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MASTER'S THESIS

RCM based Framework for Maintenance Strategy for more efficient, reliable, and effective Crane Operations.

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Abstract

The Maritime Industry is a vast, complex, and still growing business in the world. Although the focus of the Maritime sector has been very much towards digitalization and de/carbonization, old issues such as maintenance management have not yet reached its optimality. Often maintenance plans are established from the manufacturer's recommendations, but it does not necessarily prevent critical functional failures to happen. Consequently, operational costs increase, as well as the risk for accidents to happen.

This thesis aims to apply the Reliability Centered Maintenance (RCM) approach as a framework for the maintenance strategy of JIB cranes. Many maritime units such as platform rigs, construction vessels, and bulk carrier ships use cranes on its daily activities and the non-availability of this asset results in downtimes that represent a considerable loss of money. The RCM method has been successfully used by other industries such as Aerospace, Nuclear Plants, and Oil & Gas. The RCM, if correctly applied, can result in higher maintenance effectiveness, more reliable and safer operations.

Through a detailed study of the crane system, historical reports, meetings, and interviews, failure modes of the crane will be identified and registered on an FMECA worksheet. Thus, the failure modes will be ranked though its significance generating an RPN number for each failure mode concerning operation and safety. The next step of the process is to analyze the failure modes with the highest RPN through the RCM Decision Diagram. The expected result is to identify tasks that can reduce the probability of those failures modes to happen or to minimize the effect of its consequences.

Due to the short amount of time, the RCM will be applied only to the function hoisting of the JIB crane. Further recommended actions are to implement the proposed tasks to the existent maintenance plan in force, as well as the application of the RCM to the sub-system luffing, slewing, control and structure so the whole crane system can benefit from this maintenance framework strategy.

Sammendrag

Den maritime industrien er en stor, kompleks og stadig voksende næringen i verden. Selv om den maritime næringen har fokusert mest på digitalisering og dekarbonisering, har gamle saker som for eksempel, vedlikeholdsstyring ikke nådd sin optimalitet. Vedlikeholdsplaner er ofte utarbeidet basert på produsentens anbefaling, men ikke nødvendigvis nok for å hindre kritiske funksjonsfeil. Følgelig, øker driftskostnadene, samt risiko for at ullyker kommer til å skje.

Denne oppgaven tar sikte på å anvende tilnærming til Pålitelighetsstyrt Vedlikehold (RCM) som et rammeverk for vedlikeholdsstrategien til JIB kraner. Mange maritime enheter som plattformrigger, konstruksjonsskip og bulkbåter bruker kraner til sine daglige aktiviteter, og manglende tilgjengelighet av denne resursen resulterer i nedetid som representerer et betydelig tap av penger. RCM-metoden har blitt velykket brukt av andre næringer som luftfart, atomkraftverk og olje og gass. RCM, hvis den brukes riktig, kan resultere i høyere vedlikeholdseffektivitet, bedre pålitelighet og sikrere operasjoner.

Gjennom en detaljert studie av kransystemet, historiske rapporter, møter, og intervjuer, vil feilmodusene til kranen bli identifisert og registrert på et FMECA regneark. Dermed vil feilmodusene rangeres om dens betydning genererer et risikoprioriteringsnummer (RPN) for hver feilmodus angående drift og sikkerhet. Det neste trinnet i prosessen er å analysere feilmodusene med høyest RPN gjennom RCM-beslutningsdiagrammet. Det forventede resultatet er å identifisere vedlikeholdstiltak som kan redusere sannsynligheten for at disse feilmodiene skal skje eller for å minimere effekten av konsekvensene.

På grunn av den korte tiden, vil RCM kun bli brukt til funksjonen heising av JIB kranen. Ytterligere anbefalte tiltak er å implementere de foreslåtte oppgavene til den gjeldende vedlikeholdsplanen, samt anvendelsen av RCM på delsystemets *luffing*, sving, kontroll og struktur, slik at hele kransystemet kan dra nytte av denne vedlikeholdsrammestrategien.

Preface

It has never been easy to apply theory to practice. It becomes even more complicated when the industry subject to study is so unpredictable, demanding, and complex, such as the Maritime Industry. Regardless the difficulties on the way, my strong desire to contribute to more safe and cost-effective Maritime Operations has driven me to try to apply the RCM approach, already successful and well established in high-reliability organizations such as Aerospace and Nuclear Plants, at JIB cranes on board worldwide sailing Bulk-carrier vessels.

This thesis is part of the Maritime Operation Master Program at the Western Norway University of Applied Sciences in Haugesund, Norway. It is written with the collaboration of the Shipping Company Grieg Star. A special thanks go to Roar Fanebust, Head of Vessel Specialists at Grieg Star. I am very thankful for the almost three months that I could join the Grieg Star office to ask as many questions it was necessary, for the meetings, for the material that was shared with me, and for the opportunity to visit the Vessel Star Luster during her call in the Port of Antwerp. Other thanks to the whole team of Vessel Managers at Grieg Star for their patience at discussing the diverse failure modes and for sharing their knowledge with me!

I also would like to express my thanks for all the assistance from my Internal supervisor, Prof.Dr. Ajit Kumar Verma, for discussing with me the RCM process and encouraging me to proceed in search of results. Finally, thanks to my family and friends for their support and motivation all the way.

Paloma Menino Drønen

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Definitions and abbreviations

Age—A measure of exposure to stress computed from the moment an item or component enters service when new or re-enters service after a task designed to restore its initial capability, and can be measured in terms of calendar time, running time, distance traveled duty cycles or units of output or throughput (SAE 1011, 1999).

Appropriate Task—A task that is both technically feasible and worth doing (applicable and effective) (SAE 1011, 1999).

CMMS – Computerized maintenance management system.

Desired Performance—The level of performance desired by the owner or user of a physical asset or system (SAE 1011, 1999).

Environmental Consequences—A failure mode or multiple failures has environmental consequences if it could breach any corporate, municipal, regional, national, or international environmental standard or regulation which applies to the physical asset or system under consideration (SAE 1011, 1999).

Failure Consequences—The way(s) in which the effects of a failure mode or a multiple failure matter (evidence of failure, impact on safety, the environment, operational capability, direct, and indirect repair costs) (SAE 1011, 1999).

Failure Effect—What happens when a failure mode occurs (SAE 1011, 1999).

Failure Mode—A single event, which causes functional failure (SAE 1011, 1999).

Function—What the owner or user of a physical asset or system wants it to do (SAE 1011, 1999).

Functional Failure—A state in which a physical asset or system is unable to perform a specific function to a desired level of performance (SAE 1011, 1999).

Hidden Failure—A failure mode whose effects do not become apparent to the operating crew under normal circumstances if the failure mode occurs on its own (SAE 1011, 1999).

MTBF – Mean time between failures.

Operating Context—The circumstances in which a physical asset or system is expected to operate (SAE 1011, 1999).

P-F Interval—The interval between the point at which a potential failure becomes detectable and the point at which it degrades into a functional failure (also known as "failure development period" and "lead time to failure") (SAE 1011, 1999).

Plant – set of systems that function together to provide some sort of output (Rausand, 1998, p. 123).

Potential Failure—An identifiable condition that indicates that a functional failure is either about to occur or is in the process of occurring (SAE 1011, 1999).

Run-to-Failure—A failure management policy that permits a specific failure mode to occur without any attempt to anticipate or prevent it (SAE 1011, 1999).

User—A person or organization that operates an asset or system and may either suffer or be held accountable for the consequences of a failure mode of that system (SAE 1011, 1999).

RCM—Reliability-Centered Maintenance (SAE 1011, 1999).

Running rigging - refers to all ropes passing over rope sheaves or guide rolls or wound on winches, irrespective of whether or not the ropes are moved under load (DNV, 2016).

Standing rigging - refers to all wire ropes which are not turned round or wound on to winches, such as shrouds, stays, pendants, etc. Standing rigging shall be fitted with thimbles or rope sockets(DNV, 2016).

RPN – Risk priority number.

System – set of sub-systems that perform a main function in the plant. (Rausand, 1998, p. 123).

1 Introduction

1.1 Background

Maintenance plans are typically based on manufactures recommendations and regulations that guide the industry (Rausand, 1998). For this reason, companies many times end up with too many maintenance tasks, either because they are carried more often than necessary, or because it recommends replacement of resources that still have a good condition. The author has been sailing for almost six years in different types of vessels have also experience that, assets that before invasive maintenance, had a good and stable condition, started to show problems after overhauling.

RCM is a maintenance philosophy that has been used in the aviation industry since the '70s. It focuses on the system functions and aims for that the components continue "to do whatever its users want it to do," instead of focusing on the general condition of it (Moubray, 1997, p.21). The RCM requires a deep understanding of the system functions and how failures of components influence safety, environment, and operation. The RCM seeks more cost-effective maintenance costs, removing unnecessary maintenance actions (Rausand, 1998), more excellent safety and environmental integrity, and higher availability of the assets (Moubray, 1997).

Crane has been the asset chosen as the subject of study because it is an essential equipment present in most maritime segments. Furthermore, failures of such equipment can result in considerable economic losses, safety, and sometimes environmental incidents.

Grieg Star is a Ship and Operating company located with its headquarters in Bergen. It manages approximately 40 open hatch and dry bulk carrier vessels. Grieg Star is a company committed to environmental issues, and that has as a goal to be in total compliance with all applicable international agreements and regulations (Grieg Star). The newest class of vessels is Open Hatch Vessels, L-class equipped with electrical slewing cranes instead of the traditional hydraulic gantry cranes. The GLE crane has the particularity of being an electrical crane, differently of a typical hydraulic crane that uses approximately 700l of oil. For having a reduced carbon footprint, the GLE seems to be a tendency in the maritime industry, which has been continuously looking for the replacement of fossil fuels by renewable energy.

1.2 Objective

The research question that serves as the basis for this Master thesis is "How Reliability Centered Maintenance framework for maintenance strategy can contribute to a more efficient, reliable, and cost/effective crane operation?". Following the RCM steps, it aims for identifying failure modes that put in risk the safety of the operation according to the operating context to be described and select maintenance tasks that can reduce the possibility of those failures to happen. The proposed tasks will be recommended to the cooperating company to be included in their current maintenance plan.

1.3 Scope and limitations

Due to the limitation of resources and time, the analysis of the crane system will be limited to the sub-system correspondent to the function hoisting. It will focus on the mechanical failure modes once the GLE crane has a sophisticated automation system that would require a much longer time to be studied and understood.

Another limitation is the lack of quantitative data such as P-F interval and MTBF. Maintenance intervals will then be based on the opinion of the experienced professionals with whom the author will have meetings and carry out interviews in the course of the thesis.

1.4 Structure of the thesis

Chapter 2 is the theoretical background and starts with a brief history of RCM. Consequently, the RCM process will be described. Still, in chapter 2, the risk indexing method for the classification of the failure modes will also be described. In chapter 3, the author will introduce the methods for gathering data, the reason why the method was chosen, the drawbacks with the methods, and what has been done to overcome the limitations. Chapter 4 is the RCM in practice, applied to a real situation, step-by-step. The results will be registered in the RCM II Decision Worksheet and a discussion about what the RCM method aims to achieve, and its limitations will take place in chapter 5. Chapter 6 brings some comments about the challenges of the RCM Process. The conclusion and recommendation for further work will be presented in chapter 7.

2 Theoretical Background

2.1 History of RCM

Reliability-Centered Maintenance was created in 1974 by United Airlines to attend a request from the United States Department of Defense. At that time, Maintenance was based on the concept that every sub-system of equipment has a 'right age' and that a periodical overhaul was necessary to ensure safety and equipment availability. However, this methodology was not being effective. Thus, a team was formed to develop a program to analyze the factors that affect reliability and how to mitigate them. The Committee came to the main conclusions:

- The scheduled overhaul has little effect on the overhaul reliability of a complex item unless the item has a dominant failure mode. »
- There are many items for which there is no effective form of Scheduled Maintenance. (Nowlan and Heap, mentioned by Moubray, 1997, p.318).

The first RCM was then published in 1978 by Nowlan and Heap. Later, three other versions of RCM were developed and became the maintenance plan of the Boeing 747, DC10, CONCORDE et Airbus A340. (Carretero et al., 2000, p.10).

Moubray (1997, p.321) also relates that as RCM improved and started to deal with environmental issues as much as safety and diminishment of maintenance costs, RCM started to be used in many other industries all over the world. A consequence of this spread and the increase on RCM popularity without criteria resulted in many organizations creating variations of the RCM process, but that not correspond to the original RCM process. From circumstance arose the necessity for a standard that could define the RCM processes and concepts. Thus, in 1999 the SAE Standard for Reliability Centered Maintenance was published with the purpose of «to evaluate any process that supports to be an RCM process, in order to determine whether it is a true RCM process. » (SAE JA 1011, 1999). The standard, however, does not define one individual process.

For the scope of this master thesis, the RCM process described by Moubray (1997) will be used to deal with the research question "How Reliability Centered Maintenance framework for maintenance strategy can contribute to a more efficient, reliable and cost/effective crane operation?"

2.2 The Concept of Reliability-Centered Maintenance (RCM)

Before digging into the concept of RCM, it can be interesting to review the definitions of Reliability and Maintenance separately. According to the Oxford dictionary, Reliability means "The quality of being trustworthy or of performing consistently well." Maintenance is defined by "the process of preserving a condition or situation or the state of being preserved" (2019, Oxford). Moubray in his studies about RCM uses those basic definitions to create the concept of Reliability-Centered Maintenance, that is: "A process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context" (Moubray, 1997, p. 7). Thus, in order to establish a maintenance strategy framework with a basis in the RCM theory, it is essential to determine what are the functions and performance that are expected from the physical asset. However, some assets have different functions according to the operating context. For example, a fire pump on board a ship can be used either to its primary function, that is to supply water to fight a fire if a casualty happens, or it can also be used to provide water to wash the deck. Both operating contexts require a particular standard performance and availability from the pump. It is assuming that the pump has a pumping rate of 50m3/h and that the flow rate is specified on the fire plan of the vessel. In the operating context of washing the deck, it could be acceptable that the pump after some years of use no longer pumps at 50m3/h, but at 40m3/h instead. Nevertheless, for the task of extinguish fire, it is most likely that if the pump is not able to provide the expected flow rate, consequently, the pump will not be able to do what the users want it to in its present operating context, that in this case is to pressurize the fire hose with pressure enough to extinguish fire.

Moubray (1997, p.7) claims that the RCM process consists of seven basic questions about the system or the component to be analyzed:

- What are the functions and associated performance standards of the asset in its present operating context?
- In what ways does it fail to fulfill its functions?
- What causes each functional failure?
- What happens when each failure occurs?
- In what way does each failure matter?

- What can be done to predict or to prevent each failure?
- What should be done if a suitable proactive task cannot be found?

Applying the RCM process requires efficient planning in order to result in the desired improvements in maintenance effectiveness. Planning the RCM process consists basically in choosing which assets will be assessed and what will be necessary to apply the process to the assets. A good understanding of the operating context is also necessary since it will define the performance that will be expected from the asset. It is also essential that a review group is formed. The seven basic questions cannot be answered only by the maintenance team, but it also requires the inputs from the operational team. According to Moubray (1997, p. 17), the review group should count with at least:

- Facilitator: a person trained in RCM that can ensure that no critical component of the system is left out of the analysis and that can ensure that all group understand the RCM process;

- One member from the maintenance team and one member from the operational team;

When the RCM review is completed, the next step is its implementation and auditing. This step will be better clarified further in this paper. However, if correctly performed, the RCM process can achieve great results. Some of these outputs are, for example, more safe and reliable operations, higher availability of the assets, a longer lifetime of expensive components, better maintenance cost-effectiveness, and better teamwork.

2.3 Definition of functions

The first action of the RCM process is to specify the function of each asset and the expected level of performance. In this phase of the process is the participation of the users of the asset. There are particularities in the asset that only the users can give their insight. According to Moubray (1997, p. 7), the functions of the assets can be divided into two categories, primary and secondary functions. The primary functions are those that justify the existence of that component in the asset. It is the main function of the component. The secondary functions are regarding the other functions that the component may fulfill, as:

1. Environmental integrity;
2. Safety / structural integrity;

3. Control / comfort;
4. Appearance;
5. Protection;
6. Economy/efficiency
7. Superfluous functions

Other authors, such as for example, Marquéz (2007, p. 139), have other classification methods, but that is similar to Moubray's method. Marquéz has divided it into five categories:

1. Primary functions: the main function of the asset that justifies it in the system;
2. Auxiliary functions: functions to assist in the primary function being fulfilled;
3. Protective and control functions: functions that intend to protect the users and the environment;
4. Information functions: related to alarms and monitoring;
5. Interface functions: when two items have a relationship between themselves, the interface function is about the active or passive functions that an item has over another one.

However, it may be taken into consideration the operating context in which an asset is being used. It is the operating context that many times determines the secondary functions of an asset and may, therefore, be well understood. The aspects that influence the operating context are, for example, quality and environmental standards, safety hazards, shift time.

2.3.1 System breakdown concept

In order to determine the function of the assets, it is vital to identify the individual elements /operations that constitute the whole process. Mohr (2002), suggests that all available drawing, charts, and descriptions diagrams are collected and analyzed. Thus, a system breakdown can be carried out either according to its functionality and its geographical/architectural location.

Creating a coding system can also contribute to establishing a coordinated relationship between the systems, sub-systems, and components. At this point, a functional block diagram is also a tool to be used to clarify which assets/assemblies constitute the system and where they are located. Moubray (1997, p. 327) defines this functional breakdown block diagram as "plant register." A challenge here is to figure out what is the most appropriate level to perform the system breakdown, including a manageable number of assemblies, subassemblies, and components in order to do not overlook key-components and potential targets.

2.4 Functional Failures

A failure is many times associated with the deterioration of an asset. Nevertheless, a functional failure can also be characterized by a decrease in performance, so the asset is not able to do what the users want it to do, although it has not yet had a complete stop. Moubray (1997, p. 47), defines functional failures as:

" The inability of any asset to fulfill a function to a standard of performance which is acceptable to the user."

Functional failures can have the following aspects:

- **Partial and total failure:** a performance outside the established limits will characterize a partial failure. A total failure means a complete breakdown.
- **Upper and lower limits:** if an asset has upper and lower performance limits established, it means a functional failure if the component works either over the upper limit or below the lower limit. For instance, different causes can make the component over or underperform.
- **Gauges and indicators:** gauges, indicators, and other control systems can stop complete to measure and display the output or can also display the wrong value. It shall also be specified when identifying a functional failure.
- **The operational context:** a functional failure can have different meanings for the users of the asset and the maintenance personnel. Performance standards are essential in order to do not lose time and take actions before the failure occurs. The best scenario is that both users and maintenance personnel can together set the performance about how the asset should behave.

2.5 Failure Modes and Effects Analysis (FMEA)

2.5.1 Failure mode

A functional failure can result from different failure modes. According to Marquéz (2007, p. 142), only failure modes with a high occurrence possibility should be listed, and not all every single possible failure. Failure modes should be specified without too many details, but with verbs that make clear what the failure mode is. If a control panel stops working, it is not clear enough to inform, for example, that the panel failed. It is necessary to inform what caused the panel to fail, was it due to a fuse failure or a wire break?

2.5.2 Failure mode categories

Moubray (1997, p. 58) claims that it is common that only failures due to deterioration usually are taken into consideration in maintenance strategy. However, in order to obtain an effective maintenance strategy, human errors and design flaws should be included in the failure mode analysis in case it represents a threat to the asset functionality. In RCM, failure mode has been classified as follows:

Falling capability	Increase in desired performance
• Deterioration	• Sustained, deliberate overloading
• Lubrication failures	• Sustained, unitentional overloading
• Dirt	• Sudden, unitentional overloading
• Disassembly	• Incorrect process material
• 'Capability reducing' human errors	

Human-errors shall be addressed in the FMEA when the cause that generated the error will be investigated and not necessarily finding someone to blame. Many safety theories analyze the relation human-machine, and that also gives many recommendations about how to improve this relationship. It is beyond the scope of this thesis to go further in detail in human errors since this theme is quite enormous.

When the failure modes are being listed, a decision to make is how far or how deep in detail it should be done. Moubray makes it very clear that failure modes should be defined in enough detail for it to be possible to select a suitable failure management policy. (1997, p. 64). Another recommendation is regarding not to list all failure possibilities in disregard with its likelihood. Preference of failure modes to be listed can be given to failures modes that have already happened, failure modes that are already subject for proactive maintenance, and failures that have not yet occurred, but that can happen.

2.5.3 Failure Effects

The next step of the RCM is the failure effect analysis. When a component is in a state of failure, it will affect the system. The nature of the effect can be either of quality, a threat to the safety or environment, signs, and alarms given by the system. Moubray (1997, p.73) and Marquéz (2007, p.143) state that when a failure effect is going to be described, the following aspects should be related:

- What signs (if any) indicate that the failure has occurred.
- Example: alarms, sounds, noises, smoke, fire;
- What hazards (if any) it represents to safety or the environment.
- Example: risk of fire or explosion, leakage, electrocution, falling objects, structural collapse.
- What effects (if any) it has in operations.
- Example: how long time will it be necessary to put the asset in operation again. It includes the whole process from identifying the failure, joining the resources to fix it (spare part, technician), repair, and tests. Financial penalties and increased operating costs that result from the failure may also be recorded.
- Physical damages (if any) result from the failure.
- Actions that are required to eliminate failure.

2.5.4 Failure Consequences

Having analyzed which effects, what means, what happens when a failure mode occurs, the consequences that a failure mode entails may also be assessed. The classification of failure mode consequences can be into four primary consequence natures:

- Safety: if it represents a risk to injury or to kill someone;
- Environmental: If it breaks environmental regulations and standards;
- Operational & Economical: when it increases direct and operational costs, as well as it implicates in no availability of the asset.

The evaluation of fail consequences is essential to identify the measures that shall be taken in order to eliminate or minimize the effects and consequences. During the evaluation, it shall also discuss whether a failure mode is hidden or evident. An evident fault is characterized by the possibility of being observable under normal operating conditions. A hidden fault is described by Moubray (1997, p.93) as 'a fault that will not become evident to the operating crew under normal circumstances if it occurs on its own.' Examples of components that are subject to suffer a hidden failure are, for example, protective devices such as sensors and level switches. A temperature sensor that is designed to stop a motor in case the temperature rises higher than the limits will not probably have its failure noticed until further damages have happened. If there is no preventive maintenance for the protective device, multiple failures can occur if the protective device fails before the protected component/system.

Moubray (1997, p. 127) suggests then that all failure modes are classified and ranked according to their consequences and whether there are evident or hidden. This rank and classification will serve as the basis for analyzing whether proactive maintenance is worth or not worth doing, or what actions shall be taken if a suitable task cannot be found.

2.6 Risk indexing for failure modes and the RCM decision diagram

2.6.1 Three-dimensional risk scoring systems and RPN

The RCM process requires a ranking of the failure modes in order to prioritize those that require the identification of an appropriate maintenance task. There are some different approaches to assess the criticality of the failure modes and to rate them (Moubray, 1997, p.289). According to Verma et al. (2016), criticality analysis can either be performed quantitatively or qualitatively depending on the data available. The quantitative method requires data such as failure rates for each failure mode. However, not always a plant will have this information available, and thus, a qualitative method becomes the best alternative (US Department of Defense, 1990).

Emanuele (2014, p.235), explains that risk indexing scoring, such as RPN (risk priority number), results from subjective assessments of the rate of the severity of the potential effects of failures and the likelihood of occurrence. The RPN (risk priority number) consists of the product of assigned values for the severity, likelihood, and, in this thesis, detection parameters. For each failure mode, values for Severity, Likelihood, and Detection are assigned to each failure mode (Manuele, 2014, p.239). Those failure modes that attain a high RPN number require further attention so actions can be taken to reduce the risk. Afterward, when the analysis is concluded, the failure modes can be classified from the highest RPN to the lowest.

RPN = Severity x Occurrence X Detection

Risk indexing allows the prioritization of failure modes to be analyzed. It is a relatively simple and efficient method, but that according to Rosenblum & Lapp (1989, p. 184), should not be the only source to support decision making. They explain that risk index and risk analysis have the same principle, but risk analysis is normally much richer in detail, time demanding, and costly than risk indexing. For the scope of this thesis, risk indexing attends the necessities to establish maintenance priorities using the severity parameters safety, environment, and economic impacts.

Traditional risk analysis techniques use a commonly two-dimensional risk matrix to represent the outcome from the relation severity x likelihood (Watson, 2011). As represented in figure 1, the risks are plotted in a matrix as a function with the severity of the consequences and the probability of occurrence (Kristiansen, 2005, p.289). However, some industries, due to the necessity of taking into consideration other factors for risk analysis, for example, exposure or detectability, have now been using three- or even four-dimensional risk scoring systems. Emanuele (2014, p.237) describes an FMEA carried out by SEMATECH, a semiconductor equipment manufacturing company, using three criteria of numerical ranking: Severity, Occurrence, and Detection. He explains that SEMATECH had two scoring tables for severity ranking, one concerning Customer satisfaction and another regarding Product Safety guidelines. Thus, two other scoring tables are about Occurrence and Detection ranking criteria. The RPN is then calculated by the product Severity X Occurrence X Detection and entered in the FMEA. The failure modes that achieve a high RPN are listed for further actions, according to the limits of RPN values established by the Company.

Nevertheless, risk analysis with three criteria is not well displayed in a traditional two-axis matrix. For better visualization, a three-dimensional view of Severity, Likelihood, and Severity was created by the author (figure 5). Based on the three-dimensional view introduced by Watson (2011), the level of Severity increases from right-to-left, the likelihood from front to back, and the Detection is showed in a Z axis. The representation of the relationship between the three axes generates the 'tall poles' as defined by Watson (2011). The highest RPN number represents the highest pole.

Grieg Star uses on its QMS system the following parameters to perform risk analysis and to evaluate the failure mode consequences:

					Likelihood class				
					1	2	3	4	5
		Safety People	Environment	Economy	Most unlikely	Unlikely	Likely	Very likely	Most likely
Consequence class	5	Multiple fatalities	Catastrofic	Total loss	5	10	15	20	25
	4	Fatality	Extensive impact	Extensive loss	4	8	12	16	20
	3	Repatriation	Major impact	Major loss	3	6	9	12	15
	2	Lost time	Serious impact	Serious loss	2	4	6	8	10
	1	No lost time	Minor impact	Minor loss	1	2	3	4	5

Figure 1 Model of risk matrix tool for assessment of Consequence and Likelihood at Grieg Star

	Likelihood class
1	Not experienced in our company, or heard of
2	Not experienced in our company, but in the industry
3	Experienced in our company
4	Experienced several times in our company
5	Experienced several times /year in our company

Figure 2 Likelihood class

	Criteria for environmental consequences			
	Environment	Air pollution	Sea pollution	Land Pollution
5	Catastrophic	Extensive fuel and cargo fire	Fuel pollution > 2000 tons	Grounding of ship, release of fuel
4	Extensive impact	Cargo fire	Fuel pollution 100 - 200 tons	AGM released to shore
3	Major impact	Violation of ECA SOX regulations / Incidental release of CFC	Fuel pollution 10-100 tons/ Violation of Marpol reg.	Release of fuel
2	Serious impact	Fumes from cargo of garbage	Fuel pollution < 10 tons/ release of marine bio fouling from hull	Release of fuel and/or toxic waste
1	Minor impact	Noise - disturbance of surroundings	Leaks from bow thruster / Leaking stern tude seal / Noisy	

	Criteria for operational consequences			
	Assets, loss, offhire	Cost (thousand of USD)	Vessel	Unplanned offhire
5	Total loss	> 50 Mill	Loss of ship and cargo	> 60 days
4	Extensive loss	1Mill - 50 Mill	Extensive damage to ship and/or cargo	10 - 60 days
3	Major loss	100' - 1 Mill	Local damages to ship equipment or hull / Port facilities	1 - 10 days
2	Serious loss	10'-100'	Damages to part of cargo	1hr - 1 day
1	Minor loss	<10.000	Minor equipment breakdowns or damages	< 1hr

Figure 3 Additional criteria for consequence analysis used at Grieg Star

Those criteria in force at Grieg Star were created with a basis in their operational context and correspond to what they tolerate concerning safety, environment, and operational consequences. For those reasons, it seems reasonable to use the same parameters for evaluating the failure modes further on the paper.

Following the RCM approach that suggests that all failure modes are classified and ranked according to their consequences and whether there are evident or hidden (Moubray, 1997, p.

127), detection is a criterion that will also be included in the risk indexing in this thesis. The criteria for evaluation of detection is the following displayed in figure 4:

	Detection
1	The failure is observed as soon as it happens
2	There is a good chance for the failure to be detected
3	There are preventive maintenance tasks and failures can be detected
4	There is a poor chance for the failure to be detected.
5	The component is not checked or the failure can't be detected

Figure 4 Criteria for classification of failure detection

Due to the three criteria for risk indexing, the RPN values can be represented by the following diagram. The parameters vary on a scale from 1 to 5. Thus, the tall pole in the left back can be identified with the highest risk, RPN 125. For the scope of this thesis, failure modes with RPN higher than 18 will be selected for analysis of further maintenance actions.

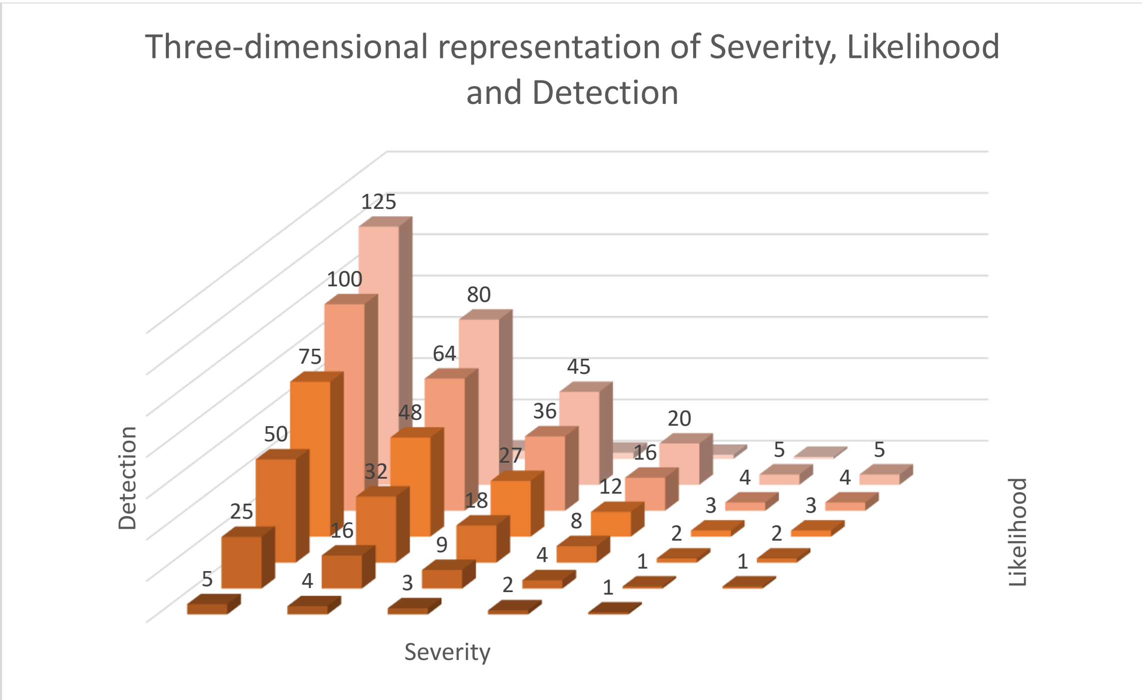

Figure 5 Three-dimensional representation of Severity, Likelihood, and Detection

2.6.2 RCM Decision diagram for selection of maintenance actions

When concluded with the risk indexing, the next step is to make a plan for what can be done to prevent each failure. For it, the RCM process joins all the decision processes into a strategic framework.

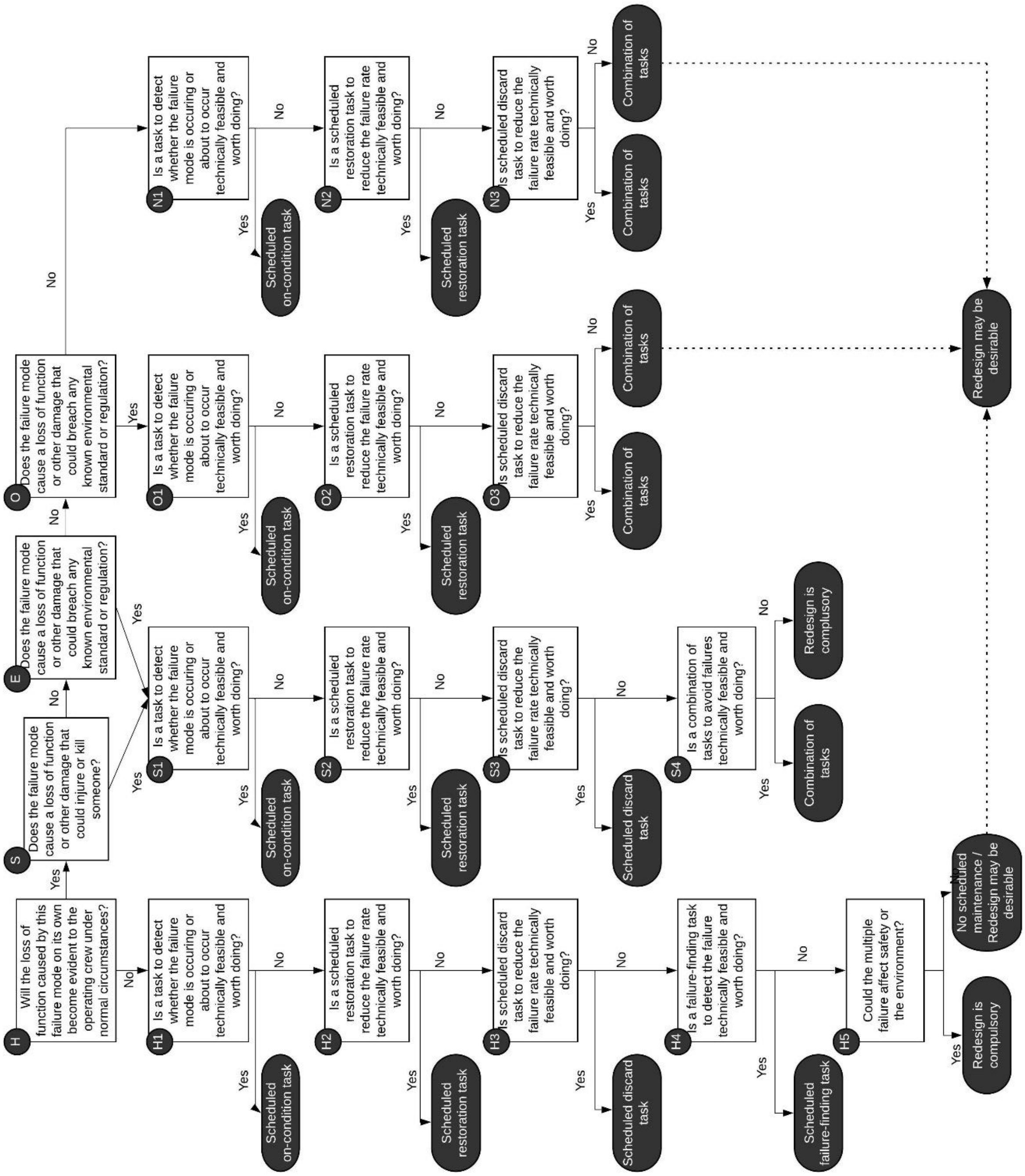

Figure 6 The RCM decision diagram (Moubray, 1997, p.200)

The decision diagram aims to assist in picking in up the most suitable task type for each failure mode. Will a scheduled discard task, a scheduled failure-finding task or a combination of tasks to be chosen? The outcomes obtained by the decision diagram must be recorded in another worksheet than the FMECA sheet. It shall also include if any maintenance is to be done, as well as to specify which maintenance task has been selected and who may perform it. Which failure modes require redesign and in which cases a wrong decision making has resulted in an accident to happen (1997, Moubray, p.198).

2.7 Proactive Maintenance

Moubray (1997, p.129) says that a maintenance task should be carried out if it can result in a reduced tolerable consequence for the correspondent failure mode. The RCM decision diagram includes six different types of maintenance tasks:

- **Proactive Tasks**

1. Scheduled on-condition task
2. Scheduled restoration task
3. Scheduled discard task

- **Default actions**

4. Scheduled failure-finding task
5. Redesign
6. Run-to-failure (when none scheduled maintenance task is feasible)

2.7.1 Scheduled on-condition task

On-condition maintenance consists of scheduled inspection to detect potential failure or when the component does not meet the required standard (Nowlan & Heap, 1978, p.51). Potential failure is defined by Moubray (1997, p.144) as "an identifiable condition which indicates that a functional failure is either about to occur or in the process of occurring." The following figure typically represents potential failure:

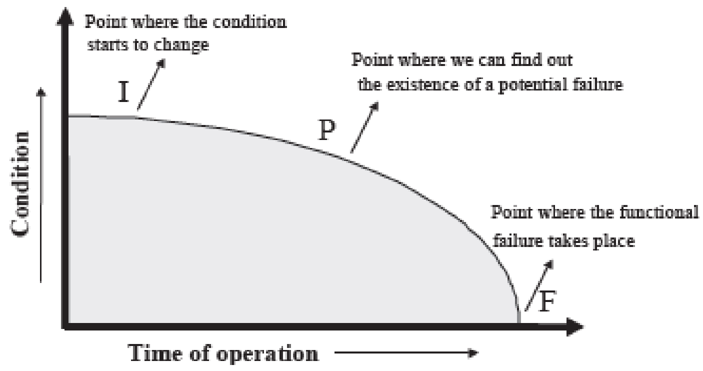

Figure 7 The P-F curve (taken from Márquez, 2007, p. 153)

Márquez (2007, p.153) explains that at the point I the equipment condition starts to decay, but that this change not necessarily can be noticed by the users. At point P, a failure can be recognized, and at point F, the equipment or component no longer can execute its functions.

There are different techniques to perform On-condition techniques. According to Moubray (1997, p. 149), the four main types of on-condition techniques are the following:

- **Condition monitoring:** tools to detect potential failure effects. Ex.: Broad Band Vibration Analysis, Proximity Analysis, Blot testing, Temperature monitoring.
- **Techniques based on variations of product quality:** alteration in the product produced by a machine can indicate a failure mode.
- **Primary effects monitoring techniques:** primary effects such for example, speed, flow rate, pressure, are monitored and shows to be outside the established limits.
- **Inspection techniques based on human senses:** the signs of potential failure are identified by looking, listening, feeling, and smell. The drawback of this method is that the P-F interval will most likely be very short, and actions to avoid failure shall be taken quickly. It also requires good awareness from the user, and he/she must be able to identify when the asset is not working under the usual conditions.

To conclude, Moubray (1997, p.149) and Nowlan & Heap (1978, p. 52) claim that the Scheduled On-Condition task should be carried out when the P-F interval can be consistently determined. Furthermore, this interval should be long enough that measures can be taken to avoid the failure or to reduce the consequences. It is not usual to use condition-based maintenance to hidden functions. Components with hidden failures many times deal with random failures, and therefore, it does not become cost-effective. Condition-based maintenance is worth doing if it reduces the safety or environmental consequences of failures or if it shows to be cost-effective over a period of time.

2.7.2 Scheduled Restoration and Scheduled Discard Tasks

2.7.2.1 The patterns of failure

Before going into the topic of scheduled restoration and discard, it is first essential to understand its relation to age-related failures. Any component is subject to stresses during its, and it is natural that the performance decays as age increases. When performance is below the decided, it means that the equipment failed. The traditional view of failure claims that equipment will have the following pattern (Moubray, 1997, p.12):

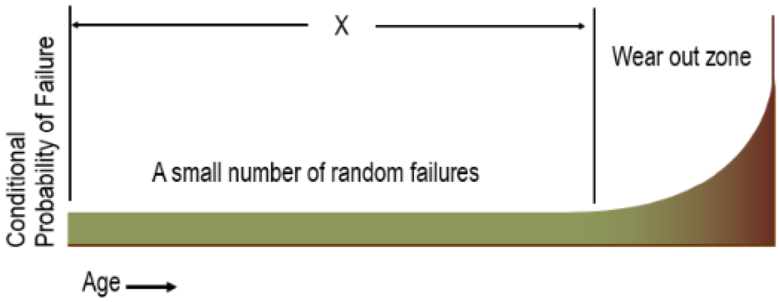

Figure 8 The traditional view of failure (Retrieved from Aladon, 2016, p. 6)

However, systems have become more complex and show other patterns of failure, as well explained by Moubray (1997) and Smith & Hinchcliffe (2004):

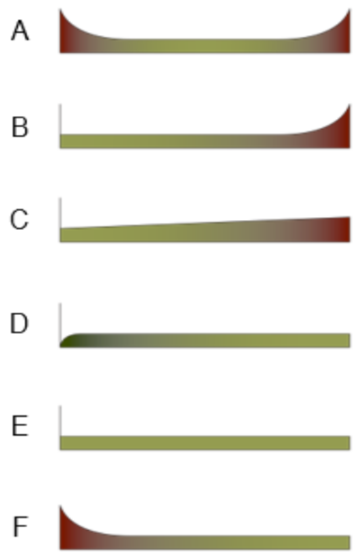

Figure 9 Six patterns of failure (taken from Aladan, 2016)

- **Pattern A:** also known as the bathtub, starts with a so-called "infant mortality," characterized by a constant failure rate. After, the equipment will suffer from random failures until it reaches its wear out.
- **Pattern B:** the probability of failure increases as the item ages. It ends out in wear out zone.
- **Pattern C:** Failure probability increases gradually. No wear-out age is determined.
- **Pattern D:** Low probability of failure when the equipment is new, but it increases at a consistent level.
- **Pattern E:** The equipment has an even probability of failure during its lifetime.
- **Pattern F:** Starts with signs of infant mortality and declines to the constant or slow increase of failure probability.

Studies carried out by the commercial aviation industry showed that only 4% of the items analysed fit to pattern A, 2% to B, 5% to C, 7% to D, 14% to E and 68% to F. It means that most of the time is not possible to predict what/when failure mechanisms will happen (Smith & Hinchcliffe, 2003, p. 61 & Moubray, 1997, p.33).

2.7.3 Scheduled restoration

Scheduled restoration consists of overhauling an item at or before some specific age limit, in order to re-establish its initial effectiveness disregarding its aspect at the time (Rausand,1998, p.127). According to Rausand (1998) and Moubray (1997, p.138), it is technically feasible to carry out a restoration task if:

- It is possible to identify the age that probability of failure increases;
- Most of the items withstand until that age;
- The original effectiveness and resistance to failure can be re-established.

In regards to overhauling, Smith & Hinchcliffe (2003, p.61), claim that overhaul actions do very little to re-establish equipment. Often it is unknown what to restore and time usually is not enough to start an overhaul. Moreover, there is always the risk of human mistakes during this kind of intervention. It can result in the "infant mortality" when the equipment is put in operation again. Typically, there is also a lack of data for determining the age-reliability pattern of the equipment and consequently, when to carry out a restoration task.

2.7.4 Scheduled discard

Scheduled discard consists of disposing an item/component at or before its specified age limit (Rausand, 1998, p.127). According to Rausand (1998) and Moubray (1997, p.138), scheduled discard is technically feasible if:

- It is possible to identify in an item the age that probability of failure increases;
- Most of the items withstand until that age;
- The item must be accountable for significant economic consequences.

2.8 Default actions

Default strategies is a conservative approach for the failure modes that are not found to be covered by proactive maintenance. (Nowlan & Heap, 1978, p. 79). When a feasible proactive maintenance task to ensure safety and operating economy can be found, a default action should be taken to deal with it.

2.8.1 Scheduled Failure-finding task

Hidden failures usually are not noticeable, and although it does not result in an immediate consequence to the system, it increases the equipment/system vulnerability for multiple failures (Nowlan & Heap, 1978, p.61). Failure-finding tasks consist of scheduled inspections to check whether the component is working or not. According to Moubray (1997, p.185), failure finding tasks is mostly applied to protective devices, such as sensor and actuators. He claims that Failure-finding measures are technically feasible if:

- It is physically possible to access the component to do the task;
- Performing the task will not increase the risk of multiple failures;
- A suitable and practical task interval is found.

2.8.2 Redesign

Redesign shall be considered when none practical, proactive tasks can be addressed to a failure mode and when the failure has safety or environmental consequences that cannot be tolerated. When the failure consequences affect mostly operation and costs, a cost-benefit assessment should be carried out (Rausand, 1998, p.128).

Moubray (1997, p.188) says that the redesign means "any change to the specification of any item of equipment, it includes, adding a new item, replacing an entire machine with one of a different make or type or relocating a machine." He also addresses training as a method of a redesign, once that training redesign the capability of the employee being trained.

2.8.3 Run-to-failure

Rausand (1978, p.128) defines Run-to-failure as a solution when the other maintenance tasks are not suitable, neither cost-effective. If a failure mode does not result in consequences that affect the safety or the environment, the redesign is not mandatory. If the failure mode has operational and economic consequences, a redesign may be preferable, but it should be worthwhile.

2.9 A brief about Opportunistic Maintenance

Borges (2015) defines opportunity maintenance as a "form of preventive maintenance based upon convenient replacement of equipment items or components by taking advantage of the unplanned or planned shutdown of a system where we have suitable maintenance resources already on location." Although opportunistic maintenance is not mentioned in the RCM theoretic framework, the principle of Opportunistic Maintenance seems very suitable for the shipping and offshore business.

Opportunistic maintenance focus on when a specific maintenance task should be carried out and which equipment/component should first be maintained (Thomas et al., 2008). Merchant vessels not rarely stay at anchorage waiting to berth in the cargo terminal. Also during navigation, cranes and other deck equipment are not in operation. Having a plan for how to benefit from those "standby" periods is already in practice ship operators, but perhaps it still could be improved more systematically.

2.10 Defining the maintenance intervals

Although the determination of formalized optimization models of maintenance interval is not part of the RCM process (Vatn, 2007, p.93), it can play an essential role at avoiding maintenance tasks to be done more often than necessary. Maintenance optimization models are part of the maintenance management that aims to find a feasible solution for a given situation, for example, to determine maintenance task intervals. Dekker (1996), explains that maintenance optimization models embrace:

- The details of the technical system, system functions, and criticalities;
- Modeling of system's degradation and its consequences;
- Description of the system's available information;
- An objective function and an optimization technique to calculate a feasible solution.

Dekker (1996), performed an analysis to check how much maintenance optimization processes have been applied successfully. In total, 112 applications were checked, and one of the common challenges between the applications was how difficult it was to gather the necessary data from the system to apply in the models. Furthermore, most of the studies carried out are done by academic researchers with little operational background. It results in papers with a high focus in mathematical analysis instead of solving real problems. Also, the language used in the article and models is not reasonably simple for maintenance practitioners to understand it and put in practice. Another drawback with most of the maintenance optimization models is that usually, only single units are taken into consideration (Rausand, 1998).

So, if an optimization model can be found or if the necessary available data is not available, a solution for choosing a feasible maintenance interval can be as suggested in the RCM handbook (mentioned by Rausand, 1998):

" The best thing you can do if you lack good information about the effect of age on reliability is to pick a periodicity that seems right. Later, you can personally explore the characteristics of the hardware at hand by periodically increasing the periodicity and finding out what happens".

3 Methodology

Many steps form the RCM method, and the methodology for gathering the necessary data for each step will be described in this chapter.

The first step of the RCM process is to have the RCM group established, define the scope of the analysis, and to gather all material that can be useful for the study. The RCM group was formed by the author, the Head of Vessel specialists at Grieg Star, and Vessels Managers involved within operations and docking for the ships class-L. A limitation in this starting phase is that most of the crane operators are stevedores placed in the different ports in the world. The Ship management company has no direct contact with them, and they could not, therefore, be included in the RCM group. To overcome that limitation, the author had the opportunity to take a trip to the vessel Star Luster (class-L) so she could talk to the crew that operates and maintains the cranes on board.

In order to find an answer to the research question "How a Reliability-Centered Maintenance Framework for Maintenance strategy can contribute to more efficient, reliable and cost-effective crane operations?", Descriptive research must be performed in the starting phase of the thesis. The first description work is the operational context that the GLE cranes from the Grieg Star operate and the expected level of performance. Then, the analysis of the hoisting function will start at the top (level 3) towards the bottom of the equipment hierarchy. The reason for this method being chosen is that the functions and performance expectations of each assembly are easier to assess, failure consequences are foreseeable, and the information worksheet for each sub-system is compact. The disadvantage of this type of analysis is that some failure modes that could make the crane not perform as expected will probably be left outside the analysis. However, it is beyond the scope of this paper to include in the analysis all possible and unlikely failures modes. The objective is to analyze those that are worthy identifying, reasonably likely to happen, and that has already happened.

Empirical research to identify the causal relationship for failures in GLE cranes through a failure mode, criticality, and effects analysis (FMECA) will also be carried out. The FMECA, as explained earlier, is one of the main tools of the RCM methodology. For the FMECA, the crane system will be divided into sub-systems, and the components of each sub-system will have its functions identified. Consequently, the failure modes will be listed and ranked according to their RPN. Here, two RPN values for each failure mode will be created: one considering a threat to the safety and the other with regards to operation. Thus, the failure modes with RPN values that are located in the red zone of the risk matrix (see sub-chapter 2.6 risk indexing) will proceed to the RCM decision diagram. The result expected from the thesis is the outcome of the decision diagram. Consequently, the proposed tasks will be recommended to the cooperating company to be implemented in their current maintenance plan.

There are some aspects of the operation that only the operators are familiar with, and therefore, it is necessary to get their feedback about possible issues that influence operations. Interview and written records seem to be an effective way to collect some of the operators' experience and considerations. Manuals also offer good support about operation procedures and manufacturer recommendations. The drawback with interviews is that the ships have not only crewmembers as crane operators but also stevedores that work in the ports of call. Thus, it may be challenging to collect all the necessary inputs. The interview will be limited to the crane operators that are part of the crew. Historical maintenance reports also can be an instrument for analysis to check which components have presented more failure. However, a constraint with historical reports is that not always all the information is inserted on the maintenance software. Another issue with historical reports is that some of the past issues have already been solved. So, it is necessary to check with the maintenance and operational team whether historical reports can be trustworthy.

As affirmed by Rausand (1998), the resources available for the analysis are usually limited, and the RCM group shall look careful at handling it, especially historical reports. Hard data about historical failure rates were not available, so qualitative methods might be used to perform failure modes criticality, as recommended by Marquéz (2007, p. 96).

4 Case study: RCM framework for maintenance strategy of cranes

4.1 The Operating Context

The cranes that will be addressed in this master thesis are variable frequency drive (VFD) electric cranes manufactured by MacGregor. Those type of cranes uses hydraulic oil only for the brake system, which makes them more sustainable and with a lower environmental impact. According to the manufacturer (MacGregor, 2019), the GLE cargo crane has much lower noise levels than a typical crane, requires less installed power on board and has reduced carbon footprint. The electric system also allows short response times and higher operational performance.

The vessels equipped with the electric crane are open hatch cargo carriers with 4 x 75 metric tons slewing cranes on deck. The vessels carry on the cargo hold mainly baled pulp, ore, grain, cement, paper, and other bulk cargoes. Each vessel has Four Cargotec / MacGregor GLE 7526 / MLC / 6030-2 / 4530gr. The lifting capacity of the cranes is 75 / 60 metric tons SWL for hook operation and 45 metric tons SWL in grab mode, log or palletized cargo. The maximum hoisting speed is 22 – 45 m/min, depending on the load, angle of slewing 360 degrees and slewing speed 0,9/0,5 rpm.

The cranes are operated only when the vessel is in port. The crane operators are stevedores in the port of call, and consequently, there is considerable rotativity in whom operate the cranes. The crane maintenance is partly carried out by the vessel crew and partly carried out by external technicians when the vessel is on the port or during docking.

4.2 The Crane system

The GLE crane is an electrical frequency drive crane (VFD). It has three degrees of freedom, hoisting, luffing, and slewing that are driven by electric motors. The function hoisting consists basically of lowering down and lifting the load, the function luffing raises, lowers and outreach the JIB (or boom). The function slewing is the rotational motion of the JIB on its horizontal axis.

The crane operator gives the command for the hoisting and slewing winches and the slewing gears through the control levers (control lever 1 for slewing and luffing, control lever 2 for hoisting). The three functions are interconnected by LINE-units, which allows power flow in both directions.

The hoisting and luffing winches have the brake integrated with the winch gear set. The brake system has the function to stop and hold the motor in a stopped position.

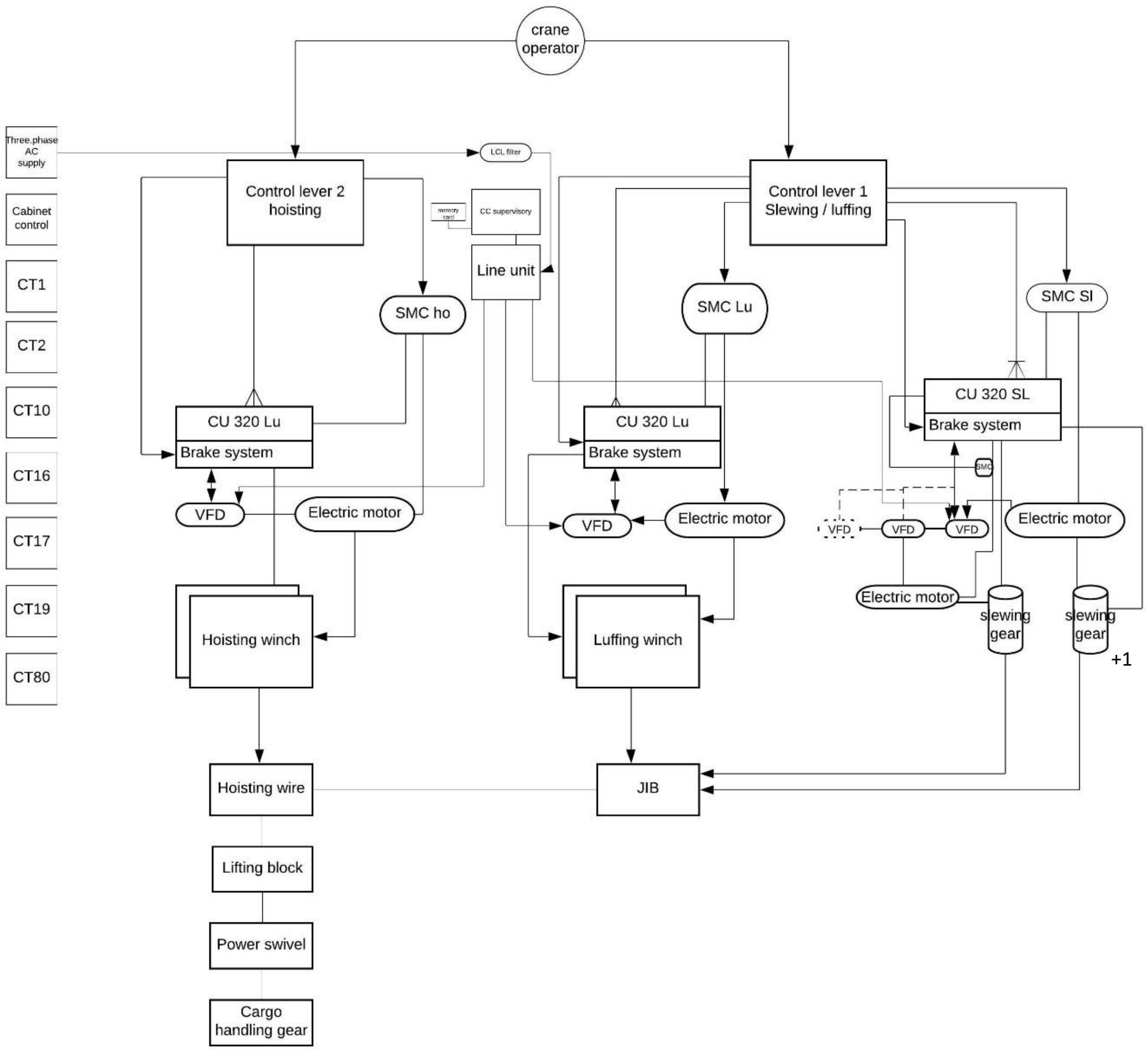

Figure 10 Crane system - simplified overview

The crane has a maximum safe workload (SWL) of 75 tons and 45 tons in grab mode. The grab mode consists in connecting additional loading equipment, such as a bucket grab for example. This reduction on the SWL is due to the fact that «when a grab digs deep into the bulk cargo, which is often of high density, and is hoisted from within the bulk material, frictional resistance and the weight of added entrained cargo may impose unknown and excessive loads on the system and components» (The Nautical Institute, 2012). However, when the operation first starts in grab mode, the crane goes continuously using grab. There are no breaks during offload, and the crane is set to remain in grab mode before the operation starts.

The crane also has many sensors and functions to ensure safety during operation and to avoid overload of the physical assets. Some of those sensors and functions are the following: The crane also has many sensors and functions to ensure safety during operation and to avoid overload of the physical assets. Some of those sensors and functions are the following:

Load cell: gives information about the weight of the load to the control system CC3000 (2016, MacGregor).

Angle encoder: measures the outreach of the JIB according to the weight of the cargo loaded. Thus, the crane control system adjusts the crane outreach to suit each load. (2016, MacGregor).

Safety cams: mechanical stop limits for hoisting and luffing is there is a failure in the software. (2016, MacGregor).

Slackwire Limit switches for hoisting and luffing: if the wire slackens during operation, the slackwire limit switch avoids the complete unwinding of the wire from the wire drum. (2016, MacGregor).

Heat sensor: all the electric motors are dowed with a heat sensor. It ramps down it every crane movement if the electric motor is about to overheat and stops the operation applying the brakes. (2016, MacGregor).

Anti-collision system: preclude collision between the crane jibs. This system calculates a safety area around each jib and crane housing. When the cranes operating in a close zone, the anti-collision system reduces the speed is and stops the crane if necessary.

The crane control system is equipped with one CC card and three MC cards. Each MC card adequately handles one all input and output for one crane motion while the CC card has the crane configuration and is used for communication with other cards and distribution of control system parameters. All cards are programmed with the same crane control software.

4.2.1 System selection and breakdown

All systems can, in principle benefit from an RCM analysis (Rausand, 1998, p.123). However, when introducing the RCM to a new plant, the resources can be limited. Thus, it is crucial to decide which system shall be prioritized. A crane is a complex system with many functions and thousands of components. Due to the variety of sub-systems that form the crane, the chosen function for this analysis is the hoisting system, since it considered to be the primary crane function. Thus, the hoisting system had its system divided according to level 3 of the following system hierarchy (figure 5), but not restricted to:

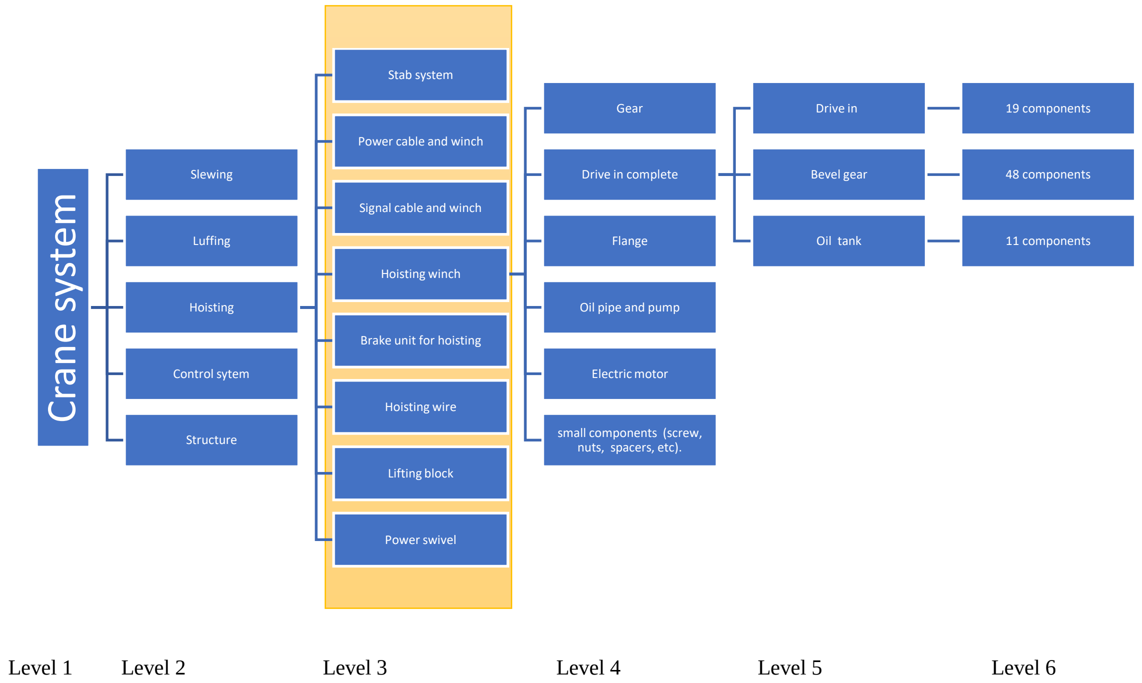

Figure 11 System Hierarchy

To keep track of the systems that will be analyzed using RCM, a plant register was carried out to offer an overview of the sub-assemblies and components that form the system.

As previously described on the Methodology chapter, the analysis of the hoisting function will start at the top (level 3) towards the bottom of equipment hierarchy once functions and performance expectations of each assembly are easier to assess, failure consequences are foreseeable.

The complete plant register with the hierarchical numbering system for sub-systems can be found in annex 1 of this paper. The next step is to identify the primary and secondary functions together with its expected performance for each system, in order to provide a framework for further analysis.

4.3 Identification of systems functions

To be able to identify how a system can fail, the system function and its expected performance must first be defined, as explained on sub-chapter 2.3 of this thesis. Having defined which systems are going to be analyzed, the systems primary and auxiliary functions have been defined as the following:

Hoisting winch:

1. To hoist and lower down a max capacity of 75tons and 45 tons on grab mode;
2. To hoist and lower down at a speed of 45-22m/min (load depending).

B. Brake unit:

1. To stop and control the load;
2. To release the load when receiving a signal from the electrical motor.

C. Hoisting wire:

1. Load wire rope: to resist the load to which it is submitted as longest as the load does not exceed the safe workload.
2. Wire rope claims: fix the loose end of the loop back to the wire rope;
3. Wire sheave: allows the wire to move freely, minimizing friction and wear on the cable.

D. Lifting block:

1. To accommodate the steel wire and connects to the hook or the power swivel;
2. To receive the stab wire on the lifting eye bolt.

E. Power swivel:

1. To be connected to the lifting block in order to rotate the load.

2. To transmit power and signals to connected lifting equipment through the slip ring unit.

F. Stab system:

1. To stabilize the load and keep it from rotating;
2. That the stab winch brake prevents the wire from unwinding when the electric motor goes off;
3. Stab wire: to resist the pull impacts when stabilizing the load.
4. That the stab wire sheaves allow the wire to move freely minimizing friction and wear on the cable.

G. Power cable system:

1. Cable winch: supply of current to cargo handling equipment.
2. Cable winch brake: prevent the wire from unwinding when the electric motor goes off
3. Power cable: to provide power to the power swivel and cargo handling gear.
4. Power wire sheave: allows the wire to move freely, minimizing friction and wear on the cable.
5. Power wire sheaves: remain safely fast on the JIB structure

H. Signal cable system:

1. Signal cable winch: provide the signal to connected lifting equipment.
2. Cable winch brake: prevent the wire from unwinding when the electric motor goes off
3. Signal cable: to establish communication between the cranes, power limitation system, and I/O box.
4. Power wire sheaves: allows the wire to move freely, minimizing friction and wear on the cable.
5. Signal cable sheaves: remain safely fast on the JIB structure

Both the system functions, functional failures, and failure modes have been recorded on the FMECA worksheet, annex 2.

4.4 FMECA

Aware of the systems functions and its expected performance, the next step was to list the functional failures, failure modes, effects and to evaluate its criticality. According to Rausand & Øien (1996), RCM analysts tend to use data sources to identify possible failure modes. However, many failure modes that currently happen are not included in the data sources. Hence for this thesis, the failure modes listed on the FMECA are based not only in data sources but also from outputs given by vessel managers, ship superintendents and crew members that have been dealing with other unexpected failures than those that are not included in the data sources. The RCM group discussed which failures were most likely to happen, and also which safety, environment, and operational consequences it brought to the company.

The system to be analyzed is specified on the top left of the FMECA. In the first column, it is described as the functions of each system. For all functions, the significant corresponding functional failure is listed in the second column. On column three, the pertinent failure mode, or cause of failure, are described, since different failure modes can motivate the same functional failure. Failure effects are registered in column seven. Columns 4-6 are used for criticality ranking concerning safety, environment, and economic consequences (taking into consideration offhire and repair costs). Column 8 is used to determine the likelihood of a failure mode to happen, and column 9 to determine how detectable the failure is. This evaluation is carried out according to the parameters for risk indexing described on sub-chapter 2.6 of this thesis.

Plant		Failure Mode and Effects Analysis (FMECA)					Prepared By			
System							FMEA Date			
Design Lead							Revision Date			
Core Team							Page			
Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economical	Failure effect (what happens when it fails)	Prob	Det	RPN	

Table 1 RCM FMECA worksheet

On columns 10, the RPN is calculated to prioritize the failure modes. The RPN, as previously explained, is the product of severity, likelihood, and detectability. However, three severity (safety, environment, and economical) parameters have been used in this FMECA, and not only one as in mostly FMECA's worksheets. Hence, three criticality ranks should be created: one in regards to safety, one for the environment and, the last one in regards to economic impacts. However, after evaluation with the RCM group, it was identified that the failure modes related to the crane function hoisting do not represent a significant threat to the environment. Electrical cranes use approximately 7x less oil than the traditional hydraulic cranes. In total the GLE crane uses around 100l of oil, that distributed between the different units such as brake units, hoisting and luffing winches and slewing gears, which represent a minor threat to the environment in case of leakage, being most likely restricted to the ship's main deck.

The values for evaluation of severity, likelihood, and detectability are based on a scale from 1 to 5, so the highest RPN that can be achieved is 125. A failure mode with correspondent RPN of 125 would mean that the referred failure mode is not detectable by inspection (or that there is not a maintenance task for the component), that the severity is the worst (either in regard to safety, environment or economically), and that it is inevitable that this failure will happen.

On the next pages, it can be seen the FMECA carried out for the hoisting function of the GLE crane. For better visualization, both RPN calculations have been included. The column in green is the RPN related to safety, and the column in blue is the RPN value for the economy.

Plant	Crane	Failure Mode, Effects and Criticality Analysis FMECA	FMECA Date	Mar-19
System	Hoisting winch		Revision Date	
Prepared by	RCM group		Page	1/3
Core Team				

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
I. Hoisting winch: hoist a max capacity of 75tons and 45 tons on grab mode	I.A) Hoisting winch does not work	1. Gearbox failure due to low oil level / overheating	1	1	2	Low oil level alarm will be activated on the crane cabin, unless the oil level sensor has also failed. Downtime to repair can take a couple of months.	2	1	2	4
		2. Gearbox failure due to fatigue and wear	1	1	2	Crane out of service. Downtime to repair can take a couple of months.	2	1	2	4
		3. Bevel gear failure due to low oil level/ overheating	1	1	2	Low oil level alarm will be activated on the crane cabin, unless the oil level sensor has also failed. Downtime to repair can take a couple of months.	2	1	2	4
		4. Bevel gear failure due to fatigue and wear	1	1	2	Crane out of service. Downtime to repair can take a couple of months.	2	1	2	4
		5. Failure on temperature switch located on the bevel gear oil tank that switches on/off oil cooler fan.	1	1	1	Alarm 212_04 will not be activated. Oil in the bevel gear can overheat and loose its tickness. Consequently, it can damage the bevel gear.	4	3	12	12
		6. Backlash between steel hubs and flexible spider. Flexible coupling between the electrical motor and bevel wore out.	1	1	2	Flexible spider must be replaced if there is not to much damage on the steel hubs.	2	4	8	16

Table 2 FMECA - hoisting winch - page 1/3

Failure Mode, Effects and Criticality Analysis
FMECA

Plant: Crane
System: Hoisting winch
Prepared by: RCM group
Core Team:

FMECA Date: Mar-19
Revision Date:
Page 2/3

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
		7. Electric motor failure	1	1	2	Electrical motor analyzed separately. The crane out of service, downtime to repair can take some months.	3	1	3	6
		8. Hoisting cams misregulated / Encoder error	1	1	1	Error 37_01 or 37_02 on. Limit switch for hoisting cam outside the working range.	4	4	16	16
		9. The sensor recognizes wire slacks.	1	1	2	Stop hoist and luffing movement.	2	1	2	4
		10. Temperature in the hydraulic system outside the working limits.	1	1	2	Error 35_03 (temp too low) /35_04 (temp too high) activated. Crane stops and multi-disc brakes are applied. Brake unit analysed separately.	1	3	3	6
		11. Failure in one of the electrical cabinets components.	1	1	3	Winch stops and alarm is activated on crane cabin. Economical failure effects will depend on availability of spare onboard and which component has failed. Good cleanliness and temperature shall be maintened inside the cabinets.	3	1	3	9
		12. Loadcell failure	1	1	3	Load cell analysed separately; in case of failure will be replaced. / Most likely the load cell cable can present problems.	3	1	3	9

Table 3 FMECA - hoisting winch - page 2/3

Failure Mode, Effects and Criticality Analysis
FMECA

Plant	Crane	FMECA Date	Mar-19
System	Hoisting winch	Revision Date	
Prepared by	RCM group	Page	3/3
Core Team			

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
I.To hoist at a speed of 45-22m/min (load depending)	I.B) Hoisting winch speed below the expected	1. The electric motor is about to overheat and the temperature sensor (klixon) ramps down the hoisting operation	1	1	1	Error 7015 activated. If the klixon fails and motor overheat, it can damage the electrical motor.	3	1	3	3
		2. Low oil level in the brake unit	1	1	2	Errors 51_50/51_52 activated - Crane ramps down and stops. Brake system to be analyzed separately.	2	1	2	4

Table 4 FMECA - hoisting winch - page 3/3

Plant	Crane	Failure Mode, Effects and Criticality Analysis FMECA	FMECA Date	Mar-19
System	Brake unit		Revision Date	
Prepared by	RCM group		Page	1/2
Core Team				

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
II. Brake unit: stop and control the load. Release the load when receiving the	II.A) Brake is not released	1. Low oil level in the oil tank.	1	1	2	Errors 51_50 / 51_52 activated - The load can't be released or hoisted.	2	1	2	4
		2. Oil level low due to leakage	1	1	1	Errors 51_60 low pressure, 51_50 low level. Complete pressure unit must be replaced). (aprox. 12 L oil - low risk to environment).	3	4	12	12
		3. Oil level & temp sensor fault.	1	1	1	Sensor does not show accurate temperature and/ or level and can interrupt the operation.	4	3	12	12
		4. Oil filter clogged	1	1	1	Oil will bypass the filter - if the oil is contaminated it can damify the brake unit.	3	3	9	9
		5. Oil overheated	1	1	2	Error 51_52 - brake will not be released - if due to low level in the tank, downtime to complete tank.	2	1	2	4
		6. Air in the hydraulic brake circuit.	1	1	1	Can cause oveheating and other damages in the hydraulic system. The recommendation is to check for leaks and to bleed the system.	1	4	4	4
		7. Direction valves failure	1	1	1	Direction valve must be replaced.	1	4	4	4
		8. Control pressure too low or no pressure. Failure on blade accumulator	1	1	1	Accumulator must be refilled.	3	4	12	12
		9. Failure in one of the electrical cabinets components.	1	1	3	Electrical cabinets to be analyzed separately.	3	1	3	9
	II.B) Brake does not hold the load properly	1. multiple discs brakes are worn out.	5	1	2	Brakes discs and springs shall be replaced. It has already been replaced every 5 years at dry-docking.	1	1	5	2

Table 5 FMECA - brake unit - page 1/2

Plant	Crane	Failure Mode, Effects and Criticality Analysis FMECA	FMECA Date	Mar-19
System	Brake unit		Revision Date	
Prepared by	RCM group		Page	2/2
Core Team				

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
		2. Discs overheated (colored dark yellow to blue).	5	1	2	Brakes discs and springs shall be replaced. It has already been replaced every 5 years at dry-docking.	1	1	5	2

Table 6 FMECA - brake unit - page 2/2

Plant	Crane	**Failure Mode, Effects and Criticality Analysis**	FMECA Date	Mar-19
System	Hoisting wire	**FMECA**	Revision Date	
Prepared by	RCM group		Page	1/1
Core Team				

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
III. Load wire rope	III.A) Wire rope rupture (or heavy fatigue)	1. Corrosion due to inefficient lubrication	4	1	3	Corrosion in the wire rope can result in rupture and consequently injuries/loss of life.	2	4	32	24
		2. Heavy wear due to high contact pressure in the sheave groove	2	1	1	Normal wear during operations, but shall not result in an extreme consequence for example fall of cargo.	4	4	32	16
	III.B) Broken wires	1. Damage on the wire during operations due to bad visibility from crane cabin.	2	1	3	Wire rope can run over sharp edges. Adjacent wires can get more damaged when running over the sheaves. If an excessive number of wires are broken, the wire rope should be discarded. This can happen if the crane operator can not see the wire when positioning the cargo on the cargo hold.	3	4	24	36
III. Wire sheave: allows the wire to move freely, minimizing friction and wear on the cable.	III.C) Bad contact position between wire and sheave	1) Worn wire sheave.	1	1	2	Progressing wear on the sheaves can decrease the lifetime of the rope, reduce load capacity, and risk the safety of operations.	3	2	6	12
III. Wire sheave: remain safely secured at wire JIB.	III.D) Sheave unsteady	1) Lockwasher and shaft deteriorated, less resistance to stresses.	2	1	2	The risk for falling objects and to hurt some involved in the operations.	2	3	12	12

Table 7 FMECA - hoisting wire - page 1/1

Plant	Crane	Failure Mode, Effects and Criticality Analysis FMECA	FMECA Date	Mar-19
System	Lifting block		Revision Date	
Prepared by	RCM group		Page	1/1
Core Team				

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
IV. Lifting block: accommodate the steel wire and connects to the hook or the power swivel	IV.A) Lifting block failure	1. Wear down and corrosion. According to the manufacturer, the limits are (p.277): -5% of any diameter; -2% of any diameter of a pin in a hole	1	1	2	If severe corrosion is identified, the lifting block shall be replaced. Risk for personal injury / death - Crane out of service.	3	1	3	6
	IV.B) Cracks in welds in steel structure	1. Overload	2	1	2	If cracks are identified, the lifting block shall be replaced. Risk for personal injury - Crane out of service.	1	1	2	2
	IV.C) Impossibility/difficulty to connect or disconnect from the power swivel	1. Shaft, nut and locking pin stuck on lifting block.	1	1	2	Very demanding to make the disconnection, downtime of some hours can occur.	4	3	12	24
	IV.D) Lifting block standing uneven on the wire	1. Circlip failure	1	1	1	The shaft is hardened above the circlip hardness, thus subject to groove deformation and shear. Downtime to replace the circlip depends on its availability onboard.	3	3	9	9
IV. To receive the stab wire on the lifting eye bolt	IV.E) Lifting eye bolt broken	1. Bad conditions of the lifting eye, corrosion or under capacity to receive the stab wire.	1	1	1	Can danify the stab wire. The operation can continue, but with less stability for the lifting block.	3	1	3	3

Table 8 FMECA - Lifting block - page 1/1

Failure Mode, Effects and Criticality Analysis
FMECA

Plant: Crane
System: Power swivel
Prepared by: RCM group
Core Team:

FMECA Date: Mar-19
Revision Date:
Page: 1/2

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
V.To be connected to the lifting block in order to rotate the load.	V.A) Power swivel does not rotate	1. Electric motor brake down	1	1	2	Power swivel out of service until the electric motor is replaced. Crane remains in operation.	3	1	3	6
		2. Low oil level on slewing gear	1	1	2	Gear can be damaged if the oil is not refilled. Crane remains in operation.	3	1	3	6
		3. Gyro of power swivel fails	1	1	2	Gyro must be replaced - Power swivel can be operated in manual mode.	3	1	3	6
		4. System error ARC failure	1	1	1	Possibility of pendulation of the cargo, power swivel connection, and cable connections shall be checked. ARC system analyzed separately.	4	1	4	4
		5. Power cable break down	1	1	2	Power cable shall be replaced. Downtime to repair can take some hours.	4	1	4	8
		6. Wear on slewing bearing	1	1	2	It can result from too small backlash between slewing gear and bearing. Slewing gear must be replaced depending on the level of wear.	1	3	3	6
		7. Anti-cond heater is not switched on/ or in a failed state.	1	1	1	Motor and box with a slip ring can be damaged.	3	4	12	12
		8. Connection box not watertight	1	1	2	Electrical components are damaged, and power swivel stops working	3	1	3	6
V. Transmit power and signals to connected lifting equipment through a slipring unit.	V.B) Lifting equipment connected to power swivel not powered.	1. Slip-ring unit brushes and/brusholder worn out.	1	1	1	Power limitation, crane - running signal missing. / Slip-ring brushes are replaced during dry-docking every 5 years.	1	1	1	1

Table 9 FMECA - Power swivel - page 1/2

Plant	Crane	FMECA Date	Mar-19
System	Power swivel	Revision Date	
Prepared by	RCM group	Page	2/2
Core Team			

Failure Mode, Effects and Criticality Analysis
FMECA

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
		2. Carbon dust in the slipring housing	1	1	1	Flashing can occur if carbon dust remains in the slipring housing.	2	3	6	6
		3. Driver pin on slip ring unit damaged	1	1	2	The power cable can get twisted on the driver pin connection. Thus, the driver pin brakes and the whole slip ring unit must be removed for corrective maintenance. It can happen when the cable is paid out abruptly.	3	1	3	6

Table 10 FMECA - Power swivel - page 2/2

Plant	Crane	Failure Mode, Effects and Criticality Analysis FMECA	FMECA Date	Mar-19
System	Stab system		Revision Date	
Prepared by	RCM group		Page	1/2
Core Team				

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
VI. Stab winch: stabilizes the load and keep it from rotating	VI.A) Stab winch does not work	1. Gearbox failure due to low oil level / overheating	1	1	2	A low oil level alarm will be activated on the crane cabin unless the oil level sensor has also failed. Downtime to repair can take a couple of months.	2	1	2	4
		2. Gearbox failure due to fatigue and wear	1	1	2	Crane out of service. Downtime to repair can take a couple of months.	2	1	2	4
		3. Bevel gear failure due to low oil level/ overheating	1	1	2	A low oil level alarm will be activated on the crane cabin unless the oil level sensor has also failed. Downtime to repair can take a couple of months.	2	1	2	4
		4. Bevel gear failure due to fatigue and wear	1	1	2	Crane out of service. Downtime to repair can take a couple of months.	2	1	2	4
		5. Electrical motor failure / motor stalled.	1	1	2	Error 55_01 - motor stalling means that the electric motor has more load on it than it is designed for and it can no longer supply enough torque to keep it spinning.	3	1	3	6
VI. Stab winch brake: prevent the wire from unwinding when the electric motor goes off	VI.B) Brake is not released	1. Low oil level in the oil tank.	1	1	2	The load can't be released or hoisted. Oil must be refilled.	3	1	3	6
		2. Oil level low due to leakage	1	1	2	Errors 51_60 low pressure, 51_50 low level. The complete pressure unit must be replaced. (approx. 12 L oil - low risk to the environment).	2	3	6	12

Table 11 FMECA - Stab system - page 1/2

Failure Mode, Effects and Criticality Analysis
FMECA

Plant	Crane	FMECA Date	Mar-19
System	Stab system	Revision Date	
Prepared by	RCM group	Page	2/2
Core Team			

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
VI. Stab wire: ensure stability of lifting block	VI.C) stab wire rupture	1. Worn out due to fail stowing for sea voyage. Procedures not correctly followed.	1	1	2	Stab wire must be replaced. Crane continues operational, but operation becomes more risk due to the rotation of cargo.	3	1	3	6
		2. Corrosion, wear and tear - normal deterioration.	2	1	2	Stab wire must be replaced. Crane continues operational, but operation becomes more risk due to rotation of cargo.	3	3	18	18
VI. Stab wire sheaves: allow the wire to move freely minimizing friction and wear on the cable.	VI.D) Uneven rotation / noisy	1.Lack of lubrication / greasing, roller deteriorated	1	1	2	Progressing wear on the sheaves can decrease the lifetime of the rope, reduce capacity and risk safety of operations.	3	2	6	12
VI. Stab wire bracket with sheave: remain safely fast on the JIB structure	VI.E) Bracket with sheave unsafely secured.	1. Deterioration of bracket,bolt, split pin and locking nut.	4	1	1	If the sheave shafts are loose, the sheave can fall and lead to serious injuries.	4	2	32	8

Table 12 FMECA - Stab system - page 2/2

Plant	Crane	Failure Mode, Effects and Criticality Analysis FMECA	FMECA Date	Mar-19
System	Power cable		Revision Date	
Prepared by	RCM group		Page	1/2
Core Team				

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
VII. Cable winch: provide the supply of current to cargo handling equipment.	VII.A) Cable drum does not rotate	1. Electrical motor failure	1	1	2	Electrical motor to be replaced.	3	1	3	6
		2. V-belt not adjusted.	1	1	1	V-belt needs to be adjusted. Bad transmission between the electric motor and turbo coupling.	1	1	1	1
		3. Low oil level / overheating in gearbox (spur gear)	1	1	2	Low oil level can damage the gear - refill the oil.	2	1	2	4
		4. Failure of the safety plug on the turbo coupling.	1	1	2	If the turbo coupling overheat and the safety plug does nor actuates, the oil can overheat and damage seals and oil. The safety plug shall be replaced.	2	4	8	16
	VII.B) Too low pulling force on cable winch	1. Oil level in turbo coupling below the indicated.	1	1	2	Variation in the pulling force. The cable can get slack and get damage. The oil level shall be refilled.	3	4	12	24
	VII.C) Too strong pulling fomce	1.Oil level in turbo coupling higher than the indicated.	1	1	2	Variation in the pulling force. The oil level shall be inside the limits.	2	2	4	8
	VII.D) Power is not transmitted to the cargo handling equipment	1. Slip-ring unit brushes and/brusholder worn out.	1	1	1	Power limitation, crane - running signal missing. / Slip-ring brushes are replaced during dry-docking every 5 years.	1	1	1	1
		2. Carbon dust in the slipring housing	1	1	2	Flashing can occur if carbon dust remains deposited in the brush holders.	1	3	3	6

Table 13 FMECA - Power cable - page 1/2

Plant	Crane	Failure Mode, Effects and Criticality Analysis FMECA	FMECA Date	Mar-19
System	Power cable		Revision Date	
Prepared by	RCM group		Page	2/2
Core Team				

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
VII. Cable winch brake: prevent the wire from unwinding when the electric motor goes off	VII.E) Brake is not released	1. Rectifier brake down	1	1	2	Rectifier and brake coil to be replaced.	2	1	2	4
		2. Fail in the solenoid valve between the electric motor and brake unit.	1	1	1	Solenoid valve to be replaced.	2	2	4	4
VII. Power cable: send power to connected lifting equipment	VII.F) Power cable broken	1. Fail to stow the cable before a sea voyage.	1	1	2	Fail to stow can damage the power cable and in last case, it must be replaced.	3	2	6	12
		2. Power cable gets stuck on power swivel during operation. Crane operators can not see the slack from the crane cabin.	1	1	2	If the power cable gets slacked and the crane operator does not see (due to bad visibility from crane cabin), the cable can get very damaged.	4	4	16	32
VII. Power cable sheaves: allows the wire to move freely, minimizing friction and wear on the cable.	VII.G. Uneven rotation / noisy	1. Lubrication failure, sealed-for-life components no longer efficient.	1	1	1	Progressing wear on the sheaves can decrease the lifetime of the cable and Increased noise levels.	3	3	9	9
VII. Power cable wheels: remain safely secured on the JIB structure	VII.H) Power cabe wheels unstable.	1. Deterioration of bolts, pins, brackets, and bushing.	4	1	1	If the power cable wheels get too deteriorated it can lead to serious injuries and risk of falling objects.	4	2	32	8

Table 14 FMECA - Power cable - page 2/2

Failure Mode, Effects and Criticality Analysis
FMECA

Plant	Crane	FMECA Date	Mar-19
System	Signal cable	Revision Date	
Prepared by	RCM Group	Page	1/2
Core Team			

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
VIII. Signal cable winch: provide the signal to connected lifting equipment	VIII.A) Cable drum does not rotate	1. Electrical motor failure	1	1	2	Electrical motor to be replaced.	3	1	3	6
		2. V-belt not adjusted.	1	1	1	V-belt needs to be adjusted. Bad transmission between the electric motor and turbo coupling.	1	1	1	1
		3. Low oil level / overheating in gearbox (spur gear)	1	1	2	Low oil level can damage the gear - refill the oil.	2	1	2	4
		4. Failure of the safety plug on the turbo coupling - if the turbo coupling overheat and the safety plug does nor actuates, the oil can overheat and damify seals and oil.	1	1	2	If the turbo coupling overheat and the safety plug does nor actuates, the oil can overheat and damify seals and oil. The Safety plug shall be replaced.	2	4	8	16
	VIII.B) Too low pulling force on cable winch	1. Oil level in turbo coupling under the indicated.	1	1	2	Variation in the pulling force. The cable can get slack and get damage. The oil level shall be refilled.	3	4	12	24
	VIII.C) Too strong pulling force	1. Oil level in turbo coupling higher than the indicated.	1	1	2	Variation in the pulling force. The oil level shall be inside the limits.	2	4	8	16
	VIII.D) Power is not transmitted to the cargo handling equipment	1. Slip-ring unit brushes and/brusholder worn out.	1	1	1	Power limitation, crane - running signal missing. / Slip-ring brushes are replaced during dry-docking every 5 years.	1	1	1	1
		2. Carbon dust in the slipring housing	1	1	2	Flashing can occur if carbon dust remains deposited in the brush holders.	1	3	3	6

Table 15 FMECA - Signal cable - page 1/2

Plant	Crane	Failure Mode, Effects and Criticality Analysis	FMECA Date	Mar-19
System	Signal cable	FMECA	Revision Date	
Prepared by	RCM Group		Page	2/2
Core Team				

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detection	RPN	RPN
VIII. Cable winch brake: prevent the wire from unwinding when the electric motor goes off	VIII.E) Brake is not released	1. Rectifier brake down	1	1	2	Rectifier and brake coil to be replaced.	2	1	2	4
		2. Fail in the solenoid valve between the electric motor and brake unit.	1	1	1	Solenoid valve to be replaced.	2	2	4	4
VIII. Signal cable: send the signal to connected lifting equipment	VIII.F) Signal cable broken	1. Fail to stow the cable before a sea voyage.	1	1	2	Fail to stow can damage the signal cable and in the last case it must be replaced.	3	2	6	12
		2. Signal cable gets stuck on power swivel during operation. Crane operators can not see the slack from the crane cabin.	1	1	2	If the signal cable gets slacked and the crane operator does not see (due to bad visibility from crane cabin), the cable can get very damaged.	4	4	16	32
Signal cable sheaves: allows the wire to move freely minimizing friction and wear on the cable.	VIII.G. Uneven rotation / noisy	1. Lubrication failure, sealed-for-life components no longer efficient.	1	1	1	Progressing wear on the sheaves can decrease the lifetime of the cable and Increased noise levels.	3	3	9	9
VIII. Signal cable wheels: remain safely secured on the JIB structure	VIII.H) Signal cable wheels unstable.	1. Deterioration of bolts, pins, brackets, and bushing.	4	1	1	If the signal cable wheels get too deteriorated, it can lead to severe injuries and the risk of falling objects.	4	2	32	8

Table 16 FMECA - Signal cable - page 2/2

4.5 Selection of the critical failure modes

In total, 85 failure modes from eight sub-systems were entered in the FMECA worksheet. The causes and effects were then described and evaluated according to Safety, Environment, and Economic Consequences. The severity consequence of each failure mode, its likelihood, and detection parameters was evaluated through many meetings carried out with vessel managers at Grieg Star. The parameters used were based on the company's QMS system once they already have the realistic parameters that fit their field of operation.

In this thesis, the numerical risk scoring RPN has been created twice. On the last two columns of the FMECA displayed from page 34 to 48, the RPN in green represents the RPN taking into consideration Safety Severity and the RPN column in blue, the RPN concerning Operational severity. No RPN classification was carried out to Environment Severity once the value for all the failure modes was one.

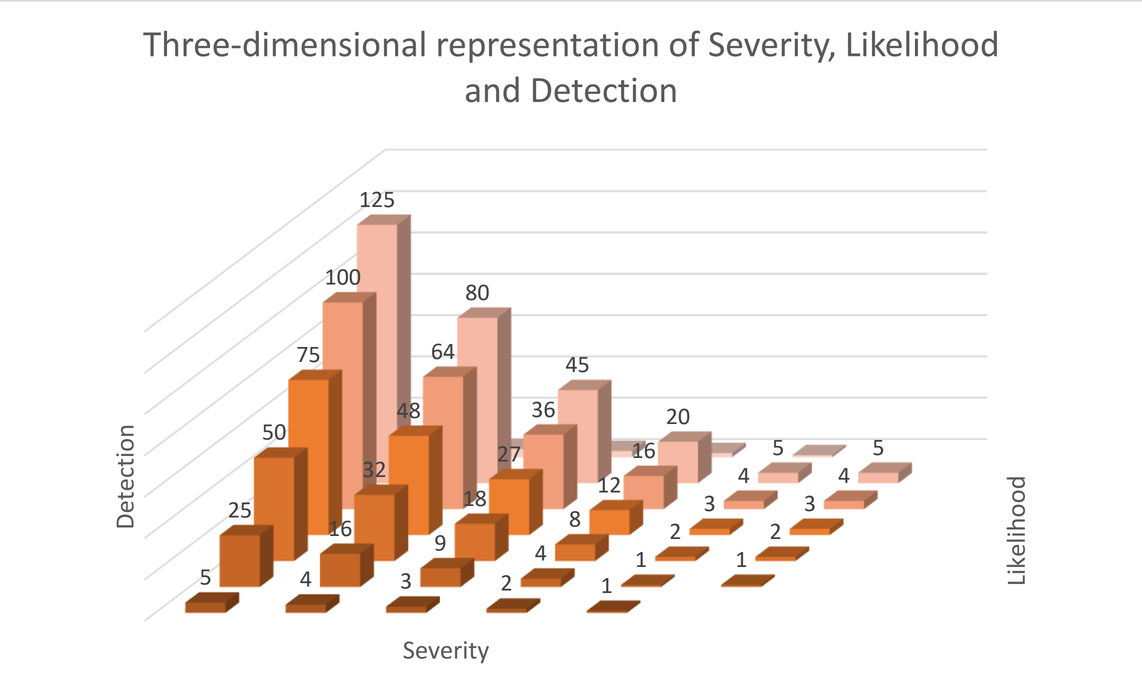

Figure 12 Three-dimensional representation of Severity, Likelihood, and Detection

Thus, the failure modes that had its RPN values represented by the tall-pole n.18 and higher will proceed for further investigation of possible maintenance actions.

From the 85 failure modes, 7 of them were considered critical to Safety, and 8 of them were considered critical to the Economy. 3 of the 15 critical failure modes were critical both for Safety and Economy. Those three failure modes will be registered only once in the RCM decision worksheet. The most critical failure mode about Safety had the RPN value 32 and the most critical failure to the Economy had RPN value 36. The list with the critical failure modes according to the RPN ranking can be checked below:

Failure modes rank (Safety consequences)

(RPN = Severity (Safety) x Likelihood x detectability)

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detectability	RPN
III. Load wire rope	III.A) Wire rope rupture (or heavy wear without rupture)	1. Corrosion due to inefficient lubrication	4	1	3	Corrosion in the wire rope can result in rupture and consequently injuries/loss of life.	2	4	**32**
III. Load wire rope	III.A) Wire rope rupture (or heavy wear without rupture)	2. Heavy wear due to high contact pressure in the sheave groove	2	1	1	Normal wear during operations, but shall not result in an extreme consequence for example fall of cargo.	4	4	**32**
VI. Stab wire bracket with sheave: remain safely fast on the JIB structure	VI.E) Bracket with sheave unsafely secured.	1. Deterioration of bracket,bolt, split pin and locking nut.	4	1	1	If the sheave shafts are loose, the sheave can fall and lead to severe injuries.	4	2	**32**
VII. Power cable wheels: remain safely secured on the JIB structure	VII.H) Power cable wheels unstable.	1. Deterioration of bolts, pins, brackets, and bushing.	4	1	1	If the power cable wheels get too deteriorated, it can lead to severe injuries and the risk of falling objects.	4	2	**32**
VIII. Signal cable wheels: remain safely secured on the JIB structure	VIII.H) Signal cable wheels unstable.	1. Deterioration of bolts, pins, brackets, and bushing.	4	1	1	If the signal cable wheels get too deteriorated, it can lead to severe injuries and to risk of falling objects.	4	2	**32**
III. Load wire rope	III.B) Broken wires	1. Damage on the wire during operations due to bad visibility from crane cabin.	2	1	3	Wire rope can run over sharp edges. Adjacent wires can get more damaged when running over the sheaves. If an excessive number of wires are broken, the wire rope should be discarded. This can happen if the crane operator can not see the wire when positioning the cargo on cargo hold	3	4	**24**
VI. Stab wire: ensure stability of lifting block	VI.C) stab wire rupture	2. Corrosion, wear, and tear - normal deterioration.	2	1	2	Stab wire must be replaced. Crane continues operational, but operation becomes more risk due to rotation of cargo	3	3	**18**

Table 17 Failure modes ranking - Safety Consequences

Failure modes rank (Economic consequences)

(RPN = Severity (Economic) x Likelihood x detectability)

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detectability	RPN
III. Load wire rope	III.B) Broken wires	1. Damage on the wire during operations due to bad visibility from crane cabin	2	1	3	Wire rope can run over sharp edges. Adjacent wires can get more damaged when running over the sheaves. If an excessive number of wires are broken, the wire rope should be discarded. This can happen if the crane operator can not see the wire when positioning the cargo on the cargo hold.	3	4	**36**
VII.Power cable: send power to connected lifting equipment	VII.F) Power cable broken	2. Power cable gets stuck on power swivel during operation. Crane operators can not see the slack from the crane cabin.	1	1	2	If the power cable gets slacked and the crane operator does not see (due to bad visibility from crane cabin), the cable can get very damaged.	4	4	**32**
VIII. Signal cable: send the signal to connected lifting equipment	VIII.F) Signal cable broken	2. Signal cable gets stuck on power swivel during operation. Crane operators can not see the slack from the crane cabin.	1	1	2	If the signal cable gets slacked and the crane operator does not see (due to bad visibility from crane cabin), the cable can get very damaged.	4	4	**32**
III. Load wire rope	III.A) Wire rope rupture (or heavy wear without rupture)	1. Corrosion due to inefficient lubrication	4	1	3	Corrosion in the wire rope can result in rupture and consequently injuries / loss of life.	2	4	**24**
IV. Lifting block: accommodate the steel wire and connects to the hook or the power swivel	IV.C) Impossibility/difficulty to connect or disconnect	1. Shaft, nut and locking pin stuck on lifting block.	1	1	2	Very demanding to make the disconnection, downtime of some hours can occur.	4	3	**24**
VII. Cable winch: provide the supply of current to cargo handling equipment.	VII.B) Too low pulling force on cable winch	1. Oil level in turbo coupling under the indicated.	1	1	2	Variation in the pulling force. The cable can get slack and get a damage. The oil level shall be refilled.	3	4	**24**

Table 18 Failure modes ranking - Economic consequences

Failure modes rank (Economic consequences)

(RPN = Severity (Economic) x Likelihood x detectability)

Item / Function	Functional failure (loss of function)	Failure mode (cause of failure)	Safety	Env	Economic	Failure effect (what happens when it fails)	Likelihood	Detectability	RPN
VIII. Signal cable winch: provide the signal to connected lifting equipment	VIII.B) Too low pulling force on cable winch	1. Oil level in turbo coupling under the indicated.	1	1	2	Variation in the pulling force. The cable can get slack and get damage. The oil level shall be refilled.	3	4	**24**
VI. Stab wire: ensure the stability of lifting block	VI.C) stab wire rupture	2. Corrosion, wear and, tear - normal deterioration.	2	1	2	Stab wire must be replaced. Crane continues operational, but operation becomes more risk due to rotation of cargo.	3	3	**18**

Table 19 Failure modes ranking - Economic consequences

4.6 Toward to the results: using the RCM decision diagram for critical failure modes

The RCM decision diagram is the next tool to be used in the RCM process. Having ranked the failure modes according to the RPN number, each one of them will go through the RCM decision worksheet. The sequence of questions in the decision worksheet helps to define the proposed task for each failure mode will be defined, the initial interval for each task and who is the person who is going to be responsible for the task. The RCM decision worksheet has the following structure (Moubray, 1997, p. 199):

RCM II		Plant: Crane											Facilitator: ________________________	Date:	
Decision Worksheet		Sub-system: ____________											Auditor: ________________________		
Information reference			Evaluation consequence				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default action					
F	FF	FM	H	S	E	O				H4	H5	S4	Proposed task	Initial Interval	Can be done by

Table 20 RCM decision worksheet

Sixteen columns form the RCM decision worksheet. The three first columns (F, FF, FM) are for information reference, where it will be entered the function, functional failure, and failure modes. In the columns H, S, E, and O, it will be registered the failure mode consequences with regards to hidden failures, safety, environment, and operation. In the following columns, it will be registered:

- H1/ S1/ O1/ N1 it will be entered with Yes or No answer for the selection of an on-condition task;
- H2/ S2/ O2/ N2 if a scheduled restoration task is found to be suitable;
- H3/ S3 /O3/ N3 if a discard task is found to be suitable;

- H4/H5/S4, in case of default questions. When the answers from the RCM Decision Diagram are registered in the Decision worksheet, a proposed task can be entered, as well as the regularity that the task should be done and who.

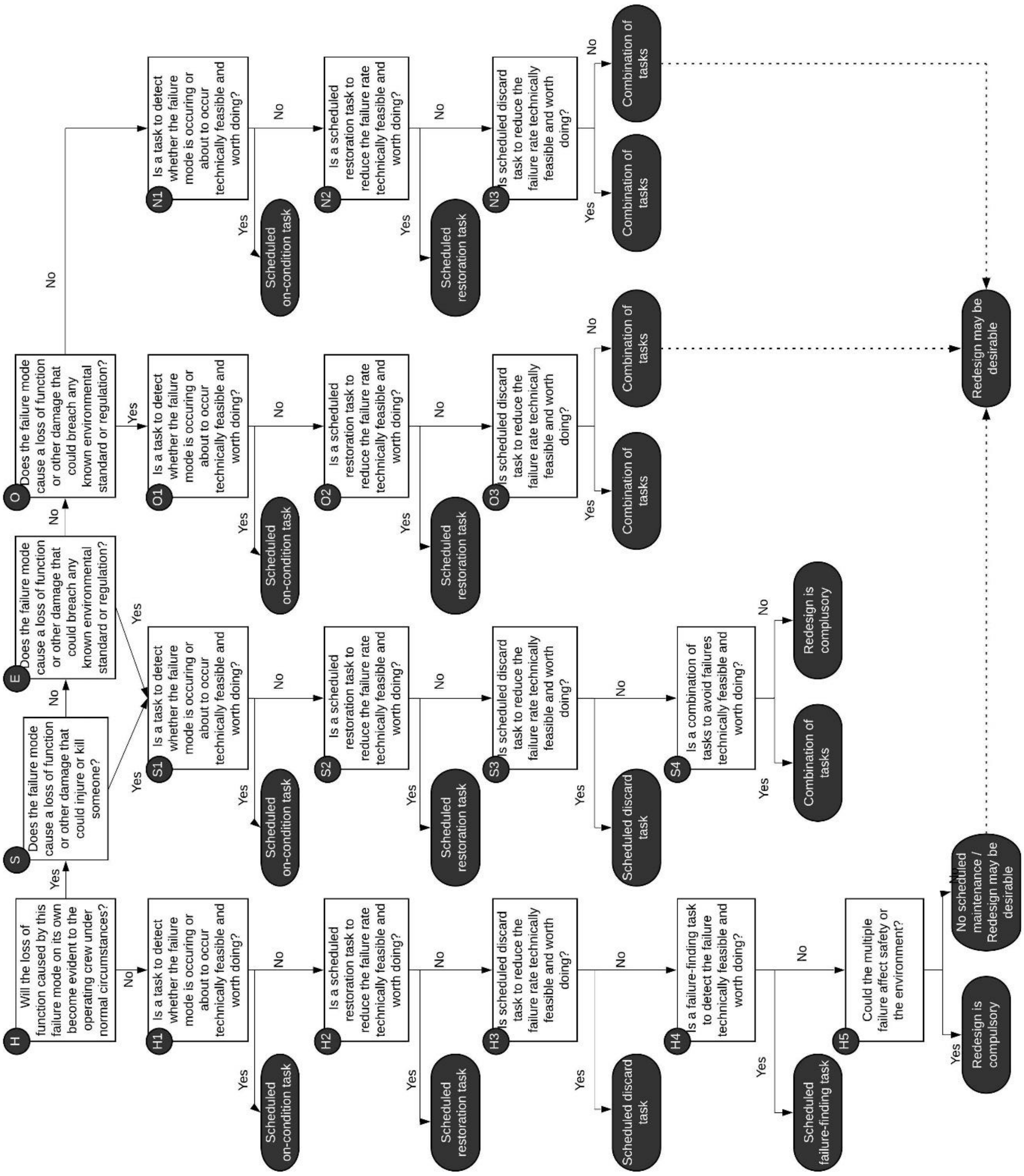

Table 21 The RCM decision diagram

4.6.1 Criteria for selection of maintenance tasks and maintenance interval

Rausand (1998) highlights two main criteria for selecting maintenance tasks. He claims that for a maintenance task to be considered suitable, it must be:

- **Applicable**: a quote from Hoch (1990) is used by Rausand (1998) and many other authors, and is very useful to clarify the applicability criteria in a very simple way: " A PM task is applicable if it can eliminate, or at least reduce the probability of occurrence to an acceptable level – or reduce the impact of failures!

- **Cost-effective**: when choosing a maintenance task, it is crucial to keep in mind that the cost of implementing it must not be more than the failure(s) it is going to prevent. Here it is possible to introduce a notion used in Economics, very useful to understand cost terms and to help in decision making:

  "The cost of doing anything consists of the receipts that could have been obtained if that particular decision had not been taken. (Coase, 1981 – mentioned by Zimmerman, 2011, p.23)."

Thus, Rausand (1998) complements saying that the cost of a PM task may include risks and costs to maintenance induced failures, the risk to personnel and to increase the likelihood of failure, unavailability during maintenance. In the other side, the costs of failure shall also be takenn into consideration. The Risk to safety and the possibility of violation of laws and regulations, damage to equipment and repairs are examples of costs related to failure, and that should be compared with the risk to implementing the PM task.

Regarding the determination of the maintenance interval, it is outside the scope of this thesis to develop or to use an existing maintenance optimization model to try to find a feasible maintenance interval for each of the critical failure modes. The still existent gap between theory and practice in the field of maintenance optimization does not make it appealing for application in real situations. Consequently, the suggestion of maintenance intervals will be based on the experience from the maintenance personnel and vessel superintendents. A recommendation for accessing the condition of the assets and its characteristics periodically in order to find a more precise P-F interval, that is, at each age the equipment start to show signs of failure will be given. It could later contribute for adjustments at the maintenance interval.

Hence the next step of the RCM process is to analyze all the critical failure modes through the decision diagram and register the results in the RCM decision worksheet.

4.6.2 RCM decision diagram applied to critical failure modes

1. **Failure mode:** Corrosion due to inefficient lubrication – **RPN (safety): 32**
    a. **Functional failure:** III.A) Wire rope rupture (or heavy wear without rupture)
    b. **Item / function:** III. Load wire rope

The first question of the RCM Decision Diagram is the following:

H: Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?

The load wire is one of the main components of the crane. If it ruptures, it will immediately be noticed by the operating crew. However, Internal corrosion is more challenging to detect than external corrosion, and they often happen together, although this might not always be obvious from a visual inspection of the rope (International Organization for Standardization, 2010, p.40). Thus, the answer to this question is YES. It leads to the following question:

S: Does the failure mode cause a loss of function or other damage that could injure or kill someone?

A rupture of a load wire rope, although unlikely to happen, could cause severe injuries to someone involved in the load operation. The answer is YES, and it leads us to question S1.

S1: Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?

According to the maintenance plan in force at Grieg Star, the load wire is replaced every 5th year, when the vessel is docking at the shipyard. However, many times, the wire is discarded still in good condition, which represents a wasteful and costly operation. Non-destructive (NDT) inspection of wire ropes able to measure the loss of metallic area (LMA) and reveal local flaws (LF) could be a solution for analyzing the wire (Intron). The general principle of the NDT consists of detection and evaluation of changes in the distribution of magnetic flux created by a magnetization system in a rope under test. Sukhorukov et al. (2014) explain that this change happens due to the irregularities on the wire rope, such as wire breaks or parts with corrosion or abrasive degradation. It is beyond the scope of this thesis to go deeper in detail in the electromagnetic inspection, see Sukhorukov et al. (2014) for further discussion.

Wires will deteriorate no matter what and have its elasticity reduced along its lifetime. However, a well-maintained wire can have its lifetime extended up to 300% if essential lubrication and relubrication is performed (Verope, 2019). Weischedel (2018) introduces the approach called Condition-Based Retirement Policy and associate it to the life of wire ropes and especially high-value ropes by several years, and possibly double their useful service life. Cost-effectivity for implantation of such a resource for condition-based replacement of wire should be evaluated.

S2: Is a scheduled restoration task to avoid failures technically feasible and worth doing?

Restoration task is not an option for load wire ropes once their original effectiveness and resistance to failure cannot be re-established.

S3: Is a scheduled discard task to avoid failures technically feasible and worth doing?

Scheduled discard is the policy that has been in force at Grieg Star. However, many times, the wires are discarded in good condition, and it is not cost-effective. Perhaps a replacement based in the condition of the wire could represent a good saving, but for it, the wire should be in such a condition that would not risk safety if the wire is to be replaced within some years.

S4: Is a combination of tasks to avoid failures technically feasible and worth doing?

According to DNV GL standard for lifting appliances (2016, p. 176), "wire ropes employed above deck shall be discarded at the latest after the following periods of employment, even when no external damage is visible:
— running rigging: 10 years
— standing rigging: 15 years."

It is unavoidable that wire ropes must be replaced at least every ten years, so it should be possible to ensure that the wire will be maintained in good conditions enough to be replaced as close as possible to the period established. For it, a combination of tasks seems to be the most suitable action for wire maintenance.

2. **Failure mode:** Heavy wear due to high contact pressure in sheave groove – **RPN (safety and economy): 32**
    a. **Functional failure:** III.A) Wire rope rupture (or heavy wear without rupture)
    b. **Item / function:** III. Load wire rope

H: Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?

Abrasive wear happens when a relatively hard surface scores a relatively soft surface. O' Connor (1991) explains that the wear process consists basically of a cutting action often with the displacement of the soft material at the sides of grooves scored in the soft material. Thus, progressing wear due to high contact with sheave grooves may become evident to the crew under normal circumstances.

S: Does the failure mode cause a loss of function or other damage that could injure or kill someone?

Heavy wear is a factor that can contribute to wire failure. Thus it represents a threat to safety.

S1: Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?

According to ISO (2010, p.11), measurement of the decrease in rope diameter is a way to assess the deterioration due to abrasive wear. In addition to that, the standard says that the assessment shall be registered as a percentage or according to a discard criterion (slight, high, very high or discard). In order to increase awareness of the crew when performing this assessment, a formal parameter should be created, so the crewmembers responsible for this task, could regardless their experience be able to perform the inspection. An example of a form created by the 2010 Standards for Care and Maintenance, Inspection and Discard of Cranes and Wire ropes, to record the assessment is on annex 2. The crane manufacturer suggests that a visual inspection is carried out every six months and includes some pictures on its manual examples of how wire damages should appear. The wire manufacturer, however, offers many more details about how to assess the wire conditions.

3. **Failure mode:** Deterioration of bracket, bolt, split pin, and locking nut.
   RPN (safety): 32
   a. **Functional failure:** VI.E) Bracket with sheave unsafely secured.
   b. **Item / function:** VI. Stab wire bracket with sheave: remain safely fast on the JIB structure

H: Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?

Yes.

S: Does the failure mode cause a loss of function or other damage that could injure or kill someone?

Deterioration of securing parts can happen for several reasons: cyclical stresses, wear, corrosion. Therefore, falling objects could eventually result in potential injury.

S1: Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?

The access to the components located on the JIB structure is physically challenging and time-consuming. An assessment of the brackets and small components condition should be carried out, so a rate of deterioration could be defined. When an average rate has been established, a scheduled discard could be determined.

4. **Failure mode:** Deterioration of wheels, bolts, pins, and bushing. – **RPN (safety): 32**
    c. **Functional failure:** VII.H) Power cable wheels unstable.
    d. **Item / function:** VII. Power cable wheels: remain safely secured on the JIB structure.

H: Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?

Yes.

S: Does the failure mode cause a loss of function or other damage that could injure or kill someone?

Deterioration of securing parts can happen for various reasons: cyclical stresses, wear, corrosion. Therefore, falling objects could eventually result in potential injury.

S1: Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?

The access to the components located on the JIB structure is physically challenging and time-consuming. An assessment of the wheels and small components condition should be carried out, so a rate of deterioration could be defined. When an average rate has been established, a scheduled discard could be determined.

5. **Failure mode:** Deterioration of wheels, bolts, pins, and bushing. – **RPN (safety): 32**
    a. **Functional failure:** VIII.H) Power cable wheels unstable.
    b. **Item / function:** VIII. Power cable wheels: remain safely secured on the JIB structure.

H: Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?

Yes.

S: Does the failure mode cause a loss of function or other damage that could injure or kill someone?

Deterioration of securing parts can happen for different reasons: cyclical stresses, wear, corrosion. Therefore, falling objects could eventually result in potential injury.

S1: Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?

The access to the components on the JIB is physically challenging and time-consuming. An assessment of the wheels and small components condition should be carried out, so a rate of deterioration could be defined. When an average rate has been established, a scheduled discard could be determined.

6. **Failure mode:** Damage on the wire during operations due to bad visibility from crane cabin. – **RPN (safety / economy): 24/36**
    a. **Functional failure:** III.B) Broken Wires
    b. **Item / function:** III. Load wire rope

H: Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?

Yes.

S: Does the failure mode cause a loss of function or other damage that could injure or kill someone?

Damage in the wire is a factor that contributes to wire failure; thus, it represents a threat to safety.

S1: Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?

Shore drivers operate the cranes and are usually supervised by the ship's crew to ensure that the equipment will not be damaged and that the cranes will be driven smoothly (Isbester, 1993, p. 271). However, only this action may not be enough to avoid damage to the wire rope.

S2: Is a scheduled restoration task to avoid failures technically feasible and worth doing?

Restoration task is not an option for load wire ropes once their original effectiveness and resistance to failure cannot be re-established.

S3: Is a scheduled discard task to avoid failures technically feasible and worth doing?

Wire ropes are discarded periodically, but this action does not contribute to avoiding damages due to insufficient situation awareness caused by lousy visibility from the crane cabin.

S4: Is a combination of tasks to avoid failures technically feasible and worth doing?

Changing anything is expensive, requires extensive planning (new parts, concerns, and maintenance tasks) and not necessarily will eliminate the problem (Moubray, 1997, p. 188). Investigating a new screen for the crane cabin so the crane driver could better position the cargo and avoid wire slacks is undoubtedly an interesting solution, but cost-effectivity shall be analyzed. Increasing awareness through better good communication between crane drivers and foreman also characterize a redesign, since it aims for improving the operation.

7. **Failure mode:** Corrosion, wear, and tear. – **RPN (safety / economy): 18/18**
    a. **Functional failure:** VI.C) Stab wire rupture
    b. **Item / function:** VI. Stab wire: contribute to the stability of the lifting block.

H: Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?

Yes.

S: Does the failure mode cause a loss of function or other damage that could injure or kill someone?

Yes, as related by the crew during the visit on board, the rupture of stab wire can result in a potential injury for someone involved in the cargo operation. Although the diameter of the stab wire is much smaller than the load wire rope, it is much more vulnerable to failure.

S1: Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?

The stab wire is not considered a critical component, although it contributes for a much more efficient load / offloading operation. As already mentioned about the components located on the JIB structure, the access to the stab wire is also troublesome. Furthermore, the item itself is not very expensive and readily available in the vessel warehouse. Thus an on-condition task is not evaluated as technically feasible.

S2: Is a scheduled restoration task to avoid failures technically feasible and worth doing?

No.

S3: Is a scheduled discard task to avoid failures technically feasible and worth doing?

If possible to determine at which age the stab wire becomes more vulnerable to rupture, a scheduled discard is a feasible task to be carried. So, for this age to be identified, assessments of the wire condition shall be carried out and recorded.

8. **Failure mode:** Power cable gets stuck on power swivel during operation. Crane operator cannot see the slack from the crane cabin – **RPN (economy): 32**
    a. **Functional failure:** VII. F) Power cable broke
    b. **Item / function:** VII. Power cable: send power to connected lifting equipment

H: Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?

Yes.

S: Does the failure mode cause a loss of function or other damage that could injure or kill someone?

No

E: Does the failure mode cause a loss of function or other damage that could breach any known environmental standard or regulation?

No

O: Does the failure mode cause a loss of function to have a direct adverse effect on operational capability (output, quality, customer service, or operating costs in addition to the direct cost of repair?)

Yes. Damage on the power cable can result in short off-hires in addition to the cost of spare parts.

O1: Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?

No.

O2: Is a scheduled restoration task to reduce the failure rate technically feasible and worth doing?

Restoration is not applicable to reduce the Likelihood of the Severity of this failure mode.

O3: Is a scheduled discard task to reduce the failure rate technically feasible and worth doing?

No. Discarding the power cable does regardless its condition does not reduce the possibility of it being damaged due to bad visibility from the crane cabin. A redesign to increase awareness of the crane operators or installing a screen in the cabin so that the crane operator can have a better view over the cable could contribute to reducing the possibility of this failure mode.

9. **Failure mode:** Signal cable gets stuck on power swivel during operation. Crane operator cannot see the slack from the crane cabin – **RPN (economy): 32**
    a. **Functional failure:** VIII. F) Power cable broke
    b. **Item / function:** VIII. Power cable: send power to connected lifting equipment

H: Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?

Yes.

S: Does the failure mode cause a loss of function or other damage that could injure or kill someone?

No

E: Does the failure mode cause a loss of function or other damage that could breach any known environmental standard or regulation?

No.

O: Does the failure mode cause a loss of function to have a direct adverse effect on operational capability (output, quality, customer service, or operating costs in addition to the direct cost of repair?)

Yes. Damage on the signal cable can result in short off-hires in addition to the cost of spare parts.

O1: Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?

No.

O2: Is a scheduled restoration task to reduce the failure rate technically feasible and worth doing?

Restoration is not applicable to reduce the Likelihood or the Severity of this failure mode.

O3: Is a scheduled discard task to reduce the failure rate technically feasible and worth doing?

No. Discarding the signal cable regardless its condition does not reduce the possibility of it being damaged due to bad visibility from the crane cabin. A redesign to increase awareness of the crane operators or installing protection at the end of the cable could perhaps reduce the cable failure incidence.

10. **Failure mode:** Shaft, nut and locking pin stuck on lifting block – **RPN (economy): 24**
    a. **Functional failure:** IV.C) Impossibility / difficult to connect or disconnect
    b. **Item / function:** IV. Lifting block: accommodate the steel wire and connects to the hook or the power swivel.

H: Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?

Yes.

S: Does the failure mode cause a loss of function or other damage that could injure or kill someone?

No

E: Does the failure mode cause a loss of function or other damage that could breach any known environmental standard or regulation?

No.

O: Does the failure mode cause a loss of function to have a direct adverse effect on operational capability (output, quality, customer service, or operating costs in addition to the direct cost of repair?)

Yes.

O1: Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?

No.

O2: Is a scheduled restoration task to reduce the failure rate technically feasible and worth doing?

Disassembly of the shaft on the power swivel/lifting assembly for cleaning, polishing, and greasing seems to be the most suitable action in order to avoid the bolt stuck on the structure. This maintenance task has already been inserted on the maintenance plan to be carried out every six months.

11. **Failure modes 14 & 15: Oil level in turbo coupling below the indicated.**
    RPN (economy): 24
    a. **Functional failure:** VII.B Too low pulling force on cable winch.
    b. Item / function: VII. Power cable winch: supply current to cargo handling equipment. / VIII. Signal cable winch: provide a signal to connected lifting equipment.

H: Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?

Yes.

S: Does the failure mode cause a loss of function or other damage that could injure or kill someone?

No

E: Does the failure mode cause a loss of function or other damage that could breach any known environmental standard or regulation?

No.

O: Does the failure mode cause a loss of function to have a direct adverse effect on operational capability (output, quality, customer service, or operating costs in addition to the direct cost of repair?)

Even small differences in the oil filling in the turbo coupling can result in significant variations on the winch pulling force. It can result in slack in the cable and consequential damages.

O1: Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?

On the turbo coupling, there is no sight glass to check the level of oil, nor there is a sensor to identify when the level is low. The use of a dipstick in this situation is not so practical to ensure the level of oil.

O2: Is a scheduled restoration task to reduce the failure rate technically feasible and worth doing?

No.

O3: Is a scheduled discard task to reduce the failure rate technically feasible and worth doing?

Discard in this situation is not an option, so no scheduled maintenance is the action according to the decision diagram. According to the original maintenance plan, oil on the turbo coupling is refilled every 24 months, following the instruction from the manufacturer. It can also be refilled if noticed too low pulling force.

4.7 Results

The outcome expected on this thesis is the recommendation of maintenance tasks, that result from the whole RCM process, which can contribute to reducing the chances of the critical failure modes to happen, or that can reduce its consequences. From the 85 failure modes collected, 15 were considered critical, representing either a threat to Safety or Economy. Since 3 of them were critical both for Safety and Economy, they were registered only once in the RCM Decision Worksheet. Thus, in total, 12 failure modes have been, and results are displayed in the next pages. Afterward, the implementation of the suggested maintenance tasks in the original maintenance plan is discussed.

RCM II Decision Worksheet			Plant: Crane Sub-system: Hoisting system							Facilitator: ______ Auditor: ______	Date: April/2019	
Information reference			Evaluation consequence				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default action					
F	FF	FM	H	S	E	O				H4	H5	S4	Proposed task	Initial Interval	Can be done by
III. Load wire rope	III.A) Wire rope rupture (or heavy fatigue)	1. Corrosion due to inefficient lubrication	y	y			n	n	n			y	Assess the wire condition using NDT. Discard the wire within less than 10 years.	1 year	Chief mate/ external wire tech.
III. Load wire rope	III.A) Wire rope rupture (or heavy fatigue)	2. Heavy wear due to high contact pressure in sheave groove	y	y			y						Carry out an assessment of the wire condition and record it.	1 year	Chief mate
VI. Stab wire bracket with sheave: remain safely fast on the JIB structure	VI.E) Bracket with sheave unsafely secured.	1. Deterioration of bracket,bolt, split pin and locking nut.	y	y			y						Carry out an assessment to check the condition of brackets, power, and signal cables wheel condition and record it.	1 year	Chief mate
VII. Power cable wheels: remain safely secured on the JIB structure	VII.H) Power cabe wheels unstable.	1. Deterioration of bolts, pins, brackets and bushing.	y	y			y						Carry out an assessment to check the condition of brackets, power and, signal cables wheel condition and record it.	1 year	Chief mate

Table 22 RCM II Decision worksheet - page 1/4

RCM II Decision Worksheet		Plant: Crane / Sub-system: Hoisting system											Facilitator: ___ / Auditor: ___	Date: April/2019	
Information reference			Evaluation consequence				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default action					
F	FF	FM	H	S	E	O				H4	H5	S4	Proposed task	Initial Interval	Can be done by
VIII. Signal cable wheels: remain safely secured on the JIB structure	VIII.H) Signal cable wheels unstable.	1. Deterioration of bolts, pins, brackets and bushing.	y	y			y						Carry out an assessment to check the condition of brackets, power, and signal cables wheel condition and record it.	1 year	Chief mate
III. Load wire rope	III.B) Broken wires	1. Damage on the wire during operations due to bad visibility from crane cabin.	y	y			n	n	n			n	Proposed modification: Installation of an extra screen so that the crane operator can have a better view of the cargo hold, wire, and cables.	N/A	External company
VI. Stab wire: ensure stability of lifting block	VI.C) stab wire rupture	2. Corrosion, wear and tear - normal deterioration .	y	y			n	n	s				Scheduled replacement of the stab wire. An initial interval shall be determined and assessment to help defining the useful life of the stab wire carried out. Thus, interval can be adjusted.	1 year	Chief mate

Table 23 RCM II Decision Worksheet page 2/4

RCM II Decision Worksheet			Plant: Crane Sub-system: _Hoisting system___										Facilitator: ______ Auditor: ______	Date: April/2019	
Information reference			Evaluation consequence				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default action					
F	FF	FM	H	S	E	O				H4	H5	S4	Proposed task	Initial Interval	Can be done by
VII.Power cable: send power to connected lifting equipment	VII.F) Power cable broken	2. Power cable gets stuck on power swivel during operation. Crane operator can't see the slack from the crane cabin.	y	n	n	y	n	n	n				Proposed modification: increase awareness of the crane operators regarding this problem through more effective pre-job meetings and effective communication deck x crane. The instalation of an extra screen could also could benefit to reduce the chances of this failure mode to happen.	N/A	QSMS department, Chief Off., deck team. For modification: External company.
VIII. Signal cable: send signal to connected lifting equipment	VIII.F) Signal cable broken	2. Signal cable gets stuck on power swivel during operation. Crane operator can't see the slack from the crane cabin.	y	n	n	y	n	n	n				Proposed modification: increase awareness of the crane operators regarding this problem through more effective pre-job meetings and effective communication deck x crane. The installation of an extra screen could also benefit from reducing the chances of this failure mode to happen.	N/A	QSMS department, Chief Off., deck team. For modification: External company.

Table 24 RCM II Decision worksheet page 3/4

RCM II Decision Worksheet			Plant: Crane										Facilitator: ___	Date: April/2019	
			Sub-system: Hoisting system										Auditor: ___		
Information reference			Evaluation consequence				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default action					
F	FF	FM	H	S	E	O				H4	H5	S4	Proposed task	Initial Interval	Can be done by
IV. Lifting block: accommodate the steel wire and connects to the hook or to the power swivel	IV.C) Impossibility /difficulty to connect or disconnect from the power swivel	1. Shaft, nut and locking pin stuck on lifting block.	y	n	n	y	n	y					To ensure that the power swivels can be disconnected. Pull out, clean, grease, and reassemble the shaft on the power swivel and lifting block.	6 months	2nd Engineer
VII. Cable winch: provide the supply of current to cargo handling equipment.	VII.B) Too low pulling force on cable winch	1. Oil level in turbo coupling under the indicated.	y	n	n	y	n	n	n				No scheduled maintenance other than refill the oil periodically.	Every 24 months according to the actual maintenance plan or shorter.	2nd Engineer
VIII. Signal cable winch: provide signal to connected lifting equipment	VIII.B) Too low pulling force on cable winch	1. Oil level in turbo coupling under the indicated.	y	n	n	y	n	n	n				No scheduled maintenance other than refill the oil periodically.	Every 24 months according to the actual maintenance plan or shorter.	2nd Engineer

Table 25 RCM II Decision Worksheet page 4/4

4.7.1 Treatment of the non-critical failure modes

73 of 85 failure modes had an RPN lower than 18, and therefore, were not considered critical and did not proceed to the RCM Decision Diagram. Rausand's (1998) suggestion is that in this case, systems already having a maintenance program, a cost evaluation should be carried out. If the current maintenance costs with regards to the non-critical failure modes are acceptable, it is reasonable to continue the program.

4.8 Implementation of RCM

Having concluded the analysis of the RCM process, that started with system selections and definitions and concluded with the task proposition, it is now time for implementing the changes in the existing maintenance plan. At this phase of the process, Smith & Hinchicliffe (2003, p. 184) remind the maintenance practitioners that RCM execution is not a one-time execution, but a once-through event. They say that RCM should be taken as a paradigm shift in how maintenance is perceived and executed.

Rausand (1998) claims that for effective implementation of the result from the RCM analysis, it is essential to ensure that organizational and technical maintenance support functions are available. On the same line of though Smith & Hinchicliffe (2003, p.188) says that a successful implementation requires adequate planning. Here it is introduced the Deming quality wheel – Plan, Do, Check, Act (PDCA) as a way to structure RCM implementation.

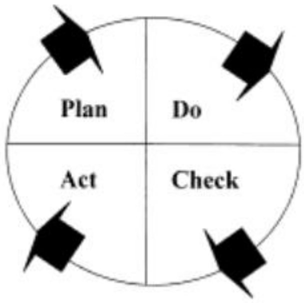

Figure 13 The Deming quality wheel - PDCA (Smith & Hinchicliffe, 2003, p. 189)

- **Plan:** four questions should guide RCM implementation:
  a) What is the end goal?
  b) What resources (workforce, materials, tools, commitments, buy-in, money) will be needed?
  c) How will the resources be secured?
  d) What hazards could come along the way?

- **Do:** Soonest the plan is ready; it shall be put into practice.
- **Check:** RCM is a continuous process, and checking is a necessary task that shall be performed. The object for check must be the results obtained from implementation, what could be improved, for example, maintenance schedules. Moubray (1997, p.215) says that the last step of the RCM audit is the RCM audit, and audits should consist in reviewing the method that RCM been applied and that the correct information has been gathered.
- **Act:** After the opportunity for improvements is identified, Act means implementing the new plan with the changes that are necessary to ensure the expected outcome from the RCM process.

5 Discussion

5.1 What RCM achieves

One of the main advantages of the RCM process is the understanding of each function of the crane system and what is necessary to ensure that each component will continue to perform its function as expected. The course of the RCM process allows the people involved to increase their knowledge about how the crane system works, to share their experiences with failure modes that have happened and to bring up ideas and solutions to reduce effects and consequences of some failure modes. According to Moubray (1997, p.292), the RCM process tends to improve teamwork between maintenance, operation, and management teams, and to result in the following outcomes:

- **The longer useful life of expensive items:** RCM aims for maximizing the life-time of the components through on-condition maintenance. In the RCM process carried out, it was identified that the use of NDT for wire rope inspections could potentially contribute to postponing the disposal of good wire ropes without representing a threat to safety.
- **A maintenance database:** the maintenance tasks are directly correlated with the component function and to a failure mode. The RCM database is also a valuable resource for new staff, that can become familiar with the crane system function, failure modes, effects, and how to prevent them.
- **Identification of areas that requires redesign:** some failure modes such as "damage of wire rope due to bad visibility from crane cabin" and "signal/power cable gets stuck on the power swivel" cannot benefit from any of the existent maintenance tasks. In these situations, an increase of situation awareness using an extra screen in the crane cabin so that the crane operator can follow up the deployment of the load in the cargo hold and the slack of the wire ropes and cables. Recommendations for emphasis in more effective communication between crane operator and deck have also been given.
- **Greater safety:** RCM wants to ensure that safety and environment are maintenance priorities, and it does not tolerate inaction to failure modes that can affect safety, and environment. As a result of the RCM process,a detailed assessment of the condition of wire ropes, sheaves, and its supporting structure is suggested. Here, an extra focus on stab wire was proposed, once it is not recognized as a critical component. It is also recommended the identification of the P-F interval for replacement of the stab wire to avoid its rupture and possible accident if it attains someone.

These are only some of the benefits that RCM can provide if the proposed tasks are implemented to the original maintenance plan, but much more can be accomplished. Moubray (1997, p.308-315) claims that if the method is correctly applied, can actively contribute to less routine maintenance by, for example, the reduction of routine maintenance frequency. It can also motivate crewmembers through the increase of knowledge about the system in general, develop their sense of ownership, and help them to have a quicker failure diagnosis since the FMECA can put together failure modes experienced in the different vessels from the class-L.

5.2 Continuousness of RCM

In the end, RCM constitutes a framework for maintenance strategy that involves everyone part of system maintenance and operation. However, for the effective outcome of the process, it shall be reviewed periodically (Moubray, 1997, p.284). The SAE JA 1011 admits that the initial analysis of RCM can be imprecise and with lack of important data from the assets. Also, performance expectations can change, and maintenance resources improve. Therefore, it is recommended periodic reviews, so overlooked failure modes and new ones can be included in the FMECA, evaluation of age-condition carried out, and no longer needed tasks can be eliminated (Nowlan & Heap, 1978, p. 367).

5.3 Limitations

The RCM approach requires that both operators and maintenance people attend the meeting and discussions concerning the determination of function, performance, and consequence of failure modes. However, in the shipping industry, where vessels managers and crane operators are sitting in different parts of the globe, it may be quite challenging to achieve. For this thesis, to reduce the impacts of this constraint, meetings were held at Grieg's office with vessel managers, and a trip to vessel Star Luster equipped with electrical cranes was taken. On board, interviews were held with the crew responsible for operation and maintenance to collect their opinion about effects and consequences of some failure modes, as well as to gather information about what challenges they face with the maintenance tasks, and what could be improved.

Another limitation is that reporting of unexpected/corrective maintenances inserted by the crew in the CMMS system when a corrective failure occurs is many times not enough detailed or not reported at all. Thus, it becomes unattainable to make evaluations and give recommendations with a basis in quantitative methods such as MTBF, since it cannot be precisely determined.

According to the RCM theory, frequency of on-condition tasks must be based on P-F intervals, that means how quickly the equipment will fail, and it starts to show signs of failure. Therefore, it will be recommended procedures to help to determine P-F interval to the components that require on-condition tasks.

5.4 Discussion and recommendation

RCM aims to achieve higher safety, environmental, integrity, and improved performance with a longer useful life of the assets and reduced waste of resources. With this objective in mind, the RCM process was applied to the mechanical systems related to the hoisting function of the electrical cranes used on board the class-L of Grieg Star fleet.

The outcome from the RCM decision tool, where the failure modes considered critical according to the RPN value was analyzed, resulting in the following recommendations for improvement of the original maintenance plan:

- The implementation of the proposed tasks listed on tables 22, 23, 24, and 25 in the company's current maintenance plan;
- The creation of specific parameters for assessment of wire, sheaves, and securing structures as exemplified on annex II. Such assessment can contribute to establish P-F intervals for condition-based maintenance and to help to find the age in which items such as stabilizing wire and sheaves exhibit an escalation in the possibility of failure.
- The installation of a camera towards the lifting block and a screen in the crane cabin. These actions would enable crane operators monitoring slacks in the wire, power and signal cables and consequently mitigate the possibility of damage on wire and cables and the consequences it involves. It can be combined with an emphasis on increasing crane operator situation awareness using more effective radio communication with the operational team on deck.

- The evaluation of the cost-benefit of acquiring NDT technology for the steel wire ropes in order to avoid wasting resources, when it is possible to use them up to 10 years according to the Class Society.
- To create a campaign where the people responsible for reporting corrective maintenance and downtimes put their best efforts at specifying the nature of failure, which component has failed and how long time was necessary to fix the problem.

6 Challenges of RCM

The RCM process is long and demanding. The systematic steps that constitute the RCM method can give great results, but achieving it is not easy. One of the challenges at performing RCM for this thesis started early, at the system breakdown phase. Choosing the appropriate level at a manageable level to perform the analysis was quite complicated. Which level should be chosen? The component level down to screws and o-rings? Alternatively, should the item level be enough? The point here is that, sometimes, when discussing the failure modes, some of the causes that result in the functional failure are due to a very low-level component. One example of it is the "impossibility/difficulty to disconnect power swivel from lifting block." The cause of this failure is merely shaft, nut, and locking pin that becomes stuck on the lifting block. Nevertheless, it is a failure mode that can result in many hours downtime and arduous work to make this disconnection. Thus, for this thesis, it was identified the necessity to make a system breakdown until the lowest level, so even essential components could get the necessary attention.

Another challenge during the process was how deep in details at describing the failure modes one should go. As Moubray (1997, p.69) explains, the process of drilling down to find out the root cause of a failure mode could continue almost forever, and the failure mode should be identified at a level that is possible to identify an applicable failure management policy.

Moving forward in the process, the people involved in the course of RCM change. Not always the entire RCM review group will be able to meet, either due to other priorities or because they will be engaged in another activity and so on. In addition to that, Operation and Maintenance people from shipside will not most likely be able to join the RCM review meetings. Ship management and ship operators are in different parts of the world, and even when Vessel Managers visit the vessel, it is busy, the operation does not stop for meetings.

Mokashi et al. (2002) in their study of Reliability-centred in maritime operations point some obstacles of applying the method in the shipping industry that has also been identified throughout this thesis:

- **Lack of failure data:** failure data such as example, MTBF, or how long time was necessary to fix a failure is not available in the databank. It is also unclear if all the unexpected/ corrective maintenances have been reported on the CMMS.
- **Ships are not close to spare facilities and shipyards:** when proposing tasks for some failure modes, it should be taken into consideration that not all ideal resources will be available neither it is so practical to obtain some spare parts.
- **Recommendations from equipment suppliers have to be followed in the guarantee period:** although some policies recommended by the manufacturer can sound excessive, as, replacing brake discs every 5th year, not following them can result in loss of guarantee in case of a claim.
- **Ship's crew changes:** Mokashi et al. (2002) claim that "there is a need to lay down clear guidelines on the way analysis is to be carried out to prevent inconsistent outcomes of the analysis of the same system carried out by different teams. From here, it is possible to understand that clear guidance should be established in order to clarify to the seafarers what kind of information should be included when reporting failure on the CMMS. Consequently, everyone could follow the same guideline, regardless of experience and which shift is on board.

7 Conclusion and Recommendations

Maintenance plans are still today very much based on manufacturers recommendation. However, it does not seem to be enough to avoid critical functional failures to happen and consequently, accidents and off-hires. The RCM approach is a method that aims to support decision making at systematically identifying maintenance tasks, taking into consideration the function of the component and the consequences that the functional failure entails. The RCM maintenance philosophy was developed and used since the '70s in the Aircraft and Aerospace, Nuclear and Oil and Gas Industries.

In this thesis, the RCM approach has been described and afterward applied to the function Hoisting of electrical cranes used at the Class-L of vessels from Grieg Star. The course of the RCM process included the definition of the operational context, system selection, and definition, FMECA, critical failures selection, selection of maintenance actions and determination of intervals. In total, 85 failure modes were included in the FMECA, 12 of them considered critical according to the tri-dimensional risk indexing carried out and taken further to the RCM decision diagram.

It is expected that the first RCM analysis will not be perfect. That some failure modes are overlooked or others that are unlikely to happen have been included in the analysis. Moreover, that is why many specialists call RCM as a living program, that must be reviewed and renewed so improvements can be carried out periodically.

Proposed tasks based on the RCM framework were recommended to be included in the current maintenance plan at Grieg Star. The nature of the tasks recommended is either Scheduled On-condition, Scheduled Restoration, Scheduled Discard, Combination of tasks, Redesign, or No Scheduled Maintenance. Those tasks aim for the longer useful life of expensive items, greater safety, and better crane availability. Some of the maintenance actions suggested are:

- The assessment of the steel wire rope condition using NDT. Discard of the wire within less than ten years. It intends to maximize the use of the steel wire rope and to avoid the waste of useful resources. Safety remains the priority, and it complies with the standard for lifting appliances (DNV GL, 2016);
- The creation of a specific assessment for wire rope condition to help to determine P-F intervals for Condition-based maintenance;

- Redesign through the installation of a camera towards the lifting block and a screen in the crane cabin. It can contribute to the increase of situation awareness of the crane operator and consequently, to reduce the possibility of damages to the power and signal cable when it gets stuck on the power swivel, and damages on the steel wire rope when it touches sharp edges of the cargo hold.
- The Scheduled Discard of the stab wire; Observation shall be done so the interval for replacement can be adjusted.

Recommendations for further analysis of the functions slewing, luffing, control system, and crane structure, are given so that the whole crane system can benefit from the RCM strategic framework. Crewmembers should also learn the RCM concept. Participating in the RCM process can raise their sense of ownership and make them share what they have learned from the different troubles they face on board. Further recommendation for determination of P-F intervals for the items that are an object for condition-based maintenance has also been presented.

8 References

ALADON. 2016. Reliability Centered Maintenance (RCM3 Tm) - The Aladon Network. Taken from: https://pdfs.semanticscholar.org/0af6/e9a208eb26eda058f50825424d4ba04d8351.pdf?_ga=2.101053445.527606897.1553248516-1101661524.1549735973 on March 22nd, 2019.

Borges, V. (2015, August 10th). Opportunistic Maintenance. Digitalization and Software solutions. Blog DNV GL. Taken from: https://blogs.dnvgl.com/software/2015/08/opportunistic-maintenance/ on March 03rd, 2019.

Carretero, J. García, F., Pérez M., Pena. J.M., Pérez, J.M, Cotaina, N., Matos, F., Chabrol, J., Djeapragache, Prete, P. (2000, January). Study of Existing Reliability Centered Maintenance (RCM). Approaches used in different industries. Facultad de Informática - Universidad Politécnica de Madrid.

Dekker, R. (1996). Applications of maintenance optimization models: a review and analysis. Reliability Engineering and System Safety 51 (1996) 229-240. Elsevier Science Limited.

DNV GL. (2016, May). Standard for Shipboard Lifting Appliances - DNV GL - ST - 0377. Taken from: https://rules.dnvgl.com/docs/pdf/DNVGL/ST/2016-05/DNVGL-ST-0377.pdf

Grieg Star. Environment. Taken from https://www.griegstar.com/csr/environment/ on May 05th, 2019.

International Organization for Standardization. (2010). Cranes - Wire ropes - Care and Maintenance, Inspection and Discard, Fourth Edition_(ISO Standard 4309:2010E). Retrieved from: https://krok.biz/info/file_download/361/ISO_4309_2010.pdf

Intron. Non-destructive Inspection of Wire Ropes. Taken from: https://www.intron.ru/en/img/PRESS/BROSHURE/ENG/Intron_broshura_Non-Destructive_Inspection_of_Steel_Wire_Ropes_prew.pdf on April 06th, 2019

Isbester, J. Captain. (1993). Bulk Carrier Practice. The Nautical Institute, UK.

Kristiansen, S. (2005). Maritime transportation. Safety Management and Risk Analysis. Elsevier Butterworth, UK.

MacGregor. (2016). Instruction and Spare Parts Manual. Crane type GLE 7526/MLC/6030-2/4530gr. Project No. 2/10034.04RHM. Not published material, made available by Grieg Star.

MacGregor. (2019, February 01st). GLE Cargo crane. Retrieved from: https://www.macgregor.com/Products-solutions/products/cargo-cranes2/gle-cargo-crane/ on February 01st, 2019.

Manuele, F. (2014). Advanced Safety Management: Focusing on Z10 and Serious Injury Prevention, Second Edition. John Wiley & Sons, Inc.

Márquez, A. C. (2007). The Maintenance Management Framework. Models and Methods for Complex Systems Maintenance. Springer-Verlag London.

Mohr, R.R. (2002, February). Failure Mode and Effect Analysis. 8th Edition. Jacobs Sverdrup. Retrieved from: http://tid.uio.no/kurs/fys4260/fmea-Sverdrup.pdf

Mokashi, A., Wang, J., Vermar, A. (2002, February 7th). A Study of Reliability-centred Maintenance in Maritime Operations. Marine Policy 26 (2002) 325-335.

Moubray, J. (1997). Reliability-centered maintenance. 2nd Edition. Industrial Press, New York.

Nowlan, F.S. and Heap, H.F. (1978). Reliability-centered Maintenance. Springfield, Virginia: National Technical Information Service, US Department of Commerce. 1978

O'Connor, Patrick. (1991). Practical Reliability Engineering. Third Edition. British Aerospace (Dynamics) plc, Stevenage. John Wiley & Sons, England.

Oxford dictionaries. (2019). Retrieved from: https://en.oxforddictionaries.com/definition/maintenance

Rausand, M., Øien, K. (1996). The basic concepts of failure analysis. Department of Production and Quality Engineering, Norwegian University of Science and Technology, Norway. SINTEF Safety and Reliability, Trondheim, Norway. Reliability Engineering and System Safety 53 (1996) 73-83. 1996 Elsevier Science Limited.

Rausand. M. (1998). Reliability Centered Maintenance. Reliability Engineering and System Safety. Elsevier Science Limited.

Rosenblum G.R., Lapp S.A. (1989) The Use of Risk Index Systems to Evaluate Risk. In: Bonin J.J., Stevenson D.E. (eds) Risk Assessment in Setting National Priorities. Advances in Risk Analysis, vol 7. Springer, Boston, MA. Taken from: https://link.springer.com/chapter/10.1007/978-1-4684-5682-0_17#citeas

SAE JA 1011. (1999, August). Surface Vehicle / Aerospace Standard Criteria for Reliability-Centered Maintenance (RCM) processes. Retrieved from: http://dl.mpedia.ir/e-books/25-[SAE]SAE-JA1011-RCM[mpedia.ir].pdf on February 01st, 2019.

Smith, A., Hinchicliffe, G. (2003). RCM. Gateway to World Class Maintenance. Elsevier Science & Technology, USA.

Sukhorukov, V., Slesarev, D., Vorontsov, A. (August, 2014). Electromagnetic Inspection and Diagnostics of Steel Ropes: Technology, Effectiveness, and Problems. Research gate - MeTechnical Paper. Retrieved from: https://www.researchgate.net/publication/287753004_Electromagnetic_Inspection_and_Diagnostics_of_Steel_Ropes_Technology_Effectiveness_and_Problems on April 18th, 2019.

The Nautical Institute. (2012). MARS - The Mariner's alerting and Reporting scheme - 201244 - Reduction of crane's SLW in grab mode. Retrieved from https://www.nautinst.org/en/forums/mars/mars-2012.cfm/201244 on February 8th, 2019.

Thomas, É., Levrat, É., Iung, B. (2008). Overview of Opportunistic Maintenance. 9th IFAC Workshop on Intelligent Manufacturing Systems. Szczecin, Poland, October 9-10, 2008. Taken from: https://www.sciencedirect.com/science/article/pii/S1474667015355737 on March 03rd, 2019.

US Department of Defence. (1990). MIL-STD-1629A. Military Standard - Procedures for Performing a Failure Mode, Effects, and Criticality Analysis. Department of Defence, Washington DC.

Vatn, J. (2007). Compedium: Veien frem til "World Class Maintenance": Maintenance Optimization. NTNU-Trondheim. Retrieved from: http://folk.ntnu.no/jvatn/pdf/MaintenanceOptimisationWCM.pdf on April 11st

Verma, A., Ajit, S., Karanki, D. (2016). Reliability and Safety Engineering. 2nd Edition. Springer Series in Reliability Engineering.

Verope. (2019, April). Technical brochure special wire ropes. Taken from: https://verope.com/wp-content/uploads/2019/03/190326_Techn_Broschu_COVER_EN.pdf on April 06th, 2019.

Watson, C. (2011, Sep). Conference Paper: Risk Assessment using the Three Dimensions of Probability (Likelihood) Severity, and Level of Control. Retrieved from: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100024129.pdf on May 16th.

Weischedel, H. (2018). Magnetic Wire Rope testing (MRT) 2018: The state of art. NDT technologies, INC - Wire rope non-destructive evaluation. Unpublished material. South Windsor, CT.

Zimmerman, J. (2011). Accounting for Decision Making and Control. 7th Edition. McGraw-Hill Irwin. New York-NY.

Appendix I

The hierarchical numbering system for the sub-system Hoisting

Hoisting system			
Level 2	**Level 3**	**Level 4**	**Level 5**
10.11 Hoisting winch	10.11.01 Gear complete	10.11.01.001 Sealing band	
		10.11.01.002 Locking band	
		10.11.01.003 socket	
		10.11.01.004 shaft	
		10.11.01.005 bearing	
	10.11.02 Drive in, complete	10.11.02.001 Drive in	10.11.02.01.001 driving sleeve
			10.11.02.01.002 washer
			10.11.02.01.00 screw
			10.11.02.01.004 shaft sealing
			10.11.02.01.005 washer
			10.11.02.01.006 disc carrier
			10.11.02.01.007 pressure unit
			10.11.02.01.008 driving sleeve
			10.11.02.01.009 shim
			10.11.02.01.010 circlip
			10.11.02.01.011ventilation filter
			10.11.02.01.012 washer
			10.11.02.01.013 screw
			10.11.02.01.014 coupling
			10.11.02.01.015 spider
			10.11.02.01.016 multiple discs, outer
			10.11.02.01.017 multiple disc inner
			10.11.02.01.018 spring
			10.11.02.01.019 spring
		10.11.02.002 Bevel Gear, complete	10.11.02.02.001 bearing
			10.11.02.02.002 bearing
			10.11.02.02.003 O-ring
			10.11.02.02.004bearing
			10.11.02.02.005 shaft sealing
			10.11.02.02.006 key
			10.11.02.02.007o-ring

			10.11.02.02.008 O-ring
			10.11.02.02.009 shim
			10.11.02.02.010 shim
			10.11.02.02.011 shim
			10.11.02.02.012 shim
			10.11.02.02.013 sealing
			10.11.02.02.014 coupling
			10.11.02.02.015 sealing
			10.11.02.02.016 restriction
			10.11.02.02.017 O-ring
			10.11.02.02.018 sealing
			10.11.02.02.019 coupling
			10.11.02.02.020 key
			10.11.02.02.021 key
			10.11.02.02.022 piping system
			10.11.02.02.023 thermo switch
			10.11.02.02.024 pin
			10.11.02.02.025 screw
			10.11.02.02.026 stopper
			10.11.02.02.027 sealing
			10.11.02.02.028 O-ring
			10.11.02.02.029 screw
			10.11.02.02.030 screw
			10.11.02.02.031 screw
			10.11.02.02.032 screw
			10.11.02.02.033 screw
			10.11.02.02.034 coupling
			10.11.02.02.035 coupling
			10.11.02.02.036 coupling
			10.11.02.02.037 coupling
			10.11.02.02.038 sealing
			10.11.02.02.039 pressure switch
			10.11.02.02.040 plug
			10.11.02.02.041 oil sight glass
			10.11.02.02.042 sealing
			10.11.02.02.043 plug
			10.11.02.02.044 plug, magnetic
			10.11.02.02.045 shim
			10.11.02.02.046 washer
			10.11.02.02.047 shim
			10.11.02.02.048 shim
		10.11.02.003 Oil tank	10.11.02.03.001 Oil tank
			10.11.02.03.002 screw

			10.11.02.03.003 ventilation filter
			10.11.02.03.004 temperature switch
			10.11.02.03.005 hose
			10.11.02.03.006 coupling
			10.11.02.03.007 coupling
			10.11.02.03.008 coupling
			10.11.02.03.009 hose
			10.11.02.03.010 oil heater
			10.11.02.03.011 oil sight glass
	10.11.03 Bevel gear, complete	See 10.11.02.002	
	10.11.04 Flange, complete	10.11.04.001 bearing	
		10.11.04.002 washer	
		10.11.04.003 circlip	
		10.11.04.004 pin	
		10.11.04.005 driver	
		10.11.04.006 screw	
		10.11.04.007 felt strip	
		10.11.04.008 grease nipple	
		10.11.04.009 screw	
		10.11.04.010 screw	
		10.11.04.011 O-ring	
	10.11.05 Oil pipe	10.11.05.001 oil dipstick	
		10.11.05.002 sealing	
		10.11.05.003 screw	
		10.11.05.004 plug	
		10.11.05.005 nut	
		10.11.05.006 sealing	
		10.11.05.007 sealing	
		10.11.05.008 ventilation	
		10.11.05.009 sealing	
	10.11.06 Oil pump		
	10.11.07 Small parts	10.11.07.001 6 x screw	
		10.11.07.002 24 x screw	
		10.11.07.003 24 x washer	
		10.11.07.004 2 x spacer	
		10.11.07.005 2x spacer	
		10.11.07.006 4x washer	
		10.11.07.007 4 nut x item 309	
		10.11.07.008 4 washer	
		10.11.07.009 4 x screw	

		10.11.07.010 4xscrew	
		10.11.07.011 4xwasher	
		10.11.07.0121 x cable fixing	
		10.11.07.013 5xscrew	
		10.11.07.014 48 x screw	
10.12 Electric motor	10.12.01 Electric motor, hoisting	10.12.01.001 incremental encoder	
		10.12.01.002 flexible coupling	
10.13 Brake unit		10.13.01.001 Level and temperature sensor	
		10.13.01.002 Oil filter	
		10.13.01.003 Pressure sensor	
		10.13.01.004 Directional valve	
		10.13.01.005 Filter indicator	
		10.13.01.006 Electric motor	
		10.13.01.007 Hydraulic pump	
		10.13.01.008 Gasket set	
		10.13.01.009 Brake unit, pressure switches	
10.14 Load wire rope /hoisting wire)			
10.15 Cargo handling gear	10.15.01 Lifting block	10.15.01.001 Sheave, complete	
		10.15.01.002 roller bearing	
		10.15.01.003 circlip	
		10.15.01.004 spacer, complete	
		10.15.01.005 hook	
		10.15.01.006 safety launch, kit	
		10.15.01.007 bolt, complete	
		10.15.01.008 split pin	
		10.15.01.009 grease nipple	
		10.15.01.010swivel complete	

		10.15.01.011 bolt, complete	
		10.15.01.012 shaft	
		10.15.01.013 retainer	
		10.15.01.014 screw	
		10.15.01.015 lifting eye bolt	
10.16 Lifting unit assembly	10.16.01 Lifting unit	10.16.01.01 lock	
		10.16.01.02 stay assembly	
		10.16.01.03 washer	
		10.16.01.04 locking unit	
		10.16.01.05 key	
		10.16.01.06 split pin	
		10.16.01.07 stay assembly	
		10.16.01.08 case	
		10.16.01.09 split pin	
		10.16.01.10 chain	
		10.16.01.11 stay	
		10.16.01.12 chain	
		10.16.01.13 shaft	
10.17 power swivel assembly	**10.17.001 slewing bearing assembly**	10.17.01.001 screw	
		10.17.01.002 washer	
		10.17.01.003 molykote 1000	
		10.17.01.004 slewing bearing	
	10.17.002 slewing gear assembly	10.17.02.001 slewing gear	10.17.02.001 drive in
			10.17.02.002 plug, magnetic
			10.17.02.003 sealing
			10.17.02.004 plug
			10.17.02.005 sealing
			10.17.02.006 plug
			10.17.02.007 sealing
			10.17.02.008 sealing
			10.17.02.009 ventilation filter
			10.17.02.010 sealing
			10.17.02.011 washer
			10.17.02.012 screw
			10.17.02.013 washer
			10.17.02.014 nut
	10.17.003 cover		

	10.17.004 shackle		
	10.17.005 plate		
	10.17.006 screw		
	10.17.007washer		
	10.17.008 screw		
	10.17.009 washer		
	10.17.010 screw		
	10.17.011 locking nut		
	10.17.012 rubber cloth		
	10.17.013 plate		
	10.17.014 locking nut		
	10.17.015 screw		
	10.17.016 screw		
	10.17.017 driver		
	10.17.018 plate		
	10.17.019 el. Assistance power swivel	10.17.19.001 junction box CT91	
		10.17.19.002 junction box CT92	
		10.17.19.003 junction box CT 94	
		10.17.19.004 slipring device	
		10.17.19.005 connector	
		10.17.19.006 cable protection	
		10.17.19.007 cab bus cable	
		10.17.19.008 connector	
		10.17.19.009 connector	
		10.17.19.010 electric motor	
		10.17.19.011 encoder	
		10.17.19.012 gyro	
		10.17.19.013 heater cable	
	10.17.020 fender assembly		
	10.17.03 shaft		
	10.17.04 shaft nut		
	10.17.05 split pin		
	10.17.06 shaft		
	10.17.07 cover		
	10.17.08 washer		
	10.17.09 screw		
	10.17.10 grease nipple		
	10.17.11 cover		
	10.17.12 washer		

	10.17.13 wire rope sheave		
	10.17.14 screw		
10.18 stab winch assembly	10.18.01 stab winch		
	10.18.02 small parts	10.18.02.001 screw	
		10.18.02.002 screw	
		10.18.02.003 screw	
		10.18.02.004 washer	
		10.18.02.005 screw	
		10.18.02.006 washer	
	10.18.03 electric motor		
	10.18.04 Gear complete		
	10.18.05 Drive in		
	10.18.06 bevel gear		
10.19 cable winch assembly signal	10.19.01 cable assembly signal	10.19.01.001 Connector	
		10.19.01.002 joint sleeve	
		10.19.01.003 shrinking hose	
		10.19.01.004 cable protection	
		10.19.01.005 cable laying	
		10.19.01.006 hose clip	
		10.19.01.007 cable	
		10.19.01.008 shackle	
		10.19.01.009 joint sleeve	
		10.19.01.010 shrinking hose	
		10.19.01.011 cable gland	
		10.19.01.012 electric motor	
		10.19.01.013 brake	
		10.19.01.014 hydraulic turbo coupling	
		10.19.01.015 spur gear	
		10.19.01.016 slipring unit	
		10.19.01.017 cable drum	
	10.19.02 cable winch signal		
	10.19.03 shrinking hose		
	10.19.04 shrinking hose		
	10.19.05 cable		
	10.19.06 cable		
	10.19.07 locking nut		
	10.19.08 cable gland		
	10.19.09 cable gland		

	10.19.10 cable terminal		
	10.19.11 cable terminal		
10.20 cable winch assembly, power	10.20.01 cable assembly, power	10.20.01.001 Connector	
		10.20.01.002 joint sleeve	
		10.20.01.003 shrinking hose	
		10.20.01.004 cable protection	
		10.20.01.005 cable laying	
		10.20.01.006 hose clip	
		10.20.01.007 cable	
		10.20.01.008 shackle	
		10.20.01.009 joint sleeve	
		10.20.01.010 shrinking hose	
		10.20.01.011 cable gland	
	10.20.02 cable winch power	10.20.02.001 Gearbox, complete	
		10.20.02.002 oil sight glass	
		10.20.02.003 plug	
		10.20.02.004 air ventilation plug	
		10.20.02.005 sealing	
		10.20.02.006 electric motor	
		10.20.02.007 V-belt sheave	
		10.20.02.008 V-belt	
		10.20.02.009 holding brake	
		10.20.02.010 brake disc	
		10.20.02.011 sealing	
		10.20.02.012 cover	
		10.20.02.013 cover	
		10.20.02.014 sealing	
		10.20.02.015 sealing	
		10.20.02.016 V-belt sheave	
		10.20.02.017 turbo coupling, complete	
		10.20.02.018 Oil filling plug	
		10.20.02.019 cover	
		10.20.02.020 sealing	
		10.20.02.021 protective device	
		10.20.02.022 Twisting sleeves	

		10.20.02.023 cable gland	
		10.20.02.024 cover	
		10.20.02.025 clamp	
		10.20.02.026brush holder , earth	
		10.20.02.027 Brush holder, phase	
		10.20.02.028 Brush holder, phase	
	10.20.03 shrinking hose		
	10.20.04 shrinking hose		
	10.20.05 cable		
	10.20.06 cable		
	10.20.07 locking nut		
	10.20.08 cable gland		
	10.20.09 cable gland		
	10.20.10 cable terminal		
	10.20.11 cable terminal		

Table 26 System breakdown of the sub-system Hoisting – Hierarchical numbering

Appendix II

Example of inspection form for wire rope inspection

ISO 4309:2010(E)

Annex D
(informative)

Typical examples of inspection record

D.1 Single record

Crane reference ....

Rope application ....

Rope details ....

Brand name (if known) ....

Nominal diameter....................................mm

Construction..

Core*: IWRC FC WSC

Wire finish*: Uncoated Zinc/Gal.

Direction and type of lay*: (Right) sZ zZ Z (Left) zS sS S

Permissible number of visible broken outer wires .... in 6*d* and.......................... in 30*d*

Reference diameter....................................mm

Permissible decrease in diameter from reference diameter .... mm

Date installed (yy/mm/dd).. Date discarded (yy/mm/dd)..

Visible broken outer wires				Diameter			Corrosion	Damage and/or deformation		Position in rope	Overall assessment i.e. combined severity rating[b] at position indicated
Number in length of		Severity rating[b]		Measured diameter	Actual decrease from reference	Severity rating[b]	Severity rating[b]	Severity rating[b]	Nature		
6*d*	30*d*	6*d*	30*d*	mm	mm						

Other observations/comments

Performance to date (cycles/hours/days/months/etc.) ....

Date of inspection (yy/mm/dd)..............................

Name (print) of competent person...................... ....Name (signature) ....

* Tick as applicable.

[b] Describe degree of deterioration as: slight, medium, high, very high, or discard.

Figure 14 Example of inspection record form for wires (ISO, 2010, p.37)