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Maintenance Planning and Optimization of Feed System and Camera System used in Norwegian Aquaculture

Using RCM approach to construct a maintenance program

Manikandan Nagarajan

Marine Technology
Submission date: July 2017
Supervisor: Ingrid Bouwer Utne, IMT

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"To my first love (Mom) and my Superhero (Dad), for their love and the sacrifices made in giving me the life I have now."

Preface

This thesis is a mandatory submission in the master program offered by NTNU. It was written during Spring 2017 at the Department of Marine Technology at NTNU and accounts for 30 credits. The author's interest towards working on the challenging tasks made him opt for the research topic "Autonomy and Risk Reduction in Aquaculture" to work on his specialization project and master thesis. This research is associated with SINTEF and SFI Exposed.

The specialization project presented the current maintenance practices carried out in the Norwegian fish farms. From the data collected during the project, important systems for daily operation of a fish farm were chosen for analysis in this thesis. It focuses on maintenance planning of feed system and camera system used in Norwegian aquaculture through Reliability Centered Maintenance (RCM) approach. The chosen systems for analysis were designed by AKVA Group.

The author had challenges to find relevant data for analysis during his research work. However, with the help from Supervisor and benevolent minds from the industry, the author has successfully completed the task.

I would like to thank my Supervisor Ingrid Bouwer Utne for her constant support and guidance throughout my research work. It was a pleasure to have had the opportunity to work under her supervision. Her guidance has been an important contributing factor to what the author believes as a good piece of work. I would like to thank Jan Inge Tjølsen, R&D Manager of AKVA Group, Bryne for giving me the opportunity to work with systems designed by AKVA and for the hospitality during my visit to their Head office in Bryne, Norway.

I would also like to thank the R&D Engineers of feed system and camera system namely Ingolf Lygren and Bjørn Pommeresche for sharing their knowledge about the systems and for providing inputs for the analysis.

Furthermore, I thank my parents, my sister and my best friend Sowmya for being a pillar of support throughout my master studies. I am obliged to my friend Naveen Velmurugan for having been there to help me with my doubts pertaining to coding in LaTeX.

Trondheim, July 11 2017

Manikandan Nagarajan

Abstract

There is an increasing global demand for seafood consumption. Fish farms in Norway has gradually moved to more exposed sites due to competition with other coast-based industries. Sea based aquaculture occupation is one of most dangerous occupation in Norway and the existing fish farms operate at the edge of safety limits.

The present state of technology in fish farms involve human interaction with cages and tools. Moving to exposed locations, also increases the challenges in terms of working environment and demand systems to be more robust and reliable. The objective of this thesis is to choose systems used in aquaculture and study them in detail to improve their availability.

The two systems that are crucial in daily operations of fish farms are, namely feed system and camera system designed by the AKVA Group are analyzed using Reliability Centered Maintenance (RCM) methodology. RCM is a structured procedure that identifies the functions, functional failures, failure modes, failure effects and consequences of the asset under consideration. Then a suitable maintenance task either corrective or preventive is recommended for the identified failure modes. The analysis suggested 23 preventive and 8 corrective tasks for feed system and 17 preventive and 4 corrective tasks for camera system. This knowledge benefits in improving system availability and to identify potential for autonomy.

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Abbreviations

RCM	Reliability Centered Maintenanc
FMECA	Failure Mode Effect Criticality Analysis
CM	Corrective Maintenance
PM	Preventive Maintenance
CCS	Centralized Control air System
CAP	Cage Access Point
HR	High Resolution
CCD	Charge-Coupled Devices
PCB	Printed Circuit Board
PT	Pan Tilt
PLC	Programmable Logic Controller
PWM	Pulse Width Modulated
ADIO	Analog Digital Input Output
FP	Failure Pattern
RI	Risk Index
CM	Condition Monitoring
MTBF	Mean Time Between Failures
ROV	Remotely Operated Vehicle
MTA	Maintenance Task Analysis
HDPE	High Desity Polyethylene
C	Consequence
F	Frequency

Chapter 1

Introduction

1.1 Background

This section explains the background and motivation of this thesis work. It comprises of three subsections, namely aquaculture, the need for aquaculture and aquaculture in Norway to accomplish the intended purpose.

1.1.1 Aquaculture

Aquaculture is defined as "the process of breeding, rearing and harvesting of plants and animals in all types of water environments including ponds, lakes, rivers and oceans".[18] Aquaculture can be broadly classified based on production, technology and location.[2] This is elucidated in the figure 1.1

Extensive Aquaculture

There are very few technologies and investment involved for this type of farming. These species are kept at low density with minimal input from artificial substances and human intervention. Sea ranching and restocking of lakes are typical examples of extensive aquaculture.[19]

Intensive Aquaculture

The extensive use of technology and artificial substances helps this particular type of farming achieve a higher production rate per unit volume. These species are farmed at optimal growth conditions. A typical example of intensive aquaculture is Salmon farming.[19]

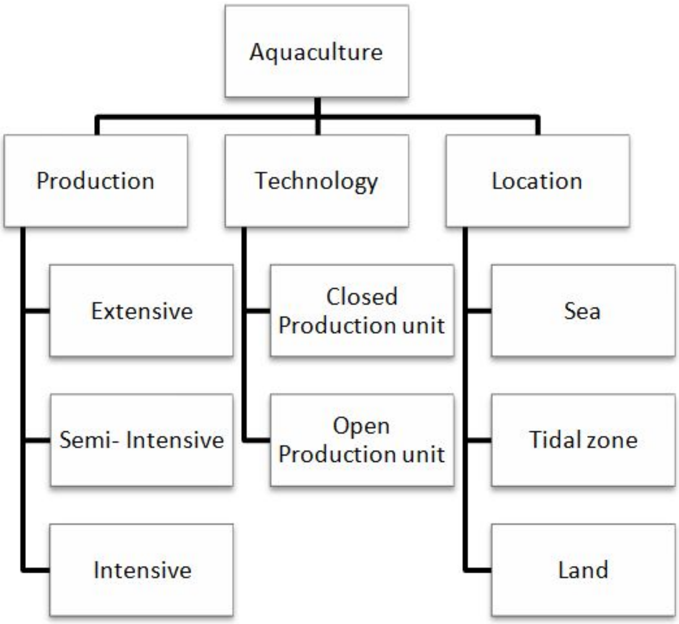

Figure 1.1: Classification of Aquaculture[2]

Semi-intensive Aquaculture

It is the combination of both of the above discussed production systems. Intensive fry production combined with extensive on-growing is an example of this type of farming.

There are different classifications based on the design and function of production units when the state of technology is taken into consideration. However, when the classification is based on the fish in the production units it is either classified as a closed production unit or an open production unit. Farming fishes by separating them from the outside environment referred to as closed production farming and that of facilitating interactions with the surrounding environment through permeable walls such as net is referred to as open.[19] Classifications based on location is either in the sea, tidal zone or on land. The focus of this thesis is intensive, open production and sea based farming. Figure 1.2 given below illustrates a scenario of intensive, open production and sea based farming carried out in HDPE cages.

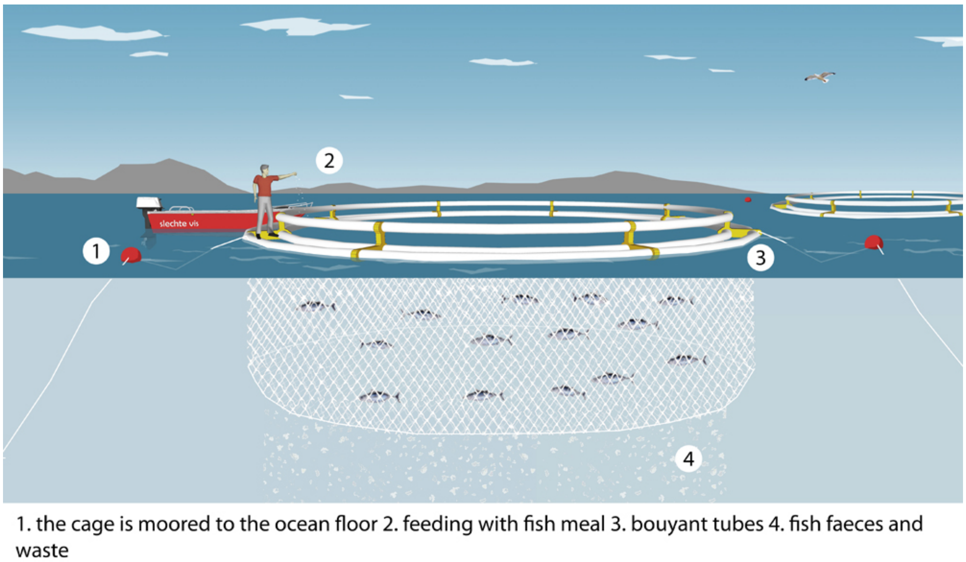

Figure 1.2: Intensive, open production and sea based farming in HDPE cages[3]

1.1.2 The need for aquaculture

The necessity for aquaculture is summarized in the following points:

1. "State of World Fisheries and Aquaculture 2008[20]" mentions that capture fisheries have reached full exploitation levels in 1990's around 95 million tonnes. However, human consumption and non food uses have increased the demand to over 144 million tonnes in 2008. This emphasizes the need for aquaculture to solve the global demand for seafood

2. The authors of "State of World Fisheries and Aquaculture 2016"[4]predict that global population is expected to increase to 9.7 billion from 7 billion by 2050

3. The 2016 report[4] also shows that global per capita fish consumption has increased above 20 kilograms a year for the first time. A graphical representation of this is depicted in figure 1.3

4. The World Bank predicts that by 2030, 62 percentage of all seafood consumed shall be farm raised[21]

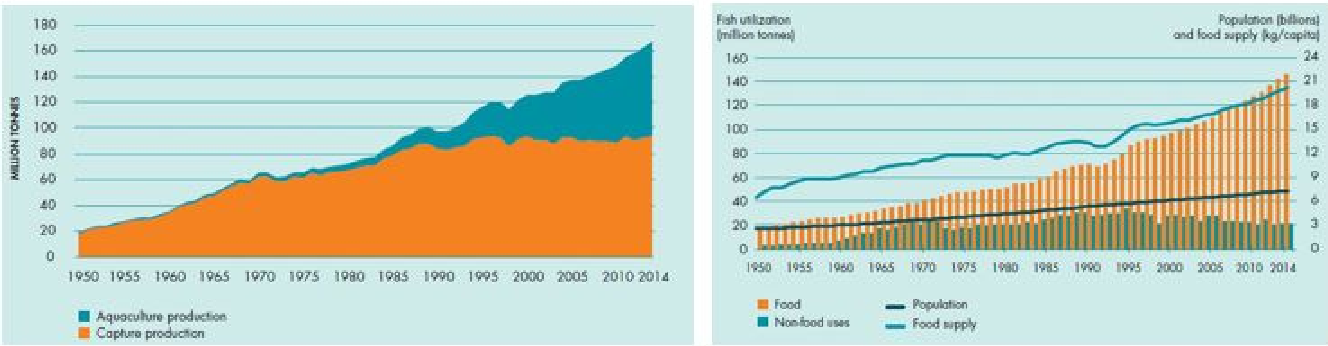

Figure 1.3: Graphical representation of the World Capture fisheries and Aquaculture production on the left & World fish utilization and supply on the right[4]

1.1.3 Aquaculture in Norway

Aquaculture in Norway was initiated in the 1970's and has grown over 1000 fish farming facilities along the coast as stated by Directorate of fisheries.[22] These farms produce Salmon and rainbow trouts. Norway, from producing 151000 tons of fish in 1990 has grown to producing 1.3 million tons of fish in 2010.[23] The Norwegian standards (NS) NS9415-2003 titled *"Marine fish farms requirements for site survey, risk analyses, design, dimensioning, production, installation and operation"*[24] initially classified sites in two ways, based on significant wave height (H_s), peak wave period (T_p) measurements and mid-current speed. In NS9415 2009 the sites were classified into 5 classes based on type of the cage and environmental conditions, such as small exposure (a), moderate exposure (b), large exposure (c), high exposure (d) and heavy exposure (e).

1.1.4 Challenges

The fish farming that started in sheltered coastal environments of Norway has gradually moved to more exposed locations due to competition with tourism and other coast-based industries.[25] Norway is in the forefront of innovation and development in aquaculture. It is the world's second largest fish exporter.[26] To retain its competitiveness and to meet the global demand, further expansions of aquaculture production is necessary. The article *"Fatalities in Norwegian fishing fleet"*[27] mentions that sea based aquaculture industry operates at the edge of safety limits and are considered as one of the most dangerous occupations in Norway. The present technology and operations carried out in the fish farms involve human interactions with tools and fish cages. Moving to further exposed locations can,

1. Increases the challenges in working environment imposing the need to make the operations less dependent on manual intervention.

2. Demand more robust structures and systems

A complete understanding of the working system and its associated failure modes is essential to improve the system's reliability and availability to perform its intended function. Thus, reducing the total down time of the system. This thesis focuses on two main daily operations of fish farming, namely feeding and monitoring cages. Further there is an aim towards discussing the possible maintenance task to ensure that the associated systems are more available for operation.

1.2 Objective

The objective of this thesis is to examine whether Reliability Centered Maintenance (RCM) method can be utilized in constructing a maintenance program for systems used in the aquaculture sector. It focuses on understanding the systems and its possible failure modes, which could serve as a tool in improving system availability and safety. This knowledge could be very beneficial when moving towards more exposed sites and also bringing forth more autonomy. The major focus in this respect are such as follows:

1. Provide an overview of the present maintenance practices carried out in aquaculture industry, choose systems for analysis and justify its selection

2. Describe RCM method in a detailed manner and discuss the pros and cons of the method

3. Perform a RCM analysis of feed system and camera system designed by AKVA Group

4. Apply RCM procedure and establish a suitable maintenance program for the systems under consideration

5. Discuss the results of analysis, potential for autonomy and maintenance data to be recorded for better decision making

1.3 Scope and Limitations

The scope of this thesis is to perform RCM analysis of feed system and camera system designed by AKVA Group. The functional failures such as no feeding and no video imaging were also analyzed in this thesis. This was done in accordance to the RCM method. The functions, functional failures, Failure Mode Effect Criticality Analysis (FMECA) and Maintenance Task Analysis (MTA) of the systems were presented.

Due to lack of failure data, the inputs for this thesis is solely based on expert judgments. The interaction with the R&D Engineers of feed system and camera system served as inputs for FMECA worksheets. A decision tree outlined in the appendix is used to decide the maintenance task in the final strategy. The identified maintenance tasks include both preventive and corrective maintenance. The results in the maintenance programs are grouped based on time interval in the maintenance packages for better understanding.

1.4 Thesis Structure

The work presented in this thesis is a result of four main steps the literature review of RCM method, system descriptions, RCM analysis of the systems, and evaluation of analysis results.

This thesis is structured as follows, Chapter 2 discusses the different aspects of maintenance and provides an overview of maintenance in the Norwegian aquaculture industry. Chapter 3 presents a detailed description of the RCM method that is used in this thesis along with information about the data gathered for analysis. Chapter 4 and Chapter 6 explain the feed system and camera system respectively. The RCM analysis of these systems is presented in Chapters 5 and 7. Chapter 8 presents the discussion and evaluation of the analysis. Chapter 9 discusses the potential direction for future work and concludes the thesis.

Chapter 2

Overview of Aquaculture & Maintenance

This chapter provides an overview of aquaculture and maintenance. The former discusses the operations in aquaculture industry and justifies the selection of feeding and monitoring operations for analysis in this thesis. The latter provides a general overview of maintenance, explains the process of developing a maintenance strategy and presents the definition of maintenance terms used in the thesis.

2.1 Operations in Aquaculture

The production cycle of finfish aquaculture begins with hatchery period that starts with the hatching of fish fry from fertilized eggs. When the fishes grow to a larger size they move to grow-out phase. It is considered as the final stage in fish production which is carried out in sea cages. Upon reaching the market size, the fishes are harvested and delivered to the process and distribution industries. During the grow-out phases different operations such as feeding, mort (dead fish) collections, size grading, monitoring of fish welfare, net cleaning and structural maintenance are carried out regularly to have profitable and sustainable production.[28] The following subsections explain the important operations in a fish farm such as feeding, monitoring, mort collections, delousing and size grading

Feeding

The process of providing food to the farmed fishes is referred to as feeding. The finfish feed on feed pellets. It is a daily operation carried out in fish farming to ensure all essential nutrients for fish growth are supplied to the fish through feed pellets. The objective of feeding is to attain optimum growth, yield and minimum waste. The feed systems help in achieving the process of feeding.[19]

Monitoring

Careful observation of the various operations carried out everyday in sea cages is called as monitoring. Different camera systems are used for monitoring. The activities monitored are surface feeding, underwater feeding, fish behaviour, fish maturation, morts at the bottom of the cage, fish parasite and general surveillance.[19]

Mort collections

Dead fishes are referred to as morts. They are collected from the bottom of the cage and are brought to the surface and then removed. This operation is performed everyday as the morts can cause disease outbreaks and pose as a serious threat to the stock. The morts are brought to the surface by a hydraulically operated scoop net which is at the bottom or by an automated mort collector system in Norwegian fish farms.[1]

Delousing

The Sea lice is a parasite that feeds on the mucous, blood and skin of the fish. A few sea lice on a large fish is not a serious damage. However, a large number of lice on the same fish or smaller number of lice on juvenile fish can be fatal. Delousing is the process of getting rid of the lice and other parasitic infections on the fish.[19] Chemical free lice treatments are preferred in Norwegian aquaculture at present. Cleaner fishes such as wrasse and lump-sucker are widely used for delousing. The fishes are inspected for sea lice during sampling but more often in summer.[1]

Size grading

As the name indicates, size grading refers to the process of segregating the fishes based on their size. The objective of the process is to foster improved fish growth as different fishes have different growth rate and to establish good production control. It is performed by sampling or by using biomass frames.[1]

2.1.1 Inspection

Like most industries, inspections are carried out in the aquaculture industry at different time intervals ranging from a daily to a yearly basis. These inspections ensures the safe operation of the farms. The details of inspections that are carried out in Norwegian fish farms is presented in the Table 2.1. These details were obtained by interacting with fish farmers in SALMAR.[1] It was confirmed during the discussion that the details shared will be of high relevance to SALMAR operated farms and other farms might add or remove tasks to the presented data.

Table 2.1: Inspections carried out in a Norwegian fish farm[1]

Inspection Interval	Task
Daily	Check mooring of cage
	Fastening of net & wear of ropes
	Engines of boat and generator
	Mort removal & logging
Weekly	Visual check of visible components
	Sensors are checked and cleaned
	Estimate amount of dead fish
	Check net for fouling and damage
Monthly	Visual inspection of sinker tube
	Chains and ropes
3 Months	Check mooring for fouling or wear by ROV or lifting lines out of water
1 year	Thorough check of mooring
	Changing oil in blowers
	Check cranes and forklifts
	Check life rafts and fire extinguisher

2.1.2 Maintenance

Maintenance is carried out when the inspections show non-conformity or according to the maintenance interval specified for the corresponding system in its user manual. The maintenance tasks are executed according to the information provided in the maintenance manual of the system. The nets are kept clean periodically by washing with high-pressure water jet washer or Remotely Operated Net Cleaners (RONC). Net replacement is done at the end of every production cycle.[1]

2.1.3 Repair

If inspections and maintenance show abnormalities, the components are usually replaced, but sometimes repairs are also carried out. It is often corrective maintenance.[1]

2.1.4 Justification for selection of feeding and monitoring process

The following points explain the selection of feeding system and camera system for RCM analysis in this thesis:

1. Both feeding and monitoring is a daily operation in a fish farm. Studying their systems in detail and increasing their availability with suitable maintenance program shall benefit the industry

2. Optimal feeding is essential to achieve the intended results of farming. Monitoring the fish behaviour with camera is essential to know whether they are satiated. This controls the decision of stopping the feeding process

3. Feed costs account for more than half the production cost as stated by the Directorate of Fisheries Norway.[29] Understanding these systems and ensuring optimal feed handling can save costs

4. Availability of feed system to carry out the intended purpose of feeding is important as fishes cannot starve due to down times. In this regard, camera system's availability is highly essential to monitor feeding, check fish maturation and for morts aim at fish welfare

The feed system and camera system are described in detail in Chapters 4 and 6 respectively.

2.2 Maintenance

The actions that retain or restore an item's condition so that it is available to perform an intended function is referred to as maintenance. These activities are a combination of technical, administrative or managerial approaches which are performed throughout the item's life-cycle.[30] In this context, item refers to either a part, component, subsystem, functional unit or a system that can be individually described and considered[31] for maintenance. Maintenance management comprises of determining maintenance objectives, implementation of planning, controlling and improving maintenance activities. The maintenance plan must be structured and contain documentation of activities, procedures, regulated time intervals between the performed actions and the time taken for its execution. Maintenance strategy is the management method to achieve the objectives of maintenance. The designed strategy should reduce or eliminate the chances of system failure that may have undesirable consequences. The figure 2.1 shows a simple structure outlined by the Norwegian Petroleum

Directorate to develop a suitable maintenance strategy.

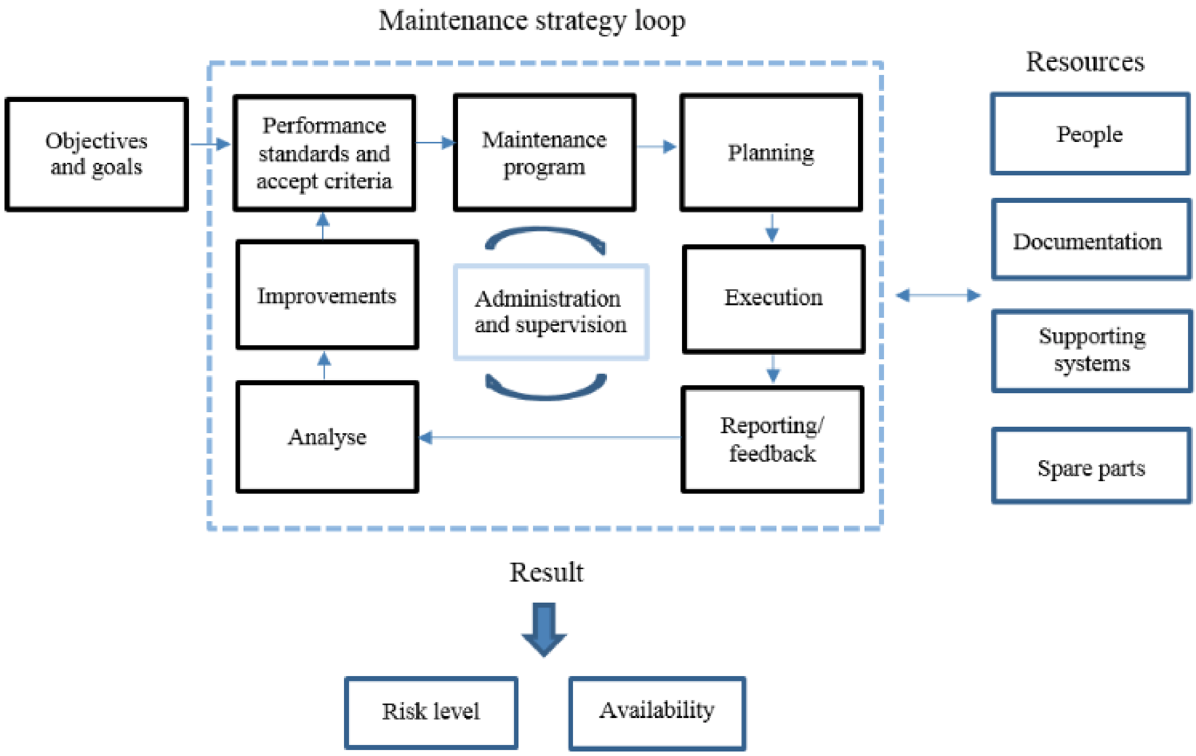

Figure 2.1: Maintenance strategy model outlined by Norwegian Petroleum Directorate[5]

2.2.1 Maintenance Strategy Model

The maintenance strategy loop demonstrates the steps to achieve the organization's maintenance objectives and goals. Firstly, the performance standards and acceptance criteria for the system under consideration should be defined. It is followed by constructing a suitable maintenance program for the system. Planning and execution of the maintenance activities are the subsequent elements within the loop. The final set of elements namely, reporting, analyse and improvements aim at continuous improvement of the maintenance strategy through feedback, analyzing and improvements. As shown in figure 2.1, the resources on the right such as people, documentation, supporting systems and spare parts serve as inputs to perform sequence of activities listed in the loop. The results of the loop are further connected to risk level and availability. The process of administration and supervision depicted in figure 2.1 ensures that the remaining activities or processes within the loop are successfully carried out.

The most important element within the loop is creating the maintenance program that is explained in the following sections. Maintenance program is defined by NORSOK Z-08 as a structure that includes maintenance intervals and written procedures for maintaining, handling and testing components.[32] Reliability Centered Maintenance is one method used to construct a maintenance program.

2.2.2 Maintenance Terminology

Maintenance terms are sometimes interchangeably used. This section aims at introducing the major terminologies used in this thesis.. The definitions are adopted from NORSOK Standard & from the book Marine structural design.[32,10]

System
A logical grouping of subsystems or main equipment that will perform a series of main functions required by the plant.

Subsystem
A logical grouping of units or equipment that mainly perform one function

Equipment
A grouping of components which can perform at least one significant function as stand-alone item

Component
The lowest level to which an equipment can be disassembled without destruction to the items involved.

Function
The equipment or system task

Failure
An event where the device is no longer able to perform its intended function.

Failure Mode
One of the possible failure modes of the device. This state of the device leads to that the intended function is not satisfied.

Uptime
Time when the unit is in operation.

Downtime
Time when the unit is inoperable until corrected.

Reliability
The unit's ability to perform an intended function under certain conditions for a given time interval.

Availability
The ability of an unit to perform its required function at stated interval of time or stated period of time.

Criticality
Numerical subscript indicating the severity of failure or error combined with the probability or frequency of the event.

Chapter 3

Method - RCM

The following chapter explains the RCM method in detail. The first section presents the history of the RCM and the sections 2 to 5 explain the steps involved in this method.

3.1 Procedure of RCM

3.1.1 History of RCM

The process of Reliability Centered Maintenance originated in the aviation industry in 1960's. During the late 1950's the cost of maintenance activities became very high and a task force was established in the 1960's to investigate the capabilities of preventive maintenance. This led to the development of Maintenance Steering Group-1 (MSG) document that outlined a series of guidelines for aircraft manufacturers and airlines, to use when establishing a maintenance program. MSG-1 is considered as the first maintenance program to use RCM concepts.[33] This was followed by the next revision MSG-2. The techniques outlined in these documents assured maximum safety and reliability of the equipment at minimum cost.[11]

In 1974 United States Department of Defense commissioned United Airlines to prepare a report on the process used in the aviation industry to develop maintenance program for aircraft. The resulting report by Stan Nowlan and Howard Heap was published in 1978 entitled as "Reliability Centered Maintenance".[34] The key findings of Nowlan and heap are as follows:

1. Some failure modes cannot be prevented even with intense maintenance activities

2. For many items, probability of failure did not increase with age

RCM is referred as MSG-3 in the aviation industry and it is still in use to develop and refine maintenance program for aircraft.[11] As discussed above, RCM was first applied in the aviation industry, and later with military forces, nuclear power plants, oil and gas and many other industries[35]

3.1.2 Definition of RCM

"Reliability Centered Maintenance: a process used to determine the maintenance requirements of any physical asset in its operating context".[11]

RCM focuses on system functions with an objective to reduce maintenance costs by focusing on important functions or eliminating maintenance tasks that are not necessary. It provides the guidelines to create a maintenance program that meets both the internal requirements of the company (company's own maintenance goal and objective) and external requirements from regulatory bodies for different types of systems and equipment.[36] The procedure of the RCM process entails asking seven questions about the system or the asset under review. Answers to these seven fundamental questions of RCM provide the guideline to construct an optimized maintenance program. The basic questions are:[11]

1. What are the functions and associated performance standards of the asset in its present operating context?
2. In what ways does it fail to fulfill its function?
3. What causes each functional failure?
4. What happens when each functional failure occurs?
5. In what way does each functional failure matter?
6. What can be done to prevent each failure?
7. What should be done if a suitable preventive task cannot be found?

The RCM concept is elucidated in several standards, reports and books. Among these Nowlan and Heap (1978), IEC60300-3-11, SAEJA1012, DEF-STD-02-45 (2000), MIL-STD 2173(AS) and Moubray (1997) are well recognized.

3.1.3 Choosing stages of RCM

The global perception regarding the results a RCM process intends to achieve is unambiguous. However, as the methodology of RCM has developed over the years there are various theories that suggest different structures to achieve the desired results.

The procedure outlined in "The System Reliability Theory: Models and Statistical methods" by Marvin Rausand,[35] describes twelve steps to perform the RCM analysis. This procedure suggests to select the items that are critical with respect to functional failure of the system and exclude other non-essential items. Thus, saving time and resources. When the RCM process was applied in the maritime context, it was suggested to use Pareto's 80-20 principle, that is only 20% of the failure that causes 80% of the risk in terms of cost or safety shall be included. Thus considering most expensive components or components that were critical in terms of safety for analysis.[37]

The International Electrotechnical Commission, IEC 60300-3-11 standards explains application of RCM process in five phases such as initiation and planning, functional failure analysis, task selection, implementation and continuous improvement.[38] Society of Automotive Engineers (SAE) defines two standards for the RCM process, namely SAE JA1011 and SAE JA1012.[39,40] SAE JA1011 provides the minimum criteria that any process must comply to be called RCM. Thus, satiating the international demand for a standard for RCM process. SAE JA1011 gives high degree of familiarity of RCM concepts and terminology. SAE JA1012, amplifies and clarifies these concepts and terminologies.[39,40] The book Reliability Centered Maintenance by John Moubray explains the RCM process in compliance with the seven basic questions discussed in the beginning of this section. The book is based on the documents SAE JA1011 and SAE JA1012.

Thus, there are two different perspectives towards choosing from different procedures discussed above. Eliminating some components for analysis can save time, resources and make the process of RCM less cumbersome. However, it can be argued that neglecting components early in the process can result in missing out on the maintenance of relevant components. Hence one must consider the specific situation and decide upon the process and number of components that should be considered for analysis. This thesis considers the RCM steps outlined in the book that is based on the international standards for analysis. The following sections in this chapter are in accordance with the book and present a detailed description of each stage in the RCM process.

3.2 Functions

Step1: "What are the functions and associated performance standards of the asset in its present operating context?[11]"

The first step in a RCM process is to establish a proper function description of the asset under consideration. The standards by SAE[39] define four key concepts that result in clear description of the functions. They are

- Functional statement
- Performance standards
- Operating context
- Primary and Secondary functions

All functions of an asset should be identified. The functional statement can be an object, a verb, and a performance standard.[39] For instance, a feed doser (object) shall transfer feed into air flow (verb) with a minimum feed rate of 200g/sec to a maximum feed rate of 2500g/sec (performance standard).

The performance standard is the level of performance that is expected by the owner or the user of the asset.[39] The upper and lower limits of the performance standards associated with a function are the desired performance and inherent reliability. A graphical illustration is shown in the figure 3.1. Any system in the real world shall fail as indicated by the laws of physics.[11] The margin for deterioration is shown in the figure 3.1. The performance standard of the functional statement must not exceed inherent reliability

- Desired performance is the what we want the asset to achieve
- Inherent reliability or built-in capacity is what the asset can do.

Operating context is the description of how the asset should be used, where it is to be used, performance criteria concerning issues such as throughput, safety, environment and so on. Most equipments have more than one function. It is important to identify all functions that are relevant for the maintenance plan. Generally, functions are divided into primary functions and secondary functions.

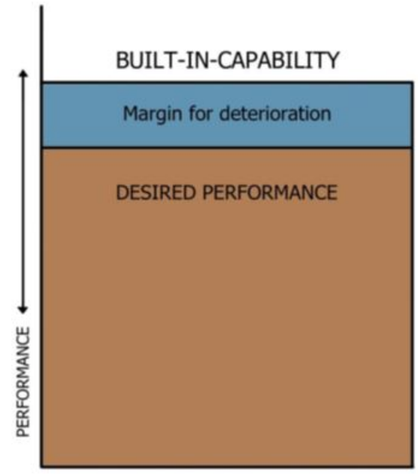

Figure 3.1: Illustration of Performance Standard[6]

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Primary function is the main reason for why the asset exists. On a component level it is easy to recognize its primary function, which is likely to be based on its name. Secondary functions are the functions expected of the asset/ equipment additional to its primary functions. The primary functions may depend on the secondary functions and so failure of secondary functions may have a severe impact. The study of functional failures helps in better understanding of such consequences.

In the requirements for RCM to improve reliability of vessel's machinery system published by American Bureau of Shipping (ABS),[41] it suggests to use functional hierarchy to understand the system's functions. The functional hierarchy helps to visualize the system's functional structure with associated small subsystem in succeeding levels. The following figure 3.2 presents an excerpt of functional hierarchy associated with the feed system. The feed transportation involves providing the air medium for transporting the fish feed to cages. It is one of the main functions that help to achieve the system's primary function of feeding. It can be seen that sub functions of providing air for transportation and cooling air before the doser help in realizing the feed transportation function.

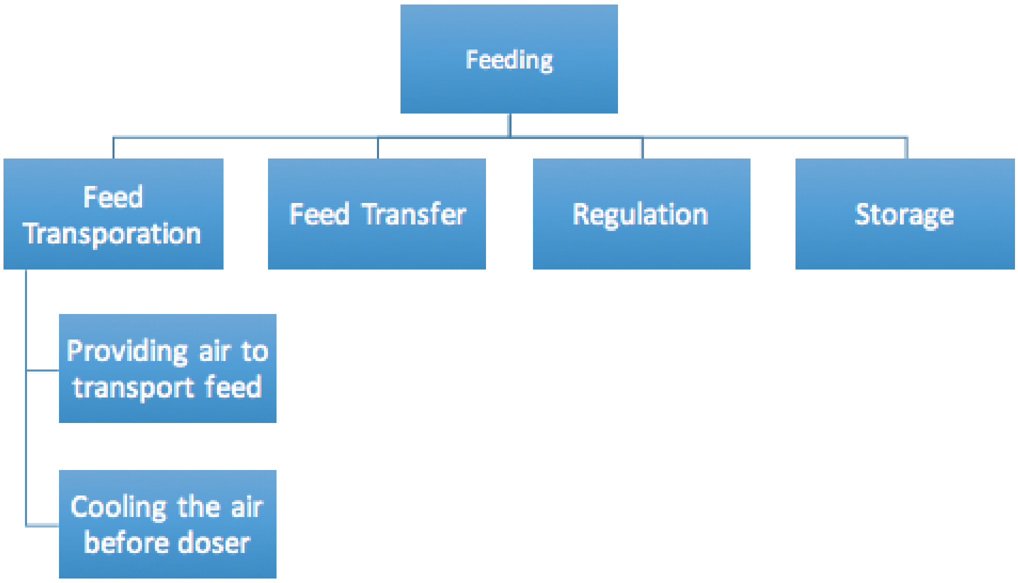

Figure 3.2: Excerpt of functional hierarchy of feed system

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3.3 Functional Failure

Step2: "In what ways does it fail to fulfill its function?"[11]

The next step after establishing the functions of the asset is to analyze the possible ways in which the asset can fail to fulfill these functions.

"Functional failure is defined as the inability of any physical asset to meet a desired standard of performance[11]*"*.

Different functional failures can apply to a single function. It can be classified as three types:[10]

- Total loss of function; A function is not achieved or quality of function is not acceptable.
- Partial loss of function; This type has a broad category that ranges from nuisance category to total loss of function.
- Erroneous function; The equipment or the item performing an action that was not intended.

For example, consider a pump that delivers fluid from A to B at a rate of 300 litres/minute. The two possible functional failures in this scenario are as follows:

- fails to pump any fluid
- pumps fluid less than 300 litres/minute

The first case is a total loss of function and the second is a partial loss of function.

3.4 FMECA

After having established the functions and functional failures of the system, the next step of RCM involves defining the source that leads to functional failures, evaluating the effect and criticality of these failures by FMECA worksheets. The Failure Mode Effect Criticality Analysis (FMECA) worksheets are the most important part of the RCM process. The FMECA can be considered as two parts, namely Failure Mode Effect Analysis (FMEA) and Criticality Analysis (CA). FMEA that identifies the failure mode and evaluates its effects and CA ranks the failure based on different categories such as safety, environment, availability and cost. These categories are subjected to change. The terms Mean Time Between Failures (MTBF) and Mean Time To Failure (MTTF) is used for repairable and non-repairable items respectively. MTBF considers only the up time and excludes the downtime between failures.[7] A graphical illustration for better understanding of the same is presented. In the figure 3.3 MTBF is the average of values of (t). In the analysis presented in further sections MTBF is considered for both repairable and non-repairable items.

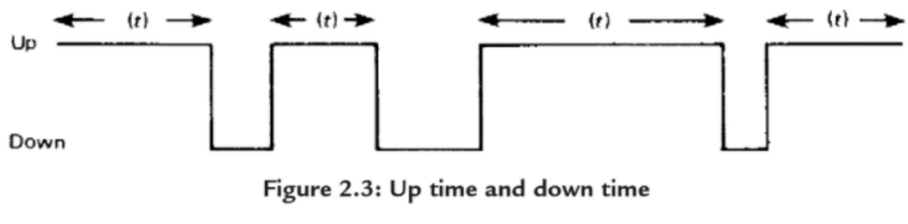

Figure 3.3: Up time and Down Time[7]

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The criticality assessment is followed by evaluating the consequence and frequency for each failure. The last column of the worksheet is the Risk Index (RI) or Risk Priority Number (RPN). In a traditional FMEA analysis, it is estimated by the product of three parameters namely, severity, occurrence and detection.[42] An alternative method to estimate the RI is presented by Rausand,[43] that considers RI as a logarithm of risk associated with the event which is the sum of frequency and consequence. This alternative approach was used in the analysis presented in the following chapters. The two approaches discussed to estimate RI differ from each other by one factor i.e detection is not considered in the latter. However, a column in the FMECA worksheet discusses whether the failure is Hidden or Evident. The values range from 1 to 5 for both consequence and frequency class thus resulting in a risk index from 2 to 10. Further explanation on risk index is presented in section 3.4.3.

FMECA is constructed by gathering a team of experts who have a better understanding of the asset/system under consideration for analysis. The structure and content of FMECA is subjected to change.

3.4.1 Failure Modes

Step3: "What causes each functional failure?"

The cause of functional failure is defined as failure mode.[11] The failure modes that are 'reasonably likely' to cause functional failure are identified.[39] The SAE International standard SAE JA1011 suggests that the user or owner of the asset identifies and decides on the failure modes that are 'reasonably likely'.[39] The failure modes that can be considered as "reasonably likely" according to John Moubray[11] are

1. Failure modes that have occurred before on the same or similar asset
2. Failure modes that already have a preventive maintenance task
3. Failure modes that have not occurred yet but have possibilities to occur

Identifying the causes of the functional failure helps in constructing a maintenance program that prevents or reduces the likelihood of the functional failure. The failure modes can be broken down into several causation levels. The thumb rule outlined by SAE standard[39] is to break it down until a suitable maintenance strategy can be discovered.

3.4.2 Failure Effects and Consequences

Step4: "What happens when each functional failure occurs?"

The fourth step of the RCM process involves listing what happens when these failures occur. This is referred to as failure effects. The failure effects describes what happens when no specific task is carried out to anticipate, detect or prevent the failure.[39] Moubray suggests that the following should be recorded when describing the failure:[11]

1. Indication that the failure has occurred
2. The ways in which it poses threat to safety or environment
3. Whether it has an impact on production or operation
4. The physical damage caused by the failure
5. The action needed to repair the failure

Step5: "In what way does each functional failure matter?"

The sequence of events following the failure can be defined as failure consequence. The failure prevention is not about preventing failure themselves but avoiding or reducing its consequence.[11] RCM process groups these failure consequence into two stages. They are:[11]

- Stage 1 : Hidden function or Evident function.
- Stage 2 : Safety and environment, operational and non-operational consequences

The failure of a hidden function does not become evident to the operating crew under normal working conditions, whereas failure of an evident function does.

A failure that can kill or hurt someone is considered to have safety consequences. When a failure could lead to a breach of environmental standards it is considered to have environmental consequences. The failure affecting production or operation has operational consequences. Failures that do not affect safety or production, but involves cost of repair are considered as non-operational consequences.[11] The consequence and frequency parameters should be established to evaluate the consequence of failure.

3.4.3 Risk matrix, Consequence & Frequency parameters

The consequences of functional failures and its failure modes are of varying severity levels. In this part of the analysis, the risk and criticality are the central aspects. The consequence that is more critical has a higher severity level than the other. The frequency and consequence inputs yields a risk index as described in 3.4. The failure modes with same risk index will approximately have same risk. These risk indices are grouped into three ranges and are expected to have the same risk. The risk matrix considered for the analysis is illustrated in the figure 3.4. These ranges were finalized through discussions with R&D Engineers of the system at AKVA Group.

Probability/ Consequence	1 Very Unlikley	2 Remote	3 Occasional	4 Probable	5 Frequent
5 Very High	6	7	8	9	10
4 High	5	6	7	8	9
3 Medium	4	5	6	7	8
2 Small	3	4	5	6	7
1 Very small	2	3	4	5	6

Figure 3.4: Risk Matrix[8,9]

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The region in red represents unacceptable risks. The yellow area represents the As Low As Reasonably Practicable (ALARP) risks that is, these risks can be further reduced if it is practicable. The green area represents acceptable risks. From the figure it is evident that the consequence and frequency are categorized on five levels from 1 to 5 resulting in a risk index between 2 to 10. When the frequency and consequence level changes the order of the risk matrix changes accordingly. These matrices help to identify, prioritize and rank the possible outcomes. Risk matrix is considered to have flaws. Some of the deficiencies of the risk matrix is risk-acceptance inconsistency, range compression, centering bias and category definition bias.[44] Thus emphasizing that risk matrix should not be used without discussion.

3.5 Maintenance Task Analysis

Step6: "What can be done to prevent each failure?"

The final step of RCM process is constructing a suitable maintenance task for the identified failure modes. The results of FMECA gives the most critical failure modes of the components that needs special attention while deciding the maintenance tasks. The suggested task aim to prevent or predict the failure mode.

3.5.1 Maintenance Task Classification

The maintenance tasks are a combination of preventive and corrective actions. Each identified failure mode is checked for whether a preventive maintenance task is applicable and effective, or will it be best to let the item run to failure and then carry out a corrective maintenance. The reasons for doing a preventive task are:[35]

- To prevent the failure from occurring
- To detect the onset of failure
- To discover hidden failure

The basic maintenance tasks that are considered during the Maintenance Task Analysis (MTA) are:[35]

1. Scheduled-on condition
2. Scheduled restoration
3. Scheduled discard
4. Scheduled function test
5. Run to failure

Scheduled-on condition

Scheduled-on condition task determines the condition of an item through condition monitoring. The on-condition tasks can be referred as *"the tasks that entails checking an equipment for potential failures, so that action can be taken either to prevent the functional failure or reduce the consequences of functional failure[11]"*. Potential failure is defined as "the state which indicates the functional failure is about to occur or is in the process of occurring".[35] The following three main criteria have to be met to choose this type of maintenance task, they are as follows:

- The detection of reduction in failure resistance towards a specific failure mode should be possible
- It should be possible to detect the potential failure condition through an explicit task
- There must be reasonable time interval between the time of detection of potential failure (P) and time of functional failure

Scheduled restoration

Scheduled restoration involves performing a general inspection of an item to determine its need for repair or replacement. It can be also defined as *"taking periodic action to restore item's original resistance to failure"*[11]. The criteria to be met for this maintenance task are:[35]

- There must be a rapid increase in failure rate function of an item after a specific age limit
- Large number of these items must survive till a particular age
- The rework carried out on the item must restore its original resistance to failure

Scheduled discard

Scheduled discard refers to replacing an item at or before a specified age or time limit.[35] Scheduled discard is the maintenance task when it meets the following criteria:[35]

- The item must be subjected to critical failure
- The failure to which the item is subjected must have major potential consequences
- There must be a rapid increase in failure rate function after a particular age
- Large number of these items must survive till this age

Scheduled function test

Scheduled function test is an inspection or a failure finding task performed for an hidden function to identify failures. It is applicable when the following criteria are met:[11]

- If a failure finding task does not increase the risk of multiple failures
- If performing such task at the suggested frequency is practical

Run to Failure

Step7: "What should be done if a suitable preventive task cannot be found?"[11]

This is the last step of the RCM that considers a scenario where a suitable preventive task cannot be found for the item under consideration. The corrective maintenance outlined in the section 3.5.1 is the appropriate maintenance task for this type of failure mode. The two corrective actions are run to failure or redesign.[11]

For failure modes that have random failure patterns as shown in the section 3.5.3, it is often hard to plan a maintenance interval to execute the maintenance task. Run to failure is the corrective action in this situation and this task is chosen when no other discussed preventive task is appropriate. It is also preferred in a scenario where letting the equipment or an item fail is cost- effective than performing a maintenance task. Redesign of the component is suggested, when these failures have severe safety or environmental consequences.

3.5.2 Decision Tree

The decision tree helps in selecting the maintenance tasks for each failure. The logic and the content of the decision tree is based on the item/asset under consideration. When deciding on a particular task it should be ensured that chosen task is applicable and it either prevents the failure or reduces its consequence. The chosen task should be a cost-effective solution.

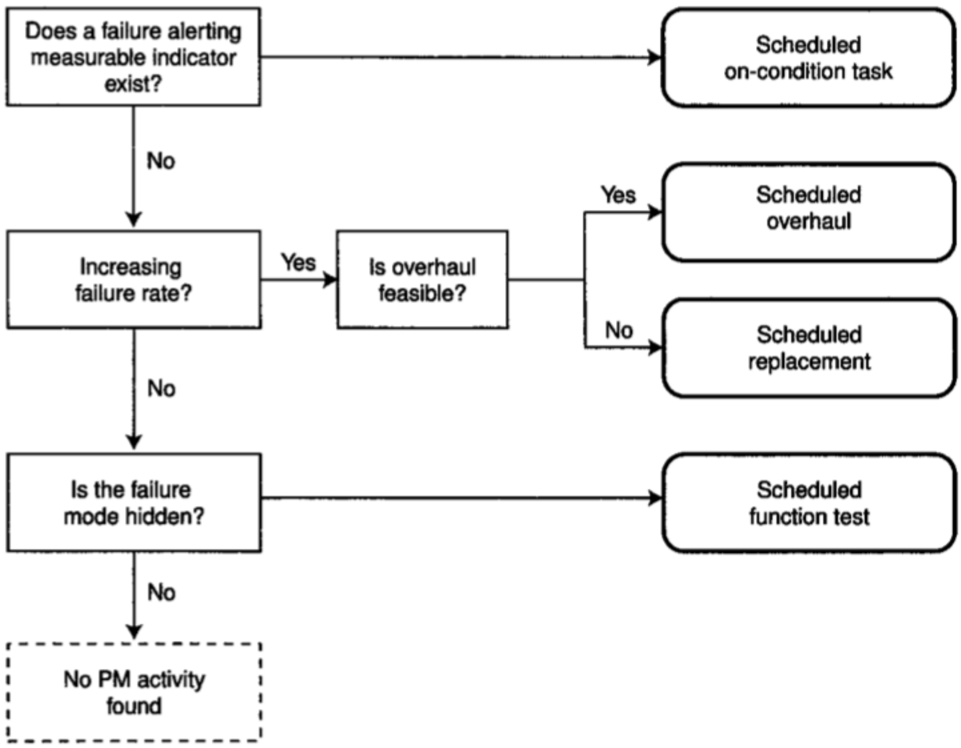

Figure 3.5: A simplified version of the decision tree[10]

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The figure 3.5 shows a simplified version of the decision tree is used for deciding on the task. This version is shown for easy understanding of the decision logic used in the RCM process. The decision tree used for the analysis was adopted from the book "Reliability Centered

Maintenance" by John Moubray.[11] It is presented in the figure F.1 in the Appendix. For each failure mode, a suitable maintenance task is identified by starting at the top left corner of the tree and assessing the binary questions at each question box. It could be seen that not all paths in the tree lead to preventive tasks. This decision tree is in accordance with the SAE standard[39,40] that considers redesign when preventive or corrective maintenance task is not applicable for the failure and it has severe environmental or safety consequence.

3.5.3 Failure Patterns

After having a clear understanding of what are the functional failures and failure modes of the asset under consideration, it is necessary to know the failure pattern of these failure modes. The failure pattern is one of the critical parameter during the maintenance task analysis. There are different types of failure pattern as shown in the figure 3.6. The failure rate function is shown on the vertical axis and time on the horizontal axis.

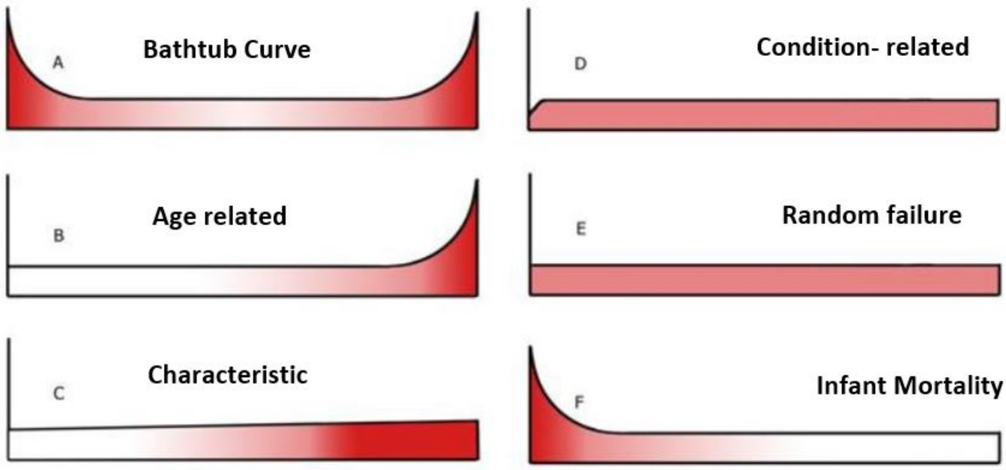

Figure 3.6: A simplified version of the decision tree[11]

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- Pattern A - "**Bathtub curve**"; The equipment may fail in the beginning of its lifetime similar to the wear out period in the end
- Pattern B - "**Age-related**"; The equipment shows increasing probability of failure throughout its lifetime
- Pattern C - "**Characteristic**"; The equipment shows slowly increasing probability of failure and there is no identifiable wear-out age

- Pattern D - "**Condition-related**"; The equipment shows low probability of failure when new and there is a rapid increase to a constant level
- Pattern E - "**Random failure**"; The equipment exhibits constant probability of failure irrespective of its age
- Pattern E - "**Infant mortality**"; The equipment exhibits high probability of failure when new and this drops to a constant or slowly increasing probability of failure

When failure patterns for each identified failure mode is listed, it gives us the characteristic of the failure mode in detail. Determining a maintenance interval to carry out the maintenance task is necessary for all preventive tasks.

3.5.4 P-F Interval

The appropriate maintenance task should be found for each failure mode and the feasibility criteria for the chosen task should be checked as discussed in the above sections. The preventive tasks are suggested along with the time interval to execute them. This time interval is referred as P-F interval. It is defined as *"the time from where a failure may be detected to the point where it decays into a functional failure"*[11] refer fig 3.7. The SAE International standards[39,40] suggests that time interval for maintenance actions must be less than P-F interval.

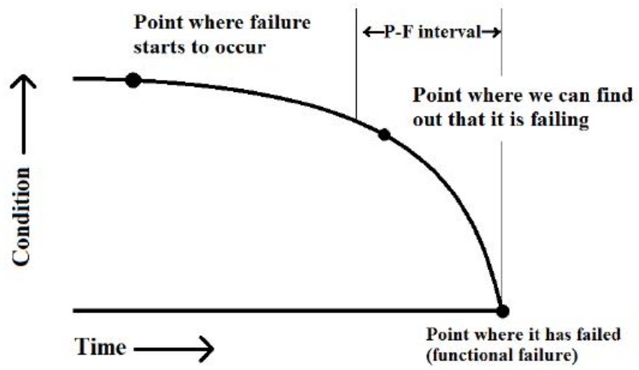

Figure 3.7: The P-F interval[12]

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3.6 Data Collection

The RCM procedure applied for these systems is largely in line with the steps described by Moubray in his book Reliability-centered Maintenance.[11] There was a lack of data regarding these systems. The data collected with respect to the systems and input to the FMECA worksheet was by studying the product manual of the systems and discussing with the R&D Engineer of the systems at AKVA Group, Bryne, Norway.[8,9] There were 2 separate meetings conducted for the data collection. The functional hierarchy and the frame work of FMECA worksheets including the list of components and possible failure modes was shared with the R&D Engineers prior to the meeting. The details of the meetings is presented below

1. 13.02.2017 at AKVA Group, Bryne, Norway

   Participants: Jan Inge Tjølsen (R&D Manager), Ingolf Lygren (R&D Engineer) and the author

   Objective: The primary objective of the meeting was to collect details of the feed system and to get input for the FMECA worksheet of the system

   Discussion was carried out with the personnel at AKVA regarding the objective of the work. The procedure of RCM process was explained to the R&D Engineer of the system. The FMECA worksheet was completed with inputs. The results were later shared with them which they further reviewed.

2. 06.06.2017 at AKVA Group, Bryne, Norway

   Participants: Jan Inge Tjølsen (R&D Manager), Ingolf Lygren (R&D Engineer), Bjørn Pommeresche (R&D Engineer) and the author

   Objective: The objective of the meeting was to present the analysis of feed system and get their review and collect data for FMECA inputs for camera system

   The completed analysis was presented and the suggested comments were incorporated. The R&D Engineers shared information about the camera system and gave inputs for the FMECA of camera system. The completed analysis was submitted for review.

These meetings have been an integral part for findings in this thesis. The subsequent chapters provides the system description and results of the analysis.

Chapter 4

Feed System

The feed system and camera system is considered for the RCM analysis. This chapter provides a detailed description of the feed system, its purpose and its associated components.

The process of providing food to the farmed fishes in cages is referred as feeding. The objective of feeding is to provide all the necessary nutrients to the fishes for good health, optimum growth, optimum yield and minimum waste. The important parameters for efficient feeding is that to transport feed pellets without damage and feed fishes until satiation. This is achieved by regulating feed storage, air transport and control, pellet transportation, and feed spread. Feed storage refers to proper handling and storing of feed in silos. Air transport and control is the process of regulating the air temperature, air pressure and back pressure of the transport air. Pellet transportation involves laying down proper pipe connections and periodic cleaning. Feed spread ensures the use of an appropriate spreader for the intended spreading area. The following reasons explain the importance of the feeding process in aquaculture

- It is an everyday process in operating a fish farm
- Correct feeding is always the key to achieve the expected farming results.
- The operating farms aim to produce high quality farmed products at lower costs. Feed cost typically accounts for 50 to 70 percent of the production cost of a farm.

There are two different vendors that supply the feed systems which are used in Norwegian aquaculture namely AKVA Group and STEINSVIK.[1] This thesis focuses on the feed system designed by the AKVA Group. The findings presented within this chapter were obtained from discussion with the R&D Engineer of the feed system and by studying the AKVA Group user manual of the feed system.[1,14]

The Centralized Control Air System Feed System (CCS) by AKVA Group is widely used in the aquaculture industry worldwide. The system is compatible for species that feed on pellets and are one of the most preferred feed system in Norwegian aquaculture. The system when integrated with camera control, pellet and environmental sensors and fish talk database can perform and control the feeding process with minimal human intervention. The figure 4.1 explains this integration. The system is delivered from a low capacity variant CCS-32 to high capacity variant CCS-110. The numbers 32 and 110 refer to the size of the feeding pipes in millimeters. The system configuration depends on transport lengths, biomass (feed amount), number of cages and species. The system capacity is dependent on the technical quality of feed pellets, the feeding regime and length of the feeding pipe which has been presented in the Appendix A.1 and A.2.

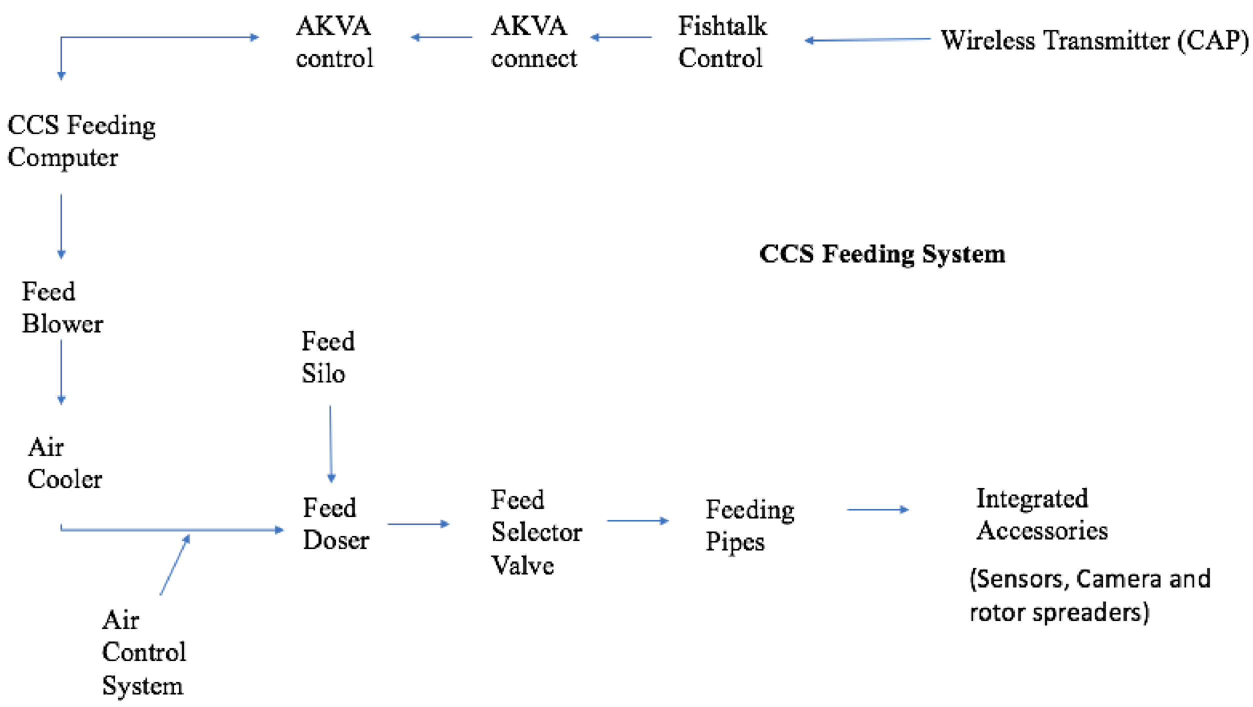

Figure 4.1: CCS Feed System designed by the AKVA Group

Cage Access Point (CAP) transmits the sensor and camera data wirelessly to the base. A detailed description of CAP is presented in section 6.3 of this thesis. Fish talk is a software solution that is designed to meet the requirements of modern aquaculture. It assists in production control and planning of biology and economics, traceability, documentation and maintenance of infrastructure and equipment. It consists of different modules for each category such as Fishtalk Control, Finance, Plan, Equipment, Tide, Benchmark, Lice, Wrasse and Environmental. AKVAconnect is a software solution designed to connect and establish optimal control on processes and activities in fish farms. A further explanation on AKVA-connect is presented in section 6.5 of this thesis. AKVAcontrol is a software solution that ensures optimal control of the feeding process. It is designed to control the feed flow based on the input of place and region, type of feeding regime (hard/short or small/long) and fish size.

The following section explains the components of the CCS Feed System. These software solutions were not considered for the analysis and more information on them can be found at AKVA Group's website. The components of the system that enable optimal feed transfer from silos to cages are Sensors, Blower, Air cooler, Air Control System, Doser, Selector, Feed pipes and Rotary spreader. These components are shown in the figure 4.2. The findings with respect to these components are discussed in the following sections. These were gathered by studying the AKVA Group User manual for the feed system and by interacting with the R&D Engineers of the system at AKVA during the visit.[8,14,45]

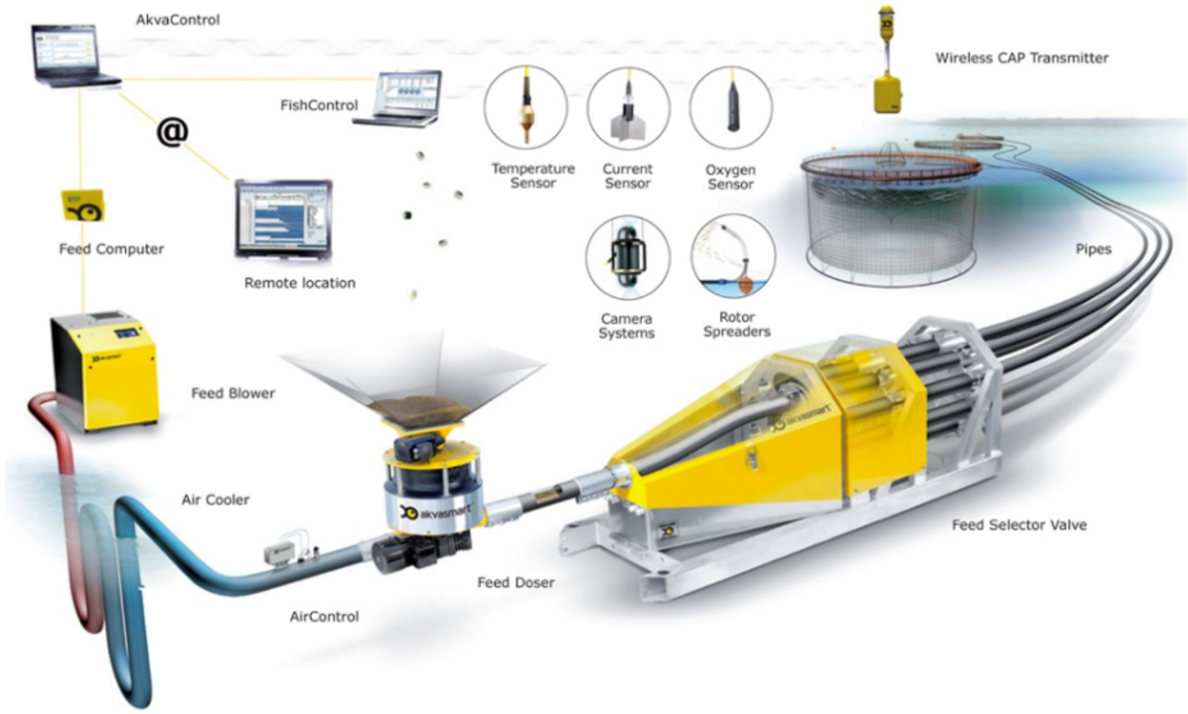

Figure 4.2: CCS Feed System designed by AKVA Group[13]

4.1 Sensors

Environmental data such as temperature, salinity, current speed and direction, oxygen, and pH are very important when feeding fish. The figure 4.3 shows the different types of sensors provided by AKVA

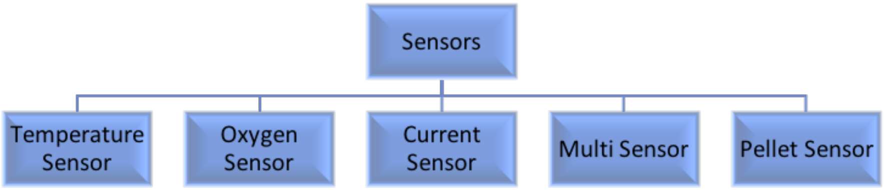

Figure 4.3: Sensors by AKVA Group

Temperature Sensor

Temperature varies at different water layers. It is important to know the exact temperature at the depth where fishes eat. The temperature sensor, oxygen sensor or multi sensor measures the temperature. This real-time data is displayed and logged into the software that estimates the expected amount of feed based on the feed table with the logged temperature data.

Oxygen Sensor

Estimation of oxygen is an important factor for fish growth and welfare. The multi sensor, RDO sensor or Sensor Oxybox measures the oxygen values. Oxybox is a stand-alone system that measure oxygen and current. These measures are logged on to the control system.

Current Sensor

The knowledge of the current speed is essential to prevent feed waste. Performing the feeding process during high current speed leads to feed waste that is, uneaten pellets. There are two variants of current sensors by AKVA, Tilt sensor that record the current speed in one layer and a Doppler current sensor that records at three different layers in the water column.

Multi Sensor

This sensor provides a complete environmental overview of the site. It consists of six water quality sensors that measure 12 different parameters, namely actual and specific conductivity, salinity, dissolved oxygen, pH, temperature, water level and ORP (Oxidation-Reduction Potential)

Pellet Sensor

The Doppler pellet sensor regulates the feeding process based on the number of pellets passing through the Doppler's sensing area. It has a built-in camera on the top for visual control of pellets.

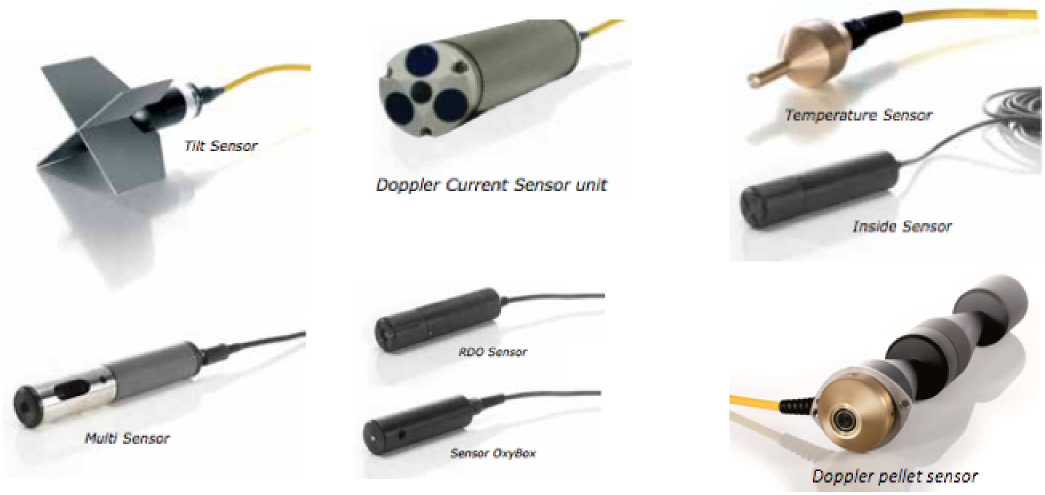

Figure 4.4: Sensors by AKVA Group[14, 13]

4.2 Blowers

The blowers provide the required air pressure to transport the feed to each unit or cage. It consists of an impeller attached to the shaft which is driven by an electric motor to generate the required air pressure. The blowers are delivered in silencer cabinets. The pellet transportation is optimized by the combination of air control system and frequency regulated blowers. Gentle feed handling and feed spread is optimized by adjusting the air speed. The type of blower used for the feed system depends on the size of the feeding pipe. AKVA supplies four different blower models for four different feeding pipe sizes. The system's back pressure depends on the pipe length, blower speed and feeding regime(kg/min).

4.3 Cooling System

The pressure of the transport air will be compressed from ambient pressure up to a maximum of 1 bar over-pressure. The pressure depends on feed pipe length and feeding regime. Compressed air generates heat up to 120°C and it is necessary to cool down transport air and surrounding components to a minimum temperature before reaching the doser down to 25°C depending on the location. High temperature can cause the lipids in pellets to be released and even lead to the denaturation of proteins. Thus, resulting in lowering of the nutritional value of the feed. Therefore, an air cooler is installed after the blower. The two type of coolers available are

- Air- water cooler, gives air temperature 5 - 10°C higher than ambient temperature
- Air- air cooler, gives air temperature 5 - 20°C higher than ambient temperature

Figure 4.5: Cooler by AKVA Group[14,13]

4.4 Air Control System

It is installed between the air cooler and feed doser. It consists of pipe air flow sensor and sensor pressure transmitter that enables real time measurement and logging of air flow, back pressure and temperature. The system is visualized in AKVAconnect by a simple graph per feeding line. The graph shows the real-time data and automatically adjusts the blower speed for gentle feed handling. This ensures optimal feed handling and reduces the risk of blockage and breakage in two of the following cases

- When air speed is too high, dust and breakage increases
- When air speed is too low, risk of pellet breakage and blockage increases

The figure 4.6 shows three different scenarios of low, optimal and high pellet speed respectively.

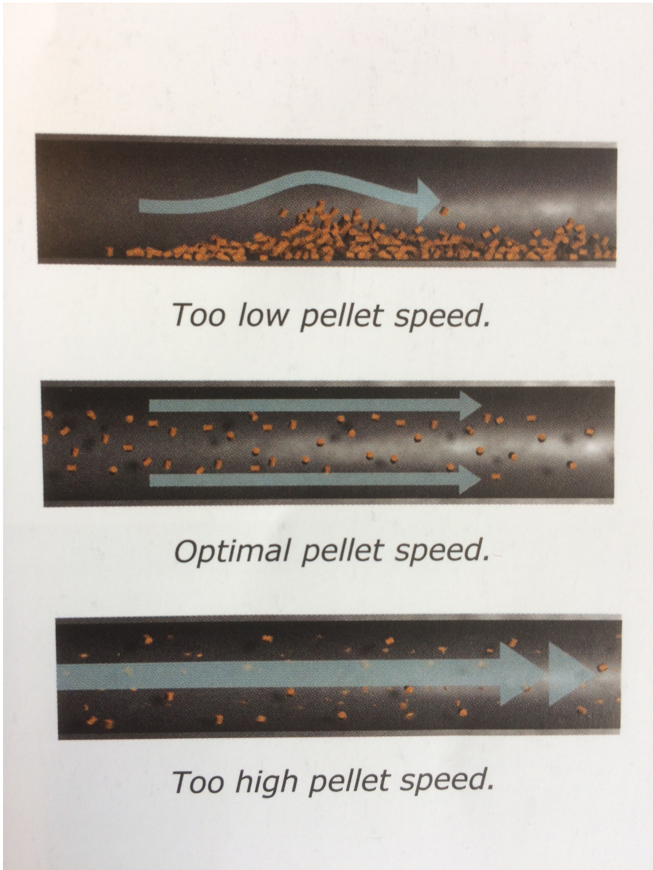

Figure 4.6: Possible scenarios of pellet speed in a feed pipe[14,13]

4.5 Silos

Silos are mostly round or square shaped large tanks that are used to store feed and protect them against danger. They are made of steel or aluminum. The number and size of silos on a farm site depends on the number of cages to be fed. The silos supply the feed to the doser for feed transportation during the feeding process.

4.6 Dosers

A smart silo outlet gate made of galvanized steel is installed at the doser top between silo flange and feed doser valve. The opening of this valve enables the transfer of feed from silos to doser. Doser transfers feed into the air flow by feed doser valves or feed augers with sluice valves. They are considered as a critical part in any feed system. Compared to the auger concept, the doser rotor helps in better feed transfer and results in minimum pressure contact and pellet damage. The doser consists of two chambers. The top chamber comprises of a fan and it is referred to as feeder unit. Its movement transfers the feed from top chamber to the bottom chamber when the feed reaches the passage. The bottom chamber is referred to as dosing chamber. It consists of the doser/sluice valves that assist in the feed transfer to the lines. The bottom chamber contains PEHD and silicon gaskets to prevent leakage during feed transfer into feed lines. The dosers are of two types

- Vari Doser and
- Doser 4000

Vari Doser

They are small dosers that are suitable for smaller cages of circumference up to 90 meters. They are widely used in hatcheries. The top and the bottom chambers have one motor each. The bottom motor is of a higher capacity than that of the top motor. Vari Doser results in continuous feed transfer into the feeding lines.

Doser 4000

They are large Dosers and are suitable for larger cages of circumference 120 -160 meters. They are widely used in ocean based farming. A single motor controls the rotation in the top and bottom chambers. These are Pulse Width Modulated, so there are breaks in feed transfer to the feeding lines.

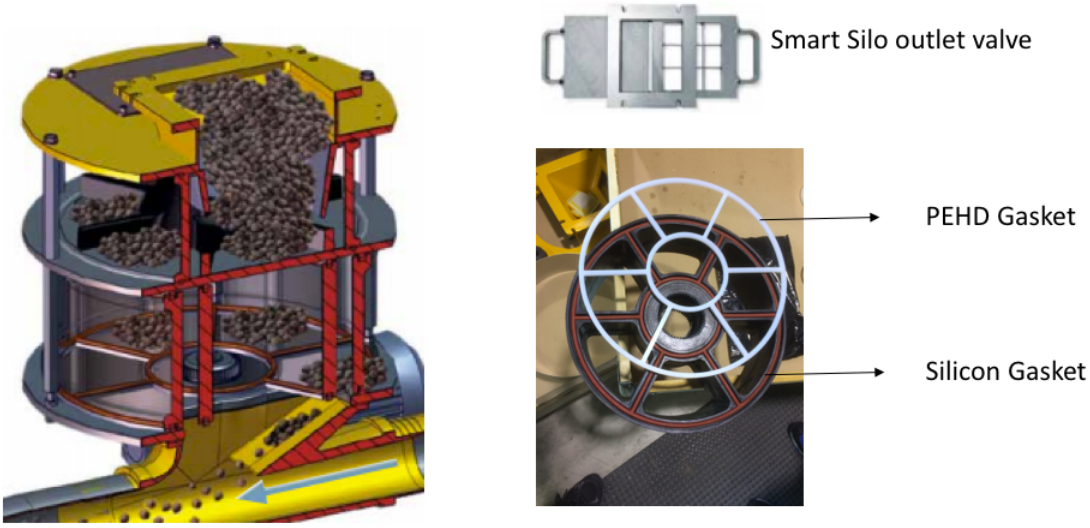

Figure 4.7: Working of doser on the left & Smart silo outlet and Gaskets on the right[14,13]

4.7 Selectors

The feed selector valve helps in distributing the feed to the selected cage and is the connection point for the HDPE feeding pipes. These pipes are exposed to severe environmental loads. A relief bracket on the selectors is designed to handle these loads. It comprises of a long S-pipe, motor and a blocking element. The long S-pipe connects the feed line to the feeding pipes. The motor helps in the movement of the blocking element. The blocking element ensures proper connection of the feed line to the correct feeding pipe by blocking the remaining feeding pipe outlets in the selector cabinet.

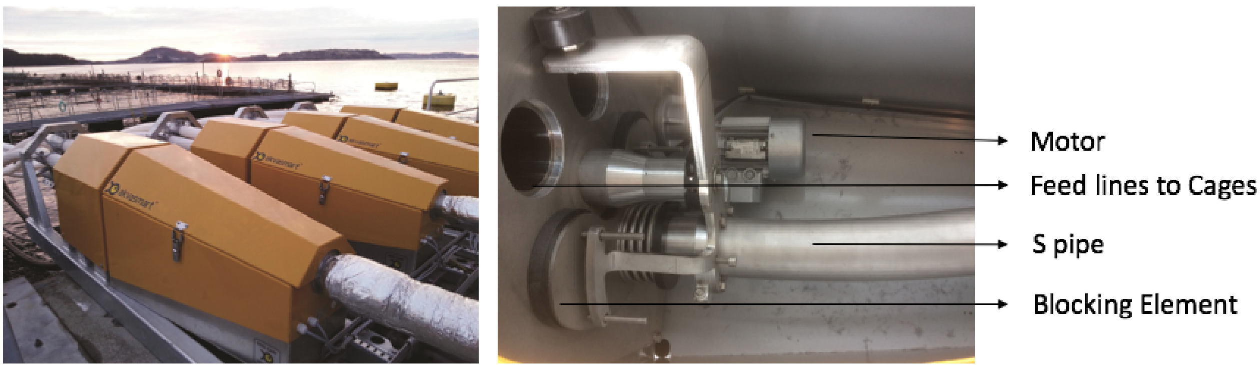

Figure 4.8: A group of selectors on the left & view inside the selctor cabinet on the right[14,13]

4.8 Feed pipes

Feed pipes help in transporting the feed from the selectors to the respective cages. The pipes are exposed to the forces of the ocean. These HDPE pipes are designed to handle the loads.

4.9 Rotor Spreader

It helps in spreading of feed in the cages. They have adjustable lightweight aluminum rotor pipes that allow lower air speed for startup and rotation. Thus, resulting in less dust and breakage, power consumption, back pressure, air temperature, noise, and wear and tear on the feed pipes. The rotor spreader consists of three main parts such as supporting pipe, rotating part and outlet pipe. The rotor spreader is supported on a heavy keel weight in galvanized steel ensuring its stability even in rough seas. The rotating part has a ventilated Zenon bearing that doesn't require regular cleaning and does not corrode.

Figure 4.9: Rotary Spreader variants by AKVA Group[14, 13]

4.10 Generators

Generators are the source of power supply for running the feed system. It consists of an engine, alternator, fuel system, voltage regulator, cooling and exhaust systems, lubrication system, a battery charger, control panel and a main assembly.

The engine is the source of mechanical energy input. The size of the engine is proportional to the maximum power output of the generator. Alternator converts the mechanical input to electrical output. It comprises of stationary and moving parts enclosed together that work to cause relative movements in electric and magnetic fields which generates electricity. The fuel system supplies the fuel for engine operation. The engines have a fuel tank as part of its base. The voltage regulator helps to maintain generator's output at full operating level. The cooling system ensures the cooling of the various components that are heated up in the process of power generation. The exhaust gases of the generator are disposed to the atmosphere by the exhaust system. Lubrication system ensures the durability and smooth operation of the engine by lubricating its moving parts through lube oil. As the start function of the generator is battery operated, the battery charger ensures that the generator battery is charged. The control panel provides the user interface to control and monitor the generator's operations. Main assembly provides a structural base support to earth the generator.

AKVA Group does not manufacture generators. The generators supplied with the feed system are from third party vendors or the operator of the farm decides on generator according to their requirements.

Chapter 5

RCM Analysis of Feed System

This chapter provides a detailed description of RCM analysis of the feed system described in the previous chapter. The following sections present the results of the analysis in accordance with the steps outlined in section 3.1 that is, identifying functions, failure modes, failure effects and consequences and finding the appropriate maintenance tasks. The components such as blower, cooler, doser, selector, feed pipes, rotary spreader, sensors, and generators are considered for the analysis neglecting the software AKVAconnect and AKVAcontrol. The analysis was carried out based on the expert judgments by R&D Engineers of the feed system at AKVA Group, this was due to the lack of reliability data. Interactions with them served to be the major inputs for the analysis.[8] The System Reliability theory by Marvin Rausand confirms that in situations of lack of data, expert judgments and input from manufacturers of the equipment are considered as the source.[35]

5.1 Functions

The function of the CCS feed system designed by AKVA Group is to transfer feed from silos to cages for fish growth and ensure optimal feed handling and even spreading of feed in the cages. The first step in a RCM analysis is understanding the system's functions. The functional hierarchy discussed in the following subsection gives the set of functions and its associated components that help in achieving the primary objective of the system.

5.1.1 Functional Hierarchy

The superior functions with its associated subordinate functions were identified for the feed system. The four superior functions were feed transportation, feed transfer, regulation and storage. The superior functions with its associated subordinate functions are presented in the hierarchy shown below in the figure 5.1

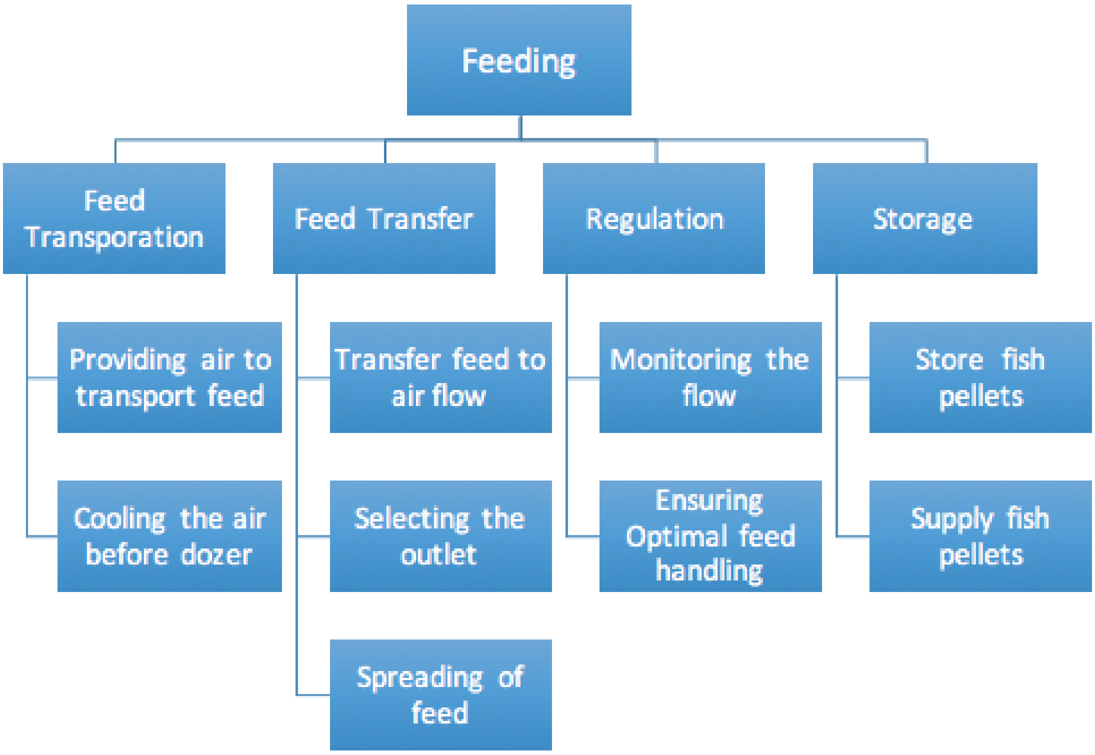

Figure 5.1: Functional hierarchy for CCS Feed System

Feed Transportation

This function helps in providing the medium for the transportation of feeds to the cages. This function is responsible for providing air to transport feed and to cool the compressed air before it reaches the dosers. Feed blowers and air coolers are the components that help in achieving this function.

Feed Transfer

This is an important function of the feeding system. The feed transfer function has three sub functions, namely transfer feed to air flow, selecting the outlet and spreading of the feed.

These sub functions are realized through dosers, selectors and rotor spreader respectively.

Regulation
This function ensures that there is optimal feed handling. Equipment such as air control system helps in real time measurement of air speed, back pressure and temperature. The temperature sensor helps in the estimating the feed amount from the feed table. The current sensor helps in storing the information about current speed in the database.

Storage
This function stores the fish pellets in the designed silos and supplies them to the doser for feeding the units or cages.

5.2 Functional Failure

The functional failure of the feed system occurs when the system fails to deliver its primary and secondary functions. The three main functional failures of the feed system are as follows:

1. No feeding (due to breakdown of a major component)
2. Improper feed spread (failure of rotary spreader)
3. Improper feed handling (when cooler/air control system or sensor fails)

The first functional failure is characterized by a failure of any of the critical component such as generator, blower, doser, selector and feed pipe thus obstructing the feeding process. A feed line consists of one blower, one or two dosers, selector, feed pipe and rotary spreader. The criticality of failure of the component varies based on the type of the feed line. The possible scenarios and the criticality during such scenarios is listed below

- When the feed line has one blower, one doser and one selector:
  failure of blower > failure of doser > failure of selector > failure of feed pipe > failure of rotary spreader
- When the feed line has one blower, two dosers and one selector:
  failure of blower > failure of selector > failure of doser > failure of feed pipe > failure of rotary spreader as the system can be run with the other doser when one fails
- In both the situations, the most critical component is the generator as the failure of generator results in loss of power supply

The second functional failure of improper feed spread occurs when the rotary spreader fails. Even in this scenario the feeding process is interrupted but the system is available with limited functionality. Despite the failure of the spreader, farmers can feed for short duration if the fishes were fed a long time ago. However, it may result in higher number of uneaten pellets. When cooler, air control system and sensors fail, it results in third functional failure of improper feed handling. The next step is constructing the FMECA to study these functional failures in detail.

5.3 FMECA

The Failure Mode Effect Criticality Analysis of the feed system is carried out on a component level. The FMECA worksheet of feed system is presented as two separate tables. The first one presents the components, their function, possible failure modes, failure cause, failure pattern, their Mean Time Between Failures (MTBF), Mean Down Time (MDT) and the effect of failure on a subsystem and system level. The second table shows the component, their failure modes, criticality assessment of failure modes, consequence, frequency and risk index.

The listed failure modes for the each component was finalized by discussing with the R&D Engineer of the feed system.[8] The intention of the FMECA worksheet is to analyze each failure modes in detail. This is performed by analyzing the cause, the failure pattern, whether the failure mode is hidden or evident and its effect on the system. MTBF refers to the time at which the failure is expected to occur when no maintenance is carried out. Mean Down Time is the time required to do the corrective action. Then it is followed by a criticality assessment of each failure mode against different parameters as shown in the section 5.3.1 . The consequence of failure mode is evaluated on a scale of 1 to 5 and the frequency is found from MTBF. These inputs gives the risk index.

Nine components of the feed system were considered for the FMECA. 31 relevant failure modes of these components were studied in detail as a part of the analysis. The function of each component and the effect of its failure on the system and its function is presented in the FMECA worksheet. The detailed FMECA worksheet is shown in the tables 5.1 and 5.2. The following figure 5.2 gives the summary of FMECA analysis of the feed system.

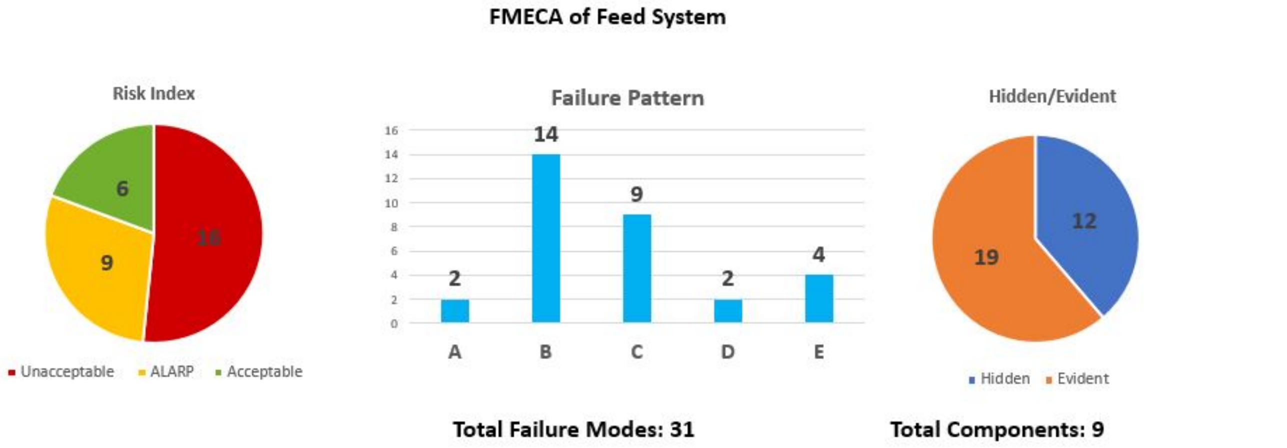

Figure 5.2: Summary of FMECA of Feed System

From the above figure 5.2, it is evident that most of the failure modes were of type B that is, age related. The ball bearings and aluminum pipe of the rotary spreader exhibit failure mode of type A (infant mortality) and senors, circuit boards and cooler have failure modes of type E (random). Characteristic failure type C was seen in failure modes of motor, cooler, blower and generator. Condition-related failure mode type D was seen in wear of air filter of blower and generator. The failure mode of break down of the generator considers failure of generator due to its other components. Most of the failure modes are evident to the operating crew under normal operating conditions except the failure modes of air filters, oil, gaskets, O rings, blocking device of the selector and supporting pipe of the rotary spreader. The MTBF ranges from 3 months for failure modes caused by lack of cleaning or lack of lubrication to a maximum of 12 years for breakdown of generator. The MDT was less than 3 hours for most of the failure modes as AKVA's design considers this as an important criteria.[8] This was followed by a criticality assessment as explained in the following subsection.

5.3.1 Criticality

The criticality of each failure mode was assessed on the following four criteria,

- Safety denoted by S
- Environment denoted by E
- Availability denoted by A
- Cost denoted by C

For safety, how feed loss can affect fish welfare was considered for the classes. For environment, the contribution to eutrophication was chosen. In the feeding process, the fish excretes nutrients such as Phosphorous, Nitrogen, and Carbon. The feed pellets which are not consumed by the fishes also adds to the release of these nutrients to soil. When the soil gets saturated because of these nutrients, it leads to the growth of harmful algal blooms.

Availability can be defined as the ability of an item (under combined aspects of its reliability, maintainability, and maintenance support) to perform its required function at a stated instant of time or over a stated period.[35] How failure modes affect the availability of the system was considered for the classes. The cost of the components obtained through discussion with the R&D Engineer were grouped into classes. These criticality classes are shown below the table 5.2.

Table 5.1: FMECA of Feed System Part 1

#	Component	Function	Failure Mode	Failure Cause	FP	H/E	MTBF	MDT	Effect of Failure: On the subsystem	Effect of Failure: On the Subsystem Funciton
	Rotary Spreader									
1	Ball Bearing	Reduce rotational friction and support radial and axial loads	Spurious stop	Lack of cleaning	C	E	3 months	0.5 hours	No rotation	Imporper spreading of feed
			Break down	Wear	A	E	480 tons of feed	0.5 hours	No rotation	Imporper spreading of feed
	Aluminum Pipe	Connects bearing assembly and outlet pipe	Failure	Wear	A	E	480 tons of feed	0.5 hours	Mechanical damage	No rotation of the spreader
	Outlet Pipe	Spread feed in the cages	Failure	Wear	B	E	1000 tons of feed	0.5 hours	Mechanical damage	Reduced spread area
	Stainless Steel pipes	Support the rotary spreader	Failure	Wear, fatigue	B	E	5 years	1 hour	Loss of support	Loss of rotor spreader
			Fracture	Impact from a physical object	B	H	5 years	-	No serious impact	No serious impact
			Corrosion	Chemical reaction	C	H	5 years	1 hour	Degradation of pipe strength	Promotes pipe failure
	Selector									
2	O ring	For sealing in S pipes	Structural deficiency	Wear	B	H	2 years	1 hour	No sealing	Leakage resulting in minimal loss of feed

	Blocking device	To block the feed getting transferred to unselected feed pipes	Failure	Wear	B	H	2 years	1 hour	No blocking	Resulting in minimal feed loss
	Motor	Power Transmission for selection of feed pipes	Break down	Wear	B	E	3 years	3 hours	No power transmitted	System stops
			Over heating	Lack of cleaning of feed dust	C	E	3 months	0.5 hours	Selector degradation	Reduced efficiency
	Dosers									
3	Gaskets (PEHD &Silicon)	To prevent leakage of pellets during feed transfer from doser	Leakage	Large clearance between seal faces	B	E	6 months	0.5 hours	Leakage of feed	Minimal feed loss
			Structural deficiency	Wear	B	H	1 year	1.5 hours	Mechanical degradation	Increases damage to the equipment due to friction
	Motor	Power transmission for rotating the top and bottom sections of the doser	Break down	Structural failure	B	E	3 years	1 hour	No power transmitted	No transfer of feed from the dozer
			Over heating	Lack of lubrication	C	E	3 months	0.5 hours	Doser degradation	Reduced efficiency
	Cooler									
4	Air to Air / Air to water cooler	To cool the air from the blower before the dozer	Structural Failure	Degradation	C	E	10 years	5 hours	Inefficient cooling	Overheated fluid
			Corrosion	Chemical reaction	B	H	5 years	5 hours	Physical damage	Reduced life time of the cooler

			Leakage	Damage	E	E	10 years	2 hours	Loss of re-circulated fluid	Less output
5	**Blower**									
	Belt	Transmits mechanical energy from the motor to the fan	Failure	Wear	B	E	12000 hours / 2 years	1 hour	No Transfer of energy	No supply of air for feed transporatation
	Air Filter	Preventing airborne contaminents from entering the flow	Blockage	Accumulation of particles	C	H	5 years	0.5 hours	Less air for circulation	Reduced output
			Failure	Wear	D	H	2500 hours / every year	0.5 hours	No filtration	Increases probability of contaminated air entering the system
	Motor	Power transmission for rotating the top and bottom sections of the doser	Break down	Structural failure	B	E	3 years	1 hour	No power transmitted	No transfer of feed from the dozer
			Over heating	Lack of lubrication	C	E	3 months	0.5 hours	Doser degradation	Reduced efficiency
	Oil	Lubrication	Fail to lubricate	Overused oil	C	H	6000 hours/ every year	2 hours	Lack of lubrication	Blower degradation due to lack of lubrication
6	**Generator**									
	Generator	Provides power for the CCS feed system for feed transfer	Break down	Wear	B	E	10 years	12 hours	No power transmitted	System stops

	Belt	Transmits mechanical energy from the motor to the fan	Failure	Wear	B	E	12000 hours / 2 years	2 hours	No Transfer of energy	No supply of power for feed transpo-ratation
	Air Filter	Preventing airborne contaminents from entering the flow	Blockage	Accumulation of particles	C	H	5 years	0.5 hours	Less air for circulation	Reduced output
			Failure	Wear	D	H	2500 hours / every year	0.5 hours	No filtration	Unfiltered air entering the system
	Oil	Lubrication	Change	Overused oil	C	H	500 hours	2 hours	Lack of lubrication	Generator degradation due to lack of lubrication
	Sensors									
7	Sensors	Provide environmental data as input to feed systems	Physical damage	Dropped objects, passing vessels , contact with sharp objects	E	E	1 year	1 hour	No detection/ incorrect values	Lack of accurate en-vironmental data for feed input
			Break down	Wear	E	E	5 years	1 hour	No detection	Lack of envi-ronmental data for feed input
	Circuit boards									
8	Circuit boards	Transmit electrical power and signal	Short circuiting	Moisture	E	E	5 years	1 hour	No transfer of power or signal	Loss of the correspond-ing system functions

	Feed pipes									
9	Feed pipes	Transports feed from the selectors to the cages	Failure	Wear	B	E	1 year	3 hours	No transfer of feed to selected cages	Loss of feed

Availability Classes		
1	Available	One function fails or a failure is initiated i.e. system functions with a limitation
2		More than one function fails
3	Unavailable	System is unavailable for feed transfer

Environment Classes		
1	N	No contribution to eutrophication
2	L	Lower contribution to eutrophication
3	M	Significant contribution to eutrophication
4	H	High contribution to eutrophication

Safety Classes		
1	Low	No or little impact on fish welfare
2	Medium	Affects fish welfare significantly
3	High	Affects fish welfare to a large extent

Cost Classes		
1	Very low	$\leq$ 500 NOK
2	Low	$\leq$ 2000 NOK
3	Medium	$\leq$ 5000 NOK
4	High	$\leq$ 8000 NOK
5	Very high	$>$ 8000 NOK

Table 5.2: FMECA of Feed System Part 2

#	Component	Failure Mode	Criticality Assessment S	E	A	C	Consequence (a)	Frequency (b)	RI (a)+(b)	Maintenance Task
	Rotary Spreader									
1	Ball Bearing	Spurious stop	2	3	1	-	1	5	6	Scheduled on-condition
		Break down	2	3	1	3	1	5	6	Scheduled on-condition
	Aluminum Pipe	Failure	3	3	1	3	1	5	6	Run to failure
	Outlet Pipe	Failure	1	3	1	1	1	5	6	Run to failure
	Stainless Steel pipes	Failure	3	3	1	1	1	2	3	Run to failure
		Fracture	1	1	1	1	1	2	3	Run to failure
		Corrosion	1	1	1	1	1	2	3	Scheduled restoration
	Selector									
2	O ring	Structural deficiency	1	1	1	1	1	3	4	Scheduled discard
	Blocking device	Failure	1	1	1	2	1	3	4	Scheduled on-condition
	Motor	Break down	1	1	1	3	3	3	6	Scheduled on-condition
		Over heating	1	1	1	-	1	5	6	Scheduled restoration
	Dosers									
3	Gaskets (PEHD &Silicon)	Leakage	1	1	1	1	1	1	2	Scheduled on-condition
		Structural deficiency	1	1	1	2	1	1	2	Scheduled on-condition
	Motor	Break down	2	1	3	2	3	3	6	Scheduled on-condition
		Over heating	1	1	1	2	1	5	6	Scheduled restoration
	Cooler									
4	Air to Air / Air to water cooler	Structural Failure	2	1	1	5	3	1	4	Scheduled on-condition
		Corrosion	1	1	1	5	3	2	5	Scheduled on-condition
		Leakage	1	1	1	5	3	1	4	Run to failure
	Blower									
5	Belt	Failure	3	1	3	1	3	3	6	Scheduled discard
	Air Filter	Blockage	1	2	1	1	1	2	3	Scheduled on-condition
		Failure	2	1	1	1	1	4	5	Scheduled discard

	Motor	Break down	2	1	3	2	3	3	6	Scheduled on-condition
		Over heating	1	1	1	2	1	5	6	Scheduled restoration
	Oil	Fail to lubricate	1	1	1	1	2	4	6	Scheduled on-condition
6	**Generator**									
	Generator	Break down	3	1	3	5	5	1	6	Scheduled on-condition
	Belt	Failure	3	1	3	2	5	3	8	Scheduled discard
	Air Filter	Blockage	1	1	1	2	2	2	4	Scheduled on-condition
		Failure	2	1	1	2	2	4	6	Scheduled discard
	Oil	Change	1	1	1	3	2	4	6	Scheduled on-condition
7	**Sensors**									
	Sensors	Physical damage	1	1	1	4	3	4	7	Run to failure
		Break down	1	1	1	4	3	2	5	Run to failure
8	**Circuit boards**									
	Circuit boards	Short circuiting	3	1	3	4	3	2	5	Scheduled on-condition
9	**Feed pipes**									
	Feed pipes	Failure	3	4	3	4	3	4	7	Run to failure

5.3.2 Risk Matrix

The level of feed loss caused by the failure mode was considered for the consequence column of the FMECA. Frequency refers to how often the failure mode is expected to occur and it was estimated from MTBF. The consequence and frequency class used in the analysis is presented in the table 5.4 and table 5.3 respectively.

Table 5.3: Frequency Classes used in the analysis

Frequency Classes		
1	Very Unlikely	Once in 10 years
2	Remote	Once in 5 years
3	Occasional	Once in 3 years
4	Probable	Once in 1 year
5	Frequent	Once in 6 months

Table 5.4: Consequence Classes for Feed System

Consequence Classes		
1	VL	Very low feed loss
2	L	Low feed loss
3	M	Medium feed loss
4	H	High feed loss
5	VH	Very high feed loss

The risk index value,

- 1-3 were considered to be Acceptable denoted by green
- 4 and 5 were considered to be ALARP denoted by yellow
- 6-10 were considered to be Unacceptable denoted by red

These values for the risk indices were finalized during the discussion with the R&D Engineer of the system.[8] As shown in the figure 5.2, 16 failure modes were found unacceptable. These seven components of feed system namely *Rotary spreader, Selector, Doser, Blower, Generator, Sensors and Feed pipe* had unacceptable risk indices. These components are shown in their appropriate risk values in the risk matrix below 5.3

Probability/ Consequence	1 Very Unlikley	2 Remote	3 Occasional	4 Probable	5 Frequent
5 Very High	G	7	G	9	10
4 High	5	6	7	8	9
3 Medium	4	5	S,D,B	SE,F	8
2 Small	3	4	5	B,G,	7
1 Very small	2	3	4	5	RS,S,D

Figure 5.3: Risk Matrix FMECA of feed System

G = Generators, S = Selectors, D = Dosers, B = Blowers, SE = Sensors, F= Feed pipe, RS = Rotary Spreader.

The ball bearing and aluminum pipe of the rotary spreader are supplied as one single unit. When either one fails, the whole unit has to be replaced. The failure modes of ball bearing, aluminum pipe and outlet pipe of the rotary spreader are critical as it results in improper feed spread. The motors of the selector and doser are critical for the feeding operation. The analysis has yielded the failure modes of overheating and break down of these motors as unacceptable. As discussed in section 5.2 blowers are critical in a feed line. The wear of belt and lack of lubrication of blowers have unacceptable risk index of 6. Generators are the source of power supply for the feed system. The failure modes of generator's break down, failure of air filters and lack of lubrication have risk index of 6 and wear of its belt has a risk index of 8. The physical damage of sensors and wear of feed pipes have an unacceptable risk index of 7 each. Of the remaining failure modes four failure modes had risk index of 3 and two had risk index of 2 which are considered acceptable. Nine failure modes of risk index 4 or 5 were considered in the ALARP region. The next step is performing the maintenance task analysis and establishing the suitable maintenance task for each failure mode.

5.4 Maintenance Task Analysis of Feed System

The last column of the FMECA worksheet presents the maintenance task for each failure mode. The decision tree outlined in the section 3.5.2 identifies the appropriate maintenance task for each failure modes. The maintenance actions are a combination of preventive and corrective maintenance.

Eight failure modes receive the maintenance task 'Run to Failure'. This maintenance task allows the failure mode to occur and then tasks to restore the component's initial state are executed after the failure. Run to failure is not a preferred maintenance task for hidden failure as the suggested maintenance task should help the operating crew to be aware of the component's condition. The fracture of the supporting stainless steel pipe of the rotary spreader is suggested for 'run to failure' action despite being a hidden for the following reasons,

1. The failure has no serious impact on the system
2. The cost of a maintenance task would exceed the cost of allowing the failure to occur
3. The same item shall be checked every year for corrosion. If found corroded shall be replaced

For the components that have 'run to failure' maintenance task, spare part management is essential. The maintenance task of scheduled restoration is for failure modes such as corrosion and overheating. Scheduled discard of air filter and belt of the blower and O-ring of the selector is recommended. Scheduled on condition is recommended for the components rotary spreader, selector, doser, cooler, blower and generator.

Table 5.5 presents a detailed Maintenance Task Analysis (MTA) of the feed system. The table shows the components, their failure mode, their pattern, risk index, the found maintenance task, maintenance interval and maintenance description.

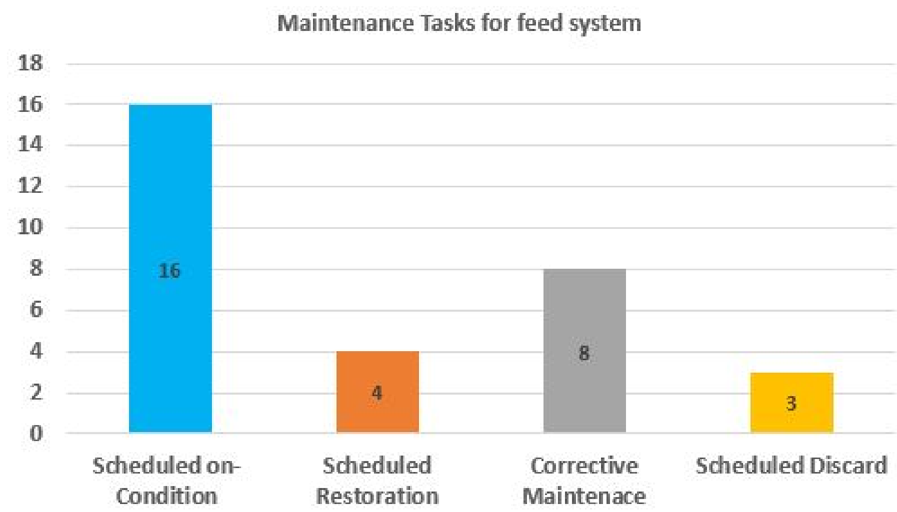

Figure 5.4: Maintenance Task Analysis of Feed System

Table 5.5: Maintenance Task Analysis of feed system

#	Component	Failure mode	FP	RI	Maintenance Task	Maintenance Interval	Maintenance Description
1	**Rotary Spreader**						
	Ball bearing	Spurious Stop	C	6	Scheduled on-condition	2 months	Unscrew the 3 unbraco bolts and remove the bearing. Clean it in warm and mild greasing soap water. If found not ok, replace the bearing
		Break down	A	6	Scheduled on- condition	6 months	Vibration measurements on bearing and casing using octave band analysis through contiguous and fractional octave filters. The average output of each filter is measured
	Aluminium pipe	Failure	A	6	Run to failure	-	The Aluminium pipe along with the bearing is supplied as a single unit. So both shall be replaced with a spare
	Outlet Pipe	Failure	B	6	Run to failure	-	Replace the outlet pipe with the spare
	Stainless Steel pipe	Failure	B	3	Run to failure	-	Replace the stainless steel pipe with the spare
		Fracture	B	3	Run to failure	-	Replace the stainless steel pipe with the spare
		Corrosion	C	3	Scheduled restoration	1 year	Lift the pipe, from water, Clean the fouling, check for corrosion. Replace it if corroded
2	**Selector**						
	O ring	Wear	B	4	Scheduled discard	1 year	Replace the O ring in the selectors with the spare
	Blocking device	Failure	B	4	Scheduled on-condition	6 months	Check the blocking element for cracks due to fatigue or wear using liquid penetrant
	Motor	Break down	B	6	Scheduled on-condition	1 year	Vibration measurements and frequency analysis - fast fourier transformation of data

		Overheating	C	6	Scheduled restoration	6 months	Clean the motor periodically to avoid salt water deposits
	Dosers						
3	Gaskets	Leakage	B	2	Scheduled on-condition	3 months	Clean the gaskets with warm mild degreasing soap water. Lubricate the gaskets with silicon grease after cleaning. Replace gaskets if found damaged
		Structural deficiency	B	2	Scheduled on - condition	6 months	Check the gaskets for damage. When found damaged, replace the gaskets
	Motor	Break down	B	6	Scheduled on-condition	1 year	Vibration measurements and frequency analysis - fast fourier transformation of data
		Overheating	C	6	Scheduled restoration	6 months	Clean the motor periodically to avoid salt water deposits
	Cooler						
4	Cooler	Structual failure	C	4	Scheduled on-condition	3 year	Vibration measurements and frequency analysis - fast fourier transformation of data
		Corrosion	B	5	Scheduled on-condition	1 year	Open the cooler, check for corroded elements and replace the cooler if necessary
		Leakage	E	4	Run to failure	-	Replace the coolers with a spare
	Blower						
5	Belt (B)	Failure	B	6	Scheduled discard	2 years	Replace the generator belt with the spare
	Air filter (B)	Blockage	C	3	Scheduled on - condition	2 years	Mechanical indicator showing pressure drop indicating clogging
		Failure	D	5	Scheduled discard	1 year	Replace air filter
	Motor (B)	Break down	B	6	Scheduled on-condition	1 year	Vibration measurements and frequency analysis - fast fourier transformation of data
		Overheating	C	6	Scheduled restoration	6 months	Clean the motor periodically to avoid salt water deposits

	Oil (B)	Change	C	6	Scheduled on-condition	1 month	Mesh obscuration particle counter. Oil passes through three meshes and particles bigger than the pores get stuck in the mesh. The pressure change is measured by the sensors.
6	**Generator**						
	Generator	Break down	B	6	Scheduled on- condition	3 months	Vibration measurements on bearing and casing using octave band analysis through contiguous and fractional octave filters. The average output of each filter is measured
	Belt (G)	Failure	B	8	Scheduled discard	2 years	Replace the generator belt with the spare
	Air filter (G)	Blockage	C	4	Scheduled on - condition	2 years	Mechanical indicator showing pressure drop indicating clogging
		Failure	D	6	Scheduled discard	1 year	Replace air filter
	Oil (G)	Change	C	6	Scheduled on-condition	1 month	Mesh obscuration particle counter. Oil passes through three meshes and particles bigger than the pores get stuck in the mesh. The pressure change is measured by the sensors.
7	**Sensors**						
	Sensors	Physical Damage	E	7	Run to failure	-	Replace the sensors and Check the spare after installation
		Break down	E	5	Run to Failure	-	Replace the sensors and Check the spare after installation
8	**Circuit boards**						
	Circuit boards	Short circuiting	E	5	Scheduled on - condition	Everyday	Check the cabinet and dry the moisture
9	**Feed pipes**						
	Feed pipes	Failure	B	7	Run to Failure	-	Replace the feed pipes

The procedures for maintenance tasks described for Scheduled on-condition are inspired by the condition monitoring techniques outlined in RCM by Moubray[11] and research papers and articles on condition monitoring.[46,47,48,49] The recommended tasks intend to prevent the failure modes. The maintenance interval suggested for the tasks is based on the MTBF from FMECA worksheet. The maintenance interval must be shorter than MTBF. Thus enabling us with the possibility to discover the failure mode before it occurs. The following figure 5.5 shows the planned preventive maintenance activities of feed system in relation with their time interval. This serves as a tool in analyzing the maintenance program and to plan and execute the maintenance tasks.

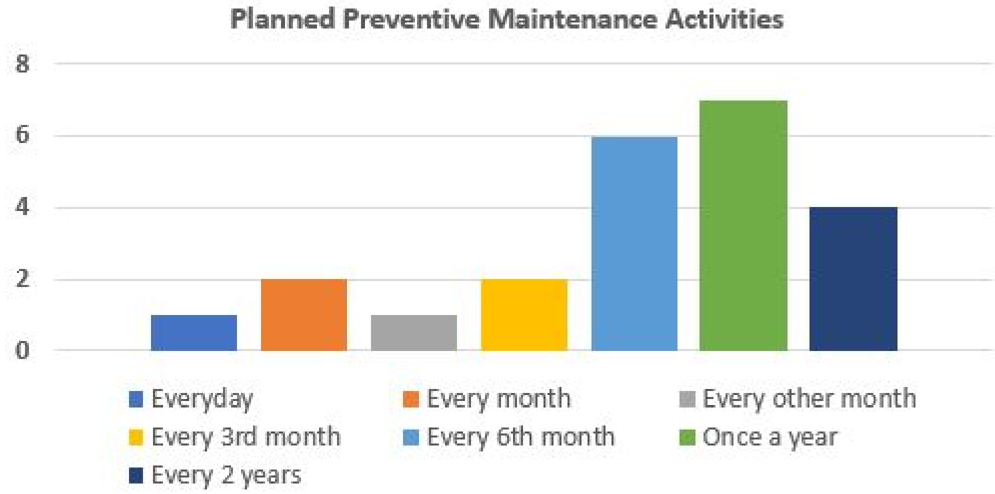

Figure 5.5: Planned Preventive Maintenance Activities of Feed System

A cost-benefit analysis was to be performed to check whether the maintenance program was cost effective. Due to the lack of data, it was not possible to perform cost-benefit analysis for the proposed maintenance program. The recommended maintenance tasks are grouped into packages as shown in the Table E.1 in Appendix. The worksheet presents a thorough explanation of the maintenance task that can be performed at the same time and suggests the personnel and equipment required during the task. The last column shows the complexity of the suggested maintenance task. Maintenance packages help in optimizing the maintenance program. The maintenance program can be improved and updated by receiving periodic feedback from the operating crew that validate the suggested maintenance task and the time interval.

The results of the analysis provide the appropriate maintenance task for the components of the feed system. Furthermore, improved knowledge about the components and the system are an added advantage of the analysis.

Chapter 6

Camera System

The camera system designed by AKVA Group is widely used in Norwegian aquaculture.[1] The advanced video cameras and sensor systems by AKVA are used for both monitoring the fishes and the feeding process. The findings in this chapter were accomplished by discussing with the R&D Engineers of the camera system and by studying the user manual of camera system[15,9] Akvasmart cameras have been designed and produced for 20 years. These cameras enable the operators to have a complete overview of surface and underwater activities through vivid video images and they are wirelessly transmitted to the farm base. Their product ranges from a basic black and white camera to advanced movable dual pan/tilt cameras. The cameras are used for the following purposes,

- Underwater feeding activity
- Surface feeding activity
- Fish maturation
- Fish behavior
- Morts at the cage bottom
- Fish parasites
- General surveillance

The figure 6.1 shows the classification of cameras designed by AKVA. The cameras provided by AKVA can be broadly classified as HR cameras and SmartEye cameras.

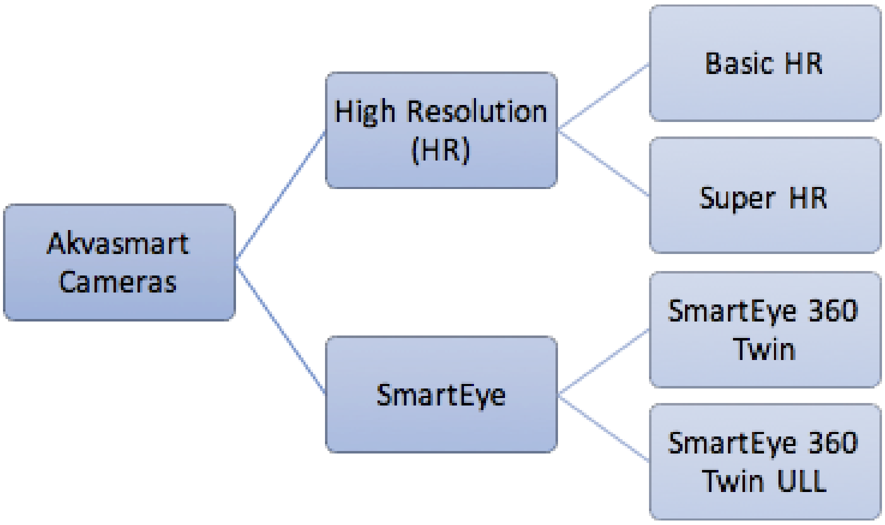

Figure 6.1: Classification of Cameras designed by AKVA Group

HR cameras are the High-Resolution cameras developed for visual control of the feeding process. These cameras are stationary and are positioned underneath the fish's eating area for easy detection of uneaten pellets passing the camera (5m-8m). They can be controlled from the cage, workboats, feeding control room via the Internet. They are of two types, namely Basic and Super. The basic version is simple, reliable and affordable camera that records monochrome images. The Super HR cameras are rugged and can record clear images even in poor light and visibility conditions. They are the world's most used feeding cameras. The figure 6.2 shows the two types of HR cameras.

Figure 6.2: Types of High Resolution Cameras (HR) by AKVA Group[15,16]

SmartEye cameras consists of upper and lower camera units that records crystal clear video images in both color or monochrome. The upper unit records in color and the lower unit records in monochrome or color. Monochrome is preferred for looking down into deep and darker cages. These cameras do not have external moving parts and are watertight which improves its operational safety by reducing the risk of leaks. These cameras combined with Smart-Winch systems designed by AKVA helps in the horizontal and vertical movement of these 360-degree Twin cameras thus enabling the operator to have accurate surveying of the processes such as feeding, fish's condition and mortality checks. It is also available with a built-in depth and temperature sensor. The two types of SmartEye cameras are SmartEye Twin cameras and SmartEye Twin ULL. The latter is preferred for use in areas of poor light conditions and records clear images to a depth of 75 meters. The SmartEye cameras are connected to the CAP (Cage Access Point) mounted on each cage through a coax video cable. The CAP wirelessly transmits the recorded video to the base station. The SmartEye camera is shown in the figure 6.3

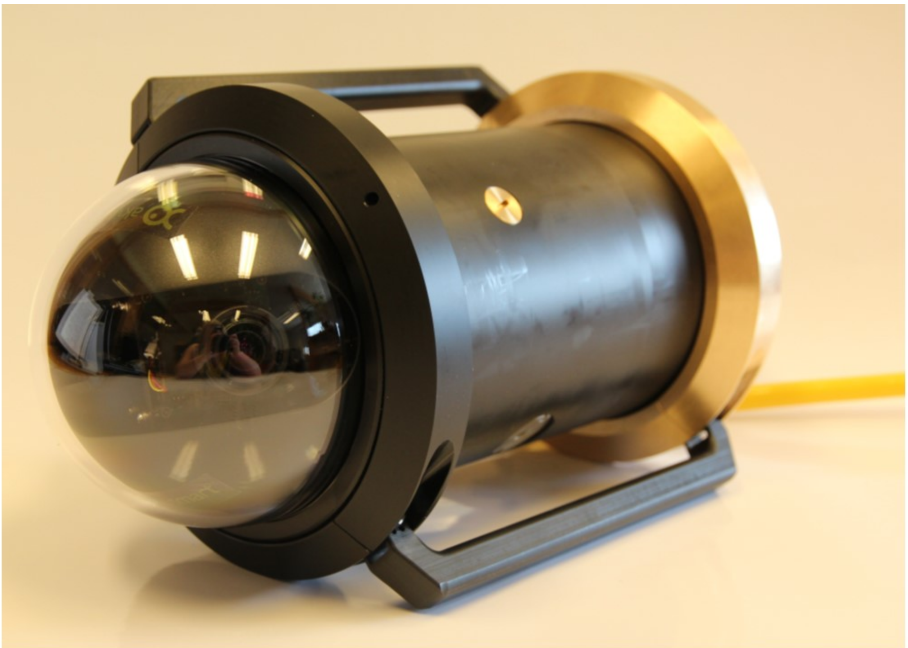

Figure 6.3: SmartEye Cameras by AKVA Group[15,16]

The SmartEye cameras are studied in detail and considered for the RCM analysis of the camera system for the following reasons,

- These cameras are more advanced and help in providing a complete overview during the monitoring activity.
- These cameras can be combined with the winch system that enables its movement both in horizontal and vertical direction inside the cages.

- The versatility of these cameras are not just limited to monitoring the feeding process. They are used in monitoring fish's condition and mortality checks.
- Further, understanding these cameras serve as an asset when moving towards more exposed conditions and while introducing more autonomous operations to replace manual interventions.

Components of the Camera System

Different components integrated together help in realizing the function of the camera system. The components of the camera system are listed below

- SmartEye 360 Twin Camera
- Winches
- Cage Access Point
- Generators
- AKVA Connect

6.1 SmartEye 360 Twin Camera

As explained above, the SmartEye 360 Twin Camera consists of two Pan Tilt camera units often referred to as PT up for the upper camera unit and PT down for the lower camera unit. The top and the bottom domes prevent the camera units from external damage. Both the PT cameras have a camera module that consists of board lens, CCD (Charge-Coupled Device) sensor and a circuit board. The CCD sensor recognizes the light and has the same resolution as the cameras. A PCB (Printed Circuit Board) Controller helps in synchronizing the top and bottom cameras and to collect environmental data from the pressure and temperature sensors. The O- rings in both the PT units ensures the sealing of the units. The camera has two lock rings namely the upper lock ring and lower lock ring to which the handles are attached on either side. The suspension system of the winch is connected to these handles enabling the movement of camera in the cages. The lock rings in the upper part are made of plastic and the lower one is made of metal to make the camera heavy enough to sink. A coax cable connects the camera to the CAP (Cage Access Point). This custom-made coax cable is used for power supply, to deliver commands and video transfer. For a detailed assembly drawing that shows the discussed parts of the SmartEye 360 Twin Camera refer Appendix B.1 and B.2

6.2 Winch System

The winch system comprises of winch, ropes and elastic bands. The ropes and elastic bands together are referred as suspension system. Winches enable the horizontal and vertical movement of underwater cameras. They are installed on each cage and the camera suspension system is attached to them. AKVA has designed three types of smart winches that are compatible with the smart cameras namely Winch V5, Winch HT Dual and Smart Winch as shown in the figure 6.4

Figure 6.4: Winch Variants by AKVA Group[15,16]

Winch V5 was studied in detail and included in the RCM analysis of the camera system for the following reasons

- It is claimed as advanced and more robust of all the other variants by AKVA
- It can be remotely operated
- AKVA has included sensors in its design that provide us with the equipment data
- Winch V5 shall serve as the reference for further designs improvements in future

Winch V5 consists of two drums on either side of the enclosure casing and is watertight. These drums are referred to as M1 and M2 as shown in the figure 6.6. The length of the rope on M1 is lesser than the length of the rope on M2 because of the shorter distance between the camera and M1 than camera and M2 as shown in the figure 6.5. Each drum has a motor powered by power supply unit. The power consumption and the speed of the motor is controlled by Pulse Width Modulation. ADIO2 (Analog Digital Input Output) card is used instead of a PLC (Programmable Logic Controller) for monitoring speed, moisture content and temperature of the card that is correlated to the motor temperature. The winch has two sensors for each drum that can record their position and have the operator informed about their location. A tiny Wi-Fi switch helps in communication with the CAP. The enclosure casing houses four connections namely analog temperature, MODBUS, Ethernet and power supply connections. The winch can also be manually operated with the help of the four buttons on the button panel.

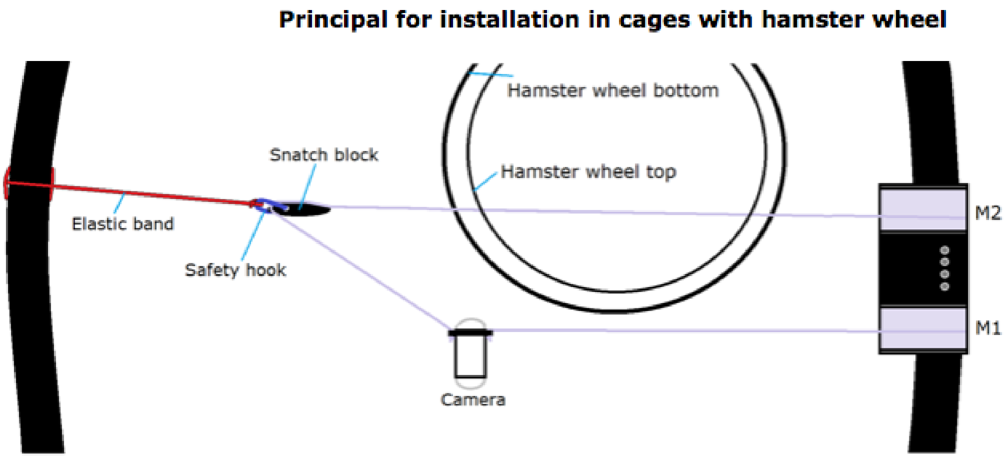

Figure 6.5: Installation of Camera in Sea cages[15]

Signals from the user reaches ADIO via Ethernet that controls the PWM which in turn controls the drum ensuring the positioning of camera in the desired location. The winch is mounted on the CAP by means of a bracket. Difference in direction of rotation of drum results in the movement of the camera. The possible combinations with the drum rotation and the respective movement of the camera is listed below.

$$\left.\begin{array}{l}\text{M1 Counter Clockwise}\\ \text{M2 Clockwise}\end{array}\right\}\text{Camera moves down}$$

$$\left.\begin{array}{l}\text{M1 Clockwise}\\ \text{M2 Counter Clockwise}\end{array}\right\}\text{Camera moves up}$$

$$\left.\begin{array}{l}\text{M1 Counter Clockwise}\\ \text{M2 Counter Clockwise}\end{array}\right\}\text{Camera moves out}$$

$$\left.\begin{array}{l}\text{M1 Clockwise}\\ \text{M2 Clockwise}\end{array}\right\}\text{Camera moves in}$$

Figure 6.6: Winch V5[15,16]

For a detailed assembly drawing that shows the discussed parts of Winch V5 refer Appendix C.1

6.3 Cage Access Point

The CAP wirelessly transmits sensor and camera data from each cage to the base. Their structure can be divided into top and bottom sections. The CAPs are equipped with cambium Wi-Fi remote sender and receiver, relay card, top dome camera, video server, router board, sealing ring in the top section and a connection box in the bottom section. Cambium Wi-Fi remote sender and receiver helps in communication between the base and the camera. Relay card enable the controlling of winch. The built-in surface camera is used for monitoring fish's surface activity and feed spread even in poor light conditions. Video server does the digital imaging of analog images captured by the camera. The router board is for communicating with the top camera. The sealing ring ensures the sealing around the top dome camera making it watertight. The connection box in the bottom section is a splash proof compartment that contains a standby battery and cable connections. The following figure shows the CAP with its parts. For a detailed assembly drawing that shows the discussed parts of the CAP refer Appendix D.1

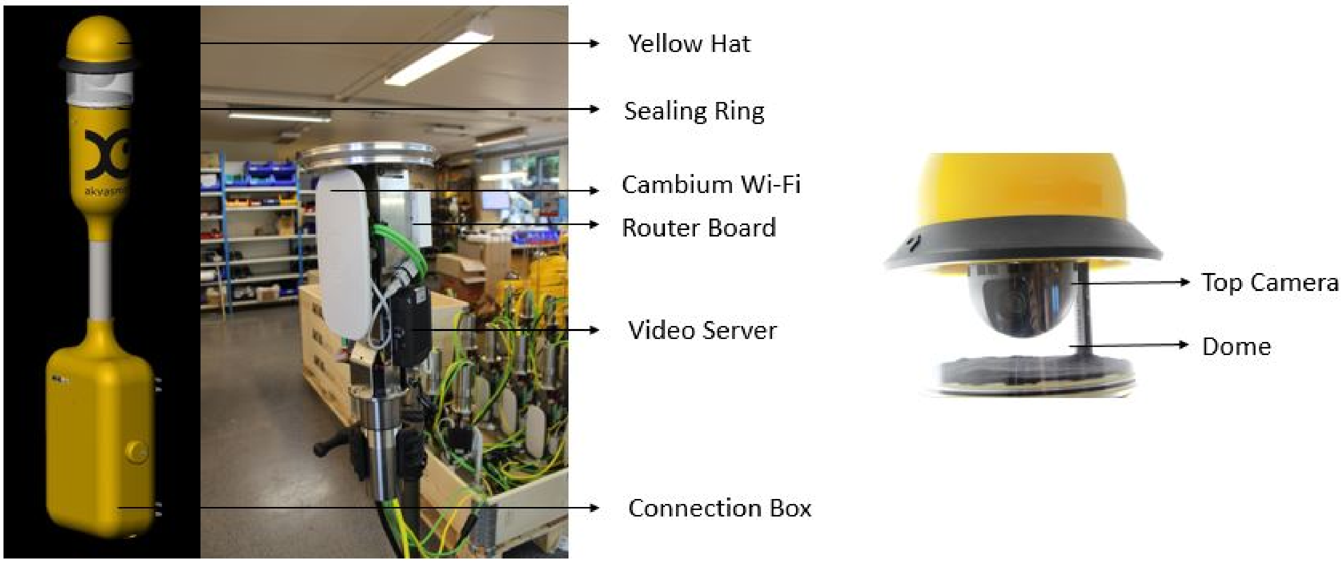

Figure 6.7: Cage Access Point by AKVA Group[15,16]

6.4 Generators

Generators are the source of power supply for the camera system. The parts and working principle of the generators were discussed in section 4.10. AKVA Group does not manufacture generators. From the system standpoint, generators are a critical component and are considered for the RCM analysis.

6.5 AKVAconnect

It is a software platform designed by AKVA that is used to connect and establish optimal control of process and activities on fish farms. It provides the means to collect data and combine information from all levels of farm operations. It is user-friendly and can be customized. The different processes on fish farms that can be controlled by AKVA Connect are shown in the figure 6.8

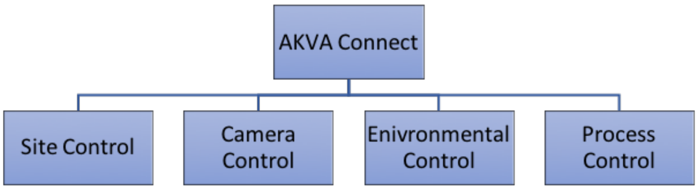

Figure 6.8: Processes that can be controlled by AKVAconnect

Site control, provides detailed surveillance information and status reports of multiple sites in real-time.

Camera control, analog cameras and digital cameras are both integrated in the system and can be controlled from any location.

Environmental Control, all parameters in production environment such as temperature, salinity, oxygen etc can be monitored and controlled.

Process Control, enables controlling and monitoring of all devices and provides information about the present state of the device with its running hours.

A detailed description of the camera system, its purpose and associated components have been established. A RCM analysis of the system was performed by following the stages discussed in the chapter 3. Components such as Cameras, CAP, Winches and Generators are considered for the analysis neglecting the software AKVAconnect. The results of the analysis yield the appropriate maintenance task for the camera system. Furthermore, improved knowledge about the components and system are an added advantage of the analysis.

Chapter 7

RCM Analysis of Camera System

The steps outlined in section 3.1 of this report are applied to the camera system. The following sections present the step wise results of the analysis. The analysis was carried out based on the expert judgments by the R&D Engineers of the camera system at AKVA Group, because of lack of reliability data. Interactions with them has been the input for the analysis.[9] This is supported by "The System Reliability theory" by Marvin Rausand, which confirms that in situations of lack of data, expert judgments and input from manufacturers of the equipment are considered as the source.[35]

7.1 Functions

The function of the Akvasmart camera system designed by the AKVA Group is to provide a complete overview of surface and underwater activities in the cages through clear video images and wirelessly transmit them to the user base. The first step in a RCM analysis is understanding the system's functions. The functional hierarchy discussed in the following subsection gives the set of functions and its associated components that helps in achieving the primary objective of the system.

7.1.1 Functional Hierarchy

For the top function in the function hierarchy, the monitoring activity while feeding is considered. The analysis holds good for other monitoring activities such as fish maturation, fish behaviour, morts and fish parasites, because the same camera system is used during those activities. The superior functions with its associated subordinate functions were identified for the camera system used in the process of feed monitoring. The three superior functions were power supply, video imaging and signal transmission. The superior functions with its associated subordinate functions is presented in the hierarchy shown below.

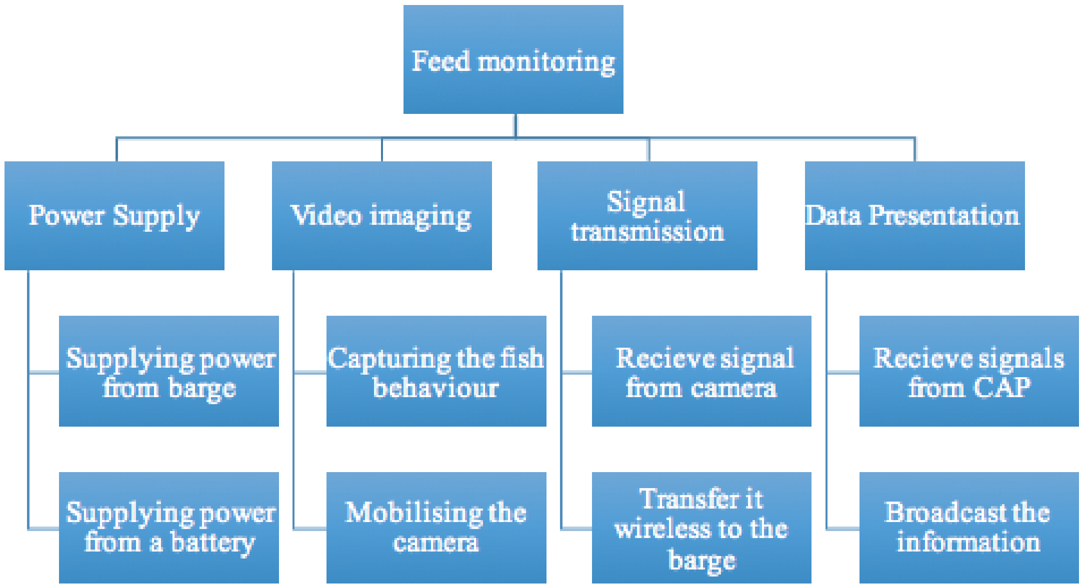

Figure 7.1: Functional hierarchy for camera system

Power Supply
This function helps in providing the power supply that is essential for the cameras to work. The cameras are powered by Akvasmart CAP. These devices transform voltage from barge to 12V. A 12V standby battery is also provided to supply the necessary power during situations of emergency.

Video Imaging
This is an important function of the Akvasmart camera system. The Video Imaging functions, has two sub functions, namely capturing fish behaviour and mobilizing the camera. These sub functions are realized through Akvasmart cameras, winches with its suspension system that comprises of ropes and elastic bands respectively.

Signal Transmission
This function is responsible for receiving the signals from the cameras positioned in the cages and transfer these signals wireless to the barge. Thus, this function plays a crucial role in realizing the intended purpose of the camera system. The Cage Access Point (CAP)

mounted on the cages helps in realizing this function.

Data Presentation
This function involves presenting the signals from the CAP as visual data for the user. The two sub functions that helps in realizing this function are receiving signal from CAP and broadcast the information.

7.2 Functional Failure

The functional failure of the camera system occurs when the system fails to deliver its primary and secondary functions. The three main functional failures of the camera system are as follows:

1. No video imaging (due to breakdown of a major component)
2. No mobilization of camera (failure of winch or suspension system)
3. No video output (when CAP fails)

The first functional failure is characterized by a failure of any of the critical component such as camera or generator (the source of power supply) that results in no video imaging. The criticality of components of the camera system can be stated as follows

- failure of generator > failure of camera > failure of CAP > failure of winch

The second functional failure and third functional failure are connected to failure of other components when the camera is working. The second functional failure is when the winch or its suspension system fails that results in no movement of the camera. The third functional failure considers the failure of CAP in transmitting the data recorded by the moving camera in the cages.

7.3 FMECA

The Failure Mode Effect Criticality Analysis of the camera system is carried out on a component level. The FMECA worksheet of camera system is presented as two separate tables. The first one presents the components, their function, possible failure modes, failure cause, failure pattern, their Mean Time Between Failures (MTBF), Mean Down Time (MDT) and the effect of failure on a subsystem and system level. The second table shows the component, their failure modes, criticality assessment of failure modes, consequence, frequency and risk index.

The listed failure modes for each component was finalized by discussing with the R&D Engineers of the camera system.[9] The intention of the FMECA worksheet is to analyze each failure modes in detail. This is performed by analyzing the cause, the failure pattern, whether the failure mode is hidden or evident and its effect on the system. MTBF refers to the time at which the failure is expected to occur when no maintenance is carried out. Then it is followed by a criticality assessment of each failure mode against different parameters as shown in the section 7.3.1 . The consequence of each failure mode was evaluated on a scale of 1 to 5 and the frequency was found from MTBF. These inputs give the risk index.

Four components of the camera system were considered for the FMECA. 21 relevant failure modes of these components were studied in detail as a part of this analysis. The function of each component and the effect of its failure on the system and its function is presented in the FMECA worksheet. The detailed FMECA worksheet is shown in the tables 7.1 and 7.2. The following figure 7.2 gives the summary of the FMECA analysis of the camera system.

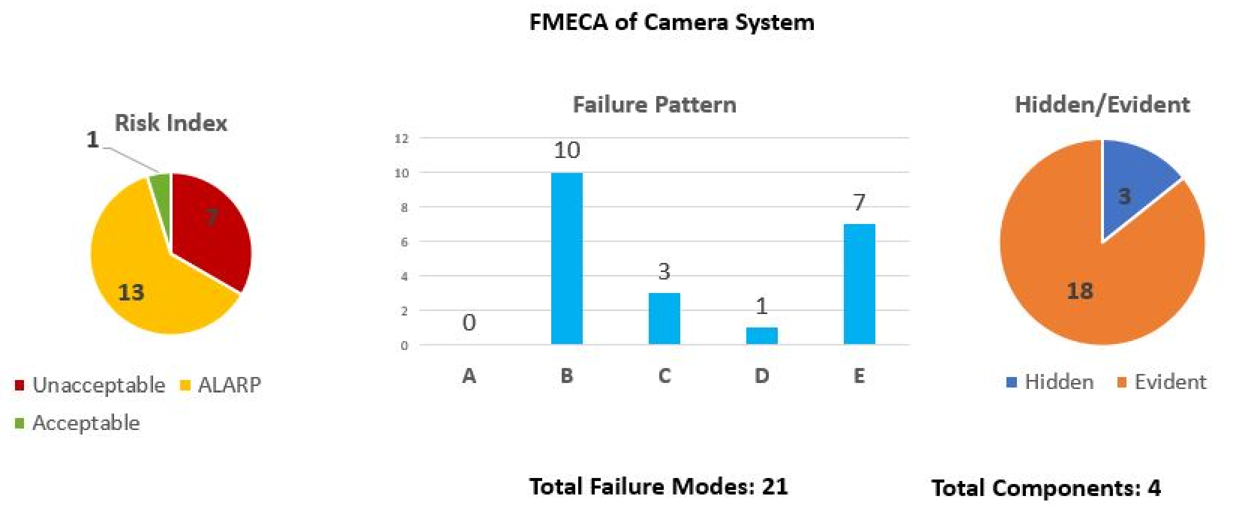

Figure 7.2: Summary of FMECA of Camera System

From the figure 7.2 it is clear that there is no infant mortality that is, type A failure mode exhibited by the components in the camera system. As it could be seen most of the failure modes were of type B that is, age related. The break down of camera, CAP components, motor of the winch, generator and its belt are more critical of other type B failure modes. Failure modes such as lack of lubrication and filter blockage of generator and over heating of motor exhibits Characteristic failure (type C). The wear of air filter was condition-related type D failure mode. Camera, winch and CAP were found having random failure modes of type E due to moisture entry into the component. 18 of the 21 identified failure modes are evident to the operating crew under normal operating condition. The remaining three hidden failure modes were for air filter and oil of the generator. The Mean Time Between Failures (MTBF) ranges from 1 year to a maximum of 10 years for breakdown of generator. The Mean Down Time (MDT) of critical failures with camera, CAP and winch ranges from 4 hours to 6 hours as it can be seen in the table 7.1. This was followed by criticality assessment of these failure modes as explained in the following section.

7.3.1 Criticality

The criticality of each failure mode was based on following four criteria

- Safety denoted by S
- Environment denoted by E
- Availability denoted by A
- Cost denoted by C

For safety, how failure affects the monitoring activity was considered. For environment, its the contribution to eutrophication was chosen. Refer section 5.3.1 for explanation on eutrophication. In case of availability classes, how failure modes affect the availability of the system was considered. The cost of the components obtained through discussion with the R&D Engineer were grouped into classes. These criticality classes are shown below the table 7.2.

Table 7.1: FMECA of Camera System Part 1

#	Component	Function	Failure Mode	Failure Cause	FP	H/E	MTBF	MDT	Effect of Failure	
									On the subsystem	On the Subsystem Funciton
	Camera									
1	Camera	To capture the fish behaviour in cage while feeding, check for morts and general monitoring	Spurious stop	Moisture causing a lag or a hang	E	E	4 years	4 hours	No movement	No video output
			Breakdown	Damage on the video cable	B	E	4 years	4 hours	No video recording	No video output
	Domes	To protect the cameras from external damage	Scratches	Improper cleaning	E	E	2 years	1 hour	Physical damage	Hindered video output
	Cage Access Point									
2	Directional Antenna	To receive signals from the camera and transmit it to the barge	Spurious stop	Moisture or leakage	E	E	4 years	6 hours	No transfer of signals	No video output
			Breakdown	Wear	B	E	6 years	6 hours	No transfer of signals	No video output
	Cables	To transfer power to camera and winches, to give command and receive video output from cameras	Short circuiting	Moisture	B	E	1 year	12 hours	No transfer of power or signal	No video output
	Clamps	To fasten the CAP on floating sea cages	Corrosion	Chemical reaction	B	E	6 years	4 hours	Physical damage	Reduced lifetime of clamps
	Winch System									
3	Winches	To facilitate horizontal and vertical movement of cameras	Spurious stop	Heavy waves flushing that causes leakage	E	E	2 years	6 hours	Loss of function	No movement of camera
			Corrosion	Lack of cleaning	B	E	4 years	6 hours	Physical damage	Reduced lifetime of winches

	Motor	Power transmission for selection of feed pipes	Breakdown	Wear	B	E	3 years	3 hours	No power transmitted	The camera's motion ceases
			Overheating	Lack of cleaning	C	E	1 year	1.5 hours	Winch system degradation	Reduced efficiency
	Ropes	To help the suspension of camera and its movement	Twisted	Weather	E	E	2 years	1 hour	Reduced efficiency	Hindrance to smooth motion of camera
			Fouling	Lack of cleaning	B	E	2 years	1 hour	Local stress	Reduced lifetime of ropes
			Wear	Friction with cage structures	E	E	4 years	1 hour	Physical damage	Loss in suspension
	Elastic bands	Nullify the damping of waves	Physical damage	Lack of cleaning	B	E	2 years	1 hour	Local stress	Reduced lifetime of bands
			Structural deficiency	Wear	B	E	2 years	0.5 hours	Physical damage	Loss in suspension
4	**Generator**									
	Generator	Provides power for the camera system for video imaging	Breakdown	Wear	B	E	10 years	12 hours	No power transmitted	System stops
	Belt	Transmits mechanical energy from the motor to the fan	Failure	Wear	B	E	12000 hrs/ 2 years	2 hours	No transfer of energy	No supply of power for video imaging
	Air filter	Preventing airborne contaminants from entering the flow	Blockage	Accumulation of particles	C	H	5 years	0.5 hour	Less air for circulation	Reduced output
			Failure	Wear	D	H	5 years	0.5 hour	No filtration	Unfiltered air entering the system
	Oil	Lubrication	Change	Overused oil	C	H	500 hours	2 hours	Lack of lubrication	Generator degradation due to lack of lubrication

Availability Classes		
1	Available	One function fails or a failure is initiated i.e. system functions with a limitation
2		More than one function fails
3	Unavailable	System is unavailable for video imaging

Safety Classes		
1	Low	No or little impact on monitoring
2	Medium	Affects Monitoring significantly
3	High	Affects monitoring to a large extent

Environment Classes		
1	N	No contribution to eutrophication
2	L	Lower contribution to eutrophication
3	M	Significant contribution to eutrophication
4	H	High contribution to eutrophication

Cost Classes		
1	Very low	≤ 1000 NOK
2	Low	≤ 3000 NOK
3	Medium	≤ 5000 NOK
4	High	≤ 15000 NOK
5	Very high	> 15000 NOK

Table 7.2: FMECA Analysis of Camera System Part 2

#	Component	Failure Mode	Criticality Assessment				Consequence (a)	Frequency (b)	RI (a)+(b)	Maintenance Task
			S	E	A	C				
	Camera									
1	Camera	Spurious Stop	3	4	3	2	2	3	5	Scheduled on condition
		Breakdown	3	4	3	5	3	3	6	Scheduled on condition
	Domes	Scratches	2	2	1	2	1	4	5	Run to failure
	Cage Access Point									
2	Directional Antenna	Spurious stop	3	4	3	4	3	3	6	Scheduled on condition
		Breakdown	3	4	3	2	3	2	5	Run to failure
	Cables	Short circuiting	3	4	3	3	3	5	8	Schedules on condition
	Clamps	Corrosion	1	1	1	1	1	2	3	Scheduled restoration
	Winch System									
3	Winches	Spurious Stop	2	2	1	4	1	4	5	Scheduled on condition
		Corrosion	1	1	1	-	1	3	4	Scheduled restoration
	Motor	Breakdown	2	2	2	3	1	4	5	Scheduled on condition
		Overheating	1	1	1	-	1	5	6	Scheduled restoration
	Ropes	Twisted	1	1	1	-	1	4	5	Run to failure
		Fouling	1	1	1	-	1	4	5	Scheduled restoration
		Wear	2	2	1	1	1	3	4	Scheduled on condition
	Elastic bands	Physical Damage	1	1	1	-	1	4	5	Run to failure
		Structural deficiency	2	1	1	1	1	4	5	Scheduled on condition
	Generator									
4	Generator	Break down	3	1	3	5	3	1	4	Scheduled on condition
	Belt	Failure	3	1	3	2	3	4	7	Scheduled discard
	Air Filter	Blockage	1	1	1	2	1	3	4	Scheduled on condition
		Failure	1	1	1	2	1	5	6	Scheduled discard
	Oil	Change	1	1	1	3	1	5	6	Scheduled on condition

7.3.2 Risk Matrix

The impact of these failure modes on the video output was considered for consequence class. Frequency refers to how often the failure mode is expected to occur. The consequence and frequency class used in the analysis is presented in the Table 7.3 and Table 5.3 respectively.

Table 7.3: Consequence Classes for Camera System

Consequence Classes		
1	Low	No or little impact on video output
2	Medium	Significant impact on video output
3	High	No video output

The risk index value,

- 1-3 were considered to be Acceptable denoted by green
- 4 and 5 were considered to be ALARP denoted by yellow
- 6-10 were considered to be Unacceptable denoted by red

These values for the risk indices were finalized during the discussion with the R&D Engineer of the system.[9] As shown in the figure 7.2, 7 failure modes were found unacceptable. All four components *Camera, CAP, Winch and Generator* had an unacceptable risk indices. These components are shown in their appropriate risk values in the risk matrix below 7.3

Probability/ Consequence	1 Very Unlikley	2 Remote	3 Occasional	4 Probable	5 Frequent
5 Very High	6	7	8	9	10
4 High	5	6	7	8	9
3 Medium	4	5	C, CAP,W,G	G	CAP
2 Small	3	4	5	6	7
1 Very small	2	3	4	5	W

Figure 7.3: Risk Matrix FMECA of Camera System

C = Camera, CAP = Cage Access Point, W = Winch and G = Generator

The break down of camera due to the damage of the video cable was considered unacceptable as it results in no video recording and video output. The same cable is used for power supply, to deliver commands and video transfer which makes this failure mode more critical. The failure mode of short circuiting of the cables in the connection box of the CAP has the highest risk index value of 8. This failure mode renders the CAP non functioning. The analysis yields the spurious stop of CAP and overheating of the winch motor as unacceptable with a risk index of 6. The lack of lubrication and wear of air filter of the generator are the other critical failure modes of the same risk index 6. The corrosion of clamps of CAP was the only failure mode that was considered acceptable with 3 as a risk index value. The remaining 13 failure modes of risk index 4 or 5 were considered to be in ALARP region. These failure modes occur mostly due to the moisture entry, lack of cleaning and wear. The next step involves performing the maintenance task analysis for the camera system and find the appropriate maintenance task for the identified failure modes.

7.4 Maintenance Task Analysis of Camera System

The last column of the FMECA worksheet presents the maintenance task for each failure mode. The decision tree outlined in the section 3.5.2 is used to identify the appropriate maintenance task for each failure modes. The maintenance actions are a combination of preventive and corrective maintenance.

Four failure modes that are evident to the operating crew under normal working condition received the maintenance task 'Run to Failure' that is, maintenance action is executed after failure has occurred. Scheduled restoration is recommended for clamps of CAP and for winch and its suspension system. The analysis yielded scheduled discard for the wear of belt and air filter of the generator. Scheduled on-condition is recommended for most of the failure modes caused due to moisture entry and for generator and its parts.

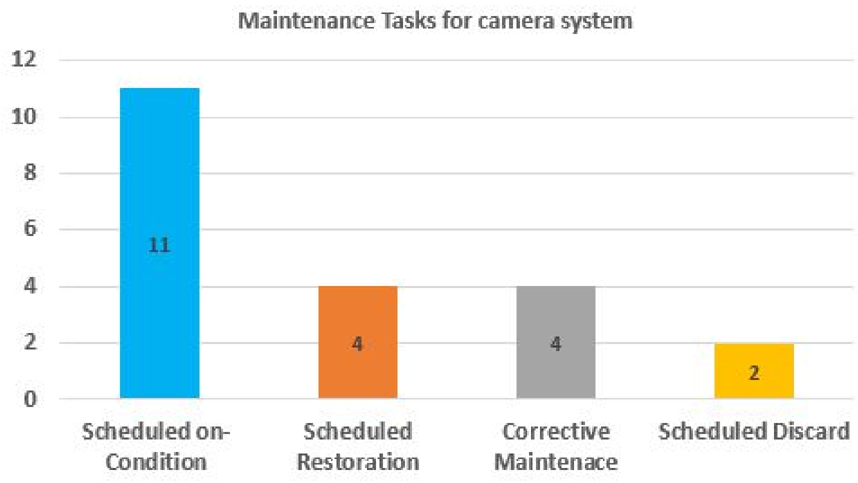

Figure 7.4: Maintenance Task Analysis of Camera System

Table 7.4 presents a detailed Maintenance Task Analysis (MTA) of the camera system. The tables show the components, their failure mode, their pattern, risk index, the found maintenance task, maintenance interval and maintenance description.

Table 7.4: Maintenance Task Analysis of Camera System

#	Component	Failure mode	FP	RI	Maintenance Task	Maintenance Interval	Maintenance Description
	Video Imaging						
1	Camera	Spurious Stop	E	5	Scheduled on-condition	Everyday	Lift the camera from the cage and bring to the base or a barge and dry it
		Break down	B	6	Scheduled on-condition	1 year	Use Line Resonance Analysis method to detect both age and non age related effects on the cable
	Domes	Scratches	B	5	Run to failure	-	Lift the cameras from the cage and replace the domes on the PT cameras
	Cage Access Points						
2	Directional Antenna	Spurious Stop	E	6	Scheduled on-condition	Everyday	Replace the CAP with the spare
		Break down	B	5	Run to failure	-	Replace the CAP with the spare
	Cables	Short circuiting	B	8	Scheduled on-condition	Everyday	Disconnect the connection box from the CAP and bring it to the barge and dry it
	Clamps	Corrosion	B	3	Scheduled restoration	3 year	Check the clamps for corrosion. If corroded, renew clamps
	Winches						
	Winches	Spurious Stop	E	5	Scheduled on-condition	Everyday	Unmount the winch from the bracket and transport it to the base or the barge and dry it
		Corrosion	B	4	Scheduled restoration	1 month	Clean the winch with fresh water and mild washing up liquid to rinse off the salt water deposits
	Motor	Break down	B	5	Scheduled on-condition	1 year	Vibration measurements and frequency analysis - fast fourier transformation of data

3		Overheating	C	6	Scheduled restoration	6 months	Clean the winch periodically to avoid salt water deposits
	Ropes	Twisted	E	5	Run to failure	-	Clear off the twirls in the ropes
		Fouling	B	5	Scheduled restoration	1 month	Clean off the sprout, salt water and salt crystals and rinse with fresh water
		Wear	E	4	Scheduled on- condition	1 year	Check the ropes for the wear and replace if necessary
	Elastic bands	Physical Damage	B	5	Run to failure	-	Replace the elastic bands
		Structural deficiency	B	5	Scheduled on - condition	1 month	Replace the bands if found defective
4	**Generator**						
	Generator	Break down	B	4	Scheduled on- condition	3 months	Vibration measurements on bearing and casing using octave band analysis through contiguous and fractional octave filters. The average output of each filter is measured
	Belt	Failure	B	7	Scheduled discard	2 years	Replace the generator belt with the spare
	Air filter	Blockage	C	4	Scheduled on - condition	2 years	Mechanical indicator showing pressure drop indicating clogging
		Failure	D	6	Scheduled discard	1 year	Replace air filter
	Oil	Change	C	6	Scheduled on-condition	1 month	Mesh obscuration particle counter. Oil passes through three meshes and particles bigger than the pores get stuck in the mesh. The pressure change is measured by the sensors.

The procedures described for Scheduled on-condition tasks are inspired by the condition monitoring techniques outlined in RCM by Moubray[11] and research papers and articles on condition monitoring.[46,47,48,49] The recommended preventive tasks helps to prevent the failure modes. The MTBF on the FMECA worksheet was the critical parameter taken into consideration in deciding the maintenance interval suggested for tasks. The maintenance interval must be shorter than MTBF. Thus, giving us high probability of discovering the failure mode before it occurs. The following figure 7.5 shows the planned preventive maintenance activities of camera system in relation with their time interval. This shall serve as tool in analyzing the maintenance program to plan and execute the maintenance tasks.

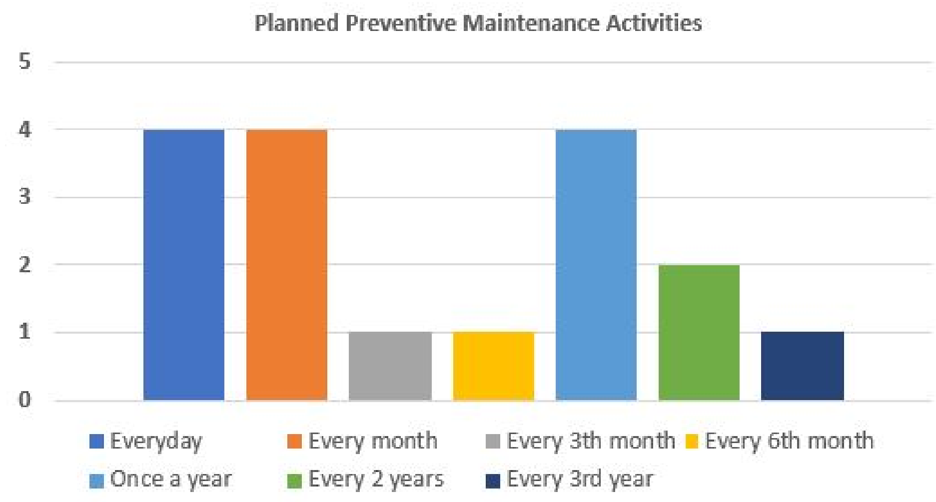

Figure 7.5: Planned Preventive Maintenance Activities of Camera System

A cost-benefit analysis of the suggested maintenance program should be performed to check whether it is cost effective. There is lack of data because either corrective maintenance or maintenance activities suggested by the equipment manufacturers, is the state of maintenance in the aquaculture industry. Hence it was not possible to perform cost-benefit analysis for the proposed maintenance program. The recommended maintenance tasks are grouped into packages as shown in Table F.1 in Appendix. A detailed explanation of the maintenance task that can be performed at the same time, the personnel and equipment required during the task is presented in maintenance package worksheet. The last column shows the complexity of the suggested maintenance task. Maintenance packages help in optimizing the maintenance program. The maintenance program can be improved and updated by receiving periodic feedback from the operating crew that validate the suggested maintenance task and the time interval.

Chapter 8

Results & Discussion

This chapter presents the results and discussion of both feed and camera system, evaluation of the method, potential for autonomy and limitations of the method. Generator is considered as a component in the analysis of both systems, as it is the source of power whose failure affects the system's operation to a big extent.

8.1 Results and discussion

8.1.1 Feed

The FMECA of feed system showed seven components that exhibit unacceptable risk, namely rotary spreader, selector, doser, blower, generator, sensors and feed pipes. Though the cooler and circuit boards are critical, the failure modes of these components have risk index values from 4 to 5, so were considered in the ALARP category according to the risk matrix. This was because of the low frequency of the failure modes of the component. The failure mode of spurious stop of bearing occurs due to lack of cleaning. The description of the rotary spreader in 4.9 states that bearing doesn't require regular cleaning. This statement holds good for the new improved Zenon bearing, whereas the old bearing does require cleaning. However, this claim about the Zenon bearing needs validation. The section 5.2 explained the criticality hierarchy in a feed line, which is confirmed by the risk index value of the motor of the blower, doser and selector. The possible failure modes of the motor were break down due to wear and over heating due to lack of cleaning. The part that was considered as high importance for blower and the generator to perform its function was its belt. It could be seen that failure modes associated with the belt has an unacceptable risk index of 6.

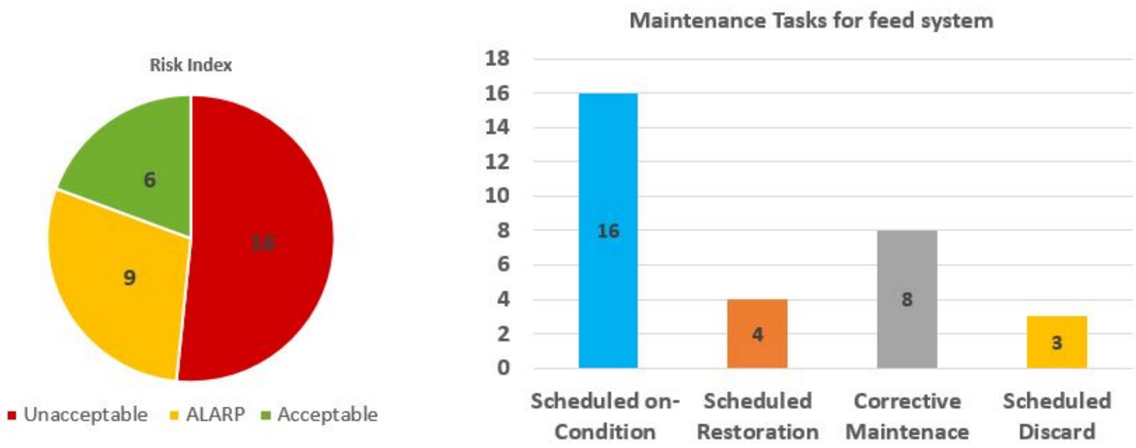

Figure 8.1: Results of RCM analysis of Feed System. With results from FMECA on the Left & results from MTA on the right

The failure modes of air filter of generator have a higher risk index than air filter of the blower. This was because of the difference in consequence value. As discussed in section 4.1, sensors provide the input for the feed system. These sensors are subjected to physical damage at least once in a year. Thus, analysis yields a risk index of 7 for the sensors because of high frequency. The Maintenance Task Analysis (MTA) yields corrective maintenance that is, 'run to failure' for two critical components, namely sensors and feed pipes when assessed according to the decision tree. The parts such as ball bearing, motor and lubrication oil of the critical components receive scheduled-on condition maintenance tasks. Scheduled-on condition was also suggested for blockage of air filter with a maintenance interval of two years based on the MTBF. The operators can consider using the air filters without discarding it every year if a scheduled-on condition task is carried out at an optimal interval. However, the manufacturer insists changing, fearing the warranty claims. The identified parts with corrective maintenance requires proper spare part management. .

8.1.2 Camera

FMECA of the camera system yielded all four components of the system as critical, namely camera, CAP, winch system and generators. Seven failure modes that pose unacceptable risks were identified. Three of these seven failure modes were associated with the same parts of the generator discussed in the above section. The failure mode of break down of the camera due to damage on the coax cable was identified to have a risk index of 6, making it unacceptable. As this failure mode can result in the obstruction of video imaging. Remaining three unacceptable risks were for the spurious stops of directional antenna and short circuiting of cables in the CAP and overheating of winch motor due to lack of cleaning.

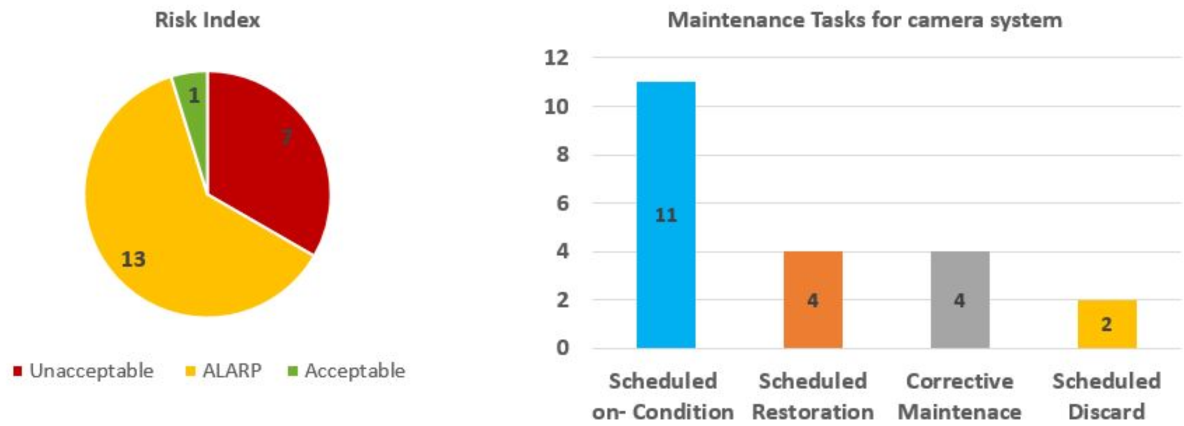

Figure 8.2: Results of RCM analysis of Camera System. With results from FMECA on the Left & results from MTA on the right

The Maintenance Task Analysis (MTA) yielded scheduled restoration for the failure modes caused due to lack of cleaning. Run to failure was suggested as maintenance task for the failure mode twisting of ropes, scratches on camera domes and physical damage of elastic bands. It can be seen from the table 7.1, that the failure mode spurious stop due to moisture entry affects all three components, such as camera, CAP and winch. This failure mode was critical as it can render the system non available to perform its intended function. Thus, the MTA considers use of moisture sensor in the CAP and camera for the following reasons:

- This failure mode is of type E that is, random and allowing the components to run to failure cannot be considered as an appropriate task because of the effect of failure
- When the CAP stops functioning, it generally takes more time to identify what caused the failure
- During the discussion with R&D Engineer,[9] it was mentioned that such sensors are placed in the winch and must be considered in future designs of camera and CAP

The maintenance task suggested for the damage of the coax cable is scheduled-on condition. As it can be seen from the table 7.1, the failure mode is of type B that is, age-related. Thus, an advanced non-destructive condition monitoring technique, *Line Resonance Analysis*(LIRA) is recommended. This technique is used to detect both age and non age-related failures in offshore and onshore wind farms.[47] However, further analysis of its limitations in this environment is to be assessed. The reasons for failure of the each component must be logged for both camera and feed system, as it will help in creating a database that can referred in future.

8.2 Potential for Autonomy with the Systems

8.2.1 Autonomy

The terms autonomy and automation are often misinterpreted. Autonomy involves self-governing behaviour that requires intelligent decision making capabilities. Automation refers to performing a well defined task without human or operator intervention. Autonomy can be defined as "*the ability of a system to achieve operational goals in complex domains by making decisions and executing actions on behalf of, or in cooperation with humans*"[17]. The levels of autonomy has different classifications. The figure 8.3 shows the classification considered for this discussion

Level	Name	Description
1	Human Operated	**All activity within the system is the direct result of human-initiated control inputs.** The system has no autonomous control of its environment, although it may have information-only responses to sensed data.
2	Human Assisted	**The system can perform activity in parallel with human input,** acting to augment the ability of the human to perform the desired activity, but has no ability to act without accompanying human input. An example is automobile automatic transmission and anti-skid brakes.
3	Human Delegated	**The system can perform limited control activity on a delegated basis.** This level encompasses automatic flight controls, engine controls, and other low-level automation that must be activated or deactivated by a human input and act in mutual exclusion with human operation.
4	Human Supervised	**The system can perform a wide variety of activities given top-level permissions or direction by a human.** The system provides sufficient insight into its internal operations and behaviors that it can be understood by its human supervisor and appropriately redirected. The system does not have the capability to self-initiate behaviors that are not within the scope of its current directed task.
5	Mixed Initiative	**Both the human and the system can initiate behaviors based on sensed data.** The system can coordinate its behavior with the human behaviors both explicitly and implicitly. The human can understand behaviors of the system in the same way that he understands his own behaviors. A variety of means are provided to regulate the authority of the system w.r.t. human operations.
6	Fully Aut-onomous	**The system requires no human intervention to perform any of its designated activities** across all planned ranges of environmental conditions.

Figure 8.3: Levels of Autonomy adopted from US Navy Office of Naval Research[17]

8.2.2 Autonomy for Feed and Camera systems

This section provides the present state of autonomy with the feed system and the camera system and discusses the potential for further autonomy.

The present state of autonomy with the camera system according to classification shown in the figure 8.3 is *Human Operated* that is, level 1 as the camera systems works directly based on human initiated inputs. The feed system belongs to level 2 that is, *Human Assisted*. The sensors of the system can sense the required data for feeding and load the feed tables when integrated through the software solutions such as AKVAconnect, AKVAcontrol and fishtalk developed by the AKVA Group. Though the system has the ability to perform feeding, it requires human input and hence can be considered as *Human Assisted*. The discussion with the fish-farm operator[1] revealed that they would like to take control over the feeding data and the process of feeding by estimating the feed amount.

Both the system has the potential for autonomy to level 3 that is *Human Delegated*. The feed system is capable of sensing data and processing it to estimate the feed data. This could be advanced to *Human Delegated* when the process is modelled in a time domain expressing every activity on a time scale, where it tracks the last feeding activity and suggests when the next activity should be initiated. The feeding session time and quantity to be fed could be estimated based on the biological and environmental data collected.

Level 3 autonomy is possible for the camera system when it is modified in a way that, when the feeding process is initiated, by sensing the feed spread in the cages, the movement of the camera can be initiated and set to follow a preset path that gives a complete overview of the occurrences in the cage.

8.3 Evaluation of the method

Performing the RCM analysis for the systems used in aquaculture has created a framework that could be set as a guideline for assessing further systems. Working on a structured process like RCM helps people to understand the system functions and associated sub functions. Though the process is considered to be exhaustive, working with the relevant personnel helps in developing a maintenance strategy that could be improved periodically through feedback.

The FMECA worksheets help in providing a better understanding of the system, its functions, failures and associated consequences of failures. They are important part of the analysis. They serve as inputs for further steps in the analysis. As FMECA worksheets are filled based on expert opinion, there are chances that personal opinions could lead to erroneous results. The risk matrix influences the overall risk picture of the analysis. The maintenance tasks analysis is the last stage in the process. It helps in finding the appropriate maintenance task for each failure mode.

8.3.1 Limitations

The limitations of this analysis of feed system and camera system are

- The analysis was solely based on experts opinion due to the lack of data. The above section 8.3 discussed the limitations of this scenario
- The experts were introduced to the process of RCM and what it achieves for the first time which questions the inputs to the analysis
- RCM generally requires a technical team of highly skilled people to perform the analysis whereas, in this case it was carried out only by the author
- There is a possibility that some failure modes and effects were overlooked completely, and suggested frequency, maintenance task and maintenance interval for the failure mode maybe incorrect
- Data for the analysis were obtained only from R&D Engineers of the system. The analysis may have yielded different results when the users or operators of the system had discussed about the failure modes

Chapter 9

Conclusion

Maintenance in aquaculture industry pertaining to the systems used is mostly of corrective actions or preventive tasks suggested by the manufacturers of the system. The time interval suggested for preventive tasks by the manufacturer is often based on experimental data from the R&D department. Thus, the time interval may not be optimal. One may argue that, the experimental data from the research department cannot be fallacious. Interactions with the R&D Engineers from the industry revealed that the time interval suggested for preventive maintenance is decided based on a point on the time-line where large number of those components under consideration fail. A scheduled discard is suggested that is, discarding the component after reaching a specific age irrespective of its condition. Thus, this maintenance task may not be optimal.

The objective of this thesis is to develop a maintenance program for critical systems used in the aquaculture industry. Hence critical systems for daily operations in a fish farm such as feed and camera system designed by the AKVA Group were considered for the RCM analysis. The procedure for RCM was in accordance with the steps outlined in "RCM by John Moubray"[11] and SAE JA1011.[39] The most important part of this analysis, after finding the functions and associated failure modes of the system was the FMECA worksheets. Interactions with the R&D Engineers of the respective system served as the input for the analysis. By performing the step wise procedure through the decision tree outlined in the previous chapters, a suitable maintenance program for each failure modes of both the feed and camera system have been established.

Generator is the source of power supply for both these systems. The analysis yielded a much expected result for generator as one of the critical component for both these systems, as break down of generators causes obstruction to both feeding and monitoring process. The other critical components that had unacceptable risks in the feed system were blower, doser, selector, feed pipe, sensors and rotary spreader. For the camera system, break down of all components such as camera, CAP and winch are critical in the mentioned order of hierarchy. The Maintenance Task Analysis (MTA) of the systems resulted in no scheduled functional test for both the systems. The feed system was recommended with 23 preventive tasks and 8 corrective tasks and for the camera system it was 17 preventive and 4 corrective actions. The suggested maintenance program should be improved periodically through feedback from the operators of the system.

The results of application of the RCM methodology to these systems used in aquaculture has proved the competence and versatility of the method in constructing a maintenance program. The major limitations of the method is being time and resource demanding. The analysis provides AKVA Group with several benefits. This includes:

- Analyzing possible failure modes of the components of the system provides a better understanding of the system and its parts
- A step closer to improving safety, availability and equipment reliability of the studied systems
- This analysis shall serve as a base, when designing new improved feed and camera solutions
- Evaluate whether the suggested maintenance practices are adequate for the systems

Performing a Cost-Benefit Analysis would have strengthened the results of the analysis. However, it was not possible due to the lack of required data. It can be summed up that how RCM process provides better understanding of the systems, which can benefit the aquaculture industry. More such analysis of critical systems should be executed as to identify potential for autonomy. The work carried out in this thesis can be a starting point towards developing better maintenance routines with an objective of increasing the up-time of the systems used in the industry.

9.1 Recommendations and Future work

This thesis analyzed the feed and camera system designed by the AKVA Group using RCM method. Based on the analysis, the following recommendations are made to the manufacturer of the systems and operators of the system:

- Evaluating the constructed maintenance program and having it implemented and tested in selected farms would identify the areas for improvement (AKVA)
- Log the reasons for failure of components (AKVA & Operators)
- Compare the results of the existing maintenance program with the proposed one (Operators)
- Amend the list of suggested maintenance practices in the user manual when found inadequate (AKVA)
- Global leading companies in the aquaculture sector like AKVA Group should take the initiative to sponsor a project organization that collects and exchanges data similar to OREDA (Offshore and Onshore Reliability Data)

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Appendix A

Feed System Configuration

System:

		CCS-32	CCS-63	CCS-90	CCS110	Comments
Feeding pipe size	[mm/"]	32/1	63/2	90/3	110/4	Imperial (North America)
Wall thickness	[mm/"]	2,9/0.11	4/0.16	7/0.28	6,3/0.25	

Feeding data (for each feed line):

Pellet sizes */**	**max.(mm)**	5-7	9-12	17-25	25+	
	min. (mm)	No.2 crumb	1.2	3	3	Must be evaluated for each cage
Max feeding capacity *//*****	**kg/hour**	648	2520	5220	5220	With VariDoser 1500
	kg/hour	-	-	11520	11520	With FeedDoser 4000
Max feeding rate *//*****	**kg/min.**	10.8	42	87	87	With VariDoser 1500
	kg/min.	-	-	192	192	With FeedDoser 4000
Min feeding rate *//*****	**kg/min.**	1.2	2.4	3	3	
Min feed dose (single dose) */**	**grams**	10	20	40	50	With VariDoser 1500
	grams	-	-	200	200	With FeedDoser 4000

**Depending on actual transport distance*

*** Depending on feed type, technical feed quality, pellet size, feed rates, system settings*

**** At continuous feeding*

Figure A.1: Feed System System Configuration[14]

Transport lengths:

Max. feed pipe length	m	300	600	800	1400	*/**
Max. feeding rate at max. feeding pipe length	kg/min.	3.6	12	10	30	***
Max. feeding rate at half of max. feed pipe length	kg/min.	5.4	21	108	150	***
Max. feeding rate at short feed pipe length */**	kg/min.	10.8	42	87	87	With VariDoser 1500
	kg/min.	-	-	192	192	With FeedDoser 4000

**Depending on actual transport distance*

*** Depending on feed type, technical feed quality, pellet size, feed rates, system settings*

Power consumption (max):

Feed Blower	kW	7.5	15-18.5	22-30	45	
Selector Valve	kW	0.18	0.18	0.18	0.18	
FeedDoser	kW	0.37	0.75	-	-	Max load/unit
VariDoser	kW	0.37	0.75	-	-	Max load/unit
Auger and sluice	kW	1.5	1.5	1.5	1.5	

Figure A.2: Feed System System Configuration continuation[14]

Appendix B

Camera Assembly

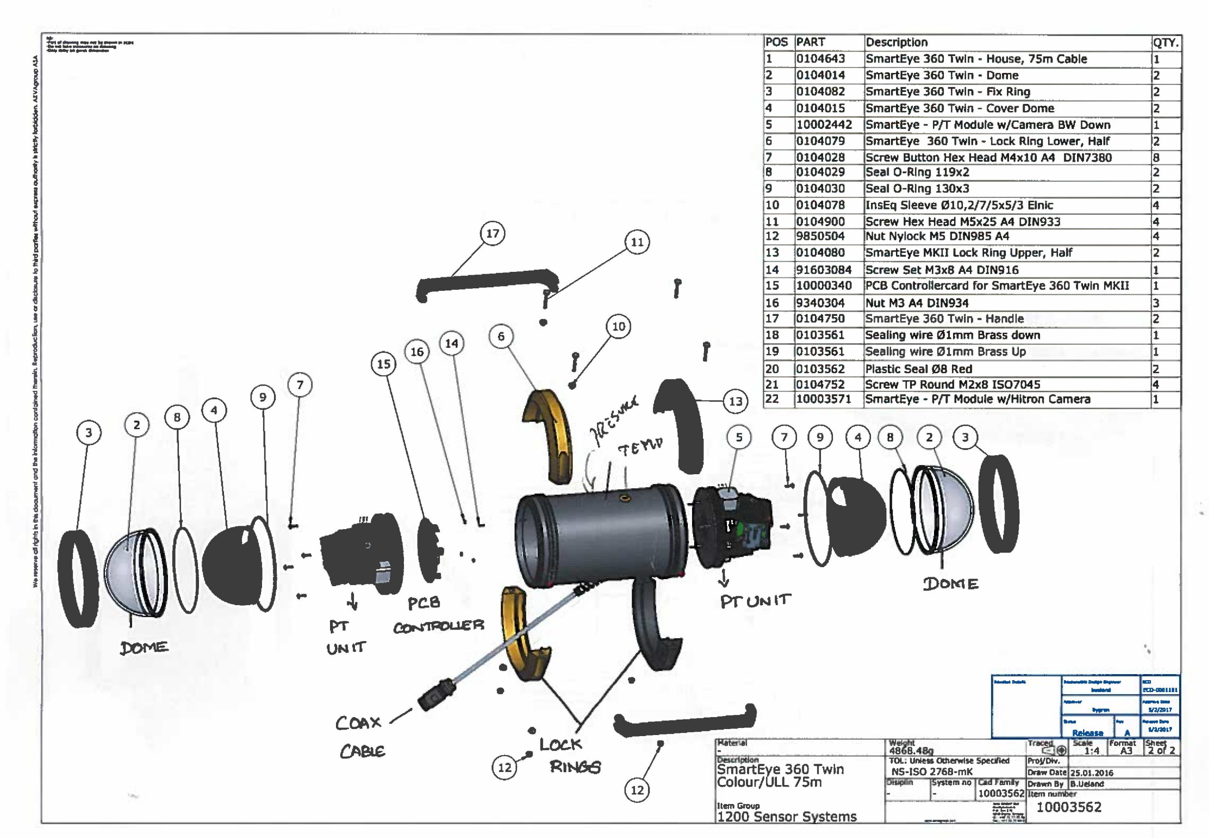

Figure B.1: Camera Assembly (parts breakdown)[15]

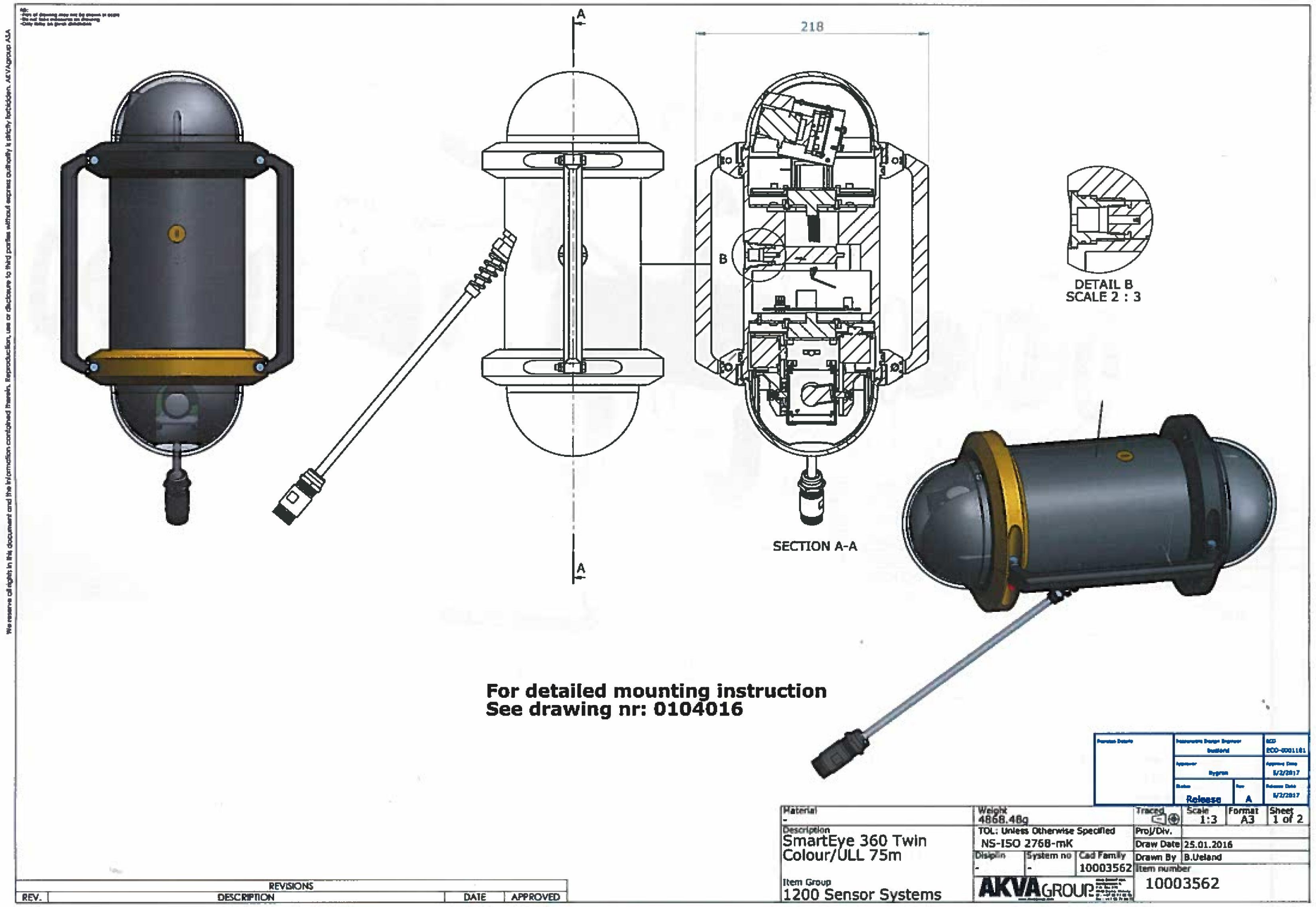

Figure B.2: Camera Assembly[15]

Appendix C

Winch Assembly

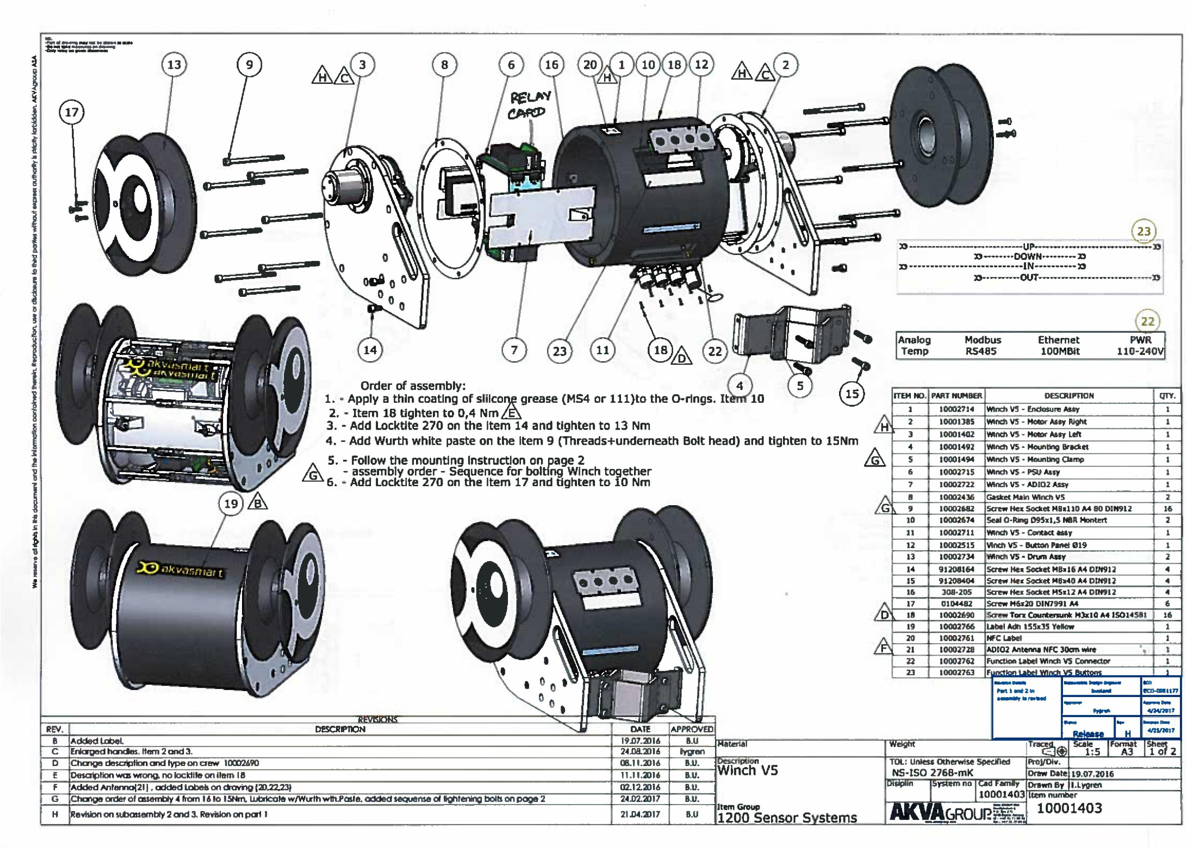

Figure C.1: Winch Assembly (parts breakdown)[14]

Appendix D

CAP Assembly

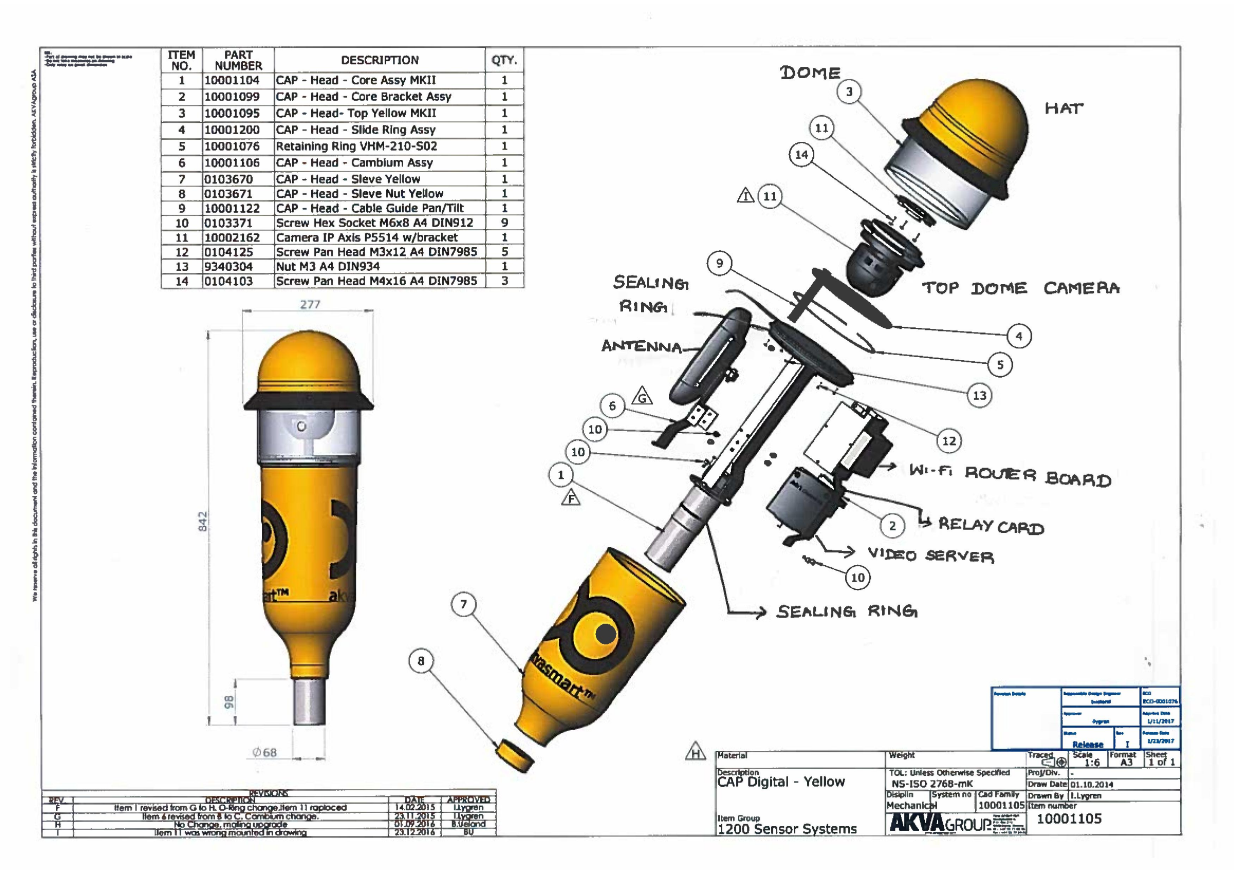

Figure D.1: CAP Assembly (parts breakdown)[14]

Appendix E

Maintenance Package of Feed System

Table E.1: Maintenance Package of Feed System

#	Maintenance Interval	Maintenance Task	Maintenance Description	Personnel	Equipment	CL
1	Everyday	Scheduled on -condition of Circuit Boards for moisture	A moisture sensor in the cabinet that measures realtive humidity and reports the operating crew	Engineers/ technicians in the farm	Moisture sensor	L
2	Once a month	Scheduled on-condition of lubrication oil in generator	Mesh obscuration particle counter. Oil passes through three high precision meshes and particles bigger than the pores get stuck in the mesh. The pressure change is measured by the sensors. It provides the number of particles that are larger than the mesh size	Engineers in the farm and skilled professional to analyse the CM data	Mesh obscuration particle counter instrument	M

		Scheduled on-condition of lubrication oil in blower	Mesh obscuration particle counter. Oil passes through three high precision meshes and particles bigger than the pores get stuck in the mesh. The pressure change is measured by the sensors. It provides the number of particles that are larger than the mesh size	Engineers in the farm and skilled professional to analyse the CM data	Mesh obscuration particle counter instrument	M
3	Every other month	Scheduled on-condition of ball bearing of rotary spreader	Unscrew the 3 unbraco bolts and remove the bearing. Clean it in warm and mild greasing soap water. If found not ok, replace the bearing	Engineers/ Technicians in a fish farm	Warm water and mild greasing soap solution	L
4	Every 3^{rd} month	Scheduled on-condition of doser gaskets	Clean the gaskets with warm mild degreasing soap water. Lubricate the gaskets with silicon grease after cleaning. Replace gaskets if found damaged	Engineers/ Technicians in a fish farm	Fresh water and degreasing soap liquid	L

		Scheduled on-condition of generator	Vibration measurements on bearing and casing using octave band analysis through contiguous and fractional octave filters. Divide the frequency spectrum into series of bands that have a constant width when plotted logarithmically. Each filter's average output is measured and the values are displayed by a meter or plotted on a recorder	Engineers/ technicians in the farm	Octave band filters, vibration meter and transducer	L
5	Every 6^{th} month	Scheduled on-condition of ball bearing of rotary spreader	Vibration measurements on bearing and casing using octave band analysis through contiguous and fractional octave filters. Divide the frequency spectrum into series of bands that have a constant width when plotted logarithamically. Each filter's average output is measured and the values are displayed by a meter or plotted on a recorder	Engineers/ technicians in the farm	Octave band filters, vibration meter and transducer	L
		Scheduled on-condition of blocking element of selector	The liquid penetrant is applied to the testing surface and with time it penetrates into the discontinuties. After removing the excess penetrant, a developer is applied. It draws the penetrant to the test surface. It is interpreted and evaluated	Semi- skilled Engineers/ Technicians trained in perfoming the CM	Visible dye kit	L
		Scheduled restoration of selector motor	Clean the motor periodically to avoid salt water deposits	Engineers/ Technicians in a fish farm	Fresh water and washing liquid	L
		Scheduled on -condition of doser gaskets	Check the gaskets for damage. When found damaged, replace the gaskets	Engineers/ Technicians in a fish farm	Fresh water and degreasing soap liquid	L
		Scheduled restoration of doser motor	Clean the motor periodically to avoid salt water deposits	Engineers/ Technicians in a fish farm	Fresh water and washing liquid	L

		Scheduled restoration of blower motor	Clean the motor periodically to avoid salt water deposits	Engineers/ Technicians in a fish farm	Fresh water and washing liquid	L
6	Every year	Scheduled restoration of stainless steel pipe of rotary spreader	Lift the pipe,from water, Clean the fouling, check for corrosion. Replace it if corroded	Engineers/ Technicians in a fish farm	Water and spare pipe if necessary	L
		Scheduled discard of O ring of selector	Replace the O ring in the selectors with the spare	Engineers/ Technicians in a fish farm	Spare O ring	L
		Scheduled on-condition of selector motor	Vibration measurements and frequency analysis - fast fourier transformation of data by data collector. The measured spectrum is compared with a baseline spectrum in excellent condition. When spectrum deviates above the baseline of more than one standard deviation, it indicates a problem	Engineers/ Technicians in the farm and skilled professional to analyse the CM data	Vibration Analyzer	M
		Scheduled on-condition of doser motor	Vibration measurements and frequency analysis - fast fourier transformation of data by data collector. The measured spectrum is compared with a baseline spectrum in excellent condition. When spectrum deviates above the baseline of more than one standard deviation, it indicates a problem	Engineers/ Technicians in the farm and skilled professional to analyse the CM data	Vibration Analyzer	M

		Scheduled on-condition of blower motor	Vibration measurements and frequency analysis - fast fourier transformation of data by data collector. The measured spectrum is compared with a baseline spectrum in excellent condition. When spectrum deviates above the baseline of more than one standard deviation, it indicates a problem	Engineers/ Technicians in the farm and skilled professional to analyse the CM data	Vibration Analyzer	M
		Scheduled discard of air filter of generator	Replace air filter	Engineers in the farm	Spare filter	L
		Scheduled on-condition of cooler	Open the cooler, check for corroded elements and replace the cooler if necessary	Engineers/ Technicians in a fish farm	Spare cooler	L
7	Every other year	Scheduled discard of blower belt	Replace the generator belt with the spare	Engineers/ technicians in the farm	Spare belt for the generator	L
		Scheduled on - condition air filter of blower	Mechanical indicator showing pressure drop indicating clogging	Engineers in the farm	Mechanical indicator	L
		Scheduled discard of generator belt	Replace the generator belt with the spare	Engineers/ technicians in the farm	Spare belt for the generator	M
		Scheduled on - condition air filter of generator	Mechanical indicator showing pressure drop indicating clogging	Engineers in the farm	Mechanical indicator	L

Appendix F

Maintenance Package of Camera System

Table F.1: Maintenance Package of Camera System

#	Maintenance Interval	Maintenance Task	Maintenance Description	Personnel	Equipment	CL
1	Everyday	Scheduled on - condition of camera	A moisture sensor in the camera that measures realtive humidity and reports the operating crew. Lift the camera from the cage and bring to the base or a barge and dry it	Engineer on the barge involved in the monitoring activity	Moisture sensor included in the PT cameras	L
		Scheduled on-condition of top section of CAP	A moisture sensor that measures realtive humidity and reports the operating crew. Replace the CAP with the spare	Engineer on the barge involved in the monitoring activity	Moisture sensor included in the CAP	L

		Scheduled on-condition of connection box of CAP	Moisture sensor inside the connection box of the CAP that measures relative humidity and reports the operating crew . Disconnect the connection box from the CAP and bring it to the barge and dry it	Engineer on the barge involved in the monitoring activity	Moisture sensor included in the connection box of CAP	L
		Scheduled on-condition of winch	A moisture sensor in the motors of the winch measures realtive humidity and reports the operating crew. Unmount the winch from the bracket and transport it to the base or the barge and dry it	Engineer on the barge involved in the monitoring activity	Moisture sensor in the motors of the winch	L
2	Once a month	Scheduled restoration of ropes	Clean off the sprout, salt water and salt crystals and rinse with fresh water	Operators in the fish farm	Fresh water	L
		Scheduled on - condition of elastic bands	Check the elasticity of the bands and replace if necessary	Engineers in the farm	Elastic bands	L

		Scheduled on-condition of lubrication oil of generator	Mesh obscuration particle counter. Oil passes through three high precision meshes and particles bigger than the pores get stuck in the mesh. The pressure change is measured by the sensors. It provides the number of particles that are larger than the mesh size	Engineers in the farm and skilled professional to analyse the CM data	Mesh obscuration particle counter instrument	M
		Scheduled restoration of winch	Clean the winch with fresh water and mild washing up liquid to rinse off the salt water deposits	Operators in the fish farm	Fresh water and washing liquid	L
3	Every 3^{rd} month	Scheduled on-condition of generator	Vibration measurements on bearing and casing using octave band analysis through contiguous and fractional octave filters. Divide the frequency spectrum into series of bands that have a constant width when plotted logarithamically. Each filter's average output is measured and the values are displayed by a meter or plotted on a recorder	Engineers/ technicians in the farm	Octave band filters, vibration meter and transducer	L
4	Every 6^{th} month	Scheduled restoration of winch motor	Clean the winch periodically to avoid salt water deposits	Operators in the fish farm	Fresh water and washing liquid	L
5	Every year	Scheduled on-condition of camera cable	LIRA Generator controls AWG and produces signal to the system. The Modulator produces a reference signal and a signal modulated by cable impedance. These are the input to DSO. The Analyzer analyses the signal and provides cable assessment. The simulator helps in performing what if analysis	LIRA Trained professionals or Trained engineers/ technicians in farms to carry out the analysis	LIRA Generator, LIRA Modulator, LIRA Analyzer , Digital storage oscilloscope and LIRA Simulator	H

		Scheduled on-condition of winch motor	Vibration measurements and frequency analysis - fast fourier transformation of data by data collector. The measured spectrum is compared with a baseline spectrum in excellent condition. When spectrum deviates above the baseline of more than one standard deviation, it indicates a problem	Engineers in the farm and skilled professional to analyse the CM data	Vibration Analyzer	M
		Scheduled discard of air filter of generator	Replace air filter	Engineers in the farm	Spare filter	L
		Scheduled on-condition of winch ropes	Check the ropes for the wear and replace if necessary	Engineers in the farm	Ropes	L
6	Every other year	Scheduled discard of generator belt	Replace the generator belt with the spare	Engineers/ technicians in the farm	Spare belt for the generator	M
		Scheduled on -condition of air filter of generator	Mechanical indicator showing pressure drop indicating clogging	Engineers in the farm	Mechanical indicator	L
7	Every 3rd year	Scheduled restoration of CAP clamps	Check the clamps for corrosion. If corroded, renew clamps	Operators in the fish farm	Spare clamps and bolts	L

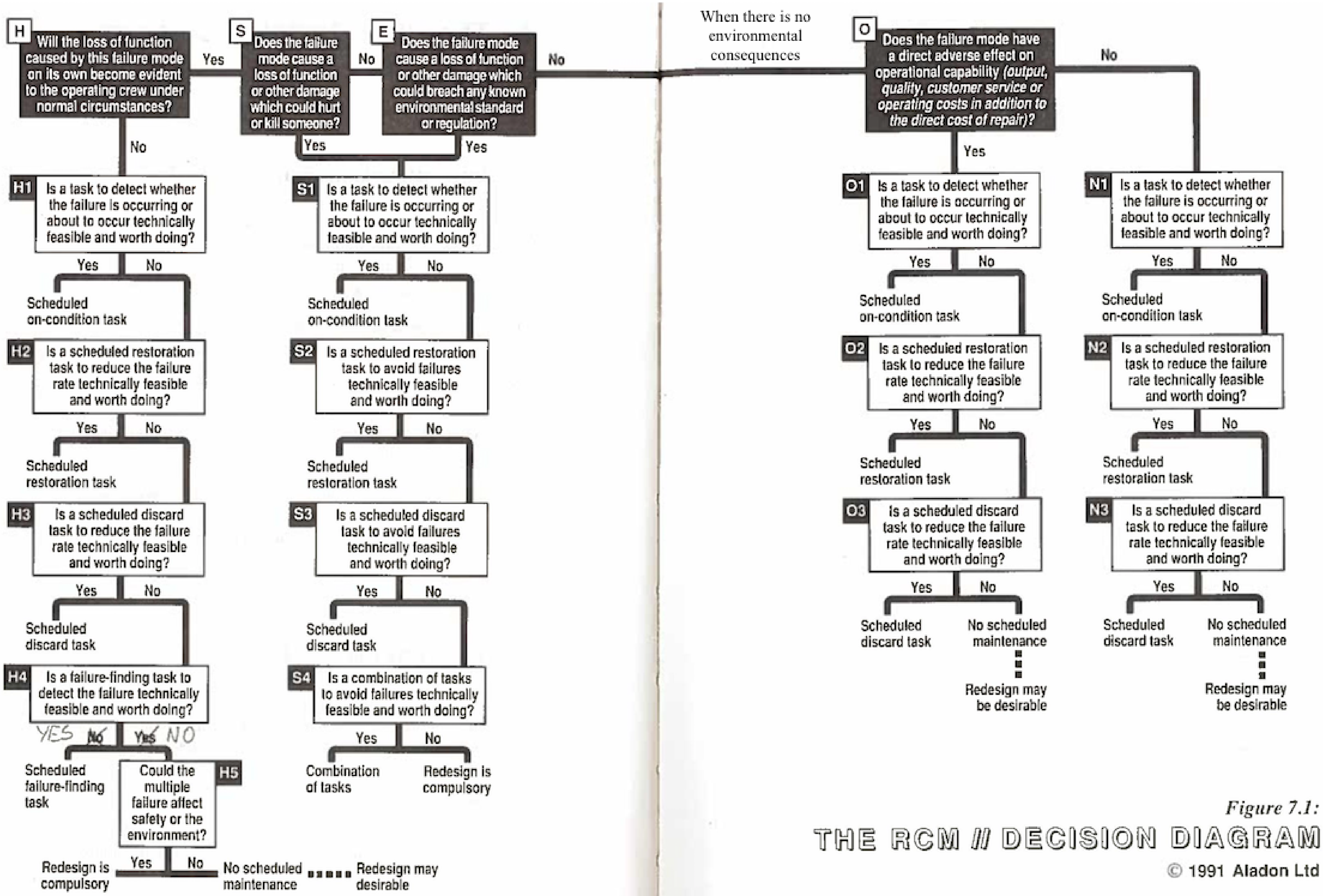

Figure F.1: RCM Decision Tree. Source: Reliability Centered Maintenance by John Moubray[11]