manufacturing companies, that can provide bank guarantees for the potential penalties incurred.
5. **Owned by capital spare parts pool in collaboration with other vessel owners with similar equipment.** The spare part investment and holding cost

per vessel will be lower if one spare part can cover a larger amount of similar systems in a region. This can be achieved by creating a capital spare parts pool in collaboration with competing companies that use similar systems. Such pools are not currently being used in the OSV industry, but it is an option that could potentially provide the same economic benefits as option number 4, but provide more direct control from the company.

The costs used in the decision tool for capital spares should of course reflect the chosen alternative, and the decision tool for capital spares can also be used to compare the different options.

8 – PROPOSED DECISION MODEL FOR OPERATIONAL SPARES

When it comes to operational spare parts and consumables, the question is not whether or not to invest. The important decisions to be made in order to optimize spare parts management for these categories are related to quantity, order point, and safety level.

If these decisions are not being made optimally, the negative results can be on one side that the spare part in question has to be scrapped, since they often have a limited life time, even in storage. On the other hand, if one does not have a spare part in storage when it is needed, it could lead to technical breakdown of equipment, and similar consequences as for the capital spare parts.

Therefore, we saw the need to develop a similar decision model for operational spare parts and consumables in order to combine scientific optimization methods with formalized experience, to create a broader, more exact, and common method for operational spare parts and consumables purchasing in the DOF Group.

8.1 – MODEL DEVELOPMENT

In chapter 4.6.4, a general version of the “Economic Order Quantity” model was presented, with the resulting equations given. The full development of the model as given by Prof. Rasmussen (Rasmussen, 2004) is given in Appendix VII.

The goal of the model is to have the optimal amount of spares available for the lowest possible total cost. It was decided that the model can be used more or less directly for OSVs, but in order to make it more user friendly, it was decided to present some more data in addition to the main outputs of the model.

We assume constant demand, and since the demand of operational spare parts and consumables is mostly based on preventive maintenance, this will be very close to the truth.

There are three major output values coming from the model:

- Economic order quantity, the optimal order size found by minimizing the total cost of ordering and holding a quantity of similar spare parts.
- Order point, the optimal time at which to order the chosen quantity of spare parts, based on a set probability of having a spare part available when needed.
- Safety level, the quantity of spare parts to be held at all times in order to make up for varying demand and delivery time.

In addition, it was decided to present some additional values, in order to visualize the situation more clearly for the user:

- Yearly spare part demand.
- Procurement lead time demand.
- Average yearly cost of spare parts, total cost including cost of ordering, cost of holding and the direct shelf cost of the spare part.
- Average number of orders per year.

- Average number of days between orders.

The equations for the major outputs were presented in chapter 4.6.4, and are used directly in the same way as the general "Economic Order Quantity" concept. For reader friendliness, the equations are repeated here, with symbols and notations corresponding with the rest of the model:

$$EOQ = \sqrt{\frac{2C_pD}{C_h}}$$

Where EOQ is the Economic Order Quantity, C_p is the average cost of ordering, C_h is the yearly cost of carrying an item in inventory, and D is the yearly item demand, based on failure rate and number of similar items.

The order point is given by:

$$P = \sum_{i=0}^{s} \frac{(n\lambda t_d)^i e^{-n\lambda t_d}}{i!}$$

Where s is the number of spares, n is the number of active components of similar type, λ is the component failure rate, and t_d is the procurement lead time. P gives a probability of having a spare available when required.

The safety level is given by:

$$z = s - D_t$$

Where z is the safety level, s is the number of spare parts at the order point and D_t is the spare part demand during procurement lead time, to be further presented below.

The equations for the rest of the output are:

$$D = \frac{n}{MTBM} \cdot 365$$

Where D is the yearly spare part demand, n is the number of similar parts on the vessel, MTBM is mean time before maintenance in days, and it is multiplied with 365 in order to get the demand per year instead of per day.

$$D_t = \frac{n}{MTBM} \cdot t_d$$

Where D_t is the spare part demand during procurement lead time, and t_d is the procurement lead time.

$$o = \frac{D}{EOQ}$$

Where o is the average number of orders per year. The average number of days between orders is derived directly from this number by relating it to the number of days in a year.

$$C_y = o \cdot EOQ \cdot C_p \cdot C_0 + \frac{s + EOQ}{2} \cdot C_h \cdot C_0 + D \cdot C_0$$

Where C_y is the average yearly cost of spare parts of the type in question, and C_0 is the shelf cost of the spare part. The first product of the equation constitutes the cost of ordering, the second product is the cost of holding, and the last product is the shelf cost of the purchased spare parts.

8.2 – DECISION TOOL FOR OPERATIONAL SPARES

After establishing the mathematical model, we can proceed to create a usable tool for operational spare parts and consumables decision making. In the same way as for capital spare parts, in order to maximize the value of the possible users of the tool, usually being the members of the technical support team responsible for the equipment in question, the tool should be made on a familiar platform. Therefore it was chosen to base it on a Microsoft Excel spreadsheet.

The needed input data for the model is:

- Number of similar parts on vessel [#] – some standard parts are used in many types of equipment, some are more specialized.
- Mean time before maintenance [days] – as set in the maintenance plan.
- Cost of spare part [NOK] – the shelf cost, not including cost of ordering.
- Average cost of ordering a spare part [% of part cost per order] – transaction fees, transport, handling and customs.
- Average cost of holding a spare part [% of part cost per year] – including storage cost, cost of capital tied up, and depreciation over the life time of the part.
- Procurement lead time [days] – Expected time from order point until the part is ready for use at a storage location on the vessel.
- Probability of having enough spares during procurement lead time [%] – to be set as a result of consequence classification, explained in chapter 6.

Below the input table in the tool, there is a table with the output values presented in chapter 7.1. On the bottom, a graph showing the relation between the cost of ordering and the inventory holding cost is presented, including the resulting graph for the total cost. The minimum value of the total cost will be found at the optimal order quantity, EOQ.

It was decided that for this tool, built in sensitivity analysis was unnecessary, since the user can easily play around with different values, and clearly see how this affects the total cost and corresponding EOQ.

In addition to the sensitivity analysis buttons mentioned above, a button to reset the input of the diagram was included, in order to easily let the user navigate between the different types of sensitivity analyses.

The decision tool for operational spares has been included as an attachment in the NTNU database for Master of Science theses archiving and deliveries, DAIM. Shown in figure 22 is the user interface of the tool with example values for demonstration purposes.

Decision tool for operational spares

Item	Value	
Input		
Number of similar parts on vessel	1	[#]
Mean time before replacement	91	[days]
Cost of spare part	3 635,00	[NOK]
Average cost of ordering a spare part	20 %	[% of part cost per order]
Average cost of holding a spare part	30 %	[% part cost per year]
Procurement lead time	30	[days]
Probability of having enough spares during procurement lead time	95 %	[%]
Output		
Yearly spare part demand	4,01	[#]
Procurement lead time demand	0,33	[#]
Average yearly cost of spare parts	19131,68	[NOK]
Economic order quantity	2	[#]
Average number of orders per year	2,01	[#]
Average number of days between orders	182	[days]
Order point	1	[#]
Safety level	1	[#]

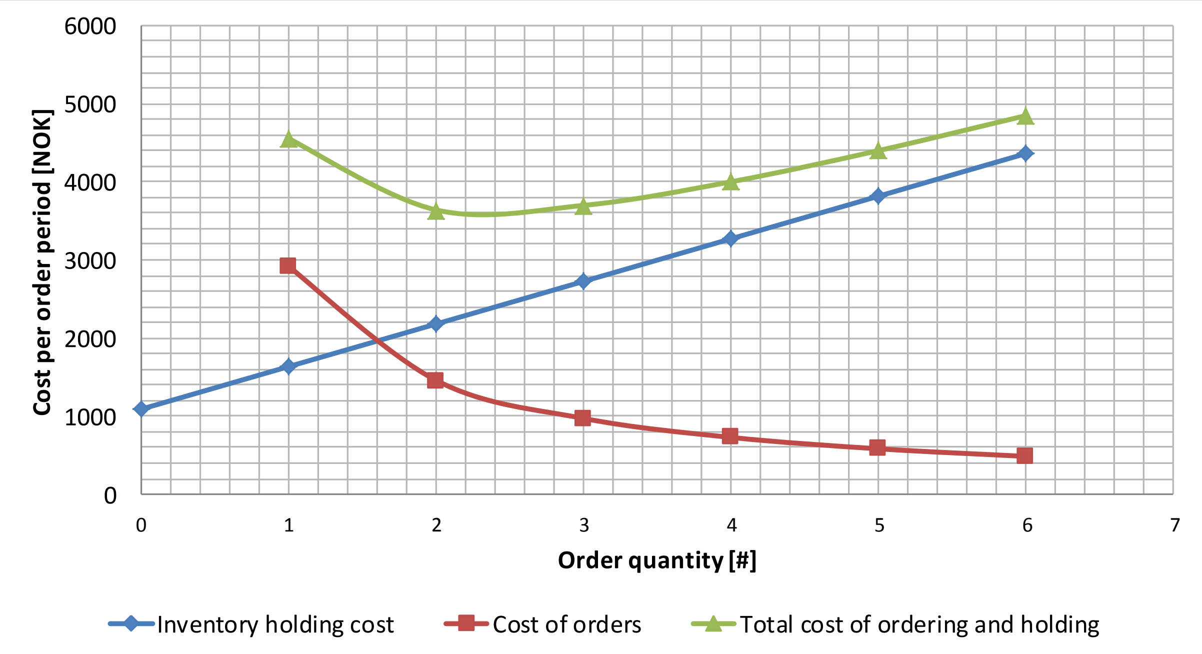

FIGURE 22: DECISION TOOL FOR OPERATIONAL SPARES, SCREENSHOT.

8.3 – USING THE TOOL, SKANDI SALVADOR CRANE CASES

Once again the list of recommended spare parts for 2 years of operation (Varco, 2012) was used as a basis for choosing which spare parts to evaluate. All operational spare parts with a recommended holding of at least 3 were considered, as shown in table 12 below. The spare parts are assumed to be unique for the crane, and thus any similar parts on other equipment are neglected in the evaluation.

Item nr.	Item name	Qty.	Qty. in op.	Unit price [NOK]	Total price [NOK]	Delivery time [weeks]
1	Wiper blade	4	1	265,00	1.060,00	4
2	Orkot bushing, orkot TXMM	4	1	2.322,50	9.290,00	4
3	Polypenco thrust bearing	4	1	990,00	3.960,00	4
4	Contact element 1xNO	4	1	42,00	168,00	4
5	Lampsocket element	3	1	69,00	207,00	4
6	Relay miniature 10A/16A	3	1	100,00	300,00	4
7	Filter element, hydraulic	4	1	5.162,00	20.648,00	4
8	Filter element, hydraulic	4	1	953,00	3.812,00	4
9	Filter element, hydraulic	8	2	3.635,00	29.080,00	4
10	Breather filter	4	2	561,00	2.244,00	4
11	Breather filter	4	2	143,00	572,00	4
12	Filter element, hydraulic	4	1	442,00	1.768,00	4
13	Filter element, hydraulic	4	1	767,00	3.068,00	4

TABLE 12: RECOMMENDED SPARE PARTS FOR 2 YEARS OPERATION, WITH RECOMMENDED QTY. OF AT LEAST 3.

The item numbers in table 12 was chosen for easy reference later in the evaluation, and is not related to NOV or DOF Group item numbers.

Mean time before maintenance was assumed to be given by the number of recommended spare parts for 2 years, based on using all the spare parts during those years. This assumption was validated by looking at the recommended maintenance plan for the crane (Varco, 2012) and the DOF Group MMS, as per the proposed work process for spare part evaluation.

In accordance with the consequence classification procedure outlined in chapter 6, all the spare parts were classified as critical to operation class 2, and hence the desired probability of having enough spares during procurement lead time was set at 95% for all the parts up for evaluation.

The values for the cost elements were estimated based on experience and engineering judgment, in cooperation with (Stangeland, 2013). The values were then validated by going through a selection of previous purchase orders.

The holding cost per year was set at 35% for all the spare parts, including cost of capital tied up (10%) and depreciation over the assumed lifetime of 4 years (25%).

The average cost of ordering an item was set at 90%, where 40% relates to transportation and handling, and 50% is import fees, since all the parts would still have to be imported from Europe to Brazil, where the import fees are set very high to facilitate growth of the Brazilian maritime industry.

The optimal decisions for the operational spare parts and consumables listed in table 12 are given in table 13, 14 and 15.

Item	**1**	**2**	**3**	**4**	**5**
Input					
Number of similar parts on vessel	1	1	1	1	1
Mean time before replacement	183	183	183	183	243
Cost of spare part	265,00	2 322,50	990,00	42,00	69,00
Average cost of ordering a spare part	90 %	90 %	90 %	90 %	90 %
Average cost of holding a spare part	35 %	35 %	35 %	35 %	35 %
Procurement lead time	28	28	28	28	28
Probability of having enough spares during procurement lead time	95 %	95 %	95 %	95 %	95 %
Output					
Yearly spare part demand	2,00	2,00	2,00	2,00	1,50
Procurement lead time demand	0,15	0,15	0,15	0,15	0,12
Average yearly cost of spare parts	1192,50	10451,25	4455,00	189,00	245,22
Economic order quantity	3	3	3	3	3
Average number of orders per year	0,67	0,67	0,67	0,67	0,50
Average number of days between orders	547,5	547,5	547,5	547,5	729
Order point	1	1	1	1	1
Safety level	1	1	1	1	1

TABLE 13: DECISIONS FOR OPERATIONAL SPARE PARTS AND CONSUMABLES, ITEMS 1-5.

Item	**6**	**7**	**8**	**9**
Input				
Number of similar parts on vessel	1	1	1	2
Mean time before replacement	243	183	183	183
Cost of spare part	100,00	5 162,00	953,00	3 635,00
Average cost of ordering a spare part	90 %	90 %	90 %	90 %
Average cost of holding a spare part	35 %	35 %	35 %	35 %
Procurement lead time	28	28	28	28
Probability of having enough spares during procurement lead time	95 %	95 %	95 %	95 %
Output				
Yearly spare part demand	1,50	2,00	2,00	4,00
Procurement lead time demand	0,12	0,15	0,15	0,31
Average yearly cost of spare parts	355,39	23229,00	4288,50	31442,75
Economic order quantity	3	3	3	5
Average number of orders per year	0,50	0,67	0,67	0,80

Average number of days between orders	729	547,5	547,5	456,25
Order point	1	1	1	1
Safety level	1	1	1	1

TABLE 14: DECISIONS FOR OPERATIONAL SPARE PARTS AND CONSUMABLES, ITEMS 6-9.

Item	**10**	**11**	**12**	**13**
Input				
Number of similar parts on vessel	2	2	1	1
Mean time before replacement	365	365	183	183
Cost of spare part	561,00	143,00	442,00	767,00
Average cost of ordering a spare part	90 %	90 %	90 %	90 %
Average cost of holding a spare part	35 %	35 %	35 %	35 %
Procurement lead time	28	28	28	28
Probability of having enough spares during procurement lead time	95 %	95 %	95 %	95 %
Output				
Yearly spare part demand	2,00	2,00	2,00	2,00
Procurement lead time demand	0,15	0,15	0,15	0,15
Average yearly cost of spare parts	2524,50	643,50	1989,00	3451,50
Economic order quantity	3	3	3	3
Average number of orders per year	0,67	0,67	0,67	0,67
Average number of days between orders	547,5	547,5	547,5	547,5
Order point	1	1	1	1
Safety level	1	1	1	1

TABLE 15: DECISIONS FOR OPERATIONAL SPARE PARTS AND CONSUMABLES, ITEMS 10-13.

8.4 – COMMENTS TO THE RESULTS

The most important thing to notice about the optimal decisions for the operational spare parts and consumables, is the fact that the economic order quantity exceeds the yearly spare part demand for all of the components. This means that for each item, less than one order is placed each year, and spare parts will be stored for over one year before they are used.

This is because of the high cost of ordering compared to the cost of holding. If this vessel was operating for example in the North Sea, close to the manufacturer that delivers the spare parts, the order quantity would be lower, and the amount of orders each year would of course increase.

In other words, the advice is to keep a higher maximum stock of operational spare parts and consumables in Brazil than in countries with a lower cost of ordering. It should be noted that the time value of money has been included in the cost of capital tied up, along with a conservative depreciation rate for the spare parts, so with the given input data, the grounds for making the decisions are considered strong.

9 – CONCLUSION

The main objective of spare parts management is to find the optimal numbers, types and locations for spare parts needed to perform the desired tasks with as high uptime as possible. In effect, to have spare parts available when they are needed, but to avoid stocking spare parts that are not needed.

At the heart of the proposed spare parts management philosophy lie fleet orientation, formalization, and scientific methods. It is the belief of this thesis that a fleet-oriented philosophy can facilitate the exploitation of economies of scale for the DOF Group. This opportunity can be exploited directly for capital spare parts, by covering multiple similar vessels in a region with one stock of capital spare parts. Indirectly, it can be exploited by sharing experience and knowledge across the fleet in a more structured way, and use scientific methods based on the shared experience and knowledge to make better decisions, less dependent on the individual in charge.

The proposed philosophy and methods were used to evaluate spare part decisions for the offshore crane on Skandi Salvador. The optimal decisions found by using the decision tool for capital spare parts were clearly to purchase all the capital spare parts on the list of recommended spare parts, even when using significantly lower delivery times than those estimated by the manufacturer. When comparing the decisions with the decisions taken by the DOF Group at the time of delivery of the vessel, it was found that the company had decided to purchase a lot less capital spare parts than what was found to be optimal.

The conclusion from this is firstly, that the company should invest in the rest of the capital spare parts on the list now. Secondly, it is concluded from this that the DOF Group can clearly benefit from using the proposed philosophy and scientific decision tools for spare parts management, in order to make better decisions. Rather than setting an initial budget for spare parts, and then purchasing the spare parts deemed most important and affordable within the budget, the budget should be set after the evaluation has been done, also considering the expected cost of downtime. The result will be a higher working capital need, but also a higher profit over time.

The proposed philosophy and methods were also utilized for the operational spare parts and consumables for the offshore crane. It was clearly demonstrated that the proposed method takes all parameters into consideration in a way that a human being is unable to do directly in his/her head, just using experience. The decision tool showed that when working in Brazil, or other regions with higher costs of ordering, a higher average spare part stock should be held, and less and larger orders should be made over time.

10 – FURTHER WORK

There are many areas of interest related to this thesis that could be further investigated and developed.

First of all, all aspects of condition monitoring related to spare parts management could be considered. Making condition monitoring a part of the proposed work process for spare part evaluation could possibly increase the quality of the decisions, but would also increase the complexity of the tasks performed by the actors responsible.

It could be investigated if algorithms for opportunity based maintenance could be used to optimize large and complex maintenance jobs for construction support vessels, since these are vessels designed to operate offshore for long periods of time and sometimes also have extensive commissioning periods in harbor. It could be further investigated how this could be implemented in the proposed philosophy for spare parts management.

For the proposed decision tool for capital spare parts, presented in chapter 7, there are three points of interest that was chosen to be neglected, that would have changed the decision tool, and might have changed the output from using the tool. It would be interesting to evaluate how these points could be implemented in the decision model.

- Other types of fault distributions than the chosen exponential distribution.
- Aspects related to the loss of dayrate insurance.
- Condition monitoring.

In order to increase the value and user-friendliness of the decision tool for capital spares two support functions in could be included:

- Confidence interval calculator, to set the limits of the sensitivity analyses.
- System MTTF calculator for parts that are connected in parallel or series, where only the MTTF of the part is known.

Both of these functions offer important output to be used in the investment decision tool. They also require a high competence level in statistics and systems engineering, if such calculators are not available, and could therefore increase the usability of the tool. The users of the tool will not always have this competence, and even for users that have it, it is a time consuming endeavor.

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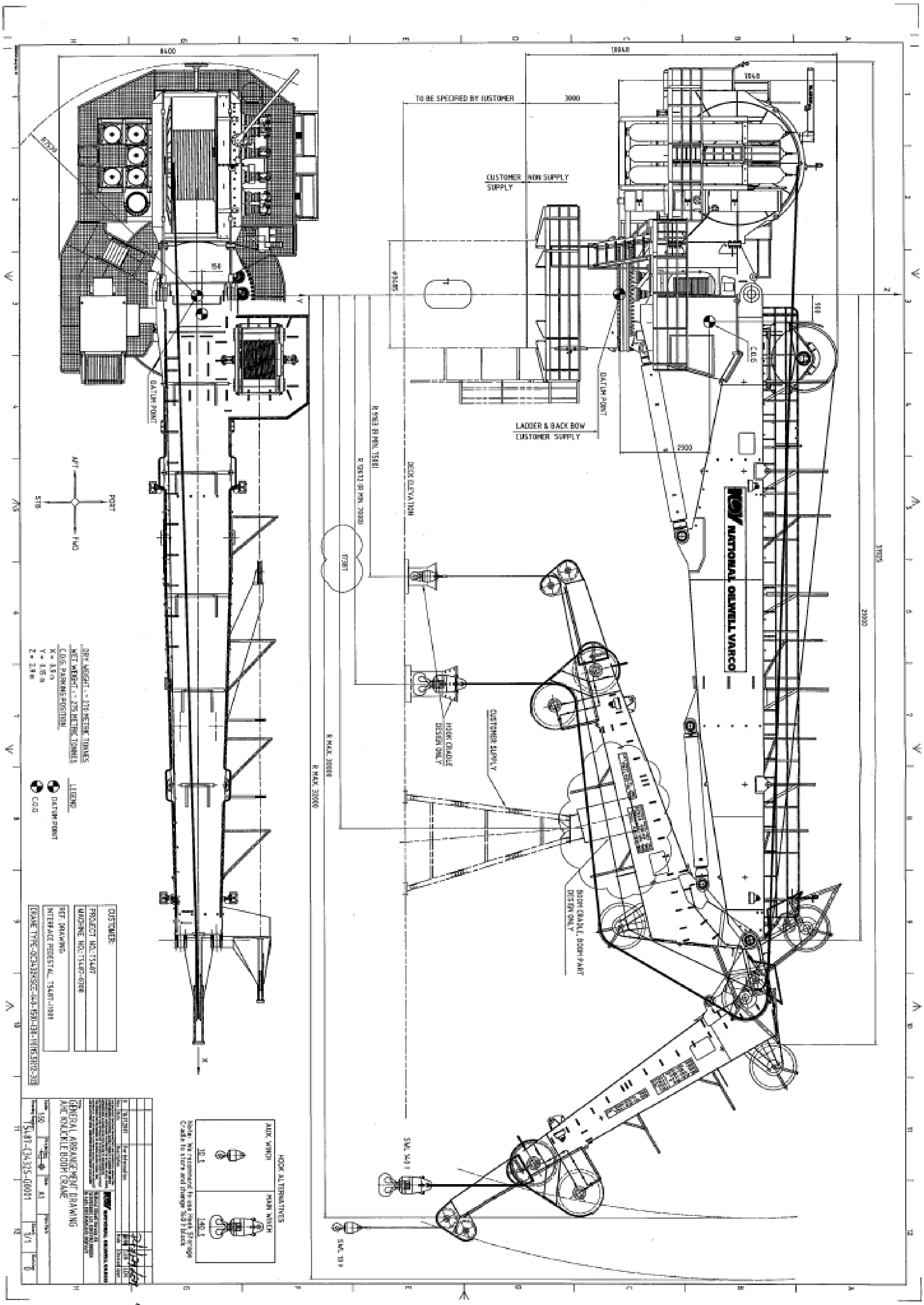
APPENDIX I – NOV 140 T AHC CRANE, GENERAL ARRANGEMENT



APPENDIX II – NORSOK Z-008, ESTABLISHING MAINTENANCE PROGRAM

8 Maintenance programme

8.1 General

The purpose of a maintenance program is to control all risks associated with degradation of equipment. Maintenance includes e.g. calendar based activities, inspection, condition monitoring and testing. The program shall include activities and maintenance intervals per equipment. The classical way of establishing a maintenance programme is using RCM analysis, see IEC 60300-3-11. However, this NORSOK standard calls for using GMCs in combination with more detailed RCM methods. The generic concepts are considered an efficient way of capturing company knowledge for traditional technology where the maintenance tasks can be standardized. It is important that the generic concepts are adjusted to local operational conditions as well as the local risks associated with the plant in question.

8.2 Work flow for establishing preventive maintenance (PM) programme for new plants

The work flow for establishment of maintenance programme for new plants is described stepwise below and illustrated in Figure 3.

No	Step	Activity
1	Grouping and classification	Input to the process is the technical hierarchy and a functional grouping and functional classification of the plant in question. See Clause 8.
2	Safety functions	If the equipment is defined as a safety function, there should exist a Performance Standard and a safety requirement specification defining basic requirements including testing frequency for hidden failures. For safety functions with given availability requirements, there exists models for how to estimate testing time, see OLF 070 or IEC 61508. Further, for many safety systems there will exist additional maintenance tasks to be done like cleaning, lubrication, etc. which should be described in generic concepts for this equipment group. These data and tasks are then input to the PM programme.
3	Generic concepts	The next step in the process is to determine if there exist generic concepts for the equipment. If that is the case, the applicability and relevance of the concept should be checked as well as if there exist specific PM requirements from authority or company.
4	Adjustment of GMCs	The generic concepts should be evaluated for the actual case considering the production value of the plant (deferred production) and repair capacity (man-power, spares and tools) at hand to handle the most common failures. Any local adjustments should be in addition to the generic concept.
5	Risk analysis/ Assignment of maintenance activities	In case no GMC is applicable or the purpose of the study requires more in-depth evaluations, it is recommended that an RCM/RBI/SIL analysis is carried out according to IEC 60300-3-11 and DNV RP- G-101. Identification of relevant failure modes and estimation of failure probability should primarily be based on operational experience of the actual equipment, and alternatively on generic failure data from similar operations. Again, the task will involve both safety assessment and cost benefit to determine the maintenance tasks, as well as including authority/company requirements. See 9.3 for unsafe failure modes.
	Cost benefit analysis	Defining intervals are to a large extent based on engineering judgement The engineering judgement should be based on a form of cost-benefit assessment including the following factors: • consequences of function or sub-function failures and functional redundancy; • probability of function or sub-function failures and its function of time or frequency of PM activities; • detectability of failure and failure mechanisms, including the time available to make necessary mitigating actions to avoid critical function or sub-function failure; • cost of alternative preventive activities.
6	Developing	The above RCM/RBI/SIL analysis can be transformed to a GMC for later use on

No	Step	Activity
	generic maintenance concepts	similar equipment. Additional experience related to use of the concepts should be included.
7	Low consequence items	For equipments classified with low consequence of failure, a planned corrective maintenance strategy may be selected (run to failure). However, a minimum set of activities to prolong lifetime may also be considered. See 9.3 for unsafe failure modes.
8	Establish maintenance programme	Finally, all the maintenance tasks should be packed and scheduled considering plant production plans, resources requirements, turnaround schedule, etc to derive to the final maintenance plan.

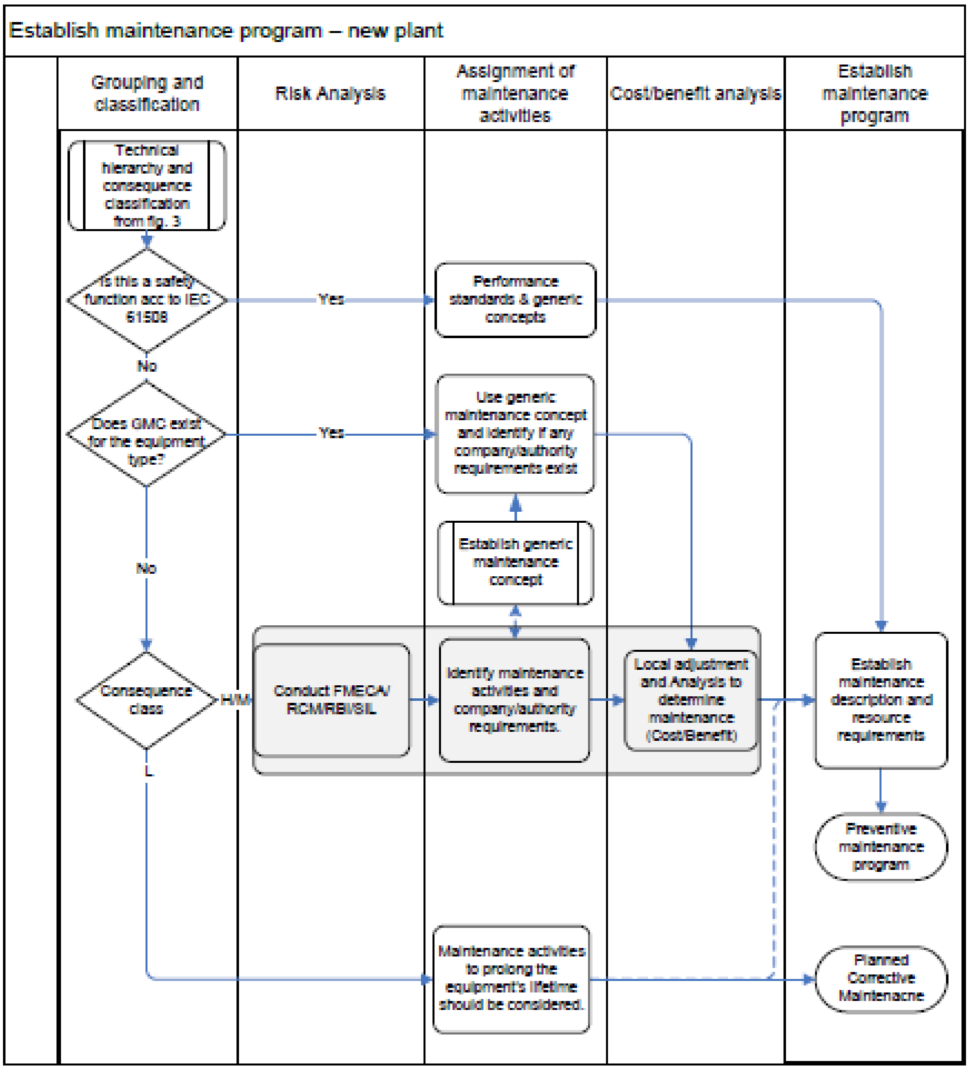
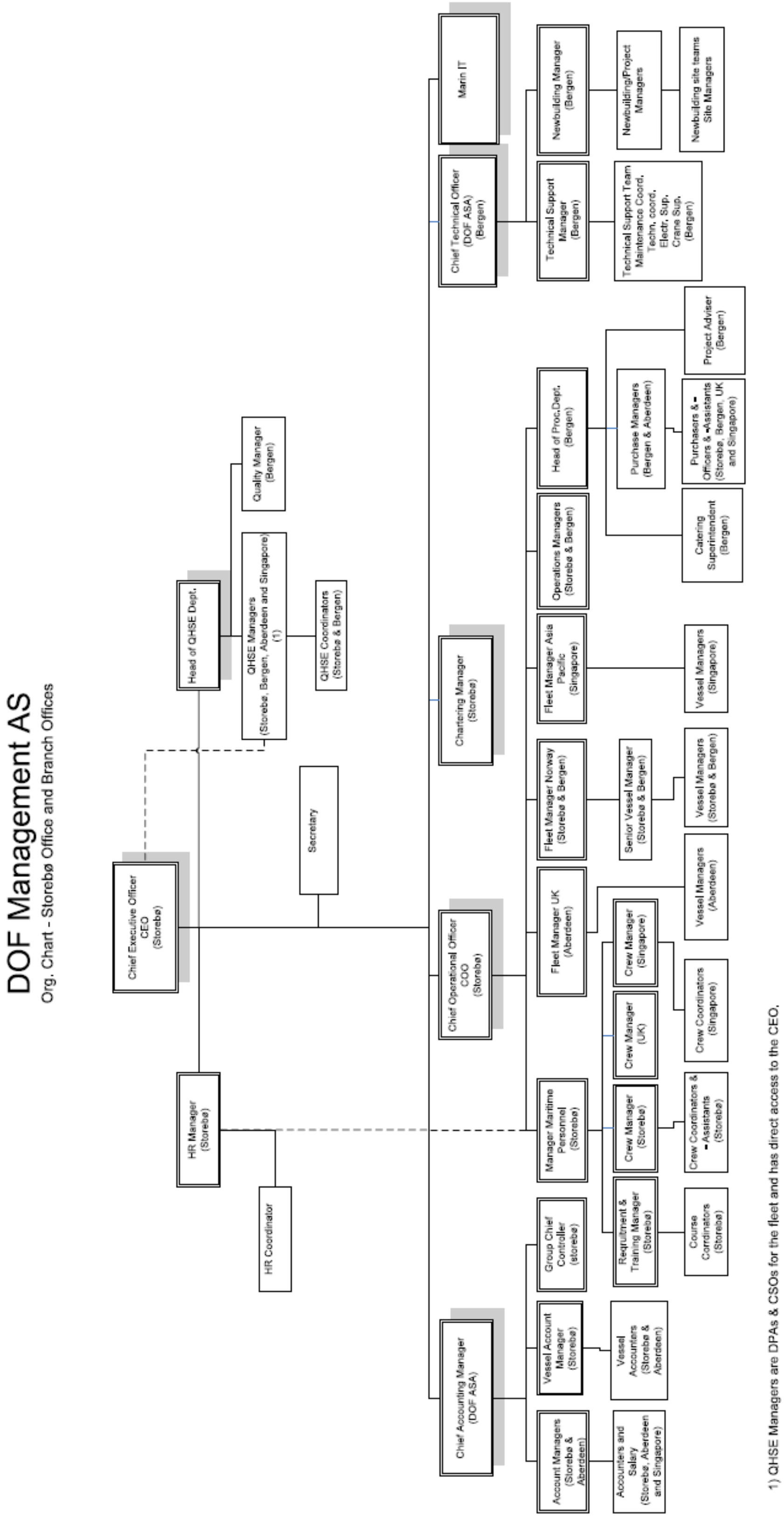
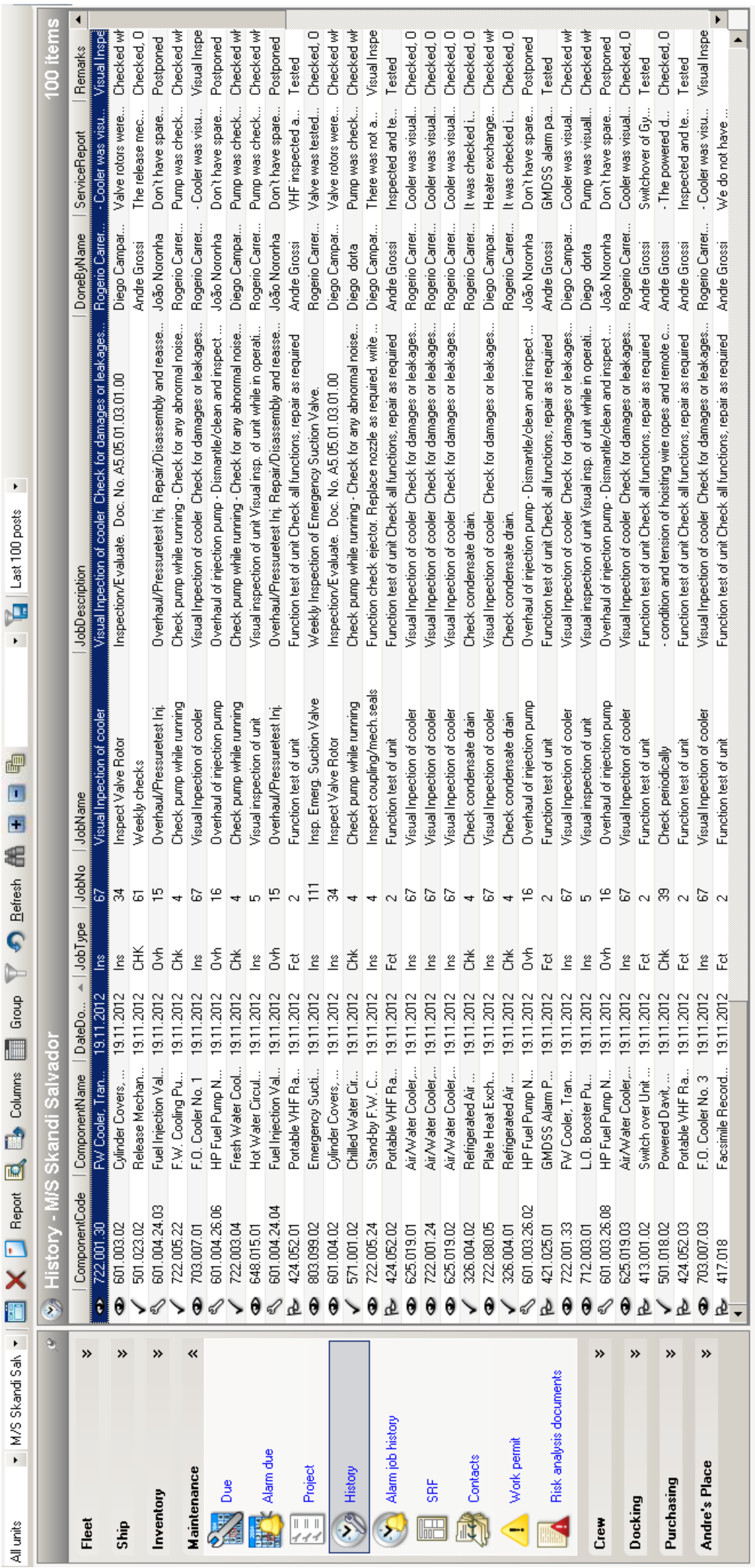


Figure 3 – Establishing maintenance programme for new plants

APPENDIX III – DOF MANAGEMENT AS ORGANIZATION CHART

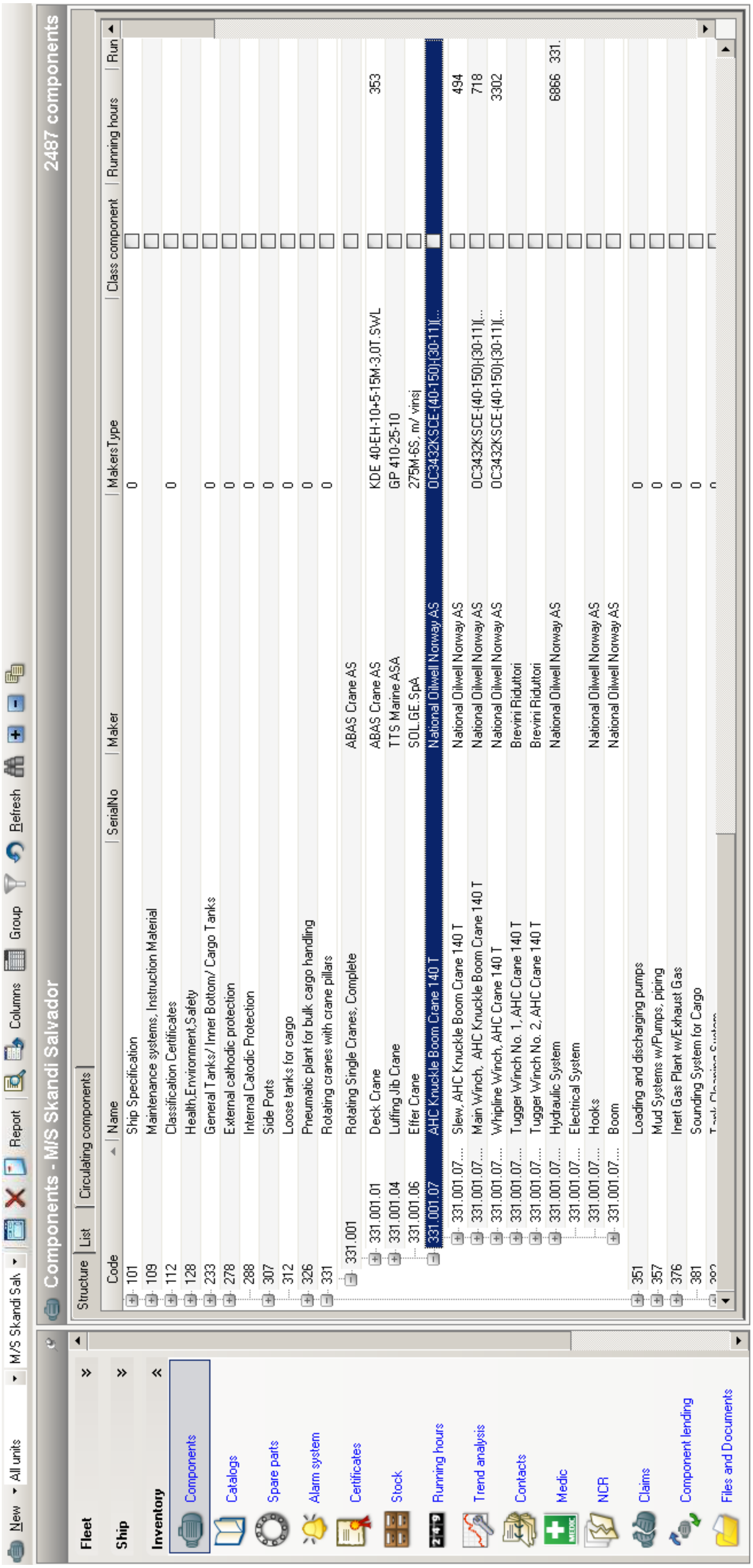


APPENDIX IV – MAINTENANCE HISTORY SCREENSHOT, TMV2



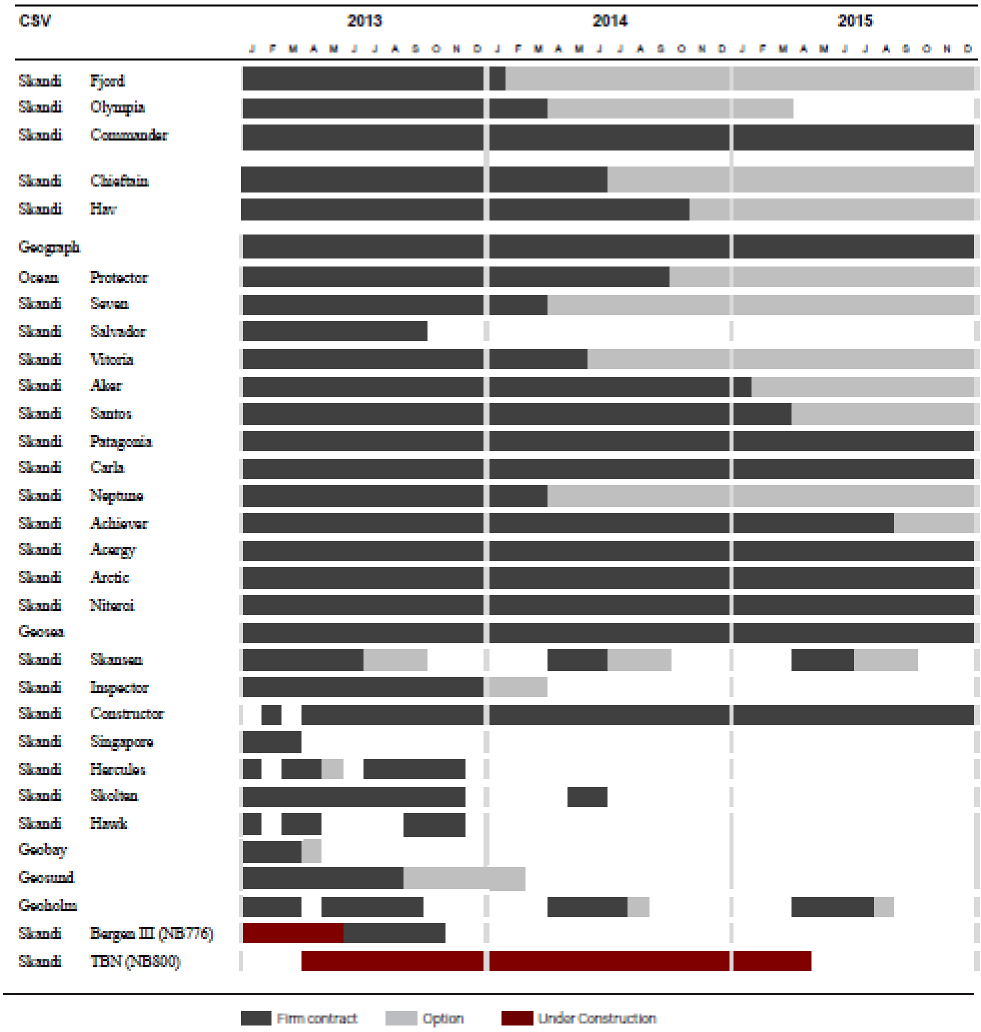
ComponentCode	ComponentName	DateDo...	JobType	JobNo	JobName	JobDescription	DoneByName	ServiceReport	Remarks
722.001.30	FW Cooler, Tran...	19.11.2012	Ins	67	Visual Inpection of cooler	Visual Inpection of cooler Check for damages or leakages...	Rogerio Carrer...	- Cooler was visu...	Visual Inspe
601.003.02	Cylinder Covers, ...	19.11.2012	Ins	34	Inspect Valve Rotor	Inspection/Evaluate. Doc. No. A5.05.01.03.01.00	Diego Campar...	Valve rotors were...	Checked wh
501.023.02	Release Mechan...	19.11.2012	CHK	61	Weekly checks		Andre Grossi	The release mec...	Checked, O
601.004.24.03	Fuel Injection Val...	19.11.2012	Ovh	15	Overhaul/Pressuretest Inj.	Overhaul/Pressuretest Inj. Repair/Disassembly and reasse...	João Noronha	Don't have spare...	Postponed
722.005.22	F.W. Cooling Pu...	19.11.2012	Chk	4	Check pump while running	Check pump while running - Check for any abnormal noise...	Rogerio Carrer...	Pump was check...	Checked wh
703.007.01	F.O. Cooler No. 1	19.11.2012	Ins	67	Visual Inpection of cooler	Visual Inpection of cooler Check for damages or leakages...	Rogerio Carrer...	- Cooler was visu...	Visual Inspe
601.004.26.06	HP Fuel Pump N...	19.11.2012	Ovh	16	Overhaul of injection pump	Overhaul of injection pump - Dismantle/clean and inspect ...	João Noronha	Don't have spare...	Postponed
722.003.04	Fresh Water Cool...	19.11.2012	Chk	4	Check pump while running	Check pump while running - Check for any abnormal noise...	Diego Campar...	Pump was check...	Checked wh
648.015.01	Hot Water Circul...	19.11.2012	Ins	5	Visual inspection of unit	Visual inspection of unit Visual insp. of unit while in operati...	Rogerio Carrer...	Pump was check...	Checked wh
601.004.24.04	Fuel Injection Val...	19.11.2012	Ovh	15	Overhaul/Pressuretest Inj.	Overhaul/Pressuretest Inj. Repair/Disassembly and reasse...	João Noronha	Don't have spare...	Postponed
424.052.01	Portable VHF Ra...	19.11.2012	Fct	2	Function test of unit	Function test of unit Check all functions, repair as required	Andre Grossi	VHF inspected a...	Tested
803.099.02	Emergency Sucti...	19.11.2012	Ins	111	Insp. Emerg. Suction Valve	Weekly Inspection of Emergency Suction Valve.	Rogerio Carrer...	Valve was tested...	Checked, O
601.004.02	Cylinder Covers, ...	19.11.2012	Ins	34	Inspect Valve Rotor	Inspection/Evaluate. Doc. No. A5.05.01.03.01.00	Diego Campar...	Valve rotors were...	Checked wh
571.001.02	Chilled Water Cir...	19.11.2012	Chk	4	Check pump while running	Check pump while running - Check for any abnormal noise...	Diego dorta	Pump was check...	Checked wh
722.005.24	Stand-by F.W. C...	19.11.2012	Ins	4	Inspect coupling/mech.seals	Function check ejector. Replace nozzle as required. write ...	Diego Campar...	There was not a...	Visual Inspe
424.052.02	Portable VHF Ra...	19.11.2012	Fct	2	Function test of unit	Function test of unit Check all functions, repair as required	Andre Grossi	Inspected and te...	Tested
625.019.01	Air/Water Cooler,...	19.11.2012	Ins	67	Visual Inpection of cooler	Visual Inpection of cooler Check for damages or leakages...	Rogerio Carrer...	Cooler was visual...	Checked, O
722.001.24	Air/Water Cooler,...	19.11.2012	Ins	67	Visual Inpection of cooler	Visual Inpection of cooler Check for damages or leakages...	Rogerio Carrer...	Cooler was visual...	Checked, O
625.019.02	Air/Water Cooler,...	19.11.2012	Ins	67	Visual Inpection of cooler	Visual Inpection of cooler Check for damages or leakages...	Rogerio Carrer...	Cooler was visual...	Checked, O
326.004.02	Refrigerated Air ...	19.11.2012	Chk	4	Check condensate drain	Check condensate drain.	Rogerio Carrer...	It was checked i...	Checked, O
722.080.05	Plate Heat Exch...	19.11.2012	Ins	67	Visual Inpection of cooler	Visual Inpection of cooler Check for damages or leakages...	Diego Campar...	Heater exchange...	Checked wh
326.004.01	Refrigerated Air ...	19.11.2012	Chk	4	Check condensate drain	Check condensate drain.	Rogerio Carrer...	It was checked i...	Checked, O
601.003.26.02	HP Fuel Pump N...	19.11.2012	Ovh	16	Overhaul of injection pump	Overhaul of injection pump - Dismantle/clean and inspect ...	João Noronha	Don't have spare...	Postponed
421.025.01	GMDSS Alarm P...	19.11.2012	Fct	2	Function test of unit	Function test of unit Check all functions, repair as required	Andre Grossi	GMDSS alarm pa...	Tested
722.001.33	FW Cooler, Tran...	19.11.2012	Ins	67	Visual Inpection of cooler	Visual Inpection of cooler Check for damages or leakages...	Diego Campar...	Cooler was visual...	Checked wh
712.003.01	L.O. Booster Pu...	19.11.2012	Ins	5	Visual inspection of unit	Visual inspection of unit Visual insp. of unit while in operati...	Diego dorta	Pump was visuall...	Checked wh
601.003.26.08	HP Fuel Pump N...	19.11.2012	Ovh	16	Overhaul of injection pump	Overhaul of injection pump - Dismantle/clean and inspect ...	João Noronha	Don't have spare...	Postponed
625.019.03	Air/Water Cooler,...	19.11.2012	Ins	67	Visual Inpection of cooler	Visual Inpection of cooler Check for damages or leakages...	Rogerio Carrer...	Cooler was visual...	Checked, O
413.001.02	Switch over Unit ...	19.11.2012	Fct	2	Function test of unit	Function test of unit Check all functions, repair as required	Andre Grossi	Switchover of Gy...	Tested
501.018.02	Powered Davit, ...	19.11.2012	Chk	39	Check periodically	- condition and tension of hoisting wire ropes and remote c...	Andre Grossi	- The powered d...	Checked, O
424.052.03	Portable VHF Ra...	19.11.2012	Fct	2	Function test of unit	Function test of unit Check all functions, repair as required	Andre Grossi	Inspected and te...	Tested
703.007.03	F.O. Cooler No. 3	19.11.2012	Ins	67	Visual Inpection of cooler	Visual Inpection of cooler Check for damages or leakages...	Rogerio Carrer...	- Cooler was visu...	Visual Inspe
417.018	Facsimile Record...	19.11.2012	Fct	2	Function test of unit	Function test of unit Check all functions, repair as required	Andre Grossi	We do not have ...	

APPENDIX V – INVENTORY COMPONENTS SCREENSHOT, TMV2



APPENDIX VI – CSV CONTRACT COVERAGE

CSV CONTRACT COVERAGE



APPENDIX VII – GLOBAL RISK ASSESSMENT WORK SHEET

Global Risk Assessment Worksheet

DOF

RISK Event Potential Matrix

							Likelihood (Probability)				
							< Low (1)	Low (2)	Medium (3)	>Medium (4)	High (5)
Severity (Consequence)		Injury / Ill Health	Environmental (any incident that....)	Company Integrity	Assets and Operations	Financial	Not credible i.e. the team have never heard of event occurring in industry	Conceivable but would require multiple failures of systems and controls	Less than average i.e. easy to postulate a scenario for accident but considered unlikely	More than average i.e. the team do not have direct knowledge but are aware a similar event has occurred and represents a credible scenario	Likely to occur and the team have direct knowledge of a similar event
	Low (1) Injury is not credible	Negligible, No treatment , not required to visit medical personnel / first Aiders	Presents no harm to the environment and requires minor corrective actions	Loss	Minor damage to asset / equipment not requiring immediate repair - undertaken outside of project Operations / Project Program continuity (no delay)	<$10,000	1	2	3	4	5
	Low (2) Only a minor injury is credible	Injury/ slight health effect which requires a one off visit to a medically qualified person. (FAI)	Presents limited harm to the environment and requires minor corrective actions	Minor Loss	Localised damage to equipment requiring onsite repair. Parts and services available or sent to site. Operations / Project program delayed(<2 days)	$10,000 - $250,000	2	4	6	8	10
	Medium (3) A single serious injury is credible	Single Serious injury with the prospect of complete recovery – MTI, RDI,,	Presents limited harm to the environment and requires general experience and resources for correction	Moderate Loss	Localised damage to assets requiring specialist repair service (onsite) and equipment. Operations / Project programs delayed (2-7 days)	$250,000 - $500,000	3	6	9	12	15
	Medium (4) Fatality or multiple serious injury is credible	Single fatality / life threatening / serious health effects or permanent disablement through work injury or occupational illness or disease LTI	Potentially harms or adversely effects the environment. Requires specialist expertise or resources for correction	Significant Damage Loss	Major damage to asset / equipment requiring specialist repair service and facilities. Operations / Project programs delayed > 7 days	$500,000 - $2,000,000	4	8	12	16	20
	High (5) Multiple fatality is credible	More than one fatality or more than one permanent disabling injuries, occupational illnesses and/or diseases.	Potentially harms or adversely affects the environment and has the potential for widespread public concern implicating DOF operations.	Serious economic liability on the business. Major Loss	Extensive Damage / Loss of Asset / equipment requiring long term repair or asset write off. Operations / Project activities terminated	>$2,000,000	5	10	15	20	25

Risk Priority Code:

1- 6	**Overall Risk Rating : Low** May be acceptable, however, review task to see if risk can be reduced further
7 – 14	**Overall Risk Rating : Medium** Task should only proceed with appropriate management authorisation after consultation with specialist personnel and assessment team. Where possible, the task should be redefined to take account of the hazards involved or the risk should be reduced further prior to task commencement.
15 – 25	**Overall Risk Rating : High** The task must not proceed. It should be redefined or further control measures put in place to reduce risk. The controls should be re-assessed for adequacy prior to task commencement.

*Currency is in US $

APPENDIX VIII – STAGES OF RISK MANAGEMENT