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Reliability Centered Maintenance (RCM) of the Autonomous Passenger Ferry in Trondheim

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Preface

This master thesis is the final delivery of the Master of science degree in Marine Technology. It was written during the spring semester 2018, at the Norwegian University of Science and Technology. The thesis accounts for 30 credits.

The thesis uses reliability-centered maintenance method to develop a maintenance strategy for an autonomous passenger ferry. Autonomous and unmanned ships are a new concept, where regulation has not yet been adapted. Consequently safety and availability are crucial elements. The maintenance program aims to be cost effective, furthermore it will aim to reduce the safety risk and optimize the availability for the ferry. The thesis has been structured through Microsoft Excel.

The work has been challenging, due to lack of information about the concept and research on autonomous and unmanned ferries. Through guidance from the supervisor the task is successfully completed.

I would like to thank my supervisor Ingrid Bouwer Utne at the Department of Marine Technology for guidance through the semester. I would like to thank Egil Eide and Edmund Frøland Brekke for their contribution with information to the thesis.

Finally I would like to thank my friends and family for the support during the years at NTNU, it has been a pleasure. A special thanks to Martin and Nano for their patience and love.

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Summary

This thesis make use of the RCM method to construct a maintenance program for an autonomous passenger ferry. The autonomous passenger ferry will work as a shuttle ferry in Trondheim, between Ravnkloa and Vestre Kanalkai. The idea is a on-demand ferry, push the button and the ferry will come shortly. The ferry will be designed to take maximum 12 passengers, have a crossing time of one minute and to be unmanned. Several challenges comes with the autonomy; will the ships be legal, will ship owners invest, what technology is needed [1]. Before the project can be realized there are several aspects related to operation and maintenance that has to be solved. The Norwegian Maritime Authority states that autonomous ships needs to be as least as safe as conventional ships [2]. This is tried accomplished through the maintenance strategy, which will identify critical components and failure modes and assign them with maintenance task, to reduce the consequences of the failures.

As mentioned, RCM is used to construct the maintenance program. This thesis makes use of the procedure from John Moubray [3], which is based on the standard SAE JA 1011 [4]. The focus is on maintaining the functions for the systems. The analysis is performed system for system. The seven questions from the standard is answered in a systematic way. Starting out by identifying the systems primary and secondary functions together with given performance standards. Next is the functional failures stated, which is based on the functions. A functional failure is when the system is no longer able to perform whats required. This is followed by a failure mode, effects and criticality analysis (FMECA) which is performed on a component level. Each failure modes criticality is assessed in the light of effects on safety, asset, environment and availability. To do this, classes ranging from one to five where five is catastrophic and one is insignificant has been used. Two of the most significant systems when it comes to the unmanned concept are the anti-collision and navigation system. Due to their importance an ETA and a FTA has been performed for both of them. Where the FTA focuses on total failure of the system, and ETA focuses on the damages to the passengers when a failure occurs. The analysis shows that there are low probabilities of a total failure in the two systems, much due to the redundancy.

Further, a maintenance task analysis is performed. Since the RCM aims to reduce maintenance costs, a maintenance task needs to be both cost effective and technically feasible. The costs calculations are performed by comparing hours available to do preventive maintenance before run-to-failure is more cost effective. The costs of run-to-failure includes loss of income, spare part costs, repair costs, injury costs and loss of reputation. The two last ones are the most significant ones. The cost calculation is only done for systems where it is needed. The maintenance task is divided in five: scheduled on-condition, scheduled discard, scheduled restoration, scheduled failure-finding and run-to failure. Where the first four are preventive maintenance tasks.

Most of the failure modes in the analysis received a high risk index, where over 55% of them are in the unacceptable area. Followed by this, there are a high use of preventive maintenance, with over 80%. The analysis performed has shown that the most critical systems are the navigation, anti-collision, propulsion and battery cooling system. These are critical in the light of the direct effects of the failures, but also the effects on loss of reputation as well. For such a new concept where new technology has been used, reputation will be important. The maintenance program suggested is grouped in maintenance packages with basis in the maintenance interval.

As mentioned before, the concept with unmanned passenger ferries is new. Consequently there are lack of information available. The systems identified in thesis are based on information given by the project manager. Where information was not available, relevant sources were used to first design the systems. Many of the failure modes, together with causes and maintenance, are based on manufacturers manuals. This includes equipment which is assumed to be chosen. It is not certain that it will or that all of the components will work together.

The master thesis will provide a framework for the maintenance plan. In addition, the plan must be implemented, and it is recommended to register failure and maintenance data when the ferry is operative. This will help in updating and implementing the plan.

Samandrag

Denne avhandlinga nyttar RCM-metoden til å konstruere eit vedlikehaldsprogram for ei autonom passasjerferje. Den autonome ferja skal fungere som ei skyttelferje i Trondheim, mellom Ravnkloa og Vestre Kanalkai. Idéen er ei ferje som kjem på førespurnad frå passasjerane. Trykk på ein knapp, og ferja kjem innan kort tid. Ferja skal kunne transportere 12 passasjerar samstundes, ha ei overfartstid på eit minutt og den skal vere utan besetning. Fleire utfordringar følg med autonomien: vil ferja vere lovleg, kjem skipseigarar til å investere og kva teknologi trengs [1]. Før prosjektet kan realiserast, må fleire aspekt knytt til drift og vedlikehald løysast. Sjøfartsdirektoratet hevdar at autonome skip må vere minst like trygge som konvensjonelle skip [2]. Dette er forsøkt gjennomført gjennom vedlikehaldsstrategien, som skal identifisere kritiske komponentar og feilmodar, og tildele dei vedlikehaldsoppgåver. Slik skal ein redusere konsekvensane av feila.

Som tidlegare nevnt, er RCM-metoden nytta til å konstruere vedlikehaldsprogrammet. Denne avhandlinga nyttar prosedyra utvikla av John Mourbay [3], som er basert på standarden SAE JA 1011 [4]. Fokuset er retta mot å oppretthalde funksjonen til systema. Analysa er gjennomført system for system. Dei sju spørsmåla frå standarden nevnt over, er svara på på ein systematisk måte. Først ved å identifisere systema sine primære og sekundære funksjonar, sett i samanheng med gitte ytelsesstandardar. Vidare er funksjonelle svikt angitt, basert på funksjonane. Ein funksjonell svikt er når systemet ikkje lengre klarar å utføre det som krevs av det. Dette er etterfølgt av ei FMECA-analyse, som er utført på eit komponentnivå. Kvar feilmode sin kritikalitet er vurdert i lys av effekter på tryggleik, eiendelen, miljøet og tilgjengelegheit. For å gjere dette er klasser rangert frå ein til fem, kor fem er katastrofalt og ein er neglisjerbart, nytta. To av dei mest monalege systema når det kjem til det umanna konseptet, er antikollisjonssystemet, og navigasjonssystemet. På grunn av kor viktige desse systema er, er det utført ETA og FTA for begge. FTA har fokus på total feil i systemet, mens ETA retter seg mot skader på passasjerane når feilen skjer. Analysen viser at det er lav sansynlegheit for totale feil i dei to systema, mykje grunna systema sin redundans.

Videre er det utført ei vedlikehaldsoppgåveanalyse. Sidan målet til RCM-metoden er å redusere vedlikehaldskostandene, må ei vedlikehaldsoppgåve både vere kostnadseffektiv og teknisk mogleg. Kostnadsberegningane er gjort ved å samanlikne tilgjengelege timar for prevantivt vedlikehald før "run-to-failure" er meir kostnadseffektivt. Kostnadane knytt til "run-to-failure" inkluderar tapt inntekt, prisen på reservedelar, reperasjonskostnadane, skadekostnadane og tap av omdøme. Her er dei to sistnevne dei viktigaste. Kostnadsberegninga er berre utført for system kor det er nødvendig. Vedlikeholdsoppgåvene er delt inn i fem: planlagt etter tilstand, planlagt utbytting, planlagt restaurering, planlagt feilsøking og "run to failure". Dei første fire er preventive vedlikehaldsoppgåver, mens den siste består av å bytte ut komponenten når den er øydelagt.

Dei fleste feilmodane i analysa får ein høg risikoindeks, og over 55% av desse er i det ikkje-akseptale spekteret. Som følgje av dette, er det lagt opp til vesentlig bruk av preventivt vedlikehald, i over 80% av feilmoduane. Analysen viser at dei viktigaste systema er navigasjonssystemet, antikollisjonssystemet, framdrifta og batterikjøingssystemet. Desse er viktige med tanke på dei direkte konsekvensane av feila, men også med tanke på tapet av omdøme. For eit så nytt konsept som dette, er omdømet viktig. Vedlikehaldsprogrammet som er lagt fram er gruppert inn i vedlikehaldspakker, med utgangspunkt i vedlikehaldsintervallet.

Konseptet med umanna ferjer er nytt. Ein konsekvens av dette er at det er lite informasjon tilgjengeleg. Først og fremst er systema identifisert i avhandlinga basert på informasjon gitt av prosjektleiaren. Der informasjon ikkje har vore tilgjengeleg, har relevante kjelder vore nytta til å designe systema. Mange av feilmodane, saman med årsakar og vedlikehald, er basert på produsentens manualar. Dette inkluderar utstyr som er antatt nytta, noko som gjer at ein ikkje kan vere sikker på at alle komponenante vert nytta, eller at dei vil fungere saman.

Denne masteravhandlinga dannar eit rammeverk for vedlikehaldsplanen. I tillegg må planen implementerast, og det er tilråda å registrere feil- og vedlikehaldsdata når ferja er operativ. Slik kan ein enklare oppdatere og implementere vedlikehaldsplanen.

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Abbreviations

AAWA	Advanced Autonomous Waterborn Application Initiative
ALARP	As low as reasonably practicable
COFA	Consequence-of-failure analysis
ESB	Emergency stop button
ETA	Event tree analysis
FMECA	Failure Mode, Effects, and Criticality Analysis
FTA	Fault tree analysis
GNSS	Global Navigation Satellite System
IMO	International Maritime Organization
IMU	Inertial Measurement Unit
IR	Infrared
MUNIN	Maritime Unmanned Navigation through Intelligence in Network
NMA	Norwegian Maritime Authority
MTA	Maintenance Task Analysis
MTBF	Mean time between failures
MTTF	Mean time to failures
MTTR	Mean time to repair
NTNU	Norwegian University of Science and Technology
RCM	Reliability Centered Maintenance
RI	Risk Index
RTK	Real-time kinematics
SAE	Society of Automotive Engineers
TPM	Total Productive Maintenance

Chapter 1

Introduction

In this chapter the background and motivation for the thesis will be outlined. This includes the meaning of autonomy, why it is important, and some of the projects and challenges that are met in the field. The objectives, scope and limitations, and structure of the report are also included in this chapter.

1.1 Background

Over the past years more and more interest has been shown to the field of autonomous vessels. This accounts for both on land, in the air, at sea and underwater. Oxford Dictionaries [5] defines autonomy to be the following:

> *"Freedom from external control or influence; independence."*

The definition includes freedom, but freedom from what? How much freedom must there be before the vessel is autonomous? Is 100% autonomy possible? There are several definitions of the levels of autonomy, one of these are from Lloyd's Register and can be seen in Table 1.1. These levels goes from 0 to 6, where 6 is fully autonomous with unsupervised operation. Rolls Royce [1] argues that the levels of autonomy for a ship may be dynamic, e.g simpler operation may be fully autonomous, while more complex operations will need more human interaction.

Some of the well known companies that has started out projects in the field of autonomous ships are Kongsberg Gruppen, Yara International and Rolls Royce [7] [1].

Yara Birkeland will be the first zero emission autonomous container vessel in the world. The project is a collaboration between the private-and the public sector. The companies that are working together are: Yara, Kongsberg, Marin Teknikk, SINTEF and ENOVA. The ship will sail between the fertilizer factory near Porsgrunn, Breivik and Larvik, which will replace 40 000 truck journeys per year. [7]

Table 1.1: Levels of Autonomy adapted from Lloyd's Register *LR code for unmanned marine systems* [6]

Level of autonomy	Description
0	Manual
1	On-board Decision Support
2	On and Off- board Decision Support
3	Active human in the loop
4	Human on the loop, Operator/Supervisory
5	Fully autonomous - rarely supervised operation
6	Fully autonomous - unsupervised operation

Furthermore one has the MUNIN project. MUNIN stands for Maritime Unmanned Navigation through Intelligence in Networks. The objective for the project is to develop and verify a concept for an autonomous ship. The project is a collaborative project, which is co-founded by the European Commissions under its Seventh Framework Program. [8]

Rolls Royce has recently (2018) opened a research facility for autonomous ships in Finland, which aims to develop the technology that are needed for unmanned and autonomous ships [9]. They have also been a part of the Advanced Autonomous Waterborn Application Initiative (AAWA) together with DNV GL, Inmarsat, Deltamarine, NAPA, Brighthouse Intelligence, Finferries and ESL Shipping. The project aims to develop the specifications and preliminary design for the autonomous ships. [1]

In Norway a forum for autonomous ships has been established in 2016. This forum consist of persons and organizations that are interested in the field of autonomous ships. Some of the members are the Norwegian Maritime Authority, SINTEF, Kongsberg and Rolls Royce. Their goal is among other things to strengthen the collaboration between users, research community, government and other organizations. [10]

So, why do we need autonomous ships? Autonomous ship can be a solution to some of the challenges that the maritime industry are facing. According to the MUNIN project [8] some of these challenges are increase in transport volumes, growing environmental requirements and shortage on seafarers. While Gemini [11], which publishes research news from SINTEF and NTNU, states that unmanned ships will be greener, cheaper and more flexible.

1.1.1 Rules and Regulations

Autonomous and unmanned ships is a new concept, still under developing and testing. Therefor rules and regulation has not adapted to the situation yet. The rules and regulation in maritime sector consists of both national and international laws. The international maritime laws are covered by International Maritime Organization (IMO). They have put autonomy and remote operation on their agenda, and are going to look closer into the following topics [2]:

- The gap between existing regulation
- Sort out regulation without interference
- The need for new regulation

In Norway it is the NMA that has the responsibility for rules and regulation. They desire that Norway shall be world leading when it comes to maritime innovation [2]. When it comes to autonomous ships they require that they are just as safe as conventional ships [2]. According to Medhaug [2] from the NMA the development of the national regulation will take up to seven years, and consists of three phases; preliminary, temporary and final.

In addition to planing changes to the regulation, several test areas has been established. In 2016 the NMA and the Norwegian Coastal Administration allowed for testing autonomous ships in Trondheimsfjorden. The first of its kind in the world. [12]

The year after, another area in Norway were opened for testing. This area, Storfjorden, is located close to 14 shipyards and 20 shipowners. Due to the traffic pattern in the area, which includes 8 ferry crossing, several fish farms, shipping and cruise tourism, this is a good location. [13]. The same year a test area in Horten were established. Horten is an important area due to the future operation of Yara Birkeland. [14]

1.1.2 Challenges

Implementing autonomous ships will bring challenges. The AAWA Initiative and the report *Analysis of Regulatory Barriers to the use of Autonomous Ships - Final Report* from the Danish Maritime Authority [1] , [15] argues that an autonomous ship needs to be as safe as an existing ship. In the white paper from the AAWA Initiative [1] four crucial questions has been set out, see below.

- What technology is needed and how can it be best combined?
- How can the autonomous ship be made as least as safe as existing ships?
- What will be ship owners motive to invest?
- Will the ships be legal?

The report from the Danish Maritime Authority identifies challenges when it comes to the rules and regulation, both national and international. The report argues that the focus in regulation should be to incorporate autonomous ships into the existing framework, due to its complexity.

Trond Langemyr from The Norwegian Coastal Administration [16] has published some challenges with autonomous and unmanned ships, some of these are as follows:

- Changes in regulation
- The high pace of development
- Efficiency improvement of ports

- Standardization
- Competence

In addition to listing these challenges, they claim that all of them are solvable.

1.2 Autonomous shuttle ferry in Trondheim

Trondheim is the fourth largest city in Norway, and by the start of 2017 it had approximately 180 000 inhabitants [17]. The city is also refereed to as the capital of technology in Norway.

Trondheim, like other cities, always wants to renovate and create. The municipality of Trondheim wants to encourage the citizens and the tourists to a more active use of the city centre, which has lead to several strategies and projects [18]. Hjertepromenaden is an example of such a project. The idea here is to have the possibility to walk around the whole city, along Nidelva and the canal. The promenade shall be available for all, and it will show some of the best spots in Trondheim. [19]

Another area that is important for the development of the city is Ravnkloa. The vision here is to make it the most attractive common land in the city [18]. As a consequence of this, a feasibility study of a pedestrian bridge from Ravnkloa to Fosenkaia has been done, and concepts from three companies has been developed [20]. The bridge will be an important piece for completing Hjertepromenaden [19]. Due to the boat traffic in the canal the bridge must be a lifting bridge.

Kystlaget Trondhjem has expressed their concern about the bridge concept. In a letter to Trondheim municipality they have listed the consequences of a bridge in the canal [21]:

- Space for maneuvering will be lost
- Difficulties regarding openings times of the bridge
- Fosenkaia will be confined
- Fløtmannsbåten will disappear

An autonomous shuttle ferry has been proposed as another alternative for crossing the canal, see Figure 1.1. The idea came from Egil Eide, which is the leader of Kystlaget Trondhjem and a Associate Professor at Department of Electronic Systems at NTNU. The concept includes a ”On-demand ferry”, push a button and the ferry will come shortly. With a crossing time of one minute, one has frequent departures and short waiting times. The ferry can take up to 12 passengers, and shall be available for both wheelchairs, bicycles and strollers. [22] A more detailed description of the concept will be provided in Chapter 4.

Figure 1.1: Graphically illustration of the concept [22]

Safety and reliability will be crucial for the concept. Some of the most vital success criteria are risk assessment, redundant navigation system, robust anti-collision system and robust design [22].

Figure 1.2 shows the planned route for the ferry, which goes from Ravnkloa to Vestre Kanalkai.

Figure 1.2: Planned route for the autonomous shuttle ferry [22]

1.3 Objectives

The objectives for this master thesis is to describe the Reliability Centered Maintenance (RCM) method and, adapt and use it for the autonomous passenger ferry in Trondheim, and to define the RCM decision logic. Then analyze and derive the maintenance strategy and plan. Followed by recommendations on which failure and maintenance data that needs to be registered to improve the decision basis during operation.

1.4 Scope and limitations

The scope of this thesis is to use RCM to construct a maintenance program for an autonomous passenger ferry, by analyzing the systems on board and at quay. This thesis focuses on a primary analysis of the concept, where all the systems are included. This causes that the components are not analyzed on a detailed level, and the functional failure are general.

Due to lack of data and information about failure history and previously maintenance programs, the failure modes and maintenance task for the components are based on available information online from manufacturers and research papers. This information may not be applicable for the ferry, but has still been used. Failure modes related to power supply failure has not been assessed in the analysis. As all of the systems are depending on power from the batteries, which would have caused the same failure mode for almost all the components.

1.5 Structure of the report

The thesis is structured in four steps; the method, the analysis, the results then a discussion. Chapter 2 presents the literature review, where the focus is on why maintenance is important and maintenance strategies. The method and procedure used are presented in chapter 3. Chapter 4 gives a description of the systems on board the ferry, while the analysis is presented in chapter 5. Followed by results and discussion in chapter 6. Finally a conclusion is presented in chapter 7, and further work in chapter 8.

Chapter 2

Maintenance overview

This chapter will address the information found in the literature search, where the main focus is maintenance. The chapter will enlighten why maintenance is important, some standards and terminology.

2.1 Why Maintenance?

Maintenance is performed to maintain a component or systems function. How and when maintenance is performed will have an impact on the system. Risk reduction, efficiency and economy, and availability are three factors that are influenced by maintenance [23].

In Chapter 1 it was stated that autonomous and unmanned ships must be as least as safe as convectional ones, therefore maintenance will be an important element in realizing these kinds of projects. The level of safety must be maintained throughout the systems lifetime.

According to John Moubray [3] there exists two different types of maintenance in an engineering point of view; maintenance and modification. Where maintenance is when the function is maintained, and modifications refers to changes in the system.

2.2 Maintenance Terminology

There are different types of maintenance, and different standards which are intended for different use. This thesis makes use of the following standard and guideline; *SAE JA1011: Evaluation Criteria for Reliability-Centered Maintenance (RCM) Process* [4] and *SAE JA1012: A Guide to the Reliability-Centered Maintenance (RCM) Standard* [24]. JA 1011 is the criteria that needs to be fulfilled to call the process a RCM process, while JA1012 is the guide to the standard. The standard is based on Nowlan and Heap's report from 1978 [4]. So, when it comes to maintenance terminology these standards are used.

2.3 Types of Maintenance

Figure 2.1 shows the relationship between different types of maintenance. In this figure the maintenance is divided in either corrective or preventive. Corrective maintenance happens after the item has failed, a reactive form of maintenance. While preventive aims to prevent the failure, and is proactive.

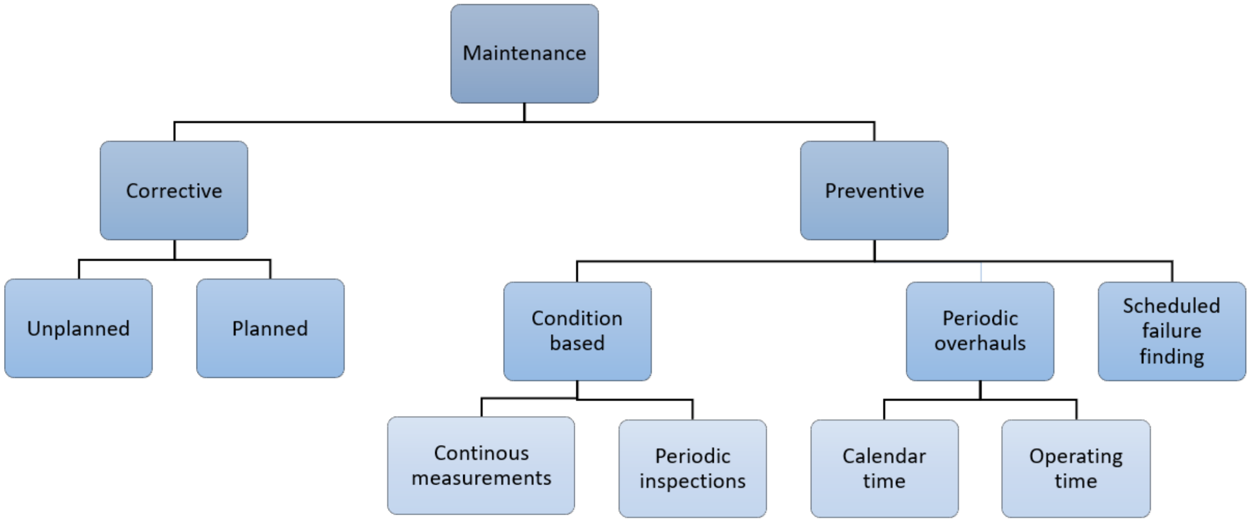


Figure 2.1: Different types of maintenance, adapted from Utne [23]

Corrective Maintenance

Corrective maintenance is a run-to-failure type of maintenance. The idea behind is easy; do not fix anything before the machine breaks. No money are used on the component until it fails, but it is the most expensive type of maintenance. Analysis has shown that the cost are typically three time higher for run-to-failure repair than for preventive modes. [25]

Figure 2.1 divides corrective maintenance further into planned and unplanned repairs. The planned repairs are for equipment where run-to failure is the cheapest way. This can be equipment that is not critical for safety or the production [23]. While the unplanned corrective actions are when unexpected events occurs.

Preventive Maintenance

Preventive maintenance is the proactive way. There exists different classifications for the preventive maintenance, but all of them are time-driven [25]. Figure 2.1 divided the preventive maintenance in condition based, periodic overhauls and scheduled failure finding.

Condition based maintenance uses the condition of the equipment to decide when maintenance is needed. The maintenance can be either continuous measurements or periodic inspections. The measurements are compared to a standard for the component or system, hence decided if corrective actions are needed or not. [23]

Another type of preventive maintenance is periodic restoration and discard. This type of maintenance is either based on calendar time or the equipment's operating time. Periodic overhauls or scheduled restoration restores the capability of a component at or before a specified age, no matter what condition the component has [3]. Some failure modes which is age-related makes restoring to initial capability impossible [3]. This situations leads to periodic replacements or scheduled discard.

The last part of preventive maintenance are scheduled failure finding. Here are hidden functions checked at periodic intervals to see if it still works [3].

2.4 Planning of Maintenance

There exists two strategies for maintenance planning [23]; Total Productive Maintenance (TPM) and Reliability Centered Maintenance (RCM).

Total productive maintenance were developed in Japan, and is an approach to maintenance management. The approach focuses on six major losses [26]:

1. Breakdown losses
2. Setup and adjustment losses
3. Idling and minor stoppages
4. Reduced speed losses
5. Defects in process and reworking losses
6. Yield losses

These losses will determine the overall equipment effectiveness, which is an indicator of how machines, production lines and processes performs when it comes to availability, performance and quality [26].

Reliability centered maintenance is defined by J. Moubray [3] to be the following: *a process used to determine the maintenance requirements of any physical asset in its operating context*. The RCM will be further described in chapter 3.

Chapter 3

Method - Reliability Centered Maintenance

The following chapter will explain the details and principles for the RCM process used in this thesis. Firstly the history of the method will be described briefly, followed by the procedure of the method.

3.1 History

How maintenance has been executed and planned over the years has changed, and RCM is a result of this. The way of maintenance changes due to the increased complexity of systems, and due to the development of new maintenance techniques. [3]. According to Moubray [3], since 1930's one can define three generations of maintenance, these are summed up in Figure 3.1.

The RCM method can be seen as an answer to the challenges that the third generation caused. These challenges includes how to select the most appropriate technique, how to deal with each type of failure process and how to make it most cost-effective [3]. RCM was first documented in a report published by the U.S Department of defence in 1978, written by F.S Nowlan and H.F Heap [24]. Since the report by Nowlan and Heap [4], RCM has been used widely in many different industries and has developed over the years. The development of the method makes the need for a standard. There are several standards for different purposes, some of them are listed below.

- SAE JA 1011: Evaluation criteria for the RCM process
- SAE JA 1012: A guide to the RCM standard
- IEC 60300-3-11:2009: Guidelines for establishing failure management policies using RCM
- NAVAIR 00-25-403: Guidelines for RCM for the U.S Naval Air System Command

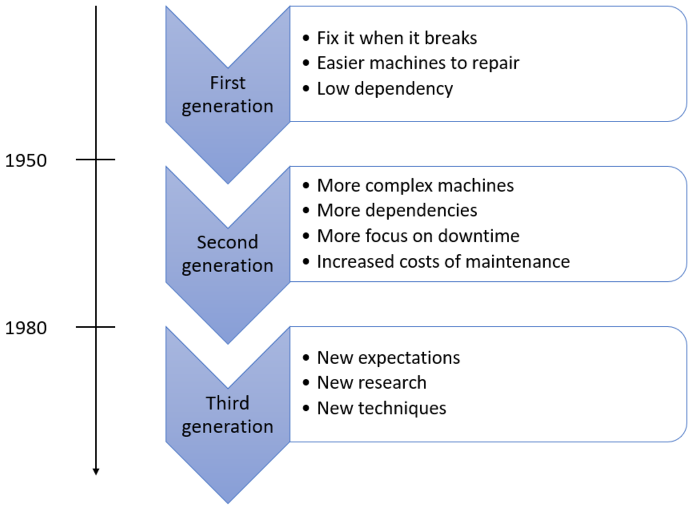


Figure 3.1: Illustration of maintenance generations, adapted from Moubray [3]

- MIL-STD-2173: RCM requirements for naval aircraft, weapon system and support equipment, U.S Department of Defense

3.2 RCM Procedure

3.2.1 Definition

As mentioned before, RCM is defined by J. Moubray [3] to be the following: *a process used to determine the maintenance requirements of any physical asset in its operating context*. The method is a systematic way to create a maintenance program for different types of equipment or systems.

RCM is performed by asking seven questions about the asset or system, the questions are listed below [3].

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 functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to predict or prevent each failure?
7. What should be done if a suitable proactive task cannot be found?

Each of the questions will be described more in detail in the following subsections.

3.2.2 Procedures of RCM

Through the ages the method of RCM has developed, and there exists several theories when it comes to RCM. Common for the all are the goal of the method, to develop a optimized maintenance strategy and plan. The aim for all of the methods is to create a maintenance strategy that are cost reducing, where the focus is on maintaining the functions for the systems or asset.

Rausand [27] presents 12 steps in performing the analysis. This method includes finding the critical items for the asset, and finding maintenance strategies for them. However the main objective of RCM is to reduce the maintenance costs.

Another procedure is presented by Bloom [28] in *Reliability Centered Maintenance - Implementation made simple*. The focus in this method is to make it more user-friendly. The COFA worksheet is one of the main focus, where the author claims that this worksheet makes a complex logic simple. COFA stands for consequence-of-failure analysis [28]. This implies that the method switches the failure mode, effects, and criticality analysis (FMECA) for the COFA.

Moubray [3] follows the procedure from the standard SAE JA 1012 and SAE JA 1011. The book gives additional explanations to the standard. This procedure has been used throughout this master thesis. The use of this leads to that non critical components are not excluded early in the analysis. Some may think that it is worthless, time consuming and loss of money. It can be, but in fact this procedure will make sure that hidden critical failure mode will not be left out. In a concept as new as an autonomous ferry this is important, and it is always important to keep in mind that autonomous ships should be as least as safe as existing ships.

3.3 Functions and performance standards

Step 1: What are the functions and associated performance standards of the asset in its present operating context?

SAE International [24] lists four key concept when it comes to the functions for the system or asset, these are:

- Operating context
- Primary and secondary functions
- Function statement
- Performance standard

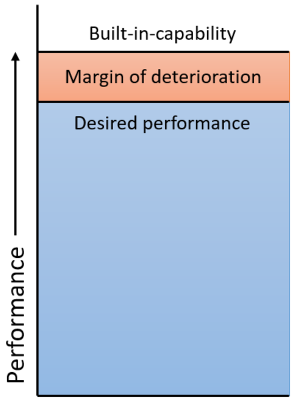


Figure 3.2: The two ways of defining performance standard, adapted from SAE JA1012 [24]

The operating context deals with the environment that the asset or system are supposed to operate under. The operating context should be as specific as possible, as it will affect the analysis further. Every asset or system has its own intended function, the reason for its existence. The functions can be divided in two; primary and secondary functions [24]. The primary functions are the main reason for the asset or system, and should be defined as specific as possible [3]. The secondary functions are the functions in addition to the primary functions [3]. The secondary functions may not be as easy to discover as the primary function. A list of secondary functions may result in a very long list, and one should always think about the relevance for the listed functions in accordance to the analysis.

For describing the functions, a function statement should be used. These statement shall contain a verb, an object, and a performance standard [4]. An example of such as functional statement is to transport passengers at a speed of four knots. Here are to transport the verb, while passengers are the object and a speed of four knots is the performance standard.

The performance standard tells about how the system shall operate, and what is demanded from it. According to SAE JA 1012 [24] the performance standard can be defined in two ways:

1. Desired performance
2. Built-in capability

Figure 3.2 shows the relation between the two definitions. The desired performance is what the owner want it to do, while the built-in capability is what it is actually capable to do. When the relation between the two are as shown in Figure 3.2 one has allowed for deterioration, and the asset is maintainable [24].

To get a better overview of the asset or system functions a functional hierarchy can be used. The hierarchy is also called a functional tree [26]. Here are primary and secondary functions presented. If it is convenient the secondary functions may be further divided.

3.4 Functional Failures

Step 2: In what ways does it fail to fulfill its functions?

When step 1 is completed, one have to look at how the system can fail. SAE International [24] has defined functional failure to be: *A state in which a physical asset or system is unable to perform a specific function to a desired level of performance.* This means that step 2 deals with failures of the functions that were stated in step 1. The definition stated above clearly state that functional failure is a state, and says nothing about how the functional failure occurred. This part of the analysis shall identify all the possible states at which the asset or system has failed.

There are different states where the asset or system can have failed. The system can have a total failure, which implies that the asset or system will not work at all. A different kind of failure state is the partial failure.

A better understanding of the two different scenarios is gained through an example. A pump should deliver water from A to B at a rate of 500 litres/minute. This pump has two potential functional failures:

1. Fails to pump fluid
2. Pumps fluid at a rate less than 500 litres/minute

The first functional failure will represent a total failure of the pump, while the second functional failure represent a partial failure.

3.5 FMECA

So far the functions for the asset or systems has been identified, together with its functional failures. The next step in the RCM analysis is to look at why the failures occurs. This is done by a failure mode, effects and criticality analysis (FMECA). In this thesis the FMECA is performed on a component level for each system. One of the most important objective of FMECA is to identify the failure modes for the components in the system, the causes and their effects [23]. FMECA can be carried out in seven steps, these steps are stated below [29].

1. Plan and prepare
2. Carry out system breakdown and functional analysis
3. Identify failure modes and causes
4. Determine the consequences of the failure modes
5. Assess the risk
6. Suggest improvements

7. Report the analysis

Even though the FMECA is performed on a component level, the effect of the failure is assessed on the asset.

Firstly the failure modes are identified, together with their causes. Next the effects each of the failure modes has on the asset are assessed. Followed by the criticality part of the analysis, which includes safety, asset, environment and availability. The analysis also includes the Mean Time Before Failure (MTBF) for the components. In fact MTBF is used for repairable items, while Mean Time to Failure (MTTF) is used for non-repairable item. For simplicity MTBF is considered for both repairable and non-repairable components.

A good way to organize the FMECA is with the help from a worksheet. Since the FMECA will be extensive the worksheet will be divided in two parts. The first part consists of the following:

- Component
- Function
- Reference number
- Failure mode
- Failure cause
- Failure pattern
- Hidden or evident
- MTBF

The second part of the worksheet will consist of the following:

- Component
- Reference number
- Failure mode
- Effect on asset
- Criticality
- Consequence category
- Frequency category
- Risk index

Each of the steps will be described further in the following subsections.

3.5.1 Failure Modes

Step 3: What causes each functional failure?

A failure mode is defined by SAE International to be [24]: *A single event, which causes a functional failure.* J.Moubray [3] states that all the failure modes that are reasonably likely to affect the asset should be identified. Failure modes can be divided into three groups [3]:

1. Capability falls below desired performance
2. Desired performance rises above initial capability
3. Asset is not capable doing what is wanted

Failure modes that can be seen as reasonably likely to occur can according to Moubray [3] be the following three:

1. Failures which have occurred before
2. Failure modes which are already the subject of proactive maintenance
3. Any other failure modes which have not yet occurred but which are considered to be reap possibilities

According to SAE International [24] the description of a failure mode should contain a noun and a verb, and contain enough details so that a appropriate failure management policy can be selected.

3.5.2 Failure Effects and Consequences

Step 4: What happens when each failure occurs?

Step four of the RCM analysis deals with the effects of the failures, both on the system and the asset. The effects tells about what happens when the failure occurs. SAE International [4] states the following when it comes to failure effects: *Failure effects shall describe what would happen if no specific task is done to anticipate, prevent or detect the failure.* Further SAE International [24] lists five items of information that should be included, these are:

1. The evidence that the failure has occurred
2. If the failure poses a threat to safety and/or the environment
3. How it affects production or operation
4. Physical damages caused by the failure
5. What is necessary to restore the function

Step 5: In what way does each failure matter?

Next in the analysis is to assess the consequences of the failure modes. The RCM process aims to reduce or avoid the consequences from failures, not so much avoiding the failure from occurring [24]. SAE International [24] groups the failure consequences into two stages in the following way:

1. Hidden or evident failures
2. Safety, environment, operational, and non-operational consequences

Evident failures will be evident for the crew under normal operating conditions, while hidden failures will not.

3.5.3 Risk matrix, Consequence and Frequency parameters

Most of the content in this subsection are adopted from *FMECA of the Autonomous Passenger Ferry in Trondheim* [30].

To assess the risk, the frequencies of the failure modes needs to be classified. The frequencies says something about how often the components fails. There are several ways to do this. In some cases one have the exact numbers for failing, in some not. When the frequencies are not available, classes of frequencies can be used. Table 3.1 illustrates the classes used in this project. The table is adopted from *Risk Assessment; Theory, Methods, and Applications* [29].

Table 3.1: Frequency categories

Category	Frequency per year
5	10 - 1
4	1 - 0.1
3	10^{-1} - 10^{-3}
2	10^{-3} - 10^{-5}
1	0 - $10^{-}5$

The autonomous and unmanned ferry will consists of several control algorithms, taking decision based on inputs. Software reliability does not follow the same principles as hardware. The software codes does not degrade, but can fail due to undetected errors [31]. The failures are mostly due to design faults, but can also be due to the specification and the coding process. All this implies that failure are due to human factors when designing the software. When failure do happen, modifications are done to it [31]. Therefor it is meaningless to speak of MTBF of software codes. For this thesis frequency class for software are estimated through guesswork. Thus, the software can be included in the further analysis.

Consequence is also called adverse effect, impact, loss or impairment [29]. The consequence is the damages due to the failure mode. For each failure mode the consequences can be classified according to the severity. This thesis consist of four consequence dimensions; safety, asset, environment and availability.

When it comes to safety the consequence classes deal with safety for humans. Table 3.2 shows how this table looks like in this thesis, and are adopted from *Risk Assessment; Theory, Methods, and Applications* [29] and from Institute Of Transport Economics [32].

Table 3.2: Consequence classes for safety

Safety		
1	Negligible	Insignificant impact
2	Minor	Slight injury
3	Major	Major injury
4	Critical	Severe injury
5	Catastrophic	Fatality

Table 3.3 shows the classification when it comes to criticality of the asset. Also this classification types is adopted from *Risk Assessment; Theory, Methods, and Applications* [29]. This criticality will depend on the failure mode. A failure mode which causes damages to the main parts of the system will fall in category four, while failure modes with insignificant effects in the system will fall in category one or two. Failure modes which has insignificant to small effects on the system are typically system that are redundant. These systems are not dependant on the component, which implies that the system will still work well after the failure mode occurs.

Table 3.3: Consequence classes for asset

Asset		
1	Negligible	Insignificant system damage
2	Minor	Minor system damage
3	Major	Considerable system damage
4	Critical	Loss of main parts of the system
5	Catastrophic	Total loss of the asset

The next consequence dimension is environment. This type will include the damages to the environment, both local and global. The classification will use the restoration time to decided the severity. Table 3.4 shows the consequence classes for the environment. It is adapted from *Risk Assessment; Theory, Methods, and Applications* [29]. The environmental damages that a marine vessel can cause ranges from oil spill to garbage pollution. The autonomous ferry will not contain any large volume of oil, nor garbage and it will be electrical so the air pollution will be minimal, therefor the severity when it comes to the environment will range from one to two.

Table 3.4: Consequence classes for environment

Environment		
1	Negligible	Insignificant impact
2	Minor	Temporary impact. Restitution time <1 month
3	Major	Short term local impact. Restitution time <1 year
4	Critical	Medium long term impact. Restitution time 1-5 years
5	Catastrophic	Long term impact. Restitution time >5 years

The last criticality category is availability, which deals with the potential downtime the failure mode causes. Downtime includes the time from the failure happens to the asset is working again, such as finding a person who can repair, time to diagnosis the fault and repairing. The classes used in this thesis can be seen in Table 3.5. Which ranges from available to very high unavailability. For a new concept as the ferry availability will be important. A ferry that has a high degree of unavailability will not gain any passengers, since they never know when it will function. 6 hours unavailability means six hours of the ferrys operating time. The classes are set by the author, on the basis on the fact that the ferry needs high availability and what should be accepted. The importance of availability is further discussed in Chapter 7.2.

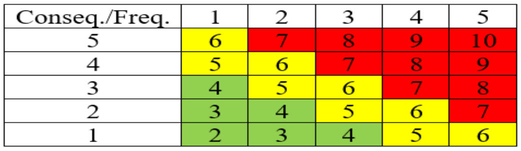
Table 3.5: Consequence classes for unavailability

Unavailability		
1	Available	0 h
2	Low	$\leq 6h$
3	Medium	$\leq 12h$
4	High	$\leq 24h$
5	Very high	>24 h

To assess the risk it is useful to calculate the Risk Index, RI. The index is defined by the logarithm of the risk associated with the event, and equation 3.1 shows the calculation [29]. The C is the consequence, while p is the probability or frequency. The C, consequence, is based on the worst case from the four consequences dimensions. Since this is the case the analysis will be conservative, and always take the worst case into account. One may argue that it much worse to have catastrophic consequence when it comes to safety than availability. To allow for this the consequence categories might be weighted. This is not done in this thesis, since such a solution will be very much affected by the person performing the analysis, but it is important to keep in mind that the analysis is conservative.

$$logR = logC + logp \tag{3.1}$$

Risk matrix illustrates the risk index in a tabular form, and uses the consequence-and frequency classes. Figure 3.3 shows the risk matrix that are used in this thesis.



Conseq./Freq.	1	2	3	4	5
5	6	7	8	9	10
4	5	6	7	8	9
3	4	5	6	7	8
2	3	4	5	6	7
1	2	3	4	5	6

Figure 3.3: Risk matrix used in the analysis

The color codes follows the ALARP principle. The green area is where the risk is acceptable, the yellow is in the ALARP region and red is not acceptable. ALARP is a abbreviation for as low as reasonable practicable. Here actions should be taken if they are practicable. Practicable in the means of costs and technology available. For the red region action shall be taken, since the risk is too high. The risk matrix shown in Figure 3.3 is a conservative matrix, where the acceptable area is narrow while the unacceptable area is wide. This is due to the fact the an autonomous passenger ferry is a completely new concept, which demands a high level of safety for the passengers. Also reputation will be important in such a new concept, so it is better to be safe than sorry.

3.6 Maintenance Task Analysis

Step 6: What can be done to predict or prevent each failure?

This is the last part of the RCM analysis, and consist of deriving a maintenance strategy and plan. Here are the results gathered from the FMECA used to find the most critical systems together with their failure modes. It is the most critical components that needs special attention when it comes to the maintenance plan.

3.6.1 Maintenance task classification

As mentioned in Chapter 2 maintenance can be divided into preventive or corrective maintenance. According to Høyland [33] the reasons for doing preventive maintenance are the following:

1. Prevent failure
2. Detect the onset of a failure
3. Discover a hidden failure

The maintenance task used in this thesis are adapted from *Reliability-Centered Maintenance* [3]. In total the analysis consists of five tasks, see below.

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

4. Scheduled failure-finding
5. Run to failure

Scheduled on-condition task
SAE International [24] defines on-condition task to be the following: *A periodic or continuous task used to detect a potential failure*. This implies that such a task is preventive maintenance. The task has to be technically feasible and worth doing to be selected. According to Høyland [33] there are three criteria for using on-condition tasks:

1. Detection of reduced failure resistance for a specific failure mode must be possible
2. There must be a possibility to define a potential failure condition that can be detected through an explicit task
3. There must be a reasonable interval of time between the detection of a potential failure and the functional failure

Scheduled restoration
Scheduled overhaul or scheduled restoration is the maintenance which restores the capability of an item [24]. Høyland [33] defines three criteria for such a maintenance to be suitable:

1. It must be possible to find an age for the item with a rapid increase in the failure rate function
2. At that age a large percentage of the items must survive
3. The original failure resistance must have the possibility to restore after the rework

Scheduled discard
This maintenance task will replace the item with a new one. Here there exists four circumstances for the maintenance task to be applicable [33]:

1. The item must be exposed for a critical failure
2. The item must be exposed for a failure that has major potential consequences
3. It must be possible to find an age for the item with a rapid increase in the failure rate function
4. At that age a large percentage of the items must survive

Scheduled function test
Scheduled function test is a task that finds the failure, a failure-finding task. This implies that the item will be in failed state until the failure is found [24]. The following criteria must be met if the maintenance tasks shall be applicable [33]:

1. The item must be subjected to a hidden failure
2. No other maintenance task is suitable nor effective

Run to failure
Step 7: What should be done if a suitable preventive task cannot be found?

The last step of the RCM analysis is to find out what actions should be taken if preventive maintenance, the maintenance tasks discussed above, are not suitable. If no other maintenance tasks is suitable nor economically sound allowing the failure mode to occur will be the option.

3.6.2 Decision Diagram

Decision tree or decision diagram is used to determine which maintenance task is suitable for the items. The decision diagram for the autonomous ferry must allow for increasing autonomy and decreasing man power. Another matter that is important when it comes to decision diagram is that the three first categories of preventive tasks; scheduled on-condition, scheduled restoration and scheduled discard, should be put ahead of the failure finding tasks in the selection process [24]. The decision diagram used in this thesis is adapted from SAE International [24] and *Reliability-centered Maintenance* [3], and can be seen in Appendix .1. Figure 3.4 shows an example of the logic in the decision diagram.

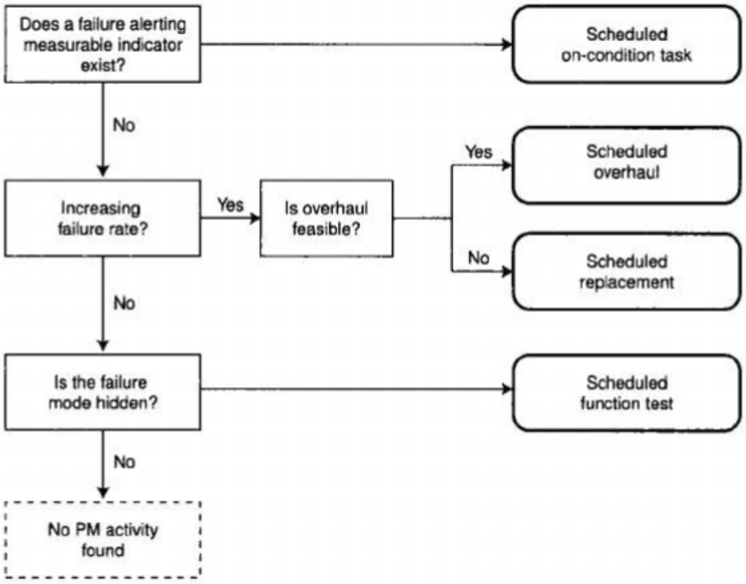


Figure 3.4: Simplified decision tree used for establishing suitable maintenance tasks, from A.Høyland [33]

For the autonomous, and unmanned ferry the situation will often be that the failure mode will not be evident for the crew. This is due to the fact that there are no crew on-board, but the failure mode can be evident to the person sitting in the shore-based control center. He or she will get alerts from sensors and alarms from the ferry.

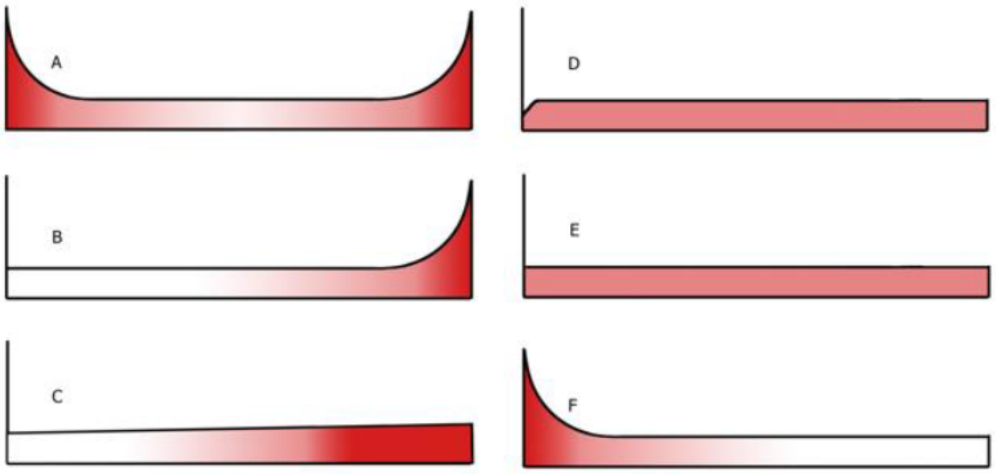


Figure 3.5: The six different patterns of failure, from J.Moubray [3]

3.6.3 Failure pattern

In the earlier stages of RCM the functional failures together with its failure modes has been established. Another fundamental aspect in the analysis are the failure patterns for the failure modes. Figure 3.5 illustrates the six different failure patterns [3]. A description of each of the patterns will follow.

Pattern A: This failure pattern is also refereed to as the bathtub curve. This pattern illustrates that the equipment has larger probability for infant mortality, and for age related wear-out.
Pattern B: The pattern shows an probability of failure which is age related.
Pattern C: The equipment has an increasingly probability of failure as the time passes. An age where the equipment is worn-out can not be identified [3].
Pattern D: Conditional probability pattern, where new equipment has lower probability of failure, but increases rapidly
Pattern E: Random failure pattern.
Pattern F: This pattern shows infant mortality. The equipment has a higher probability for failing in the beginning of its lifetime.

For this thesis there are limited information about the failure modes for the components. This also includes information about the failure patterns. Therefore the failure modes has been roughly divided into mechanical, electrical, electromechanical and software. Failure modes related to the mechanical of a component are often characterizes by degradation and wear [34]. Therefore these are assumed to have failure pattern B in Figure 3.5. Failure modes that are related to electrical components does not wear in the same manner as mechanical components. The failure modes are more often caused by design deficits, process errors, process variations, wrong usage and mounting error [35]. Therefor these failure modes are associated with failure pattern F in Figure 3.5. When it comes to failure modes

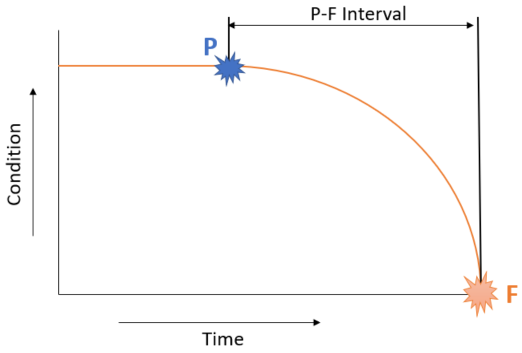


Figure 3.6: Illustration of the P-F Interval, adapted from [3]

that are a combination of mechanical and electrical, electromechanical, it is assumed that also the failure pattern is a combination. Failure pattern A in Figure 3.5 is such a combination.

As mentioned earlier, software failures can be due to design faults, specifications or the coding process. All of them implies random failures with human factors Therefore the failure pattern for software failure modes are set to be E, random, in Figure 3.5. Some other failure modes that does not involve software are set to be random. These are failure modes that involves random events, such as damage under transport.

3.6.4 P-F Interval

The P-F Interval is defined as the following [3]: *the interval between the occurrence of a potential failure and its decay into a functional failure*. Figure 3.6 shows such a interval. This interval is important since it tells how often a on-condition task must be executed. It is convenient if the functional failure are detected before it occurs, therefor the time interval of the on condition task must be less than the P-F interval. [3]

3.6.5 Maintenance costs

One of the main objectives for the RCM method is to construct a cost effective maintenance program. To make sure the maintenance task is cost effective a cost benefit analysis has to be done.

In this thesis the cost analysis is done by comparing preventive maintenance with the run-to-failure task. The analysis focuses on how many hours can be spent on for example on-condition task and still be the most cost effective task. If preventive maintenance is worth doing, the selection process follows the decision three stated above. This implies that the next factor is that the task is technically feasible. The costs associated with run-to-failure and preventive maintenance will be shown below.

Cost of run-to-failure

Run-to-failure is a default action. If there existed no maintenance plan, each of the failure modes would run to failure and then be repaired. When a failure mode runs to failure it may imply downtime for the ferry. The costs includes these downtime costs, which is associated with the loss of income. It also includes costs of potential injuries to passengers, loss of reputation and repair costs. Equation 3.2 shows how the calculation is done.

$$Cost\ of\ run\ to\ failure = downtime\ costs + spare\ part + cost\ of\ repair \tag{3.2}$$

The down time costs are, as mentioned, earlier due to loss of income, loss of reputation and potential injuries, this is shown in Equation 3.3.

$$Downtime\ costs = loss\ of\ income + loss\ of\ reputation + injuries \tag{3.3}$$

It is assumed that the ferry's income comes from tickets. The parameters used in the calculation are shown in Table 3.6. The average passengers is based on a passenger profile. This profile can be seen in Appendix .3. In this profile it is assumed that the ferry operates from 08:00 to 18:00, 10 hours operating time. The numbers of passengers per trip is based on guesswork in the light of time of the day of the trip.

Table 3.6: Parameters used in calculation of income

Ticket price	30	NOK
Crossing time	1	Minute
Mooring time	2	Minute
Idling time at quay	5	Minute
Total time	8	Minutes/trip
Max trips	7	trips/hour
Average passengers	3.7	passengers/trip
Income	777	NOK/hour

When the ferry has downtime the reputation will be affected. The reputation will also be affected by any potential consequences of the failure mode. A exact value of reputation is hard to measure. Damage to the reputation depends on both the trust that is lost, effort, patient and the cost [36]. Since the value of reputation is measured rarely it is often underestimated [36]. Due to this the loss of reputation is divided into five levels, see Table 3.7. This table is adapted from *A Short Guide to Reputation Risk* [36]. Each of the levels has an associated cost, which will be used in the calculations. The costs has been established based on the investment cost. If the failure mode will not affect the reputation, the cost is set to 0. A discussion of what loss of reputation will mean to the ferry and the technology can be seen in Chapter 7.2. This chapter will also discuss the quantification of loss of reputation.

Table 3.7: Levels of loss of reputation

Level	Characteristics	Costs [NOK]
5	Outrage - Trust completely lost, not recoverable	1 000 000
4	Disgust - Trust severely damaged, never fully recoverable	800 000
3	Concern - Trust diminished, recoverable at considerable costs	200 000
2	Surprise - Trust dented, recoverable with time and good PR	5000
1	Disappointment - Trust questioned, but recoverable quickly	1000

A failure mode may also affect the safety of the passengers. They could be injured, or in worst case killed. This will cost money, both for the operator of the ferry and the society. The numbers used in this analysis are gathered from Norwegian Centre for Transport Research [32] and can be seen in Table 3.8. These numbers are the costs associated with accidents on the road. The numbers includes real economic components, such as medical, material and administrative costs [32]. In addition to these are peoples valuation of risk reduction, the willingness to pay to prohibit an accident [32].

Table 3.8: Costs of injuries and fatalities [32]

	Total accident cost [NOK]
Fatality	30 220 000
Severe injury	22 930 000
Major injury	10 590 000
Slight injury	614 000
Insignificant	0

In addition to the costs mentioned above are the costs of the actual repair. The repair costs will be as shown in Equation 3.4. The labour costs are adapted from [37], and are set to be 538 NOK per hour. Since there will be uncertainty among the duration repair it is decided to be excluded it from the calculation. However this will not greatly affect the costs, as loss of reputation and injury costs are much higher.

$$Repair\ costs = Duration\ of\ repair \times Labour\ costs \tag{3.4}$$

Cost of preventive maintenance

The preventive maintenance task consists of scheduled on-condition, scheduled restoration, scheduled overhaul and scheduled failure-finding. The associated costs may vary from task to task, e.g transport costs if a machine needs to be transport to do scheduled restoration, spare part. Due to lack of information all of the costs has been calculated the same way, which is shown in Equation 3.5.

$$Preventive\ maintenance\ costs = Duration \times Labour\ costs \tag{3.5}$$

Chapter 4

System description

This chapter will give a detailed description of the concept. The information is gathered from the master thesis *Design of a Small Autonomous Passenger ferry* [37], the EiT- project *Ombordstigningssystem for den autonome fergen milliAmpere* [38], the master thesis *Development of a Dynamic Positioning System for the ReVolt Model Ship* [39], the project manager and the project thesis *FMECA of the Autonomous Passenger Ferry in Trondheim* [30]. For some of the systems there are insufficient information and as a result of this, decisions about some of the system designs has been taken on the way.

4.1 Overview

The main ideas behind the concept are listed below. [22]

- On-demand ferry
- 1 minute travelling time
- Electrical propulsion
- Automatic charging
- High precision GNSS
- Anti-collision system

The ferry will have a capacity limited to 12 passenger and 12 bicycles at the same time. The ferry will have a LOA of 12m, beam of 4m and a design draught of 0.515m. [37].

4.2 Systems

The concept consist of several sub-systems whit own functions and components. This thesis makes use of the systems identified in the project thesis *FMECA of the Autonomous Passenger Ferry in Trondheim* [30], with some changes as more information is now available. The ferry consists of 13 sub-system, see below.

1. Navigation system
2. Anti-collision system
3. Propulsion system
4. Electric power system
5. Bilge system
6. Battery cooling system
7. Safety system
8. Mooring system
9. Communication an visibility system
10. Passenger comfort system
11. Quay system
12. Passenger registration system
13. Structural integrity

The sub-systems will be described further in this section. The numbers for each systems are used through out the analysis.

4.2.1 Navigation system

The navigation systems purpose is to navigate the ferry safely over the canal. The components in the system were identified by the use of the master thesis *Development of a Dynamic Positioning system for the ReVolt Model Ship* [39] and by information from the project manager.

A total of 6 different components were identified, see below.

1. Embedded computer
2. Guidance system
3. Control system
4. IMU

5. 2 GNSS receiver with RTK
6. Radio link

The embedded computer has the purpose to connect all the components in the system, which is done either by USB or RS232 [39]. The system consists of two control algorithms, the guidance system and the control system. The guidance system is the reference filter, which is used to generate a path for the vessel. The control system is where signals are processed and actions are taken. [39] There are three navigational sensors in the system that measures position, velocity and heading. The inertial measurement unit (IMU) will measure both velocity, acceleration and heading. The global navigation satellite system (GNSS) consist of two receivers, which makes it possible to obtain both the position, velocity and heading. This receivers will also be equipped with real time kinematic (RTK), which will increase the accuracy. The radio link will feed the RTK correction data to the GNSS receiver.

4.2.2 Anti-collision system

To avoid colliding into ships and other obstacles, the ferry is equipped with an anti-collision system, also called collision avoidance system. The components identified in the project thesis [30] were camera, IR, lidar, radar, control algorithm and a computer, and these are used further.

The camera will be used for computer vision by object recognition. Its purpose is to detect ships nearby, these can have different color, shape and light settings. The IR will also be used for detecting objects, it will see the hinders in dark or in fog. [30] The radar will be used for detection of objects by transmitting radio signals, and timing the instants of reception of the returned echo from a target [40]. High accuracy for position and track is needed to have a reliable radar. A lidar is a laser radar system. The system works the same way as the radar, the time delay between emissions and detection is measured [40]. To process the signals and take actions a control algorithm/software code is needed. When obstacles are detected the ferry will either stop or go around [41].

4.2.3 Propulsion system

The ferry needs to be able to move forward. To do this, it must be equipped with a propulsion system. The idea with the ferry is that it does not have to turn, so propellers must be mounted in front and back of the hull. This ferry will have podded propulsion [37], which implies that the ferry can use the propellers to manoeuvre with.

The batteries that powers the pods are assumed to be Li-Ion battery packages delivered by PBES [37]. There will be two modules installed in the ferry, where each of them will have a capacity of 26 kWh. The required power calculated in the design thesis [37] were stated to be uncertain, therefore the battery modules are treated as one through the thesis, which will assure enough power to the propulsion system. The podded propulsion will be from the manufacturer Torqeedo [37]. Several safety functions are mounted on the podded propulsion, these includes fuses, electronic protection, over temperature protection and motor protection [42].

4.2.4 Electric power system

In addition to power for propulsion, the ferry need power for the other systems on board such as the navigation system, bilge system and mooring system. To supply the remaining systems, two batteries with a total capacity of 5.370 kWh are included [37]. In addition to generation of the electricity the system distributes where it is needed. The system consist of three different components, battery modules, electrical cables and distribution board.

4.2.5 Bilge system

The ferry will be subjected to water inside the hull under operation. The water has to be removed, which is done by a bilge system. The system consists of a bilge pump and a non-return valve. Each bilge pump has to have a minimum capacity of 75 litres per minute [43]. The ferry will be equipped with one bilge pump in each battery room, and one for the rest of the rooms below deck [37]. In total the system consist of 6 pumps, where two of them are emergency pumps. The emergency pumps will be connected to separate battery modules. The non-return valve is installed in the hull, and will make the water flow in only one direction

4.2.6 Battery cooling system

The battery cooling system has the purpose to keep the temperature of the battery in the range of $18°C\pm 3 ° C$ [37]. The system will aim to keep the optimal conditions for the battery, and since the battery will generate heat there must be a way to remove it from the system. The system will be crucial for safety, life time and performance of the batteries, and costs [44]. This project uses a liquid cooling system, where the coolant is ionized water [37].

Figure 4.1 shows a simplified schematic illustration of how the battery cooling system is composed. The pump will be a circulation pump, and will circulate the coolant through the pipes. To create redundancy in the system two pumps are mounted [37]. The heat exchanger will be a outboard heat exchanger, after recommendations from PBES [37]. This means that the seawater is used for cooling, and pipes for the system are mounted underneath the hull [37]. According to Havdal et. al [37] this will avoid the risk of litter and particles in the system.

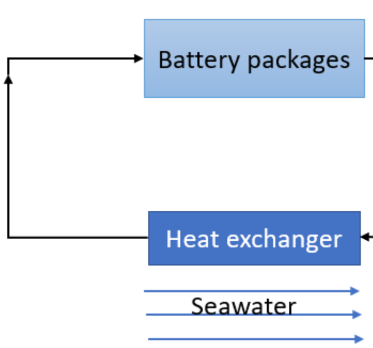


Figure 4.1: Schematic illustration of the battery cooling system

In addition to the components shown in Figure 4.1 are the temperature and pressure sensor and the temperature regulating valve. To achieve the proper redundancy the cooling system will be doubled [37].

4.2.7 Passenger safety system

The safety system is the one that shall protect the passengers on board against the hazards that can arise. For the ferry the situation primarily concerns fires and man over board. The system consists of a sprinkler system, a external fire extinguisher, fire alarm, life jackets and life buoy.

The sprinkler system will use Novec 1230 fluid, which has non-environmental consequences [45]. In all rooms below deck there will be fire detectors, which will alarm the shore-based station [37].

4.2.8 Mooring system

The mooring system will be the system that connects the ferry with land. This is how passengers can get on and off. The system will also secure the ferry to the quay when moored. Figure 4.2 illustrates the mooring concept [37]. The idea is that the ferry can moor at each bow side, and will therefore have two identical mooring systems on each side [37]. As the figure shows, there will be a notch at the ferry, which will be hooked at the quay.

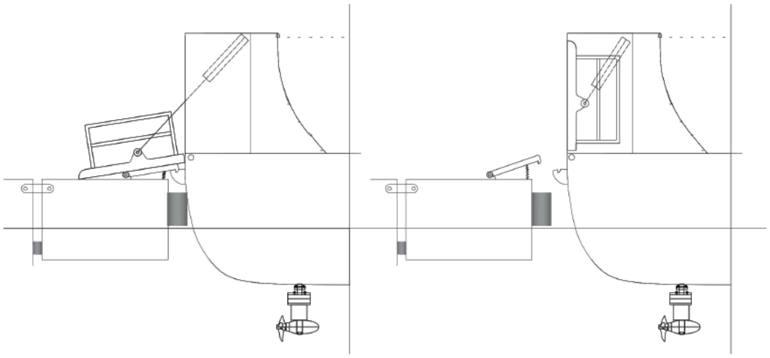


Figure 4.2: Illustration of mooring concept from *Design of a small Autonomous Passenger Ferry* [37]

The ramp will be lowered and lifted by a hydraulic system. The components included in the system are:

- Ramp
- Hydraulic cylinder
- Hydraulic pump
- Filter
- Reservoir
- Pressure relief valve
- Directional control valve
- Hydraulic fluid

Where the hydraulic pump will be of a centrifugal pump, which is suitable for smaller systems [46]. The rest of the components in the systems are not set, consequently they are treated as generic components.

In the master thesis *Design of a Small Autonomous Passenger Ferry* [37] some requirements are set to the mooring system, and they are as follows:

- Be able to hold the ferry without constant need of power
- Be able to provide passengers a safe passage on and off the ferry
- Not harm the passenger on board during transit

In addition to the components mentioned above are an alarm which will make a sound when the ferry is mooring or unmooring, this alarm is supposed to prevent injuries during the operation. The mooring system also requires a system at the dock which is adapted for the mooring. Neither of the two issues mentioned here are further included in the analysis.

4.2.9 Communication and visibility system

The ferry must be able to communicate with the shore-based station, which is done through wireless connection. The shore-based station shall at all time be updated with relevant information from the ferry, such as velocity and heading. The shore-based station will also be alarmed in case of any emergencies. In addition to the data transmission between the two is a two way radio for communication between the station and the passengers. This radio will be placed on deck in the passenger area, and gives them the possibility to alarm in case of any irregular situations.

The system also consists of the lanterns that makes it visible to other ships. This ferry must be designed in accordance with the regulation of life saving appliance on ships, and will be equipped with five lanterns.

In addition to the components mentioned above is the emergency stop button (ESB). This is a button which the passengers can trigger in case of an emergency, contact with shore-based station will then happen. When the ferry has stopped it will then hold its position through a dynamic position system, which must be a part of the autonomous control system [37].

4.2.10 Passenger comfort system

Even though the crossing time over the canal is only one minute, the passengers should be comfortable. For this purpose the ferry has been equipped with some components to do so, this includes chairs/benches, lights and self-regulating heating cables.

4.2.11 Quay system

I addition to the systems on board the ferry are the system on the land side. These systems has the purpose to facilitate the ferry. The quay system consists of the quay it self, a gangway, self-regulating heating cables, a charger and a demand button.

As mentioned before, the concept will have automatic charging. This part of the design is not finished yet, but there are several companies researching and investing in such an idea. For example Fjord1 which will have automatic charging for their fully automated electric ferries [47].

In this thesis it is assumed that there will be a shore-based station, which will also facilitate the ferry. This station will have the control over the ferry, and will act if a emergency situation occurs. The stations function is included in the analysis, but not the station it self.

4.2.12 Passenger registrations system

The concept intentions is an unmanned ferry, which implies that there will be no one in the docking process either. The ferry will be designed to take maximum 12 passengers, which creates the need for a system that counts passengers. Such a passenger registration system has been developed in the student project *Ombordstigningssystem for den autonome fergen miliAmpere* [38], and the information in this subsection is adapted from that report.

The counting system will consist of two independent systems, a primary system and a secondary system. The primary system will be a physical barrier which can control the number of passengers, which is done by swing door gates.

The secondary system consists of computer vision and has the purpose to double check the primary system, and to make sure that all passengers has left the ferry. The system consists of six ordinary video cameras, and will cover a sufficient area.

Due to legal reasons, there will also be a need for a statement of the risk and a disclaimer of liability. This will be done wither with an app on a smart-phone or a QR dispenser. Both the app and the QR-dispenser will print QR-codes when the form is signed, which can be used to open the gates.

4.2.13 Structural integrity

The ferry needs to be able to float on the water, therefore a sufficient hull must be made. The hull must have the ability to float, and take all the 12 passengers and 12 bicycles at the same time. Aluminum will be the material used for making the hull [37].

Chapter 5

Data collection

The autonomous shuttle ferry is, as mentioned earlier, not a realized concept yet. It is still under development. Hence not all information about the systems is available. Some information is gathered from previously master thesis and student projects about the ferry, such as [37], [39], [38], [30]. The systems are based on the work done in the project thesis *FMECA of the Autonomous Passenger Ferry in Trondheim* [30], which is developed using the Skipsteknisk Forskningsinstitutt (SFI) Group System.

Information about how the components can fail, and what the causes are, are found by learning to know the component through manufacturer manuals and articles. The failure modes and causes are also depending on what system the component is operating in and the external environment. In addition to using written material, professors and other workers at the university has been asked when an issue needs clarification.

The MTBF for the failure modes are found using different sources, mostly manufacturer manuals. When MTBF is not found, guesswork by the author has been done. The guesswork has taken the failure cause of the failure mode into account, in addition to the effects. Often MTBF is stated for the component, and not the failure mode. In these situations it is assumed that each failure mode has this stated MTBF. Since the analysis makes the use of classes, the effect of this will not be significant. The MTBFs marked with * in the worksheet are the ones that are based on guesswork.

The maintenance costs calculation includes the spare part costs for the components, where the sources used are shown in the Appendix .3. The ones not listed here are based on guesswork. Some of the cost calculations are presented in the report, while the others can be found in Appendix .5.

Chapter 6

Analysis

This chapter describes the RCM analysis that has been performed for the asset. The chapter contains all the information and assumptions that were made during the analysis. The analysis is done system for system, and the results are presented in Section 7.1.

The ferry will operate in Trondheim, in the canal between Ravnkloa and Vestre Kanalkai. The operating context for the ferry can be divided in two: at quay or crossing. The most critical of these two will be the crossing, as it is further away from land and the consequences for events such as fire, navigation error and man over board will be more severe. Therefore the operating context will always be in crossing in this analysis.

The ferry is supposed to operate all year round, so the ferry will be subjected to different weather as the seasons changes. Figure 1 in Appendix .2 shows the average air temperature, water temperature, wind speed and perception for Trondheim in 2017 [48] [49]. The wind speed is almost even through out the year. The lowest water temperature and air temperature are in the winter season, here from January to March. Lower water- and air temperature implies greater consequences if someone fall into the water.

The ferry is designed to fulfill a need, to transport passengers over the canal. In addition to this are the secondary functions for the ferry, these can be summed up by the sub systems presented in section 4. The performance requirements for the asset is to transport 12 passengers and 12 bicycles safely over the canal with a crossing time of 1 minute, and to reach a speed of five knots.

6.1 Navigation system

6.1.1 Functions

The navigation system shall navigate the ferry over the canal with a crossing time of one minute. In addition, the system has some secondary functions. The functional hierarchy, which shows both the primary and the secondary functions, can be seen in Figure 6.1.

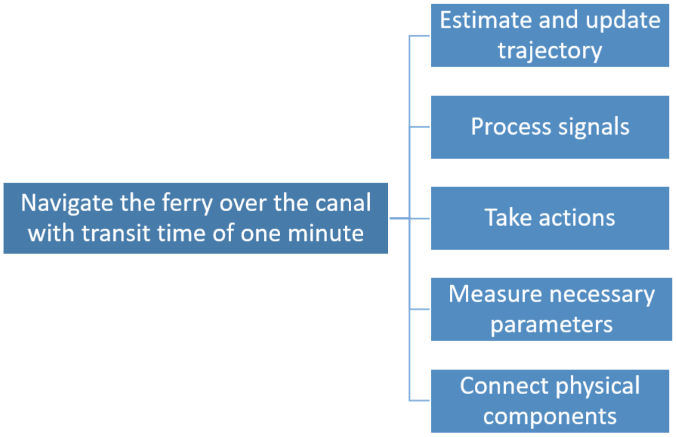


Figure 6.1: Illustration of primary and secondary functions for the navigation system

The three first secondary functions; estimate and update trajectory, process signals and take actions, are carried out by the control algorithms in the system. Necessary parameters that needs to be measured are position, velocity and heading, and these are measured by the IMU and the two GNSS receivers with RTK. All of the components are connected via a embedded computer.

6.1.2 Functional Failures

Four functional failures were found relevant for the system. These are listed below.

1. Failure to generate a suitable path over the canal
2. Signals are not processed and actions are not taken
3. Parameters are not measured
4. No connections of the physical components in the system

The first functional failure is due to a failure in the control algorithm, more precisely the guidance system. While the second one is due to failure in the control system. The next functional failure, parameters are not measured, are due to failures in the navigational sensor platform. As previously mentioned the sensors will measure the position, velocity, acceleration and heading. Two different types of navigational sensors are used, IMU and GNSS receiver with RTK. The last functional failure for the navigation system occurs when the physical components in the system are not connected.

The navigation system will be a crucial part of the ferry and will bring new ideas. Therefore a fault tree analysis (FTA) has been preformed for the system, see Figure 6.2.

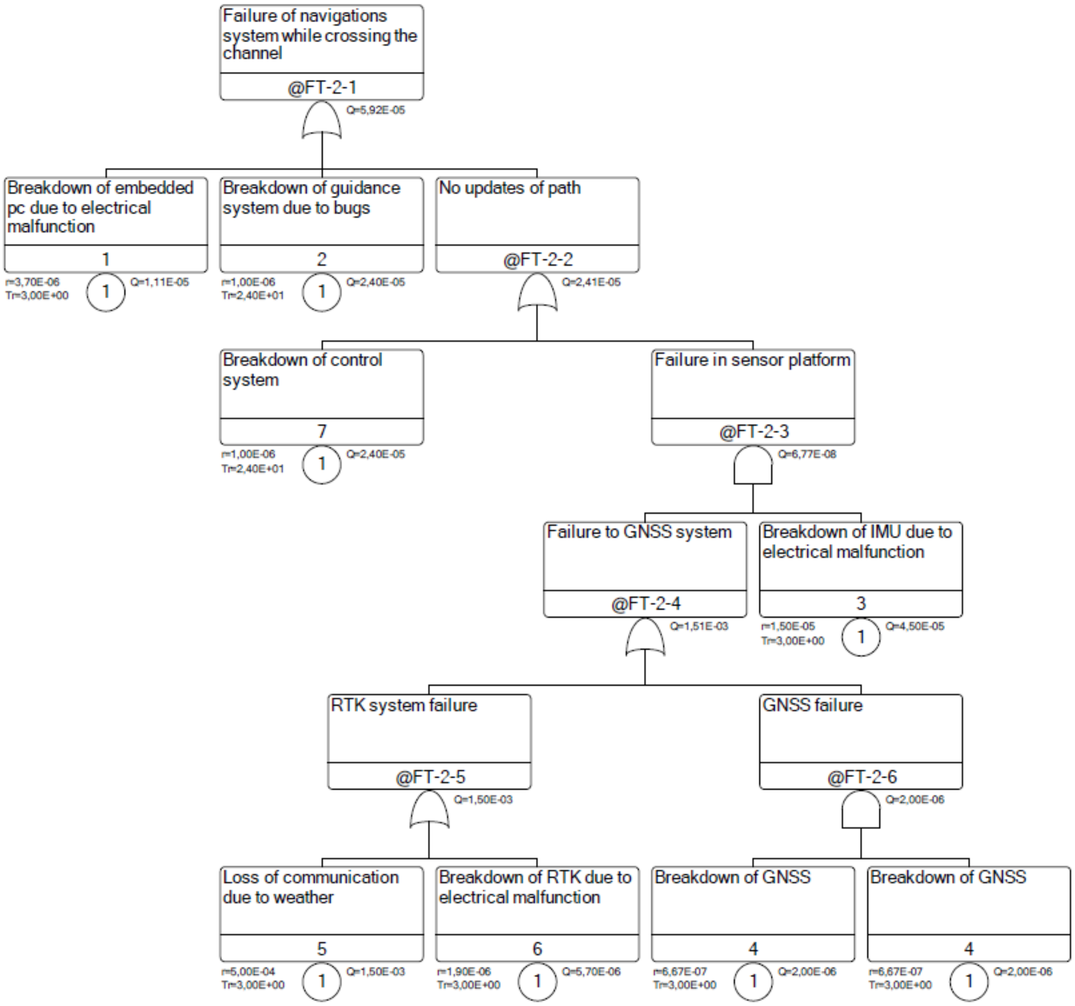


Figure 6.2: FTA for the navigation system

The top event is total failure of the navigation system while crossing the canal. The tree shows how the system can fail, and it is quantified. To do the quantification it is assumed that all of the components are repairable, and the MTBF is used. In addition a mean time to repair (MTTR) is assumed for the different components, which can be seen in the figure. These numbers are purely based on guesswork as the hours of repair will depend on the worker and external environment. The analysis shows that the probability for a failure of of the navigation system is 0.00059 %. The low probability of failure is due to the redundancy in the navigational sensor platform, and the generally high MTBF for the components.

6.1.3 FMECA

The components analyzed in the FMECA are as follows:

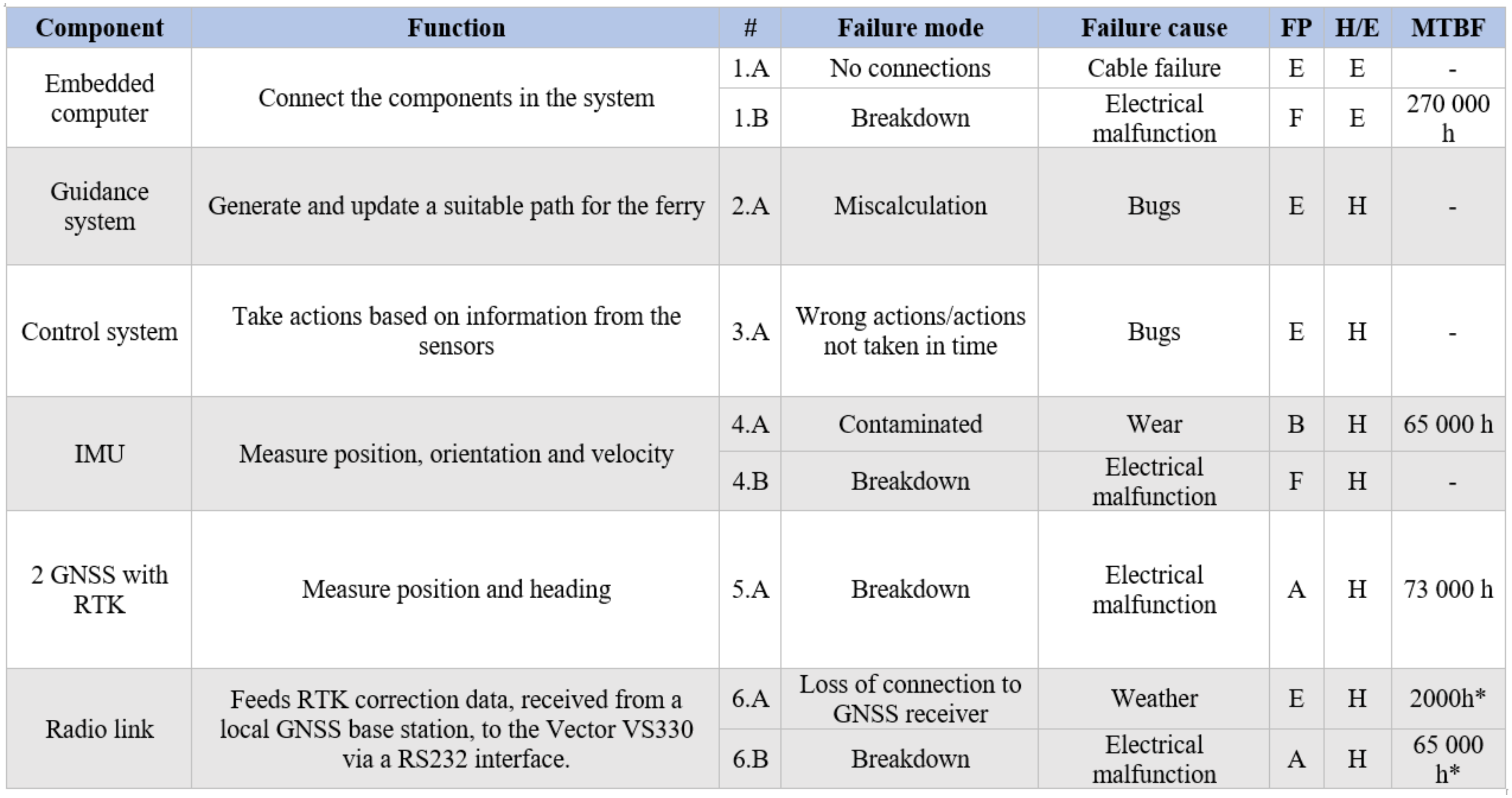
- Embedded computer
- Guidance system
- Control system
- IMU
- 2 GNSS receivers with RTK
- Radio link

Figure 6.3 and 6.4 shows the FMECA worksheets for the system.

The failure modes for the components in the navigation system were developed using the master thesis *Development of a Dynamic Positioning System for the ReVolt Model Ship* [39] and the functions for the components. For three of the failure modes, relevant MTBFs were found; embedded computer [50], IMU [51] and GNSS [52]. Information about MTBF for the radio link were not found, hence the component is assumed to have the same MTBF as IMU. As mentioned before, MTBF for software codes are not relevant, thus a frequency category has been assumed. For some of the failure modes and causes manufacturers manuals where used: IMU [53], GNSS [54], Radio link [55].

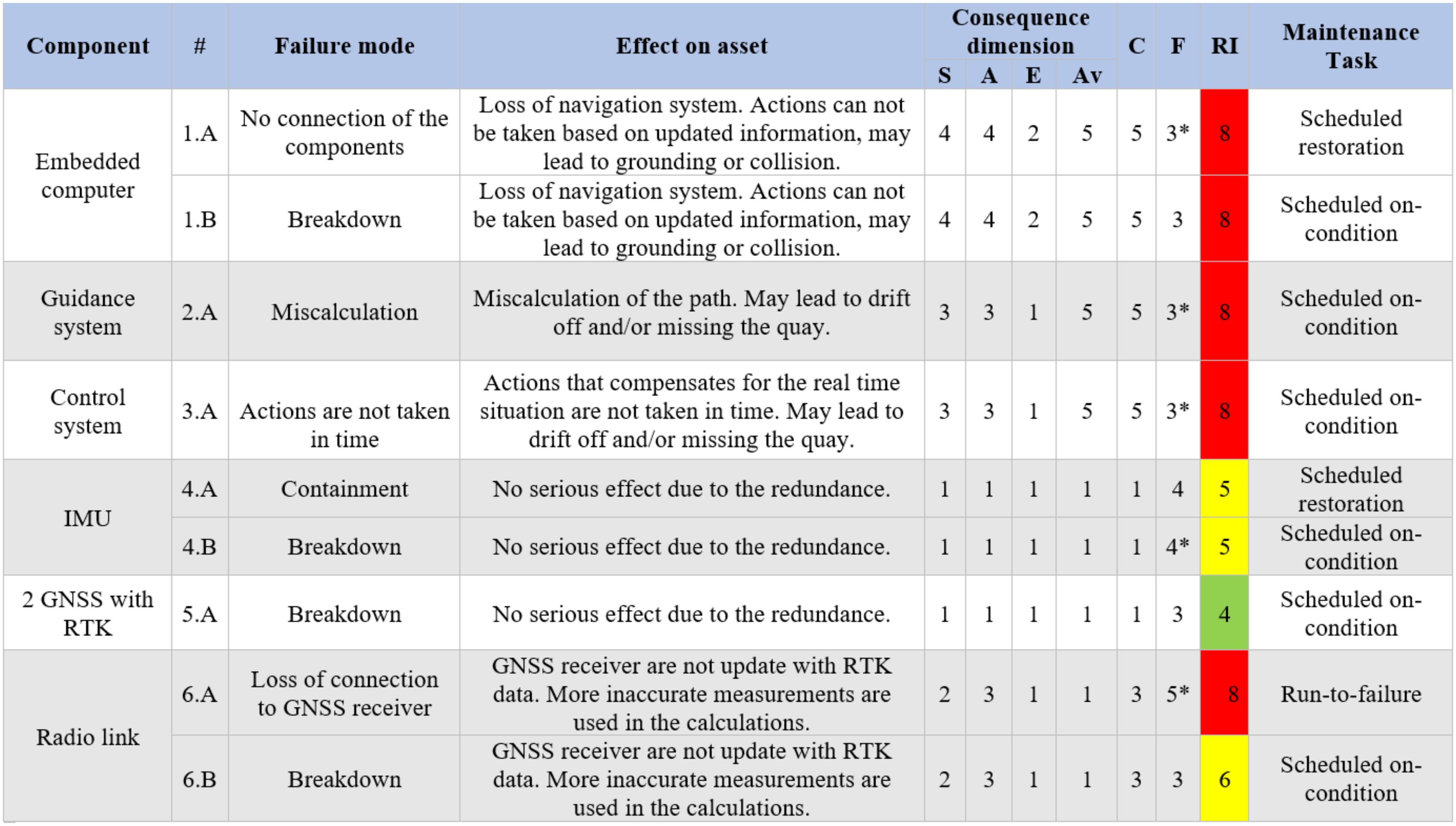
In total 9 failure modes were considered relevant for the system. Two of the failure modes are evaluated to be evident, while the rest are hidden. The embedded computer connects all the components in the navigation system, and a failure will cause a total failure of the system. Here safety and asset are evaluated to be 4 regarding criticality, as both failure modes can lead to grounding and/or collision. However the ferry will cross the canal with a speed of maximum 5 knots, and the crossing distance is short which implies that the most severe consequences will not occur. Failure modes that may result in drift off and/or missing the quay are evaluated as three when it comes to safety. This event is not as severe as a collision or grounding. A failure to the components in the navigational sensor platform is not critical due to the redundancy in the system. To have a failure in the sensor platform both of the two GNSS receivers has to fail in addition to the IMU sensor.

All of the components are evaluated to one when it comes to environment, since none of the failure modes will have any significant impact to it. A failure to the algorithms and the embedded computer are assumed to have the highest unavailability, due to their effects. Here competent personnel needs to identify and repair the fault. While for the rest of the component the unavailability is evaluated to be either two or three.



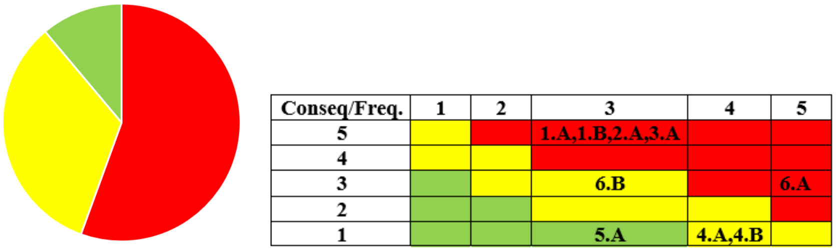
Component	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
Embedded computer	Connect the components in the system	1.A	No connections	Cable failure	E	E	-
		1.B	Breakdown	Electrical malfunction	F	E	270 000 h
Guidance system	Generate and update a suitable path for the ferry	2.A	Miscalculation	Bugs	E	H	-
Control system	Take actions based on information from the sensors	3.A	Wrong actions/actions not taken in time	Bugs	E	H	-
IMU	Measure position, orientation and velocity	4.A	Contaminated	Wear	B	H	65 000 h
		4.B	Breakdown	Electrical malfunction	F	H	-
2 GNSS with RTK	Measure position and heading	5.A	Breakdown	Electrical malfunction	A	H	73 000 h
Radio link	Feeds RTK correction data, received from a local GNSS base station, to the Vector VS330 via a RS232 interface.	6.A	Loss of connection to GNSS receiver	Weather	E	H	2000h*
		6.B	Breakdown	Electrical malfunction	A	H	65 000 h*

Figure 6.3: FMECA of navigation system, part 1



Component	**#**	**Failure mode**	**Effect on asset**	**Consequence dimension**				**C**	**F**	**RI**	**Maintenance Task**
				S	**A**	**E**	**Av**				
Embedded computer	1.A	No connection of the components	Loss of navigation system. Actions can not be taken based on updated information, may lead to grounding or collision.	4	4	2	5	5	3*	8	Scheduled restoration
	1.B	Breakdown	Loss of navigation system. Actions can not be taken based on updated information, may lead to grounding or collision.	4	4	2	5	5	3	8	Scheduled on-condition
Guidance system	2.A	Miscalculation	Miscalculation of the path. May lead to drift off and/or missing the quay.	3	3	1	5	5	3*	8	Scheduled on-condition
Control system	3.A	Actions are not taken in time	Actions that compensates for the real time situation are not taken in time. May lead to drift off and/or missing the quay.	3	3	1	5	5	3*	8	Scheduled on-condition
IMU	4.A	Containment	No serious effect due to the redundance.	1	1	1	1	1	4	5	Scheduled restoration
	4.B	Breakdown	No serious effect due to the redundance.	1	1	1	1	1	4*	5	Scheduled on-condition
2 GNSS with RTK	5.A	Breakdown	No serious effect due to the redundance.	1	1	1	1	1	3	4	Scheduled on-condition
Radio link	6.A	Loss of connection to GNSS receiver	GNSS receiver are not update with RTK data. More inaccurate measurements are used in the calculations.	2	3	1	1	3	5*	8	Run-to-failure
	6.B	Breakdown	GNSS receiver are not update with RTK data. More inaccurate measurements are used in the calculations.	2	3	1	1	3	3	6	Scheduled on-condition

Figure 6.4: FMECA of navigation system, part 2



Conseq/Freq.	1	2	3	4	5
5	🟨	🟥	🟥 1.A,1.B,2.A,3.A	🟥	🟥
4	🟨	🟨	🟥	🟥	🟥
3	🟩	🟨	🟨 6.B	🟥	🟥 6.A
2	🟩	🟩	🟨	🟨	🟥
1	🟩	🟩	🟩 5.A	🟨 4.A,4.B	🟨

(a) (b)

Figure 6.5: Summary of risk index for navigation system

The distribution of the risk index is shown in Figure 6.5(a). From the figure it is clear that most of the failure modes are in the red area, the unacceptable one. The risk matrix for the navigation system is shown in Figure 6.5(b). The matrix shows that only one failure mode is in the acceptable area. The reference numbers in the risk matrix corresponds to the ones in the FMECA worksheets, Figure 6.3 and 6.4.

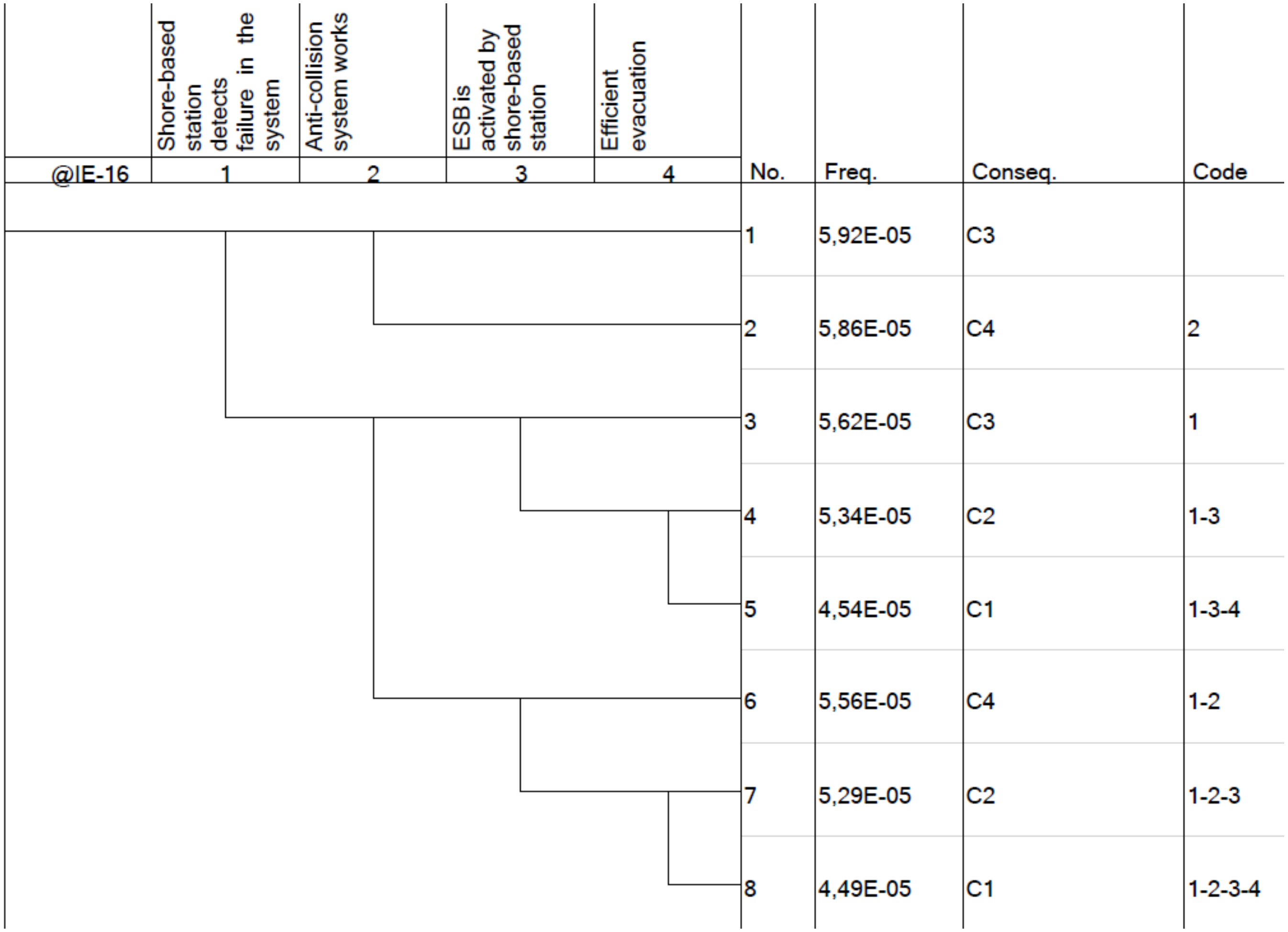
As mentioned before, the system is a crucial part of the new concept, thus an event tree analysis has been performed. See Figure 6.6. The initiating event is based on the top event from the FTA; failure in the navigation system. The functioning event are the barriers that are present in the system, which are linked with probabilities. These probabilities are mainly based on guesswork, where the operating context and the external environment are taken into account. Table 6.1 shows the events and the probabilities. The probability for a working anti-collision system is not based on guesswork, but gathered from the FTA for the anti-collision system, see Figure 6.9. The description and summation of each consequence category is shown in Table 6.2.

Table 6.1: Probability linked with functioning event in ETA for navigation system

Functioning event	Probability
Shore-based station detects	0.95
Anti-collision works	0.99
ESB activated	0.95
Efficient evacuation	0.85

Table 6.2: Consequence categories with probabilities for navigation system

Category	Description	Summation of probabilities
C1	Slight injury	9.03e-5
C2	Severe injury	1.063e-4
C3	Fatality	5.92e-5
C4	Material damage	1.142e-4



No.	Freq.	Conseq.	Code
1	5,92E-05	C3	
2	5,86E-05	C4	2
3	5,62E-05	C3	1
4	5,34E-05	C2	1-3
5	4,54E-05	C1	1-3-4
6	5,56E-05	C4	1-2
7	5,29E-05	C2	1-2-3
8	4,49E-05	C1	1-2-3-4

Figure 6.6: ETA for navigation system

6.1.4 Maintenance Task Analysis

The MTA can be seen in Figure 6.7. It is only one component that has been given the task run-to-failure. This is a failure mode that will "fix it self", it will find better signal again. The failure mode is caused by bad weather such as fog, which affects the signal. Failure mode 1.A and 4.A has been assigned to scheduled restoration, which implies cleaning and connecting cables.

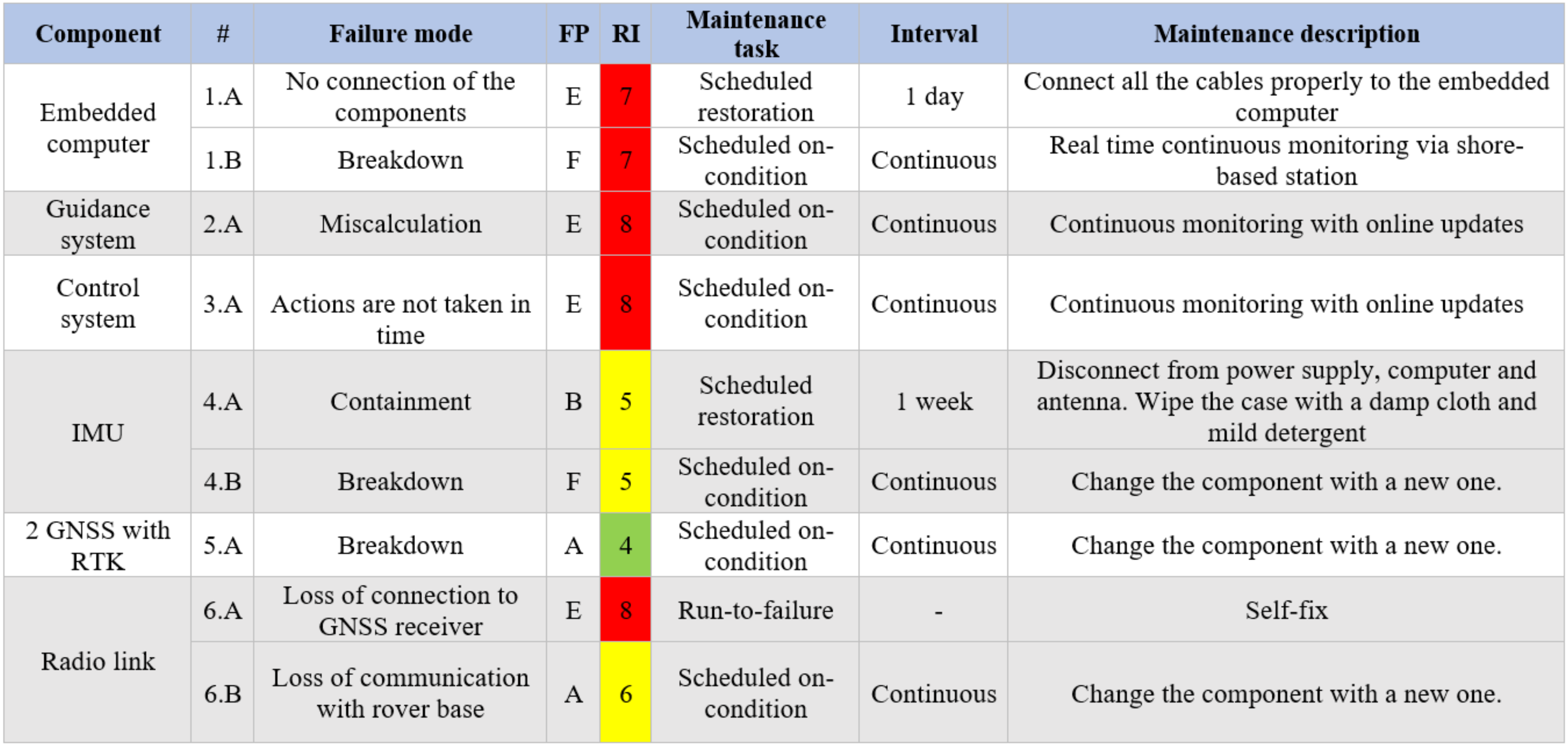
The failure modes which involves breakdown of the navigational sensors, embedded computer and control algorithms are all assigned to continuous scheduled on-condition via the shore-based station. This involves that the shore-based station will always be updated with the health of the components. The monitoring will also include online updates of the control algorithms. This transforms the failure modes from hidden to evident, since the operator will be alarmed in case of any failure.

The expense items used for the cost calculation can be seen in Table 6.3. Only the most significant items are included. This implies that loss of income is excluded. It is not relevant to find spare cost for control algorithms since it is not hardware, hence this has been excluded from the cost analysis.

The costs analysis shows that for failure mode 4.B and 5.A respectively 60 and 115 hours are available to do preventive maintenance before run-to-failure is more cost effective. One may argue than that the continuous monitoring is not cost effective. Since the concept is new and the failure modes hidden are this seen as a precaution action. It is assumed that monitoring extra components will not be an great expense, as there will be a person at the shore-based station.

Table 6.3: Expense items for cost calculation for navigation system

FM	Spare part costs	Loss of Reputation level	Injury costs	Hours available
1.A	7400	4	Severe injury	44321
1.B	7400	4	Severe injury	44321
2.A	-	4	Major injury	21285
3.A	-	4	Major injury	21285
4.A	30100	0	Insignificant	56
4.B	30100	0	Insignificant	56
5.A	40 000	0	Insignificant	109
6.A	-	0	Slight injury	1158
6.B	4500	0	Slight injury	1158



Component	#	Failure mode	FP	RI	Maintenance task	Interval	Maintenance description
Embedded computer	1.A	No connection of the components	E	7	Scheduled restoration	1 day	Connect all the cables properly to the embedded computer
	1.B	Breakdown	F	7	Scheduled on-condition	Continuous	Real time continuous monitoring via shore-based station
Guidance system	2.A	Miscalculation	E	8	Scheduled on-condition	Continuous	Continuous monitoring with online updates
Control system	3.A	Actions are not taken in time	E	8	Scheduled on-condition	Continuous	Continuous monitoring with online updates
IMU	4.A	Containment	B	5	Scheduled restoration	1 week	Disconnect from power supply, computer and antenna. Wipe the case with a damp cloth and mild detergent
	4.B	Breakdown	F	5	Scheduled on-condition	Continuous	Change the component with a new one.
2 GNSS with RTK	5.A	Breakdown	A	4	Scheduled on-condition	Continuous	Change the component with a new one.
Radio link	6.A	Loss of connection to GNSS receiver	E	8	Run-to-failure	-	Self-fix
	6.B	Loss of communication with rover base	A	6	Scheduled on-condition	Continuous	Change the component with a new one.

Figure 6.7: MTA for navigation system

6.2 Anti-collision system

6.2.1 Functions

Anti-collision system or collision avoidance system is installed in the ferry to avoid colliding into ships or other obstacles, which is the primary function for the system. The functional hierarchy can be seen in Figure 6.8.

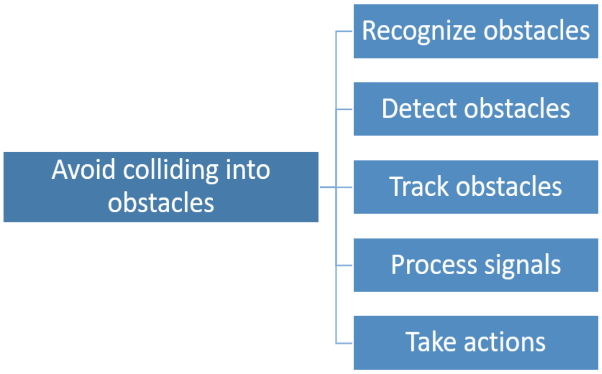


Figure 6.8: Illustration of primary and secondary functions for the anti-collision system

6.2.2 Functional Failures

The functional failures identified and found relevant for the system are listed below.

1. Does not recognize ships and/or other obstacles
2. Does not detect and/or track obstacles
3. Signals are not processed and actions not are taken

The first functional failure implies a failure on the camera or the IR. The camera is programmed to recognize ships by images, while the IR uses infrared radiation waves. The second functional failure happens due to a failure of the radar or the lidar. The radar will serve far-field. while the lidar will serve near-field. The last functional failure for the anti-collision system is when the system does not process the information, and does not take actions based on the information from the sensors. This functional failure can be caused both by a failure in the control algorithm, or by the transfer of information from the sensors to the control algorithm.

As this is a crucial system for the autonomous passenger ferry, a FTA has been made, and is shown in Figure 6.9. The top event is failure of the anti-collision system while crossing the canal. The analysis is quantified by using the MTBF's for the components, and assuming that all of them are repairable. In addition a MTTR has been assumed based on guesswork for each failure mode.

The overall probability for a failure in the system is calculated to be 0.00024%. Which is most affected by a failure in the control algorithm, as no redundancy exists. The probability for failure in the sensors platform is low, due to the redundancy and the high MTBFs.

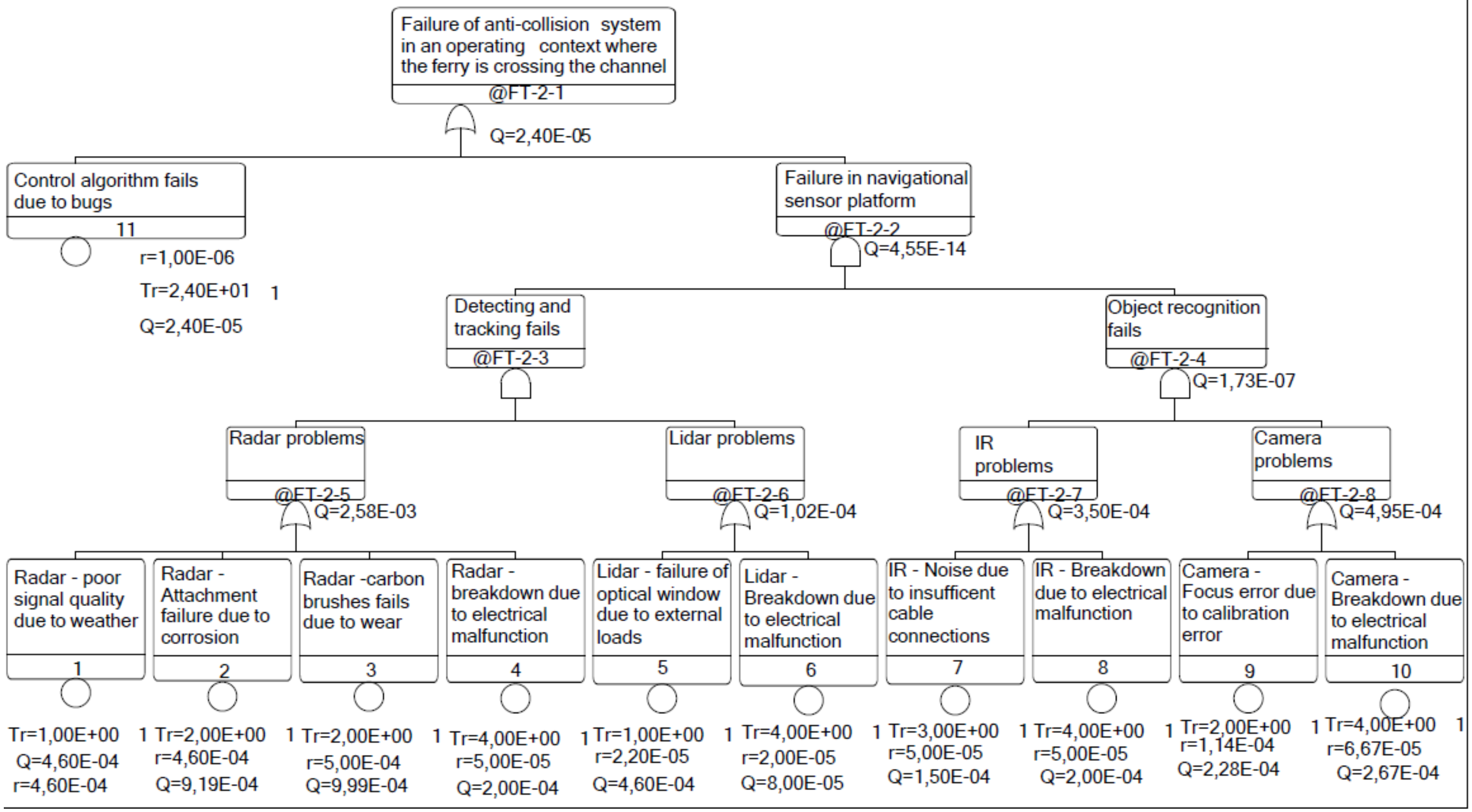


Figure 6.9: FTA of anti-collision system

6.2.3 FMECA

The components that are analyzed in the FMECA are the following:

- Camera
- IR
- Lidar
- Radar
- Control algorithm

The worksheets for the anti-collision system can be seen in Figure 6.11 and 6.12.

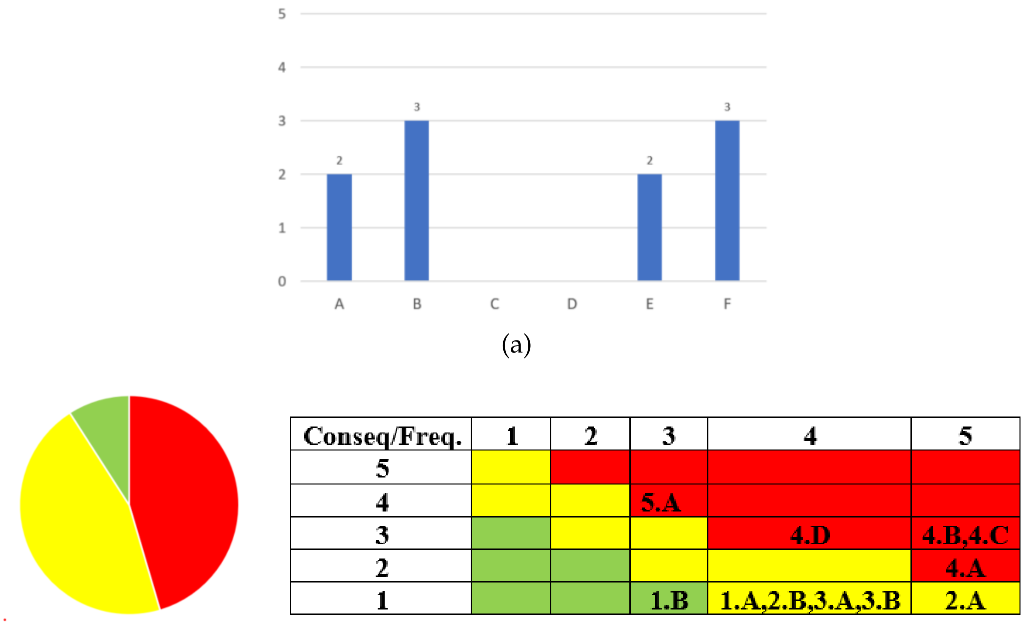
All of the senors in the system has been assigned to the failure mode breakdown due to electrical malfunction. The failure modes in addition to this, are gathered from the manufacturers manual for the specific components, camera [56], IR [57], lidar [58] and radar [59]. Only the MTBF's for breakdown of the components were found, where the sources are the following: camera [60], IR and radar [61], lidar [62]. The rest were assumed based on guesswork done by the author.

The assessment involves 11 failure modes, where all of them are evaluated to be hidden. This is a consequences of the autonomous and unmanned concept. The system is programmed to be smart: information is processed and actions are taken without involving human intellect.

A failure to one of the sensors in the system, camera, IR, lidar, radar, will not affect the safety, asset or environment much. This is due to the fact that all of the sensors works as a redundant system, where there are two components for each function. The two components uses two different techniques, for example object recognition by images or recognition by IR. Even though one of them fails, there will be three other components which will fulfill the functions. The only failure mode that has been assessed with higher criticality is the breakdown of the radar. The radar's functions is object detection and tracking in the far-field. This implies that this equipment will detect the obstacles before the other sensors, and a failure to it may give too little time to take action.

The safety for miscalculation in the control algorithm is assessed to category 3, major injury. The failure mode may result in a collision with a obstacle, which can be another boat, quay or a stake.

The distribution of the failure patterns are shown in Figure 6.10(a). From the figure one can see that the failure modes are distributed between A,B,E and F. The failure modes are both due to wear, electrical malfunction, bugs and external loads. Figure 6.10(b) shows the distribution of the risk index. One of the failure modes is in the acceptable area, while there is an equal split between failure modes in the yellow and the green area. The risk matrix is shown in Figure 6.10(c). The numbers corresponds to the failure modes, which can be seen in Figure 6.12.



(a)

(b)

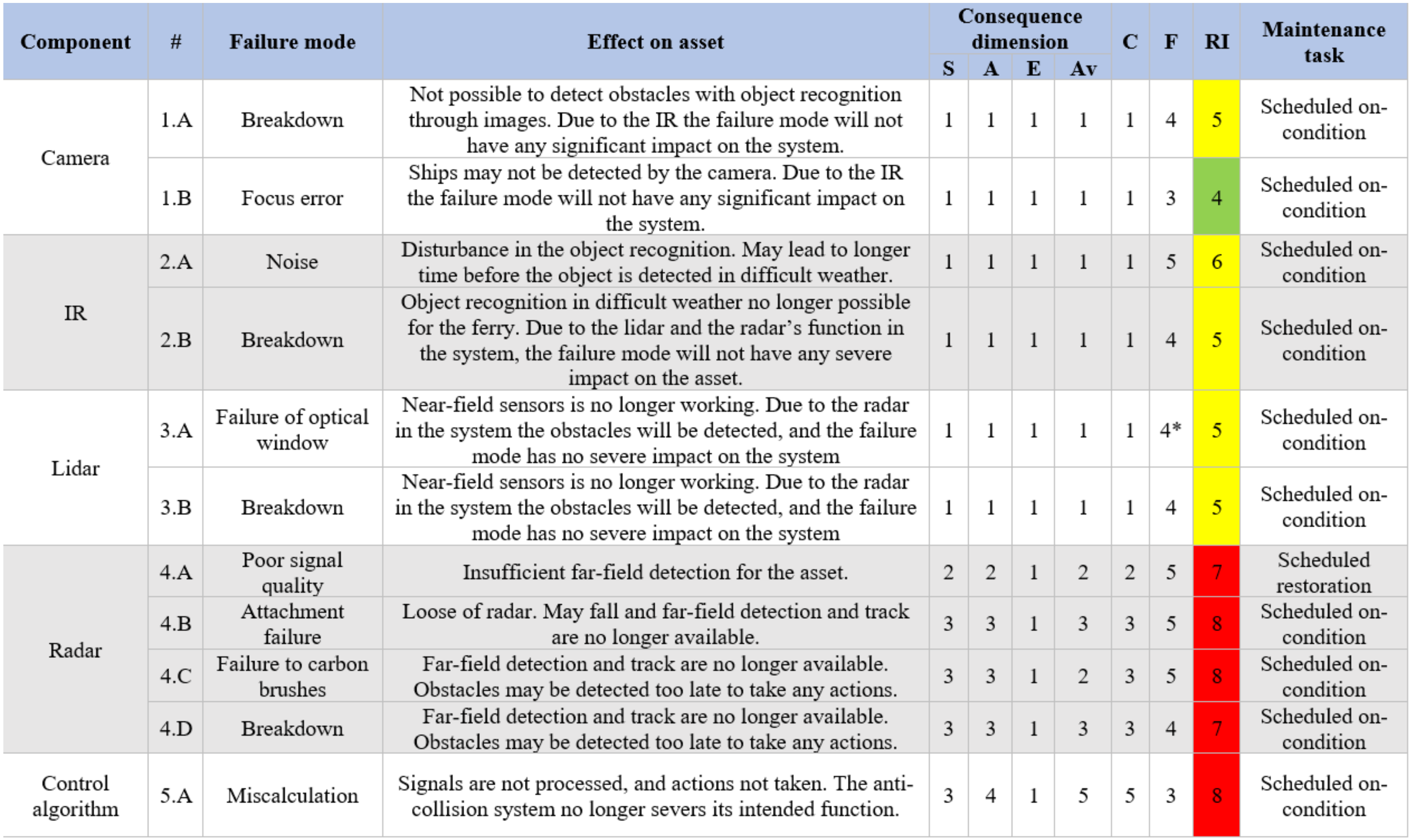
(c)

Conseq/Freq.	1	2	3	4	5
5	🟨	🟥	🟥	🟥	🟥
4	🟨	🟨	🟥 5.A	🟥	🟥
3	🟩	🟨	🟨	🟥 4.D	🟥 4.B,4.C
2	🟩	🟩	🟨	🟨	🟥 4.A
1	🟩	🟩	🟩 1.B	🟨 1.A,2.B,3.A,3.B	🟨 2.A

Figure 6.10: Summary of FMECA for anti-collision system

Component	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
Camera	Recognize ships with different shape and colour in different light	1.A	Breakdown	Wear External loads	F	H	15 000 h
		1.B	Focus error	Calibration error	F	H	8760 h*
IR	Recognize obstacles in difficult weather	2.A	Noise	Cable connections	E	H	20 000 h*
		2.B	Breakdown	Electrical malfunction	F	H	20 000 h
Lidar	Detecting and tracking obstacles with laser light, near-field	3.A	Failure of optical window	External loads	B	H	5 years*
		3.B	Breakdown	Electrical malfunction	F	H	50 000 h
Radar	Detecting and tracking obstacles with radio waves , far-field	4.A	Poor signal quality	Weather	A	H	3 months*
		4.B	Attachment failure	Corrosion	B	H	3 months*
		4.C	Failure to carbon brushes	Wear	B	H	2000 h
		4.D	Breakdown	Electrical malfunction	A	H	20 000 h
Control algorithm	Process signals and take actions	5.A	Miscalculation	Bugs in algorithm	E	H	-

Figure 6.11: FMECA for anti-collision system, part 1



Component	#	Failure mode	Effect on asset	Consequence dimension				C	F	RI	Maintenance task
				S	A	E	Av				
Camera	1.A	Breakdown	Not possible to detect obstacles with object recognition through images. Due to the IR the failure mode will not have any significant impact on the system.	1	1	1	1	1	4	5	Scheduled on-condition
	1.B	Focus error	Ships may not be detected by the camera. Due to the IR the failure mode will not have any significant impact on the system.	1	1	1	1	1	3	4	Scheduled on-condition
IR	2.A	Noise	Disturbance in the object recognition. May lead to longer time before the object is detected in difficult weather.	1	1	1	1	1	5	6	Scheduled on-condition
	2.B	Breakdown	Object recognition in difficult weather no longer possible for the ferry. Due to the lidar and the radar's function in the system, the failure mode will not have any severe impact on the asset.	1	1	1	1	1	4	5	Scheduled on-condition
Lidar	3.A	Failure of optical window	Near-field sensors is no longer working. Due to the radar in the system the obstacles will be detected, and the failure mode has no severe impact on the system	1	1	1	1	1	4*	5	Scheduled on-condition
	3.B	Breakdown	Near-field sensors is no longer working. Due to the radar in the system the obstacles will be detected, and the failure mode has no severe impact on the system	1	1	1	1	1	4	5	Scheduled on-condition
Radar	4.A	Poor signal quality	Insufficient far-field detection for the asset.	2	2	1	2	2	5	7	Scheduled restoration
	4.B	Attachment failure	Loose of radar. May fall and far-field detection and track are no longer available.	3	3	1	3	3	5	8	Scheduled on-condition
	4.C	Failure to carbon brushes	Far-field detection and track are no longer available. Obstacles may be detected too late to take any actions.	3	3	1	2	3	5	8	Scheduled on-condition
	4.D	Breakdown	Far-field detection and track are no longer available. Obstacles may be detected too late to take any actions.	3	3	1	3	3	4	7	Scheduled on-condition
Control algorithm	5.A	Miscalculation	Signals are not processed, and actions not taken. The anti-collision system no longer severs its intended function.	3	4	1	5	5	3	8	Scheduled on-condition

Figure 6.12: FMECA for anti-collision system, part 2

Due to the importance of the system, in the light of the new concept and new technology, an ETA has been performed, Figure 6.13 shows the analysis. The initiating event is the failure of the anti-collision system, and is based on the FTA shown in Figure 6.9. The function event is the barriers that are present in the system, and they are all linked with probability. Table 6.5 shows the function events with the probabilities. All of the probabilities are based on guesswork done by the author. The first probability, obstacle in the channel, is set to be low. As the canal is relatively long and the traffic is slow. It is assumed that there will be a high probability for the shore-based station to detect the obstacle than the passengers. If the obstacle is detected, there is a high probability that the ESB is activated.

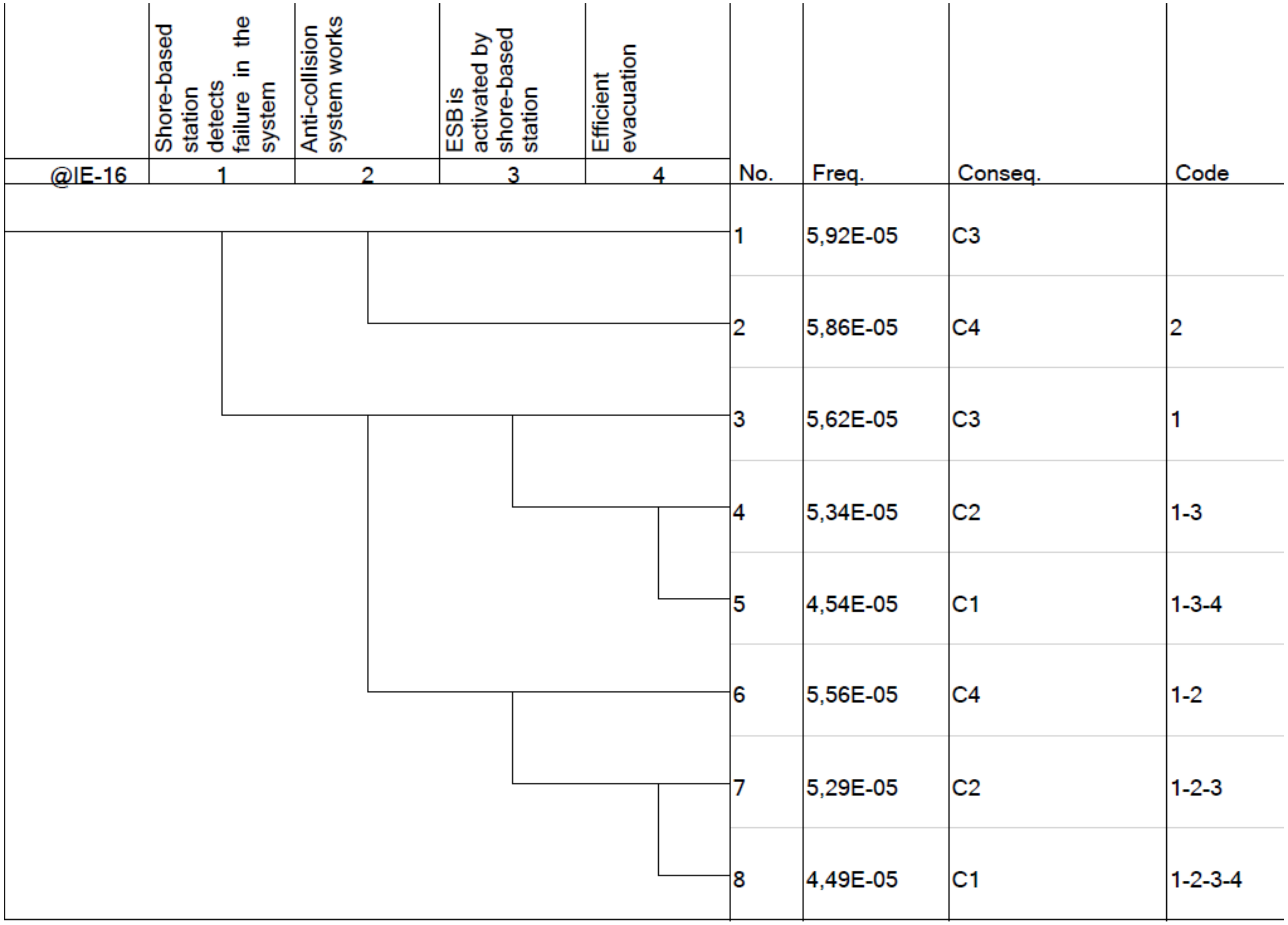
Table 6.4: Functioning events with probabilities for ETA of anti-collision system

Function event	Probability
Obstacle in the channel	0.05
Passengers detects obstacles	0.5
Shore-based station detects obstacle	0.7
ESB is activated	0.95
Efficient evacuation	0.85

The consequence categories are described in Table 6.5, here are the summation of the probability for each category included.

Table 6.5: Consequence categories for ETA of ant-collision system with summation

Category	Description	Summation of probabilities
1	Slight injury	1.7e-6
2	Severe injury	1.86 e-6
3	Fatality	1.2e-6
4	Material damage	2.4e-5
5	No harm	1.5e-6



No.	Freq.	Conseq.	Code
1	5,92E-05	C3	
2	5,86E-05	C4	2
3	5,62E-05	C3	1
4	5,34E-05	C2	1-3
5	4,54E-05	C1	1-3-4
6	5,56E-05	C4	1-2
7	5,29E-05	C2	1-2-3
8	4,49E-05	C1	1-2-3-4

Figure 6.13: ETA of anti-collision system

6.2.4 Maintenance Task Analysis

The MTA worksheet is shown in Figure 6.14. As one can see, all of the failure modes are assigned with some sort of preventive maintenance. Either scheduled on-condition or scheduled restoration. The main reason for this is due to the fact that all of them are hidden and crucial for the system, and the system is important for the autonomous concept. This implies that run to failure is not appropriate. Also in this system the sensors has been assigned to scheduled on-condition with real time monitoring, the argumentation follows the same as in the navigation system.

Even tough the sensors has between 10 to 216 hours available before run-to-failure is more cost effective, continuous monitoring has been chosen. This is discussed further in Section 7.2. The hours available to do preventive maintenance for each failure mode can be seen in Table 6.6.

Table 6.6: Expense items used in cost calculation for MTA of anti-collision system

FM	Spare part costs	Loss of Reputation level	Injury costs	Hours available
1.A	5800	0	Insignificant	11
1.B	5800	0	Insignificant	11
2.A	116 000	0	Insignificant	216
2.B	116 000	0	Insignificant	216
3.A	32 000	0	Insignificant	59
3.B	32 000	0	Insignificant	59
4.A	-	0	Minor	1150
4.B	14 400	2	Major	19 798
4.C	-	0	Minor	1150
4.D	14 400	0	Insignificant	31
5.A	-	4	Severe injury	44 279

Component	#	Failure mode	FP	RI	Maintenance task	Interval	Maintenance description
Camera	1.A	Breakdown	H	5	Scheduled on-condition	1 month	Examine all cables for sighs of damages, and check that they are securely connected.
	1.B	Focus error	H	4	Scheduled on-condition	2 weeks	Check the focus. If deviations are found, recalibrate the camera.
IR	2.A	Noise	H	6	Scheduled on-condition	1 month	Ensure proper cable separation and short video cable.
	2.B	Breakdown	H	5	Scheduled on-condition	Continuous	Real time monitoring via shore-based station
Lidar	3.A	Failure of optical window	H	5	Scheduled on-condition	6 months	Check that optical window is still intact. If not replace it.
	3.B	Breakdown	H	5	Scheduled on-condition	Continuous	Real time monitoring via shore-based station
Radar	4.A	Poor signal quality	H	7	Scheduled restoration	3 months	Wipe the antenna clean with freshwater moisture cloth.
	4.B	Attachment failure	H	8	Scheduled on-condition	3 months	Check bolts for tightness and corrosion, replacing any corroded bolts and coating new bolts with anticorrosion sealant.
	4.C	Failure to carbon brushes	H	8	Scheduled on-condition	3 months	Check the scanner drive motor brushes. Change if needed.
	4.D	Breakdown	H	7	Scheduled on-condition	Continuous	Overhaul by qualified personnel.
Control algorithm	5.A	Miscalculation	H	8	Scheduled on-condition	Continuous	Real time continuous condition monitoring with online updates

Figure 6.14: MTA for anti-collision system

6.3 Propulsion system

6.3.1 Functions

The primary function for the propulsion system is to give the ferry a velocity of five knots. This speed will be the max speed of the ferry, thus it will have a service speed of four knots. The primary functions for the system are shown in Figure 6.15.

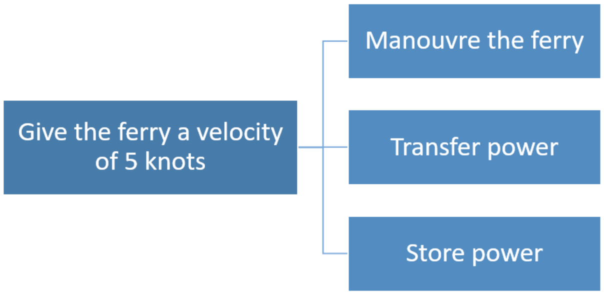


Figure 6.15: The primary and secondary functions for the propulsion system

The maneuvering of the ferry is done by the pod drives with input from the navigation system. This system is not included in the analysis of the propulsion system, since it already has been analyzed. The next secondary function is done by the battery cables which goes from the battery modules to the electronic box in the pod drives. Finally the storing of power is done by the battery modules in the system, which is assumed to be Li-Ion battery packages [37].

6.3.2 Functional Failures

The relevant functional failures identified in the analysis are as follows:

- Unable to manoeuvre
- Unable to give the ferry a velocity of five knots
- Unable to transfer power from batteries to pod drive
- Unable to store power

The first functional failure results in a situation where the ferry can not take actions from the control algorithm. In a worst case scenario this can cause collision and/or grounding of the ferry. The second functional failure causes that the ferry does not full-fill the functional requirements that are set. The crossing may take longer than one minute. This functional failure can be caused by insufficient power transfer from the batteries, or malfunction to the propellers. Next is the functional failure where the system gets no power, which results in total failure. This is true also for the last functional failure. This functional failure is due to failure of the battery modules.

6.3.3 FMECA

The components analyzed in the FMECA are the following.

- Propeller
- Gear shaft
- Motor
- Electronic box
- Seals
- Cables
- Attachment bolts
- Battery modules
- Battery cables

The worksheets for the system can be seen in Figure 6.17 and 6.18.

The failure modes for the pod drives are adapted from the manufacturers manual [63] and from *Marine Propellers and Propulsion* [64]. In addition to this, the functions for the components are used. For the battery modules the failure modes are adapted from the project thesis [30]. Relevant MTBF was only found for the battery modules [65]. For the rest of the failure modes, frequency classes are assumed based on the failure mode and cause.

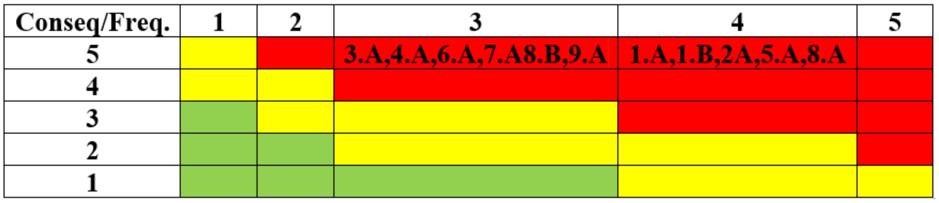
A total of 11 failure modes were found relevant, and were analyzed further. Both of the failure modes for the propellers leads to damage to the propeller, which will affect the propulsion of the ferry over time. This is not a safety issue, consequently safety is evaluated to one for both failure modes. As mentioned, both of the failure modes will over time affect the ferry's ability to move forward, therefore both are evaluated to three when it comes to asset, considerable system damage. A situation where the failure modes develops over time will cause considerable unavailability for the ferry and is evaluated to 5. The same way of thinking is applicable for failure mode 2.A. The criticality for failure mode 3.A,4.A,6.A,8.B and 9.A has been equally evaluated when it comes to criticality. This is due to that all of them will cause a sudden stop by the ferry, where actions can not be taken. Such a situation can be severe if the ferry is close to land or to a obstacle.

Deterioration of the seals between the hull and attachment bolts will cause leakage of water in to the hull. Given that this leak is small, the bilge pumps will handle it. Seals that has been subjected to deterioration for a while will cause high unavailability for the ferry, since it has to be taken up from water to be fixed. A failure to the attachment bolt, which holds to motor to the hull, causes water to flow into the hull. Depending on the opening between the motor and the hull, this situation may be severe. Here safety is evaluated to 4, and asset to 5. This failure mode will obviously cause high unavailability for the ferry.

Thermal runaway for the battery modules is a severe failure mode. The situation may cause even more heat, which again can result in a fire [66]. A failure mode that may result in fire will affect the safety and the asset highly, so both of them are evaluated to 5. A fire will also affect the local environment, and cause high unavailability.

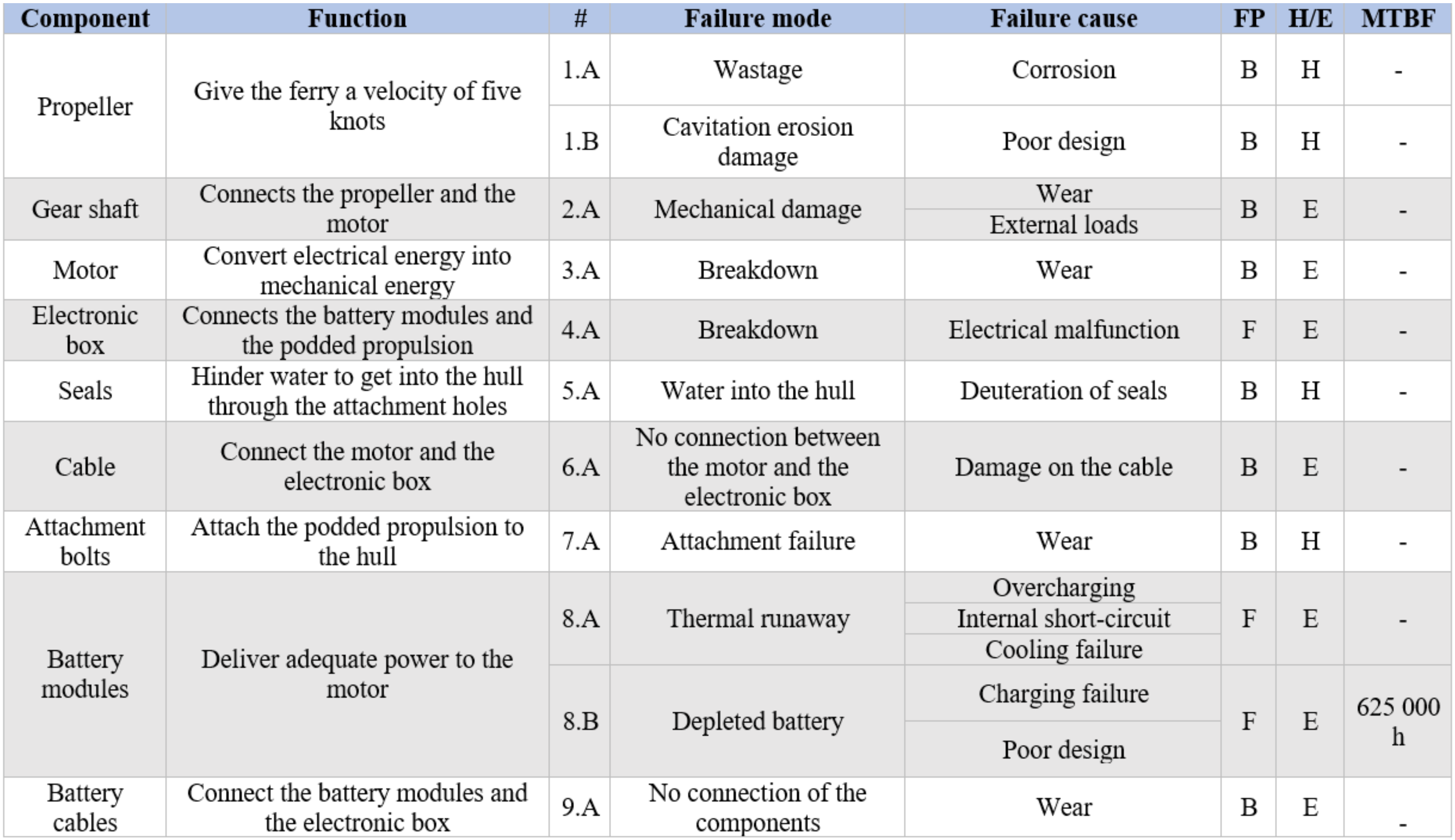
8 of the 11 failure modes are assigned to failure pattern B, because they are mechanical components that are exposed to wear and tear. While the three remaining has failure pattern F. The failure modes that involves deterioration of the equipment are evaluated as hidden, while the ones resulting in sudden stop are evaluated to be evident.

Figure 6.16 shows the risk matrix from the analysis. The figure shows that all of the components are in the red area; unacceptable risk. This is much due to the high consequence class, which is affected by the high unavailability the failure modes causes.



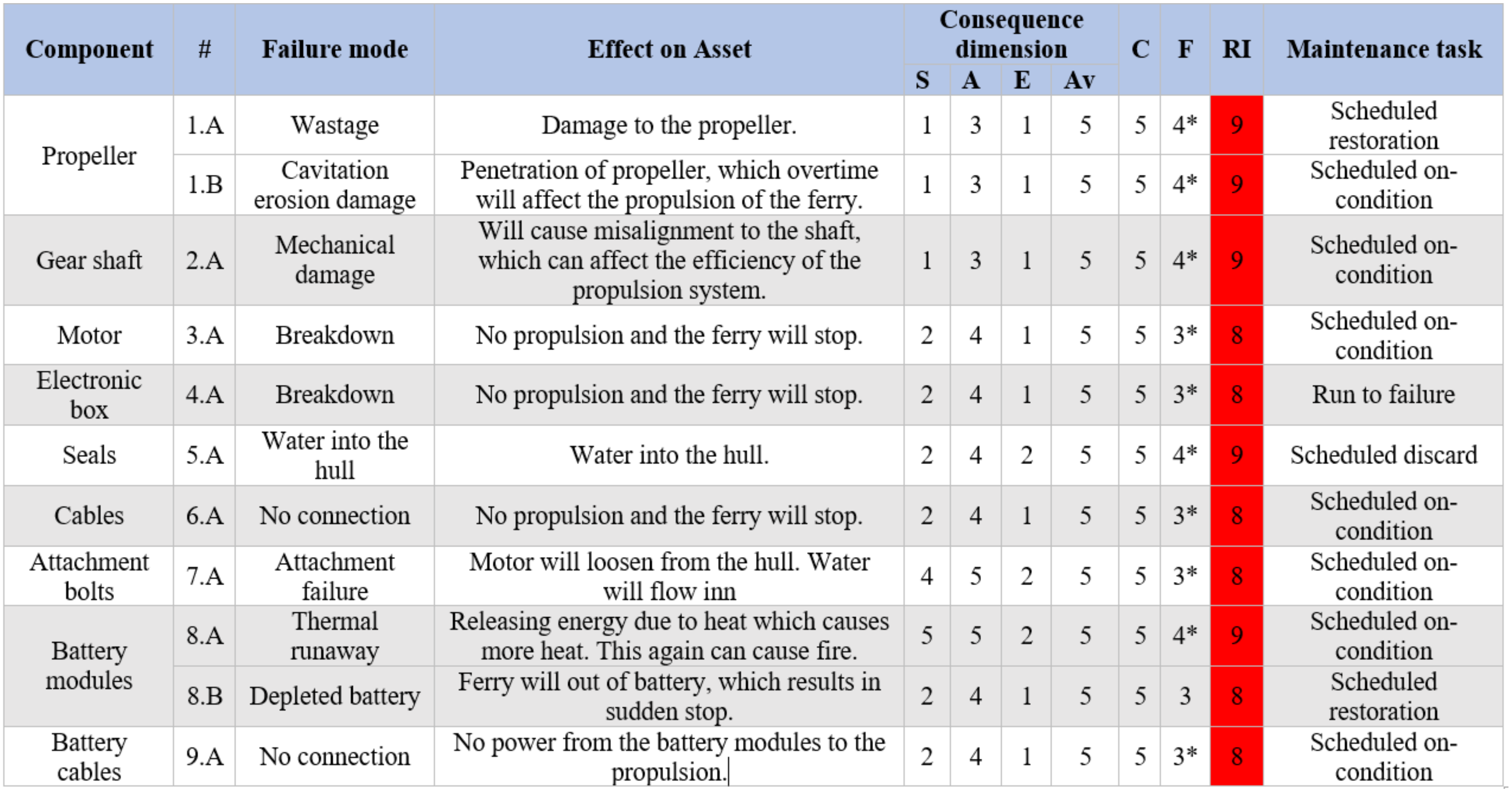
Conseq/Freq.	1	2	3	4	5
5	🟨	🟥	🟥 3.A,4.A,6.A,7.A8.B,9.A	🟥 1.A,1.B,2A,5.A,8.A	🟥
4	🟨	🟨	🟥	🟥	🟥
3	🟩	🟨	🟨	🟥	🟥
2	🟩	🟩	🟨	🟨	🟥
1	🟩	🟩	🟩	🟨	🟨

Figure 6.16: Risk matrix for propulsion system



Component	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
Propeller	Give the ferry a velocity of five knots	1.A	Wastage	Corrosion	B	H	-
		1.B	Cavitation erosion damage	Poor design	B	H	-
Gear shaft	Connects the propeller and the motor	2.A	Mechanical damage	Wear External loads	B	E	-
Motor	Convert electrical energy into mechanical energy	3.A	Breakdown	Wear	B	E	-
Electronic box	Connects the battery modules and the podded propulsion	4.A	Breakdown	Electrical malfunction	F	E	-
Seals	Hinder water to get into the hull through the attachment holes	5.A	Water into the hull	Deuteration of seals	B	H	-
Cable	Connect the motor and the electronic box	6.A	No connection between the motor and the electronic box	Damage on the cable	B	E	-
Attachment bolts	Attach the podded propulsion to the hull	7.A	Attachment failure	Wear	B	H	-
Battery modules	Deliver adequate power to the motor	8.A	Thermal runaway	Overcharging Internal short-circuit Cooling failure	F	E	-
		8.B	Depleted battery	Charging failure Poor design	F	E	625 000 h
Battery cables	Connect the battery modules and the electronic box	9.A	No connection of the components	Wear	B	E	-

Figure 6.17: FMECA worksheet for propulsion system, part 1



Component	#	Failure mode	Effect on Asset	Consequence dimension				C	F	RI	Maintenance task
				S	A	E	Av				
Propeller	1.A	Wastage	Damage to the propeller.	1	3	1	5	5	4*	9	Scheduled restoration
	1.B	Cavitation erosion damage	Penetration of propeller, which overtime will affect the propulsion of the ferry.	1	3	1	5	5	4*	9	Scheduled on-condition
Gear shaft	2.A	Mechanical damage	Will cause misalignment to the shaft, which can affect the efficiency of the propulsion system.	1	3	1	5	5	4*	9	Scheduled on-condition
Motor	3.A	Breakdown	No propulsion and the ferry will stop.	2	4	1	5	5	3*	8	Scheduled on-condition
Electronic box	4.A	Breakdown	No propulsion and the ferry will stop.	2	4	1	5	5	3*	8	Run to failure
Seals	5.A	Water into the hull	Water into the hull.	2	4	2	5	5	4*	9	Scheduled discard
Cables	6.A	No connection	No propulsion and the ferry will stop.	2	4	1	5	5	3*	8	Scheduled on-condition
Attachment bolts	7.A	Attachment failure	Motor will loosen from the hull. Water will flow inn	4	5	2	5	5	3*	8	Scheduled on-condition
Battery modules	8.A	Thermal runaway	Releasing energy due to heat which causes more heat. This again can cause fire.	5	5	2	5	5	4*	9	Scheduled on-condition
	8.B	Depleted battery	Ferry will out of battery, which results in sudden stop.	2	4	1	5	5	3	8	Scheduled restoration
Battery cables	9.A	No connection	No power from the battery modules to the propulsion.	2	4	1	5	5	3*	8	Scheduled on-condition

Figure 6.18: FMECA worksheet for propulsion system, part 2

6.3.4 Maintenance Task Analysis

The MTA is shown in Figure 6.19. All failure modes except one is assigned with preventive maintenance. The failure mode breakdown of the electronic box is the only one assigned with run-to-failure. This failure mode does not fulfill the requirements for the preventive maintenance tasks. Since the failure mode is evident, run to failure will be applicable. When the box fails the whole component will be replaced. As mentioned, the rest of the failure modes are assigned with some sort of preventive maintenance, where the most have scheduled on-condition as preventive maintenance.

The failure mode thermal runaway for the battery can have a severe outcome. It will affect both the safety, the asset and the environment. To manage the issues that concerns the battery modules, it is proposed to implement a battery management system. The systems purpose is to guarantee for safety and reliability of the battery [67]. This is done by state monitoring and evaluation, charging control and cell balancing [67]. The system will have two aspects; monitoring and control [68]. When the system detects irregular situations the user will be notified. In this case the shore-based station. This is called real time monitoring of the batteries in the MTA worksheet.

The most important expense items used in the cost calculation of hours available for preventive maintenance for the system can be seen in Table 6.7.

The cost of propeller was given by Torqeedo to be 13 000 NOK and cables to be 200 NOK. The rest of the parts for the pod drive where not given, however the total cost of a pod drive is used to calculate the cost for each part. The battery cables are assumed to be 500 NOK.

Table 6.7: Expense items used in cost calculation for MTA of propulsion system

FM	Spare part costs	Loss of Reputation level	Injury costs	Hours available
1.A	13 000	1	Insignificant	66
1.B	13 000	1	Insignificant	66
2.A	21 000	1	Insignificant	80
3.A	30 000	3	Minor	1616
4.A	12 200	3	Minor	1578
5.A	50	3	Minor	1556
6.A	200	3	Minor	1525
7.A	50	4	Severe	44 317
8.A	305 000	5	Fatality	58 870
8.B	305 000	3	Minor	2115
9.A	500	3	Minor	1527

Component	#	Failure mode	FP	RI	Maintenance task	Interval	Maintenance description
Propeller	1.A	Wastage	B	9	Scheduled restoration	1 year	Change zinc anodes.
	1.B	Cavitation erosion damage	B	9	Scheduled on-condition	1 year	Inspect the propellers for cavitation erosion damage. If severe damages are found, change the propellers.
Gear shaft	2.A	Mechanical damage	B	9	Scheduled on-condition	1 year	Inspect the shaft. If misalignment is found align it.
Motor	3.A	Breakdown	B	8	Scheduled on-condition	1 year	Vibration measurements to check for faults.
Electronic box	4.A	Breakdown	F	8	Run to failure	-	Replace the component if failed.
Seals	5.A	Water into the hull	B	9	Scheduled discard	2 years	Change the seals with new ones.
Cables	6.A	No connection	B	8	Scheduled on-condition	6 months	Check the connections and the cables for wear. Change if needed.
Attachment bolts	7.A	Attachment failure	B	8	Scheduled on-condition	10 days	Inspect the bolts. Correct if required.
Battery modules	8.A	Thermal runaway	F	9	Scheduled on-condition	Continuous	Real time monitoring of battery modules through battery management system.
	8.B	Depleted battery	F	8	Scheduled restoration	5 years	Change of battery cells.
Battery cables	9.A	No connection	B	8	Scheduled on-condition	6 months	Check the connections and the cables for wear. Change if needed.

Figure 6.19: MTA for propulsion system

6.4 Electric power system

6.4.1 Functions

The primary function for the electric power system is to supply the ferry with enough power to run the systems on board. Figure 6.20 shows the functional hierarchy for the system.

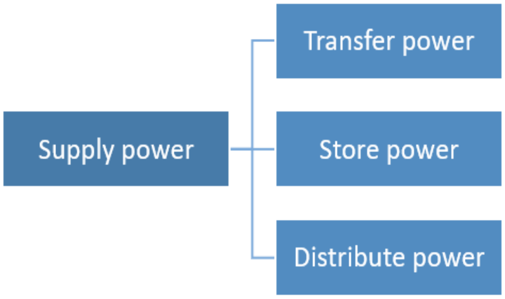


Figure 6.20: Functional hierarchy for the electric power system

6.4.2 Functional Failures

To have an efficient electric power system, all of the functions in Figure 6.20 has to function. An electric power system that is not able to transfer the power is useless. The functional failures for the system are listed below:

1. Insufficient transfer of power to the systems
2. Insufficient storage of power
3. Insufficient distribution of power

All of the three functional failures will cause a non-working system. The first functional failure results in the fact that the power is not transferred from the battery modules to the systems that requires the power. The functional failure is caused by a malfunction to the electrical cables in the system. The second functional failure means that there are no electric power in the battery modules, which indicates a failure in the battery modules. The last functional failure deals with the distribution of the power, which is done by the distribution board.

6.4.3 FMECA

The components analyzed in the FMECA are as follows.

- Battery modules
- Electrical cables
- Distribution board

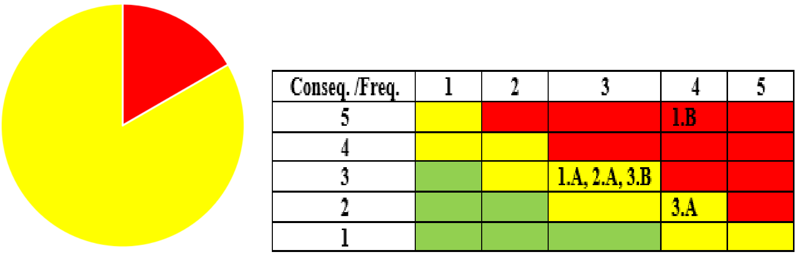
The worksheets for the analysis can be seen in Figure 6.22 and 6.23.

The failure modes for the components are developed using the functions for the components, and by understanding how they work. Only MTBF for the battery modules were available [65], the rest is based on guesswork done by the author. The failure modes were assigned with either frequency class 4 or 3. Breakdown of distribution board and wire break of the electrical cables is assumed to happen rarely. Frequency class three represent a frequency of 1 - 0.01 failures per 10th year. On the other hand, failure modes broken fuse and thermal runaway is assumed to happen more often.

A total of 5 failure modes were found relevant for the analysis. All of the failure modes will cause power failure, therefore all of them are characterized as evident. One of the failure modes, 2.A, is due to wear and tear and is assumed to have failure pattern B. The rest of the failure modes are electrical, and are assigned to failure pattern F.

The criticality of the failure modes for the battery modules follows the same as for the battery modules in the propulsion system. The electrical cables are distributing the electricity to the various systems on board. A wire break will hinder this, which implies a loss of main parts of the system. Though the failure mode will not cause large impact on the safety for the passengers. A broken fuse will not cause any large damage to the ferry, and the repair is quick. This is not the case for a breakdown of the distribution board, where the repair will take time and the asset is affected largely.

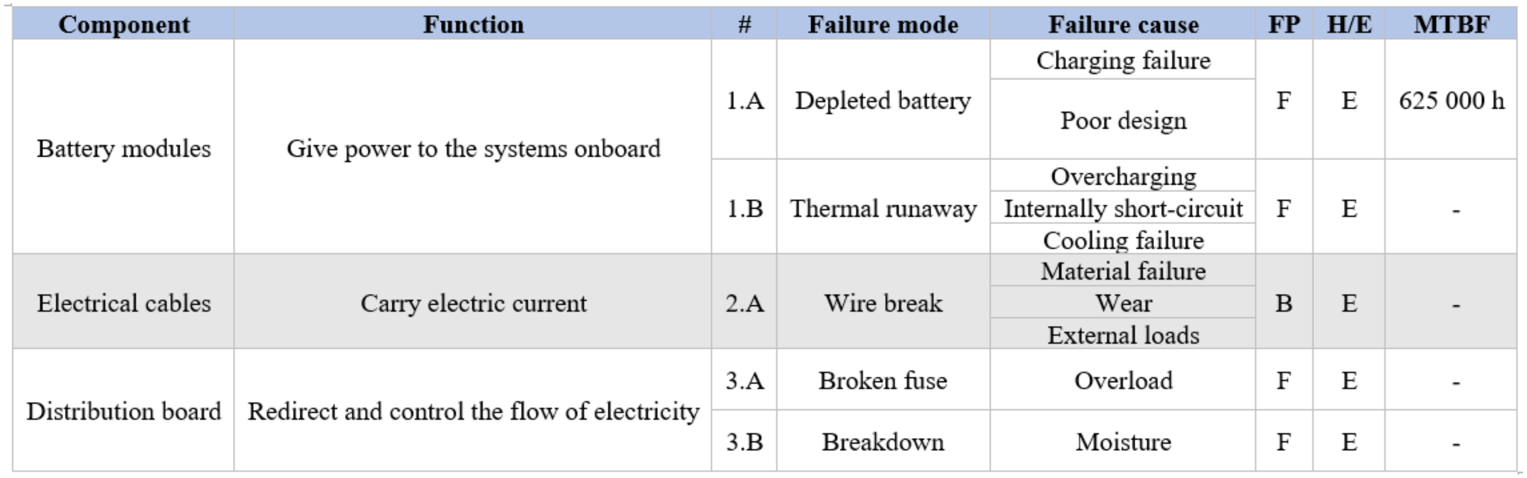
The risk index for the failure modes are shown in Figure 6.21(a), while Figure 6.21(b) shows the risk matrix. The matrix shows that the only failure mode in the red area is 1.B, which is thermal runaway for the battery modules. The rest of the failure modes are in the ALARP area.



Conseq. /Freq.	1	2	3	4	5
5	🟨	🟥	🟥	🟥 1.B	🟥
4	🟨	🟨	🟥	🟥	🟥
3	🟩	🟨	🟨 1.A, 2.A, 3.B	🟥	🟥
2	🟩	🟩	🟨	🟨 3.A	🟥
1	🟩	🟩	🟩	🟨	🟨

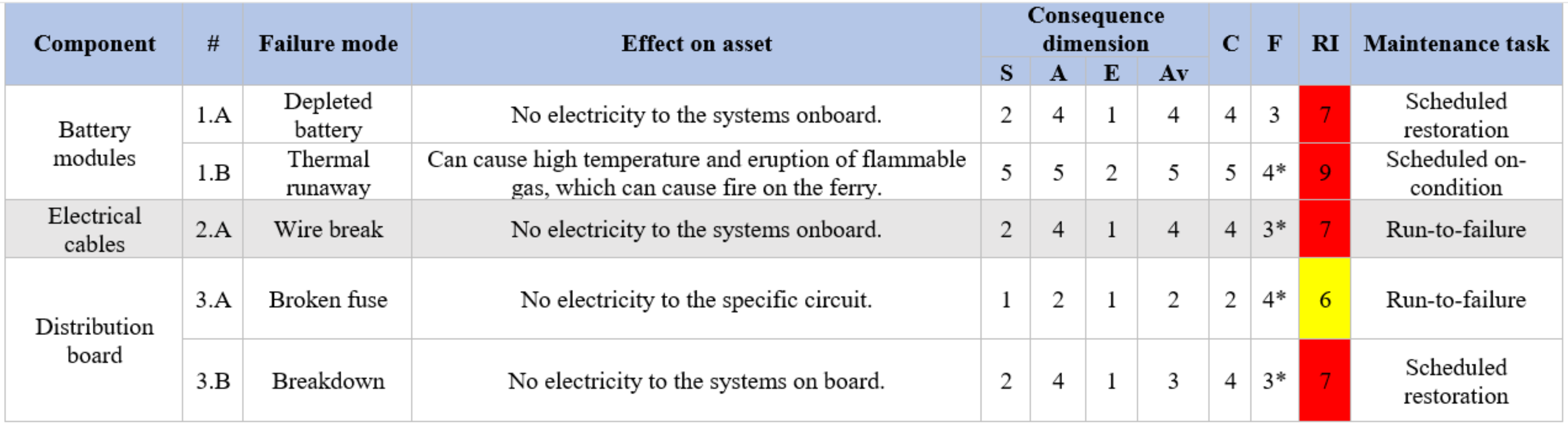
(a) (b)

Figure 6.21: Summary of risk index for electric power system



Component	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
Battery modules	Give power to the systems onboard	1.A	Depleted battery	Charging failure	F	E	625 000 h
				Poor design			
		1.B	Thermal runaway	Overcharging	F	E	-
				Internally short-circuit			
				Cooling failure			
Electrical cables	Carry electric current	2.A	Wire break	Material failure	B	E	-
				Wear			
				External loads			
Distribution board	Redirect and control the flow of electricity	3.A	Broken fuse	Overload	F	E	-
		3.B	Breakdown	Moisture	F	E	-

Figure 6.22: FMECA of electrical power system, part 1

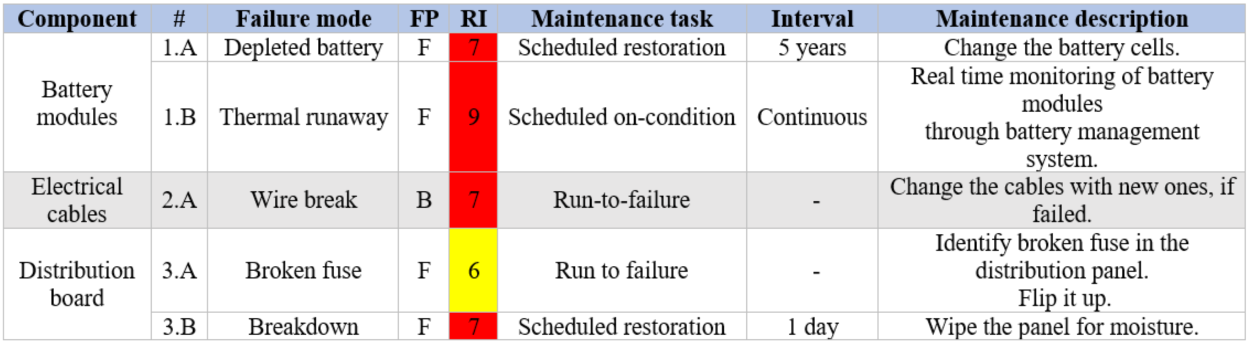


Component	#	Failure mode	Effect on asset	Consequence dimension				C	F	RI	Maintenance task
				S	A	E	Av				
Battery modules	1.A	Depleted battery	No electricity to the systems onboard.	2	4	1	4	4	3	7	Scheduled restoration
	1.B	Thermal runaway	Can cause high temperature and eruption of flammable gas, which can cause fire on the ferry.	5	5	2	5	5	4*	9	Scheduled on-condition
Electrical cables	2.A	Wire break	No electricity to the systems onboard.	2	4	1	4	4	3*	7	Run-to-failure
Distribution board	3.A	Broken fuse	No electricity to the specific circuit.	1	2	1	2	2	4*	6	Run-to-failure
	3.B	Breakdown	No electricity to the systems on board.	2	4	1	3	4	3*	7	Scheduled restoration

Figure 6.23: FMECA of electrical power system, part 2

6.4.4 Maintenance Task Analysis

The worksheet from the MTA is shown in Figure 6.24. The battery modules maintenance follows the same argumentation as in propulsion system, also the costs and hours available to do preventive maintenance will be the same. For wire break, the maintenance task is set to run-to-failure. Here it is assumed that the installation of the cables is correct. The cables will be inside the hull, therefore they will not be subjected to the same wear as components directly exposed to weather. The decision is also based on the fact that the cables will be designed for the ferry, where the capacity will be sufficient. Also the failure mode broken fuse is assigned with the task run-to-failure. Here no preventive maintenance were technically feasible nor worth doing. Scheduled restoration to the distribution board is done each day. The environment will cause moisture and particles, which makes cleaning important.



Component	#	Failure mode	FP	RI	Maintenance task	Interval	Maintenance description
Battery modules	1.A	Depleted battery	F	7	Scheduled restoration	5 years	Change the battery cells.
	1.B	Thermal runaway	F	9	Scheduled on-condition	Continuous	Real time monitoring of battery modules through battery management system.
Electrical cables	2.A	Wire break	B	7	Run-to-failure	-	Change the cables with new ones, if failed.
Distribution board	3.A	Broken fuse	F	6	Run to failure	-	Identify broken fuse in the distribution panel. Flip it up.
	3.B	Breakdown	F	7	Scheduled restoration	1 day	Wipe the panel for moisture.

Figure 6.24: MTA for electrical power system

6.5 Bilge system

6.5.1 Functions

The bilge system's purpose is to empty the ferry's hull for any water. As mentioned earlier, there will be six bilge pumps in the ferry, where two are emergency pumps. The functional hierarchy for the system can be seen in Figure 6.25. The figure shows the primary function, remove bilge water, and the secondary functions.

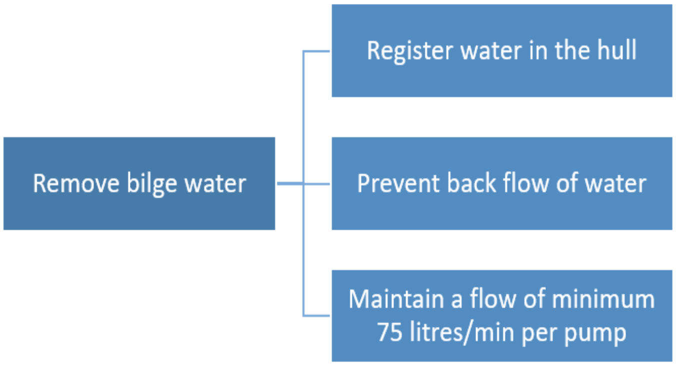


Figure 6.25: Functional hierarchy for the bilge system

6.5.2 Functional Failures

The relevant functional failures identified for the bilge system are listed below.

1. Does not register water in the hull
2. Backflow of water
3. Less than 75 litres per minute per pump

The first functional failure will lead to that the pump does not know that there is water in the hull, and the system will not work. Each pump is equipped with a float switch, which will be the device that detects the water. The non-return valve will hinder water from outside the ferry to get in. A malfunction to the valve will cause water to flow back into the hull, which is the second functional failure. The last functional failure is set by the regulations [37]. The fact that there are six bilge pumps where two are emergency bilge pumps makes the system redundant.

6.5.3 FMECA

The FMECA is performed on a component level, with the following components:

- Bilge pump
- Non return valve

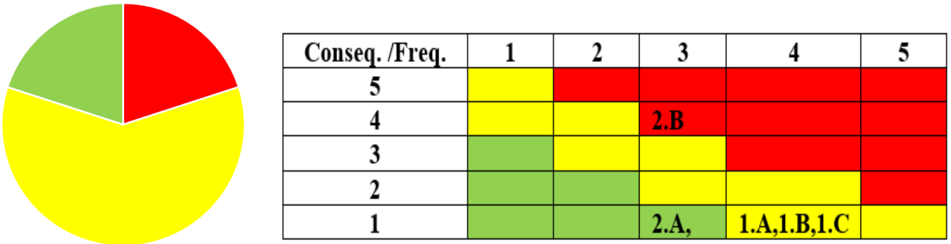
The FMECA worksheets from the analysis can be seen in Figure 6.27 and 6.28.

The failure modes for the bilge pump are based on forums and articles online that deals with troubles of bilge pumps [69]. The non-return valve is based on the functions for the component. The MTBF was found by using mechanical reliability data. Each failure mode for the components has the same MTBF, as the MTBF were only give for the whole component.

The system will operate under deck as an automatic system, which implies that all the failure modes will be hidden. Both of the components are mechanical components that are exposed to wear and tear, therefore all the failure patterns are age related failures.

The criticality of each of the failure modes for the two components are assessed. Due to the redundancy in the system none of the failure modes in the analysis will have severe effects on the system and asset. All of the failure modes are assessed to one when it comes to safety and environment, and to two when it comes to asset. None of the failure modes will affect the availability of the ferry.

The distribution of the risk index for the failure modes can be seen in Figure 6.26(a). The figure shows that only one of the failure modes are in the unacceptable area, and one in the acceptable area. Figure 6.26(b) shows the risk matrix for the system. All of the failure modes, expect the backflow of water, are placed low on the consequence category, this reflects the redundancy in the system. A total failure of one pump, will not affect the operation of the other pumps.



Conseq. /Freq.	1	2	3	4	5
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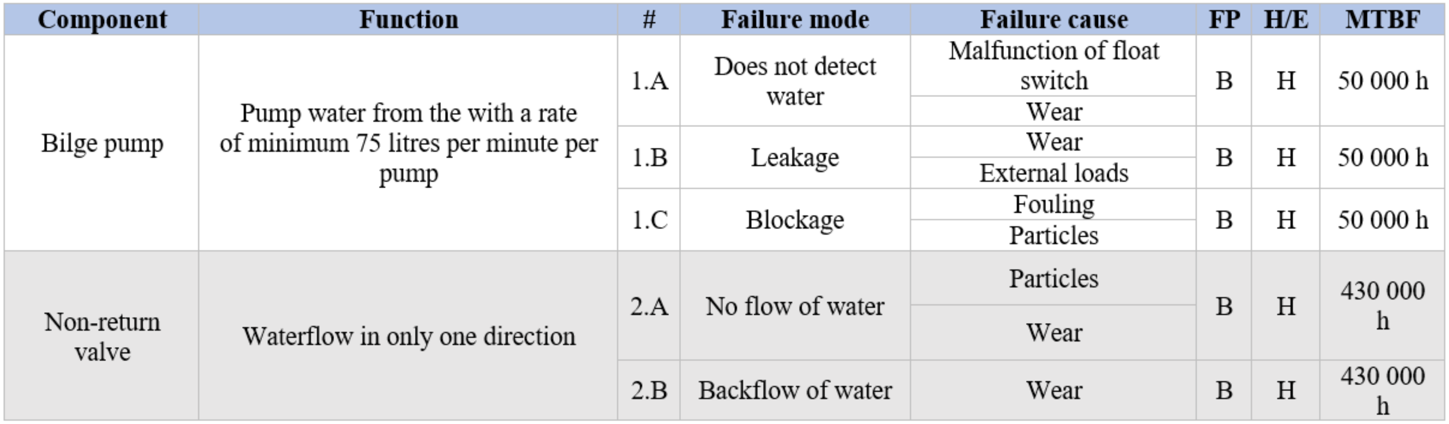
4	🟨	🟨	🟥 2.B	🟥	🟥
3	🟩	🟨	🟨	🟥	🟥
2	🟩	🟩	🟨	🟨	🟥
1	🟩	🟩	🟨 2.A,	🟨 1.A,1.B,1.C	🟨

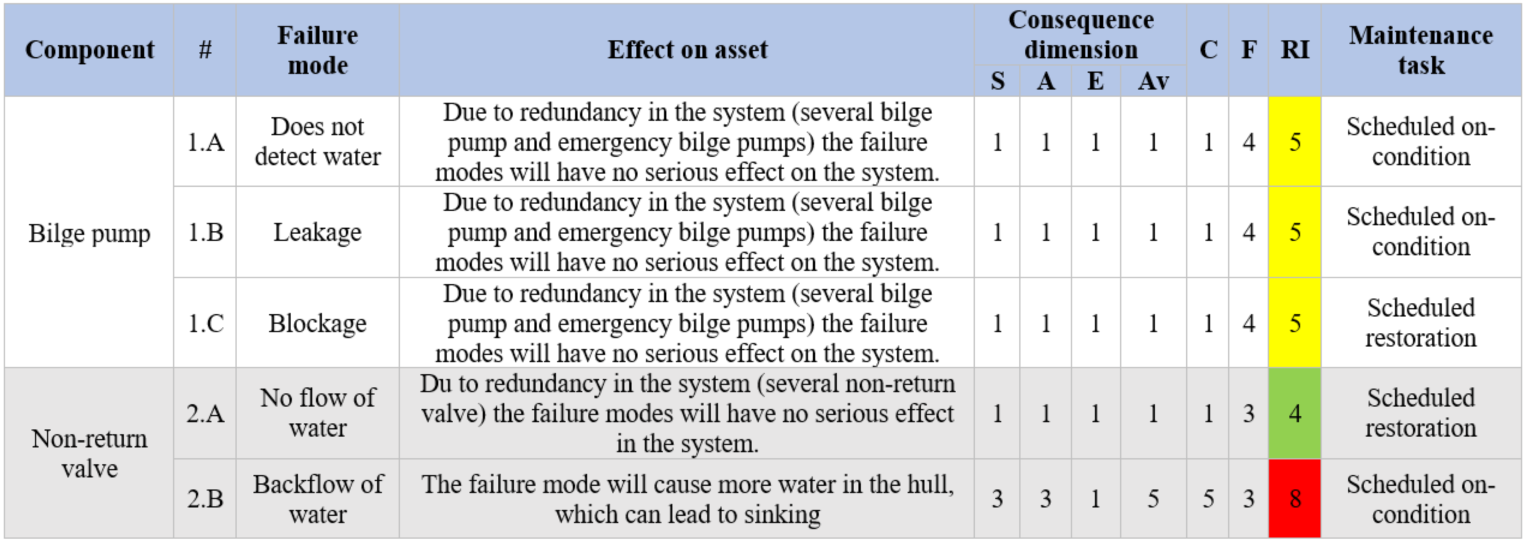
(a) (b)

Figure 6.26: Summary of risk index for bilge system



Component	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
Bilge pump	Pump water from the with a rate of minimum 75 litres per minute per pump	1.A	Does not detect water	Malfunction of float switch Wear	B	H	50 000 h
		1.B	Leakage	Wear External loads	B	H	50 000 h
		1.C	Blockage	Fouling Particles	B	H	50 000 h
Non-return valve	Waterflow in only one direction	2.A	No flow of water	Particles Wear	B	H	430 000 h
		2.B	Backflow of water	Wear	B	H	430 000 h

Figure 6.27: FMECA worksheet for bilge system, part 1



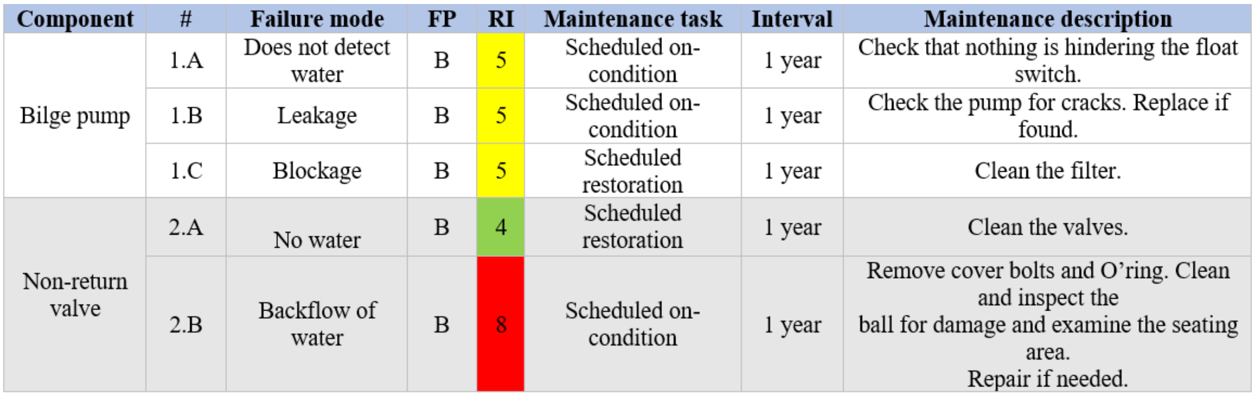
Component	#	Failure mode	Effect on asset	Consequence dimension				C	F	RI	Maintenance task
				S	A	E	Av				
Bilge pump	1.A	Does not detect water	Due to redundancy in the system (several bilge pump and emergency bilge pumps) the failure modes will have no serious effect on the system.	1	1	1	1	1	4	5	Scheduled on-condition
	1.B	Leakage	Due to redundancy in the system (several bilge pump and emergency bilge pumps) the failure modes will have no serious effect on the system.	1	1	1	1	1	4	5	Scheduled on-condition
	1.C	Blockage	Due to redundancy in the system (several bilge pump and emergency bilge pumps) the failure modes will have no serious effect on the system.	1	1	1	1	1	4	5	Scheduled restoration
Non-return valve	2.A	No flow of water	Du to redundancy in the system (several non-return valve) the failure modes will have no serious effect in the system.	1	1	1	1	1	3	4	Scheduled restoration
	2.B	Backflow of water	The failure mode will cause more water in the hull, which can lead to sinking	3	3	1	5	5	3	8	Scheduled on-condition

Figure 6.28: FMECA worksheet for bilge system, part 2

6.5.4 Maintenance Task Analysis

The MTA can be seen in Figure 6.29. All of the failure modes has been assigned to some sort of preventive maintenance task. One of the main reason for this is due to the fact that all of the failure modes are hidden, therefor run-to-failure is not appropriate.

The tasks for the two failure modes for non-return valves are based on description from manufacturer [70]. While the maintenance task for the bilge pumps are based on articles found online about maintenance of bilge pumps [71], [72]. The interval for the maintenance task is based on the MTBF and the fact that the tasks are simple. This means that they will not demand a great deal of time.



Component	#	Failure mode	FP	RI	Maintenance task	Interval	Maintenance description
Bilge pump	1.A	Does not detect water	B	5	Scheduled on-condition	1 year	Check that nothing is hindering the float switch.
	1.B	Leakage	B	5	Scheduled on-condition	1 year	Check the pump for cracks. Replace if found.
	1.C	Blockage	B	5	Scheduled restoration	1 year	Clean the filter.
Non-return valve	2.A	No water	B	4	Scheduled restoration	1 year	Clean the valves.
	2.B	Backflow of water	B	8	Scheduled on-condition	1 year	Remove cover bolts and O'ring. Clean and inspect the ball for damage and examine the seating area. Repair if needed.

Figure 6.29: Maintenance task analysis for bilge system

6.6 Battery cooling system

6.6.1 Function

The battery cooling system's purpose is to keep the temperature of the battery in the range of 18 °C ± 3°C [37]. The secondary functions are summed up in the functional hierarchy, shown in Figure 6.30. The top functions is the primary function for the system, which is to cool the battery to appropriate level. The three secondary functions are the ones supporting the top function, and these can be summed up to be circulation, regulation and monitoring.

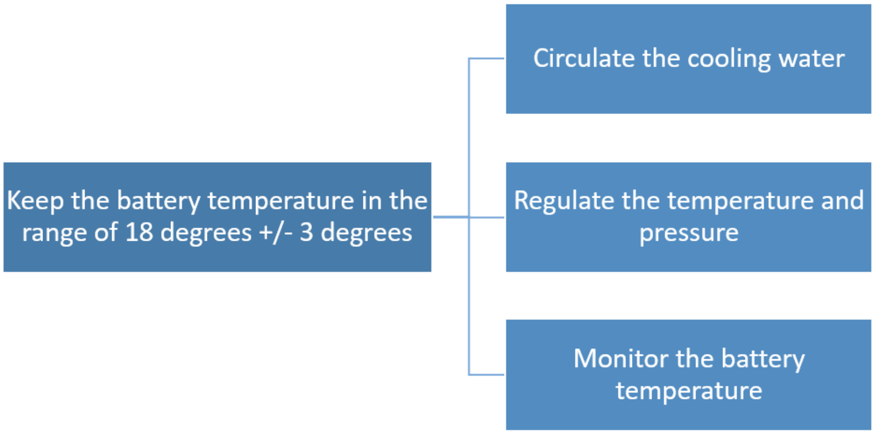


Figure 6.30: Functional hierarchy of the battery cooling system

The batteries are cooled with ionized water, which must be circulated through the system to have any effect. The systems also need a function which regulate the temperature and pressure in the system, in such a way that the temperature of the battery will always be in the right range.

6.6.2 Functional Failures

The functional failures identified for the battery cooling system are listed below.

1. No circulation of cooling water
2. Unable to regulate the temperature of the cooling water
3. Battery temperature is not monitored

All of these three functional failures will lead to the fact the battery cooling system will not work. The first functional failure involves that the ionized water will not flow through the pipes, which implies that the battery packages will not be cooled. As mentioned earlier, the battery packages will generate heat and if they are not cooled it can have fatal consequences. This functional failure can be caused by a failure in the circulation pump or failure to the pipes.

The second functional failure is when the system is unable to regulate the temperature and pressure of the coolant. If this failure continues over time the temperature of the battery packages can end up too warm, and even cause a fire.

The last functional failure is when the temperature of the battery packages is not monitored. This will lead to a situation where it is unknown how much cooling or heating the packages need. This can be caused by a failure in the temperature or pressure sensor.

6.6.3 FMECA

The components analyzed in the FMECA are:

- Pipes
- Circulation pump
- Temperature sensor
- Pressure sensor
- Temperature regulating valve

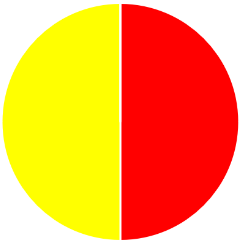
The FMECA worksheets for the battery cooling system are shown in Figure 6.32 and 6.33.

In total 8 failure modes were found relevant for the system. They were developed using the function statement for each component, and relevant sources. Failure modes for the pipes are adapted from the master thesis *Application of RCM to construct a Maintenance Program for a Maritime Vessel* [73], here it is assumed the same failure modes for smaller system as for bigger ones. It is also assumed that all pipes carrying any liquid will have the same performance. Relevant sources from the industry were found for failure modes and causes for the pressure and temperature sensor [74]. The temperature regulating valve is based on *Industrial Machinery Repair* [75]. The failure causes for the circulation pump are adapted from the seawater cooling system in the master thesis *Application of RCM to Construct a Maintenance Program for a Maritime Vessel* [73]. Here it is assumed that a circulation pump in a smaller system will have the same failure modes and causes as one in a more complex system. Also the MTBF were gathered there for the components. The MTBF were found for all components except the pipes, where they are assumed to have a MTBF of 10 years. The sources for the rest of the components are as following: circulation pump [76], temperature sensors [77], pressure sensor [78], temperature regulating valve [79].

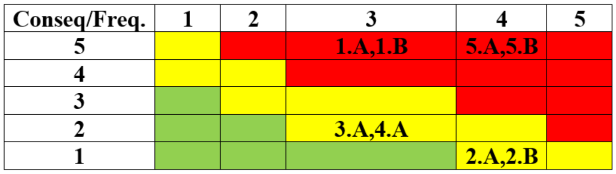
4 out of 8 failure modes in the system are in the unacceptable area. As mentioned they are ranked high on the consequence due to risk of fire. A fire will have a high impact on the safety, asset and environment. Since the ferry is small and fully electrical, the environment will not be affected to the same extent as the other categories.

All of the 8 failure modes are characterized as hidden. The system will operate automatically below deck. Since the ferry will be without any crew, there is no possibility to discover the failures by operating crew. The two sensors are assigned to failure pattern A, while the rest are assigned to failure pattern B.

The distribution of risk index is shown in Figure 6.31(a), and the risk matrix in Figure 6.31(b). Only two of the failure modes are in the ALARP-area, while the rest are in the unacceptable area. This is due to a combination of high consequence category and high frequency category. Many of the failure modes might result in fire, due to overheating of the battery and are therefore ranked high on the consequence scale.



(a)



Conseq/Freq.	1	2	3	4	5
5	🟨	🟥	🟥 1.A,1.B	🟥 5.A,5.B	🟥
4	🟨	🟨	🟥	🟥	🟥
3	🟩	🟨	🟨	🟥	🟥
2	🟩	🟩	🟨 3.A,4.A	🟨	🟥
1	🟩	🟩	🟩	🟨 2.A,2.B	🟨

(b)

Figure 6.31: Summary of risk index for battery cooling system

Component	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
Pipes	Contain and transport coolant	1.A	Leakage	Corrosion External loads	B	H	10 years*
		1.B	Blockage	Fouling Particles	B	H	10 years*
Circulation pump	Circulate the water through the pipes	2.A	Leakage	Wear	B	H	3.5 years
		2.B	Blockage	Fouling	B	H	3.5 years
Temperature sensor	Temperature control	3.A	No control of coolant temperature	Calibration error Mechanical damage Overheated	A	H	500 000 h
Pressure sensor	Pressure control	4.A	No control of coolant pressure	Calibration error Mechanical damage Overheated	A	H	2 000 000 h
Temperature regulating valve	Regulate the flow of coolant to keep the batteries in the right temperature range	5.A	Fails to open	Wear Corrosion Particles	B	H	82 000 h
		5.B	Fails to close	Wear Corrosion Particles	B	H	82 000 h

Figure 6.32: FMECA for battery cooling system, part 1

Component	#	Failure mode	Effect on asset	Consequence dimension				C	F	RI	Maintenance task
				S	A	E	Av				
Pipes	1.A	Leakage	Overheated battery which can cause fire.	5	5	2	5	5	3	8	Scheduled on-condition
	1.B	Blockage	Overheated battery, which can cause fire.	5	5	2	4	5	3	8	Scheduled restoration
Circulation pump	2.A	Leakage	Due to redundancy in the system, the failure mode has no serious effect on the asset.	1	1	1	1	1	4	5	Scheduled on-condition
	2.B	Blockage	Due to redundancy in the system, the failure mode has no serious effect on the asset.	1	1	1	1	1	4	5	Scheduled restoration
Temperature sensor	3.A	No control of temperature	Reduced lifetime of battery packages.	1	2	1	1	2	3	5	Scheduled discard
Pressure sensor	4.A	No control of pressure	Reduced lifetime of battery packages.	1	2	1	1	2	3	5	Scheduled discard
Temperature regulating valve	5.A	Fails to open	Overheated battery which can cause fire.	5	5	2	5	5	4	9	Scheduled discard
	5.B	Fails to close	Overheated battery which can cause fire.	5	5	2	5	5	4	9	Scheduled discard

Figure 6.33: FMECA for battery cooling system, part 2

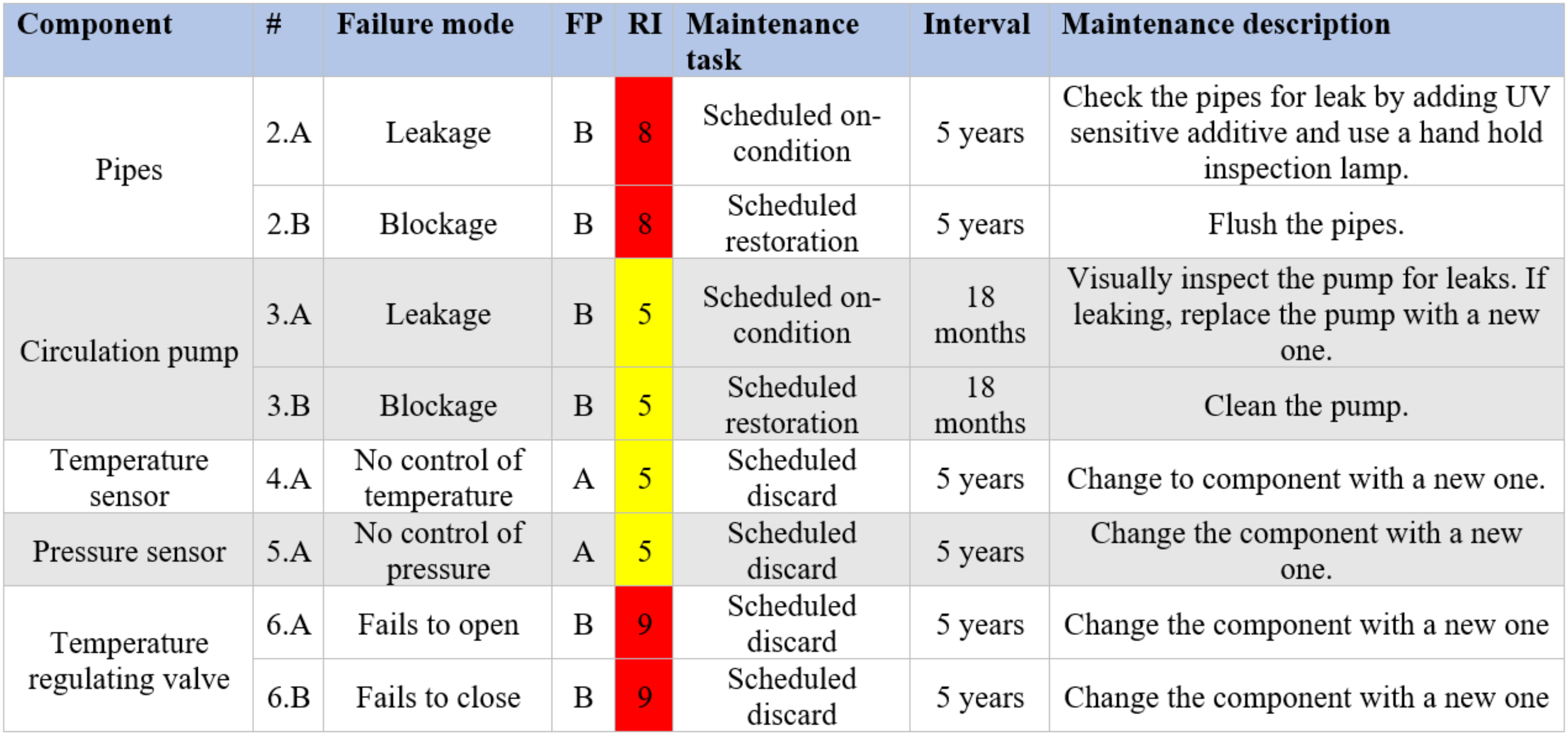
6.6.4 Maintenance Task Analysis

Figure 6.34 shows the MTA for the system. From the figure it is clear that all of the failure modes has been assigned to preventive maintenance, either scheduled on-condition, scheduled restoration or scheduled discard. One of the reasons why preventive maintenance is chosen is the fact that the failure modes are hidden and in the unacceptable or in the ALARP area. The pipes, which works both to circulate the water and as outboard heat exchanger, may be subjected to leak or blockage. They are checked with regular intervals for leakages. The simplest approach to check for leaks are through visual inspection [80]. The inspection includes adding a UV sensitive fluid to the system, and use of an inspection lamp to check for leaks. Blockage is prevented by flushing the pipes. It is assumed that there will be easy access to the pipes, and that there is a possibility to connect them to a high-pressure cleaner.

The circulation pump needs to be cleaned and checked for leaks as well. The scheduled on-condition interval for both failure modes are set to 1.5 years, even though the MTBF is 3.5 years. This is because the circulation pump is a critical component in the system, which needs attention. Many of the pumps that are on the marked to day are so called maintenance free pumps, which implies that maintenance should not be needed. Therefore the action is to change the pump if any deviations are noticed.

For the components temperature sensors, pressure sensor and temperature regulating valve scheduled discard is recommended. All of them has hidden failure modes, placed either in the ALARP area or the unacceptable one.

Since some of the effects of the failure modes may in worst case result in a fire, these failure modes must be subjected to preventive maintenance. This will be cost effective since the effects of the failure mode may lead to loss of the investment. The rest of the failure modes will have an impact on the performance of the system. For a system as battery cooling it is crucial that it will operate efficiently, if not it may impact the other components in the system.



Component	#	Failure mode	FP	RI	Maintenance task	Interval	Maintenance description
Pipes	2.A	Leakage	B	8	Scheduled on-condition	5 years	Check the pipes for leak by adding UV sensitive additive and use a hand hold inspection lamp.
	2.B	Blockage	B	8	Scheduled restoration	5 years	Flush the pipes.
Circulation pump	3.A	Leakage	B	5	Scheduled on-condition	18 months	Visually inspect the pump for leaks. If leaking, replace the pump with a new one.
	3.B	Blockage	B	5	Scheduled restoration	18 months	Clean the pump.
Temperature sensor	4.A	No control of temperature	A	5	Scheduled discard	5 years	Change to component with a new one.
Pressure sensor	5.A	No control of pressure	A	5	Scheduled discard	5 years	Change the component with a new one.
Temperature regulating valve	6.A	Fails to open	B	9	Scheduled discard	5 years	Change the component with a new one
	6.B	Fails to close	B	9	Scheduled discard	5 years	Change the component with a new one

Figure 6.34: MTA for battery cooling system

6.7 Safety system

6.7.1 Function

The primary function for the safety system will be to keep the passengers safe at all time. Figure 6.35 shows the functional hierarchy for the system.

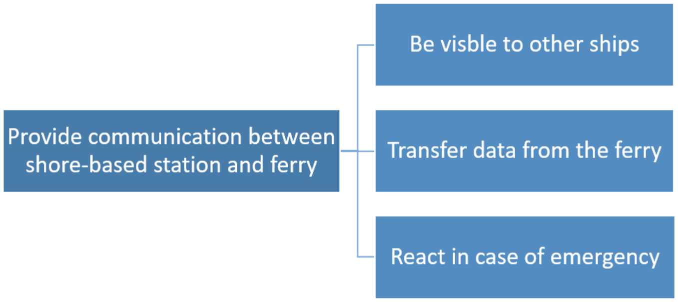


Figure 6.35: Functional hierarchy for the safety system

6.7.2 Functional Failures

A total of three functional failures were found relevant for the safety system, see below.

1. Not enough life jackets
2. Fails to extinguish fires
3. No detection and alarming of fires

The first functional failure is a violation of the regulations given by the NMA. A situation where the jackets are needed is a critical situation, therefore it can have severe consequences if there are not enough for all of the passengers. The systems shall also be able to protect the passengers against fires. This is done through the sprinkler system and the external fire extinguisher. A situation where the system is not triggered in case of fire, will harm the reputation for the ferry greatly. The last functional failure is when the detectors are not able to detect and alarm the shore-based station, also this will affect the reputation.

6.7.3 FMECA

The components analyzed in the FMECA are as follows.

- Fire alarm
- Novec 1230 facility
- External fire extinguisher

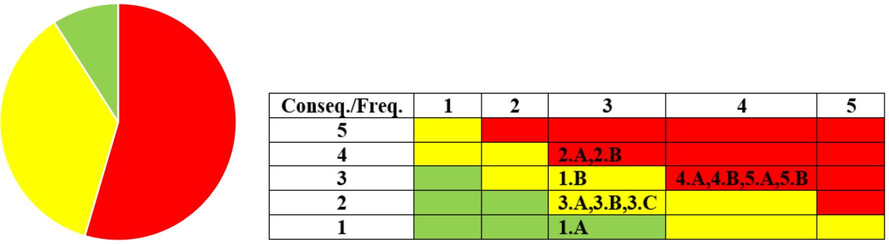
- Life jackets
- Life buoy

In the analysis the Novec 1230 facility is treated as one component. This is due to lack of information. The FMECA worksheets can be seen in Figure 6.37 and 6.38.

The failure modes are based on the functions for each component. In addition are NS 3910 used for failure modes for the external fire extinguisher [81]. When it comes to MTBF it is assumed that the life jackets and life buoy will have a MTBF of 3 years. Here factors like the environment taken into account. The Novec 1230 and external fire extinguisher are based on the same source [82], while the fire alarm is based on [83].

In total 11 failure modes were found relevant for the system. All of the failure modes were evaluated to be hidden. The system will only operate when a situation occurs, for example fire, therefore the failure modes will be hidden.

Failures to the safety system can have severe consequences for the passengers. In addition to the consequences for the passengers are the consequences for not following rules and regulations. Figure 6.36(a) shows the distribution of risk index for the failure modes, while 6.36(b) shows the risk matrix. The figure shows that most of the failure modes are in the unacceptable or the ALARP-area.



Conseq./Freq.	1	2	3	4	5
5	🟨	🟥	🟥	🟥	🟥
4	🟨	🟨	🟥 2.A,2.B	🟥	🟥
3	🟩	🟨	🟨 1.B	🟥 4.A,4.B,5.A,5.B	🟥
2	🟩	🟩	🟨 3.A,3.B,3.C	🟨	🟥
1	🟩	🟩	🟩 1.A	🟨	🟨

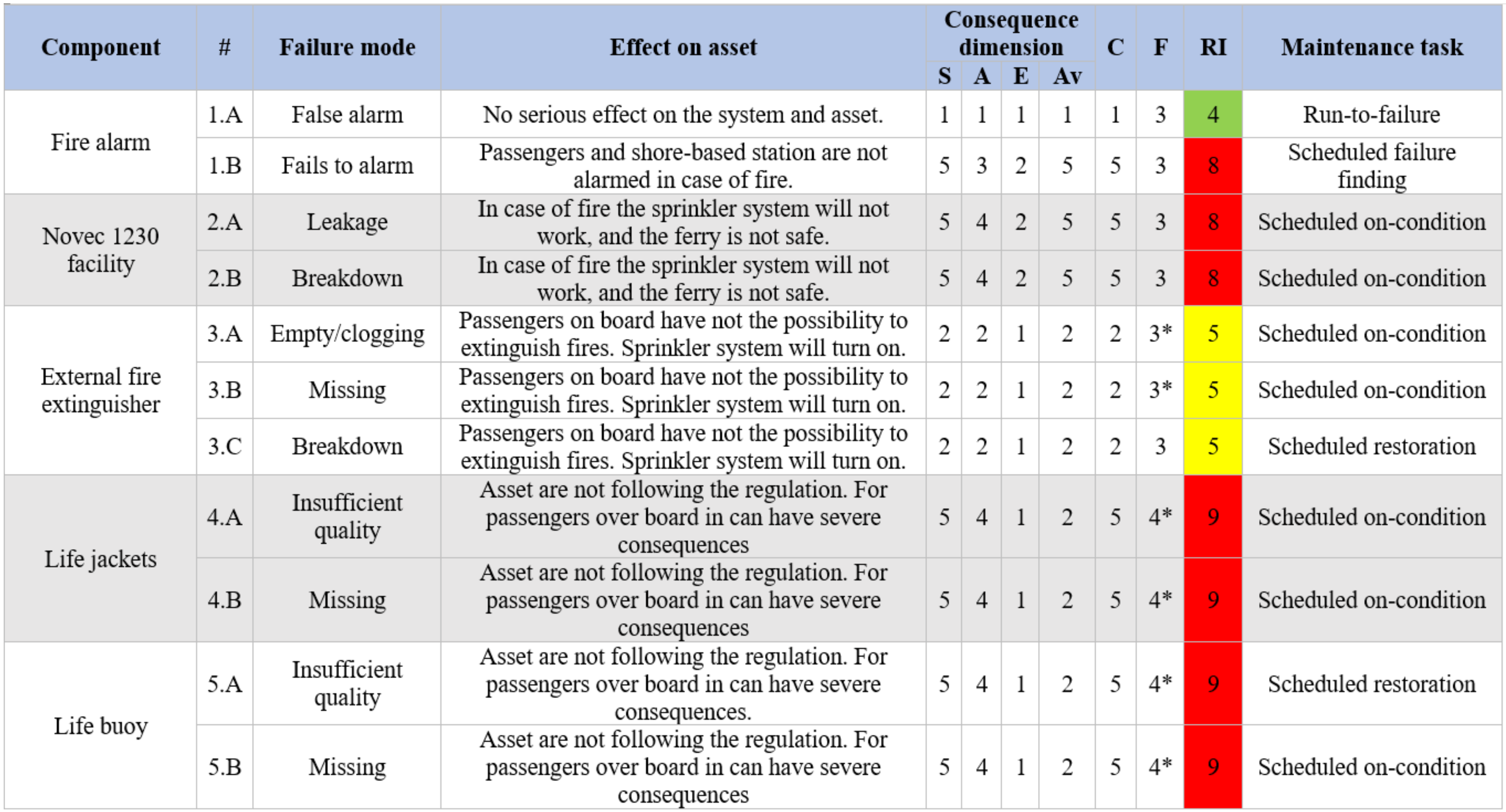
(a) Risk index for safety system

(b) Risk matrix for safety system

Figure 6.36: Summary of FMECA for safety system

Component	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
Fire alarm	Alarm passenger and shore-based station in case of fire	1.A	False alarm	Electrical malfunction	A	H	330 000 h
		1.B	Fails to alarm	Electronic malfunction	A	H	330 000 h
Novec 1230 facility	Put out fire	2.A	Leakage	External loads	B	H	250 000 h
				Wear			
		2.B	Breakdown	Malfunction	A	H	250 000 h
External fire extinguisher	Put out fire	3.A	Empty/clogging	Human actions	B	H	-
				Leakage			
		3.B	Missing	Human actions	E	H	-
		3.C	Breakdown	Malfunction	A	H	250 000 h
Life jackets	Keep passengers afloat in the water	4.A	Insufficient quality	Material failure	B	H	3 years*
				Wear			
		4.B	Missing	Human actions	E	H	-
Life buoy	Keep passengers afloat in the water	5.A	Insufficient quality	Material failure	B	H	3 years*
				Wear			
		5.B	Missing	Human actions	E	H	-

Figure 6.37: FMECA for safety system, part 1



Component	#	Failure mode	Effect on asset	Consequence dimension				C	F	RI	Maintenance task
				S	A	E	Av				
Fire alarm	1.A	False alarm	No serious effect on the system and asset.	1	1	1	1	1	3	4	Run-to-failure
	1.B	Fails to alarm	Passengers and shore-based station are not alarmed in case of fire.	5	3	2	5	5	3	8	Scheduled failure finding
Novec 1230 facility	2.A	Leakage	In case of fire the sprinkler system will not work, and the ferry is not safe.	5	4	2	5	5	3	8	Scheduled on-condition
	2.B	Breakdown	In case of fire the sprinkler system will not work, and the ferry is not safe.	5	4	2	5	5	3	8	Scheduled on-condition
External fire extinguisher	3.A	Empty/clogging	Passengers on board have not the possibility to extinguish fires. Sprinkler system will turn on.	2	2	1	2	2	3*	5	Scheduled on-condition
	3.B	Missing	Passengers on board have not the possibility to extinguish fires. Sprinkler system will turn on.	2	2	1	2	2	3*	5	Scheduled on-condition
	3.C	Breakdown	Passengers on board have not the possibility to extinguish fires. Sprinkler system will turn on.	2	2	1	2	2	3	5	Scheduled restoration
Life jackets	4.A	Insufficient quality	Asset are not following the regulation. For passengers over board in can have severe consequences	5	4	1	2	5	4*	9	Scheduled on-condition
	4.B	Missing	Asset are not following the regulation. For passengers over board in can have severe consequences	5	4	1	2	5	4*	9	Scheduled on-condition
Life buoy	5.A	Insufficient quality	Asset are not following the regulation. For passengers over board in can have severe consequences.	5	4	1	2	5	4*	9	Scheduled restoration
	5.B	Missing	Asset are not following the regulation. For passengers over board in can have severe consequences	5	4	1	2	5	4*	9	Scheduled on-condition

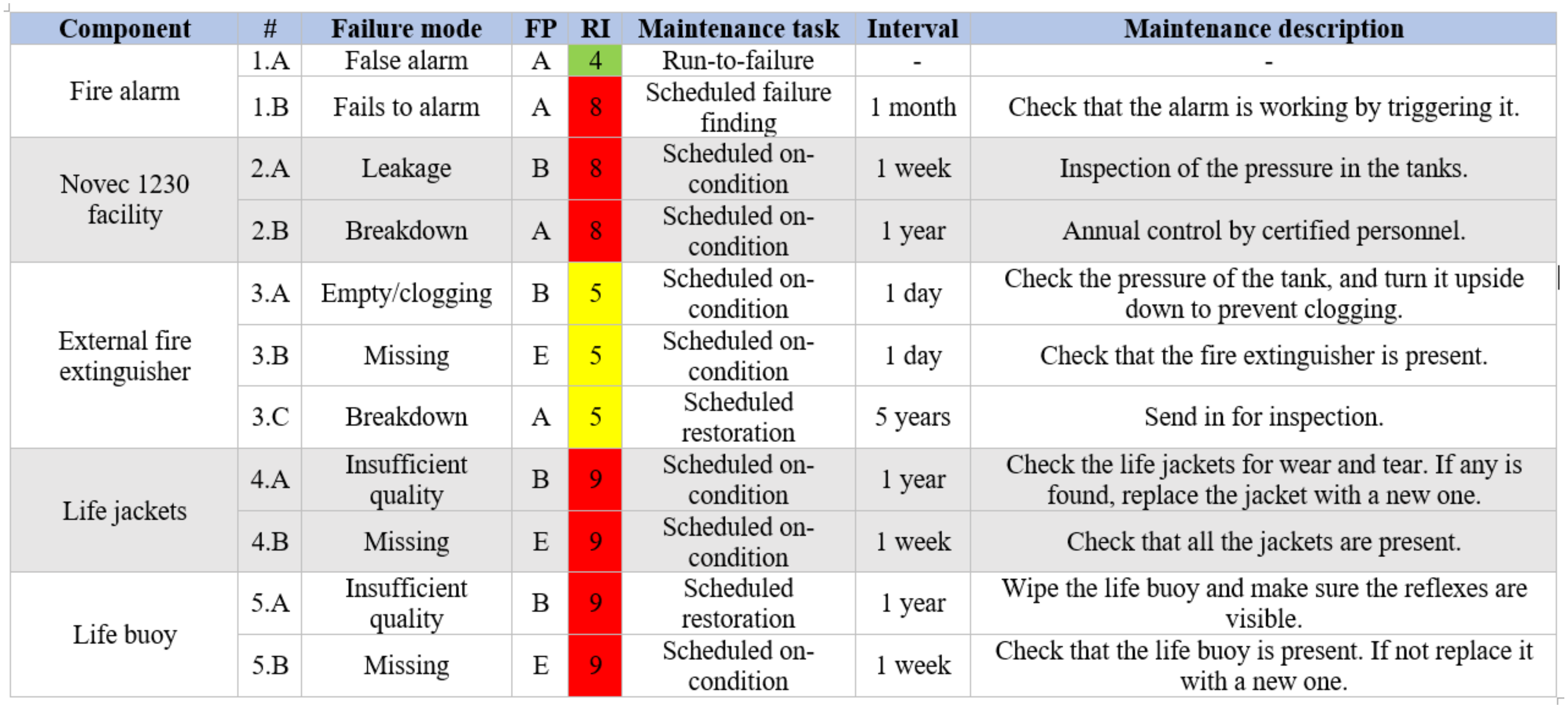
Figure 6.38: FMECA for safety system, part 2

6.7.4 Maintenance Task Analysis

Figure 6.39 shows the MTA for the system. The figure shows that only one failure mode is assigned to run-to-failure, while the rest are assigned to some sort of preventive maintenance. A false alarm will not affect the safety nor the asset, and to do some sort of preventive maintenance here is not feasible.

The Novec 1230 facility needs preventive maintenance. Firstly the tanks needs to be checked against leakage, which is done once a week [37]. In addition an annual control done by certified personnel is needed [37].

The standard NS 3910 deals with maintenance of external fire extinguishers, and is used in this thesis. Each quarter of a year an inspection is needed. Here the placement is checked and that it has easy access. In addition the extinguisher needs to be turned up side down to prevent the content to clog. Also a periodic restoration performed by qualified personnel each 5th year has to be performed.



Component	#	Failure mode	FP	RI	Maintenance task	Interval	Maintenance description
Fire alarm	1.A	False alarm	A	4	Run-to-failure	-	-
	1.B	Fails to alarm	A	8	Scheduled failure finding	1 month	Check that the alarm is working by triggering it.
Novec 1230 facility	2.A	Leakage	B	8	Scheduled on-condition	1 week	Inspection of the pressure in the tanks.
	2.B	Breakdown	A	8	Scheduled on-condition	1 year	Annual control by certified personnel.
External fire extinguisher	3.A	Empty/clogging	B	5	Scheduled on-condition	1 day	Check the pressure of the tank, and turn it upside down to prevent clogging.
	3.B	Missing	E	5	Scheduled on-condition	1 day	Check that the fire extinguisher is present.
	3.C	Breakdown	A	5	Scheduled restoration	5 years	Send in for inspection.
Life jackets	4.A	Insufficient quality	B	9	Scheduled on-condition	1 year	Check the life jackets for wear and tear. If any is found, replace the jacket with a new one.
	4.B	Missing	E	9	Scheduled on-condition	1 week	Check that all the jackets are present.
Life buoy	5.A	Insufficient quality	B	9	Scheduled restoration	1 year	Wipe the life buoy and make sure the reflexes are visible.
	5.B	Missing	E	9	Scheduled on-condition	1 week	Check that the life buoy is present. If not replace it with a new one.

Figure 6.39: MTA for safety system

6.8 Mooring system

6.8.1 Functions

The primary function of the mooring system is to let passengers on and off the ferry when arriving the quay. The functional hierarchy is shown in Figure 6.40.

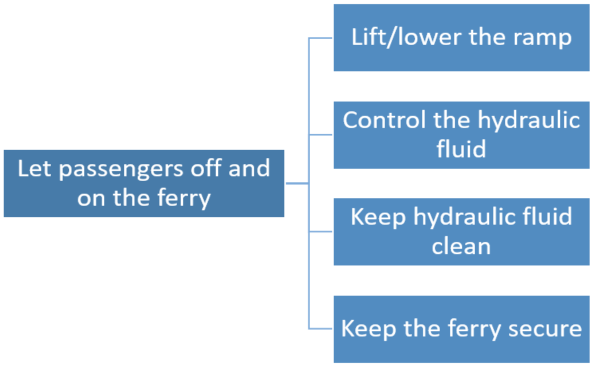


Figure 6.40: Functional hierarchy for the mooring system

The hydraulic system will lower and lift the ramp, while the ramp will be the connection to land. The ferry is secured to land through a notch at the quay. This notch is not included further in the analysis, due to the lack of information. There are more functions that has not been included in the analysis. These are functions such as cooling the oil and separation of fluid, which is done by the reservoir.

6.8.2 Functional Failures

The functional failures identified for the system are listed below.

- No connection between the ferry and land
- No control of hydraulic fluid
- Contaminated hydraulic fluid
- Ferry not secured

The first functional failure is due to a failure in the ramp or the hydraulics. This causes that the ramp can not be lowered or lifted. The next functional failure is due to failure of either pressure relief valve of directional control valve. These two components are supposed to have control over the fluid, the ramp is lifted or lowered and over pressure is prevented. To have a well working system, the hydraulic fluid needs to be kept clean. This is done by filtering the fluid, and being precocious when it comes to dirt and particles. The last functional failure are due to a failure in the notch system and/or ramp, which is not analyzed further.

6.8.3 FMECA

The component analyzed in the FMECA are the following:

- Ramp
- Hydraulic cylinder
- Hydraulic pump
- Filter
- Reservoir
- Pressure relief valve
- Direction control valve
- Hydraulic fluid

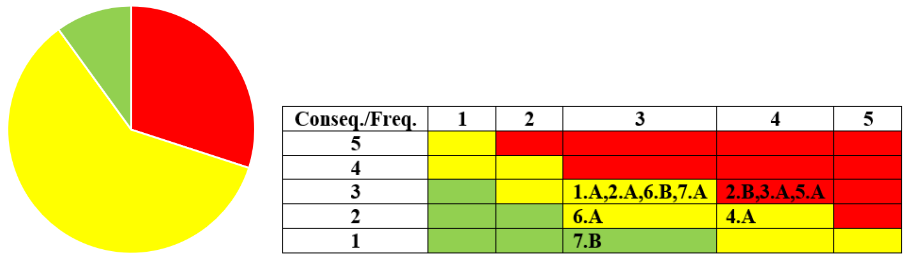
The FMECA worksheets can be seen in Figure 6.42 and 6.43.

12 failure modes were found relevant for the analysis. The failure modes are developed using the functions for each component, which is done with the help from *Oil Hydraulic Systems; Principles and Maintenance* [46]. MTBF for damaged ramp was decided not to be relevant, a frequency category was assumed based on guesswork. In addition no relevant MTBF for leaking of hydraulic cylinder, failure modes for hydraulic pump, filter or contaminated reservoir were found either. A frequency class for each failure modes were assumed. For the other components the following sources were used: misalignment of hydraulic cylinder [84], pressure relief valve and directional control valve [85], hydraulic fluid [46].

The criticality of each failure mode has been assessed in the light of the four categories. None of the failure modes will affect the safety in a negative way. One might think that a failure to the pressure relief valve would be harmful, but the pressure in the system will no be that large. It is the asset category and availability category that is the most affected by the failure modes.

When it comes to the asset category, it is assumed that a loss of mooring function will give a severity of 3. This is due to the fact that this will lead to loss of main parts of the system. The failure modes that concerns the filter and pressure relief valve are set to have an severity of two. This is due to the fact that they will not lead to immediately loss of function, and are characterized as minor system damages.

The system will be a system that the passengers are total dependant on to get on and off the ferry, and the system will either work or not. All of the failure modes are categorized as B when it comes to failure pattern. Since all of the components are mechanical, and will be exposed to wear. Figure 6.41 shows a summary of the risk index given for the failure modes and the split between unacceptable, ALARP and acceptable. There are two failure modes which are in the unacceptable area, while one is in the acceptable area.

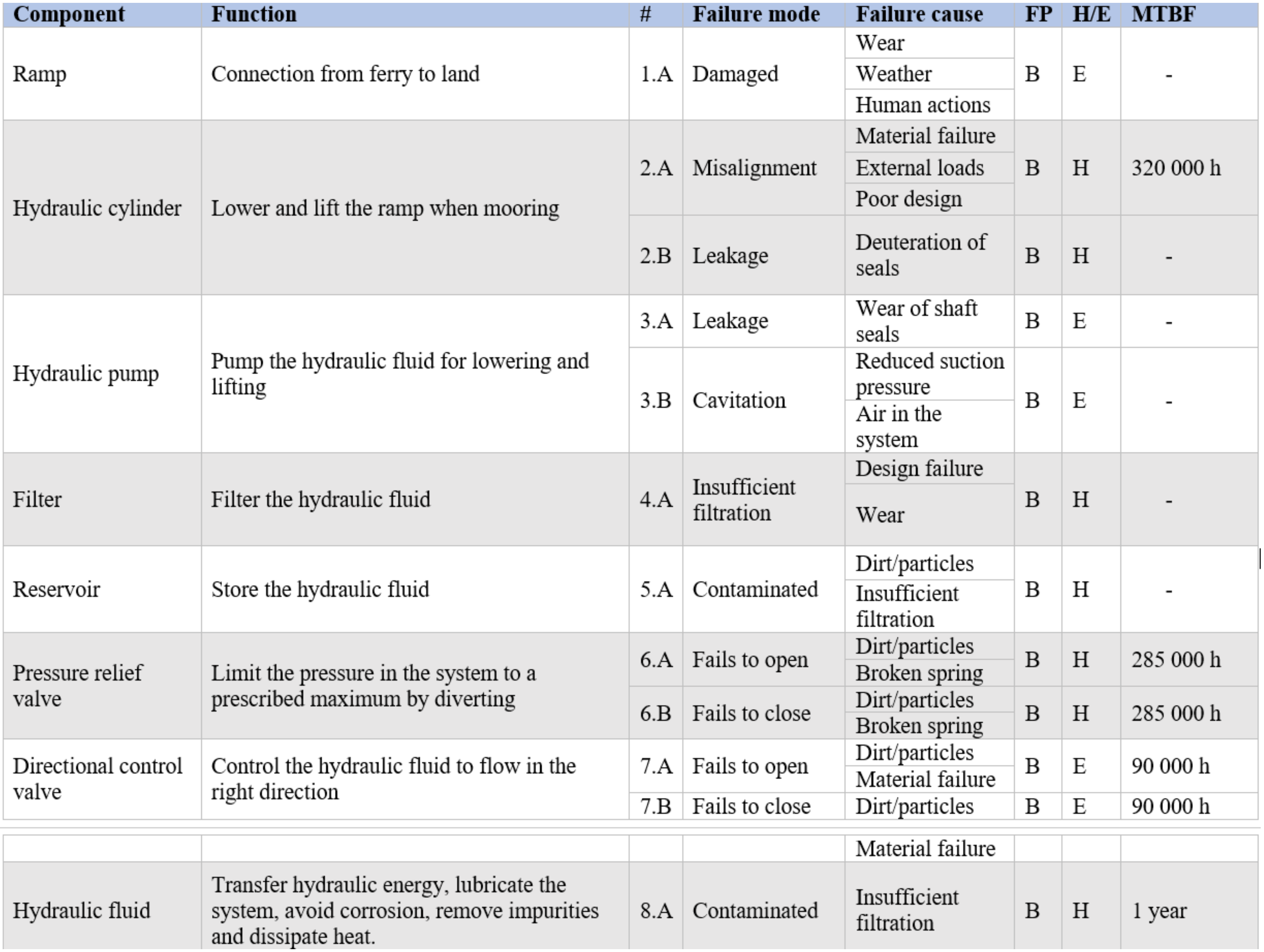


Conseq./Freq.	1	2	3	4	5
5	🟨	🟥	🟥	🟥	🟥
4	🟨	🟨	🟥	🟥	🟥
3	🟩	🟨	🟨 1.A,2.A,6.B,7.A	🟥 2.B,3.A,5.A	🟥
2	🟩	🟩	🟨 6.A	🟨 4.A	🟥
1	🟩	🟩	🟩 7.B	🟨	🟨

(a) Risk index for the mooring system

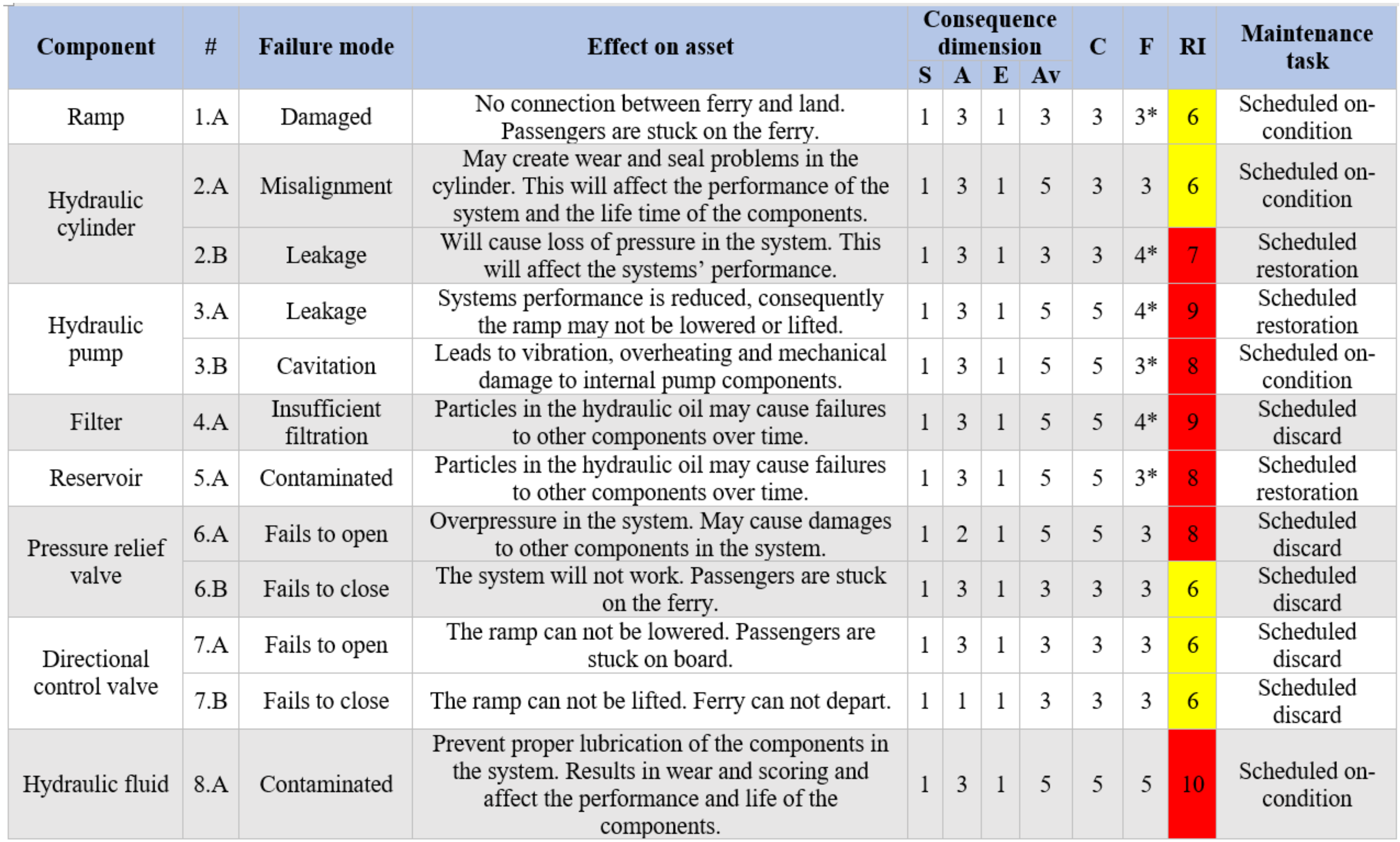
(b) Risk matrix for the mooring system

Figure 6.41: Summary for risk index for mooring system



Component	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
Ramp	Connection from ferry to land	1.A	Damaged	Wear Weather Human actions	B	E	-
Hydraulic cylinder	Lower and lift the ramp when mooring	2.A	Misalignment	Material failure External loads Poor design	B	H	320 000 h
		2.B	Leakage	Deuteration of seals	B	H	-
Hydraulic pump	Pump the hydraulic fluid for lowering and lifting	3.A	Leakage	Wear of shaft seals	B	E	-
		3.B	Cavitation	Reduced suction pressure Air in the system	B	E	-
Filter	Filter the hydraulic fluid	4.A	Insufficient filtration	Design failure Wear	B	H	-
Reservoir	Store the hydraulic fluid	5.A	Contaminated	Dirt/particles Insufficient filtration	B	H	-
Pressure relief valve	Limit the pressure in the system to a prescribed maximum by diverting	6.A	Fails to open	Dirt/particles Broken spring	B	H	285 000 h
		6.B	Fails to close	Dirt/particles Broken spring	B	H	285 000 h
Directional control valve	Control the hydraulic fluid to flow in the right direction	7.A	Fails to open	Dirt/particles Material failure	B	E	90 000 h
		7.B	Fails to close	Dirt/particles Material failure	B	E	90 000 h
Hydraulic fluid	Transfer hydraulic energy, lubricate the system, avoid corrosion, remove impurities and dissipate heat.	8.A	Contaminated	Insufficient filtration	B	H	1 year

Figure 6.42: FMECA of mooring system, part 1



Component	#	Failure mode	Effect on asset	Consequence dimension				C	F	RI	Maintenance task
				S	A	E	Av				
Ramp	1.A	Damaged	No connection between ferry and land. Passengers are stuck on the ferry.	1	3	1	3	3	3*	6	Scheduled on-condition
Hydraulic cylinder	2.A	Misalignment	May create wear and seal problems in the cylinder. This will affect the performance of the system and the life time of the components.	1	3	1	5	3	3	6	Scheduled on-condition
	2.B	Leakage	Will cause loss of pressure in the system. This will affect the systems' performance.	1	3	1	3	3	4*	7	Scheduled restoration
Hydraulic pump	3.A	Leakage	Systems performance is reduced, consequently the ramp may not be lowered or lifted.	1	3	1	5	5	4*	9	Scheduled restoration
	3.B	Cavitation	Leads to vibration, overheating and mechanical damage to internal pump components.	1	3	1	5	5	3*	8	Scheduled on-condition
Filter	4.A	Insufficient filtration	Particles in the hydraulic oil may cause failures to other components over time.	1	3	1	5	5	4*	9	Scheduled discard
Reservoir	5.A	Contaminated	Particles in the hydraulic oil may cause failures to other components over time.	1	3	1	5	5	3*	8	Scheduled restoration
Pressure relief valve	6.A	Fails to open	Overpressure in the system. May cause damages to other components in the system.	1	2	1	5	5	3	8	Scheduled discard
	6.B	Fails to close	The system will not work. Passengers are stuck on the ferry.	1	3	1	3	3	3	6	Scheduled discard
Directional control valve	7.A	Fails to open	The ramp can not be lowered. Passengers are stuck on board.	1	3	1	3	3	3	6	Scheduled discard
	7.B	Fails to close	The ramp can not be lifted. Ferry can not depart.	1	1	1	3	3	3	6	Scheduled discard
Hydraulic fluid	8.A	Contaminated	Prevent proper lubrication of the components in the system. Results in wear and scoring and affect the performance and life of the components.	1	3	1	5	5	5	10	Scheduled on-condition

Figure 6.43: FMECA of mooring system, part 2

6.8.4 Maintenance Task Analysis

The MTA for the mooring system can be seen in Figure 6.44. All of the failure modes has been assigned to preventive maintenance. This is a consequence of expensive components, loss of reputation and loss of income. The expense items used in the cost analysis are shown in Table 6.8. This table does not include loss of income and duration of repair, since these costs will have little impact. As mentioned, none of the failure mode will affect the safety for the passengers.

The smallest components such as filter, pressure relief valve and directional control valve are assigned to scheduled discard. These components has small parts, which will make it difficult to restore them to initial capability.

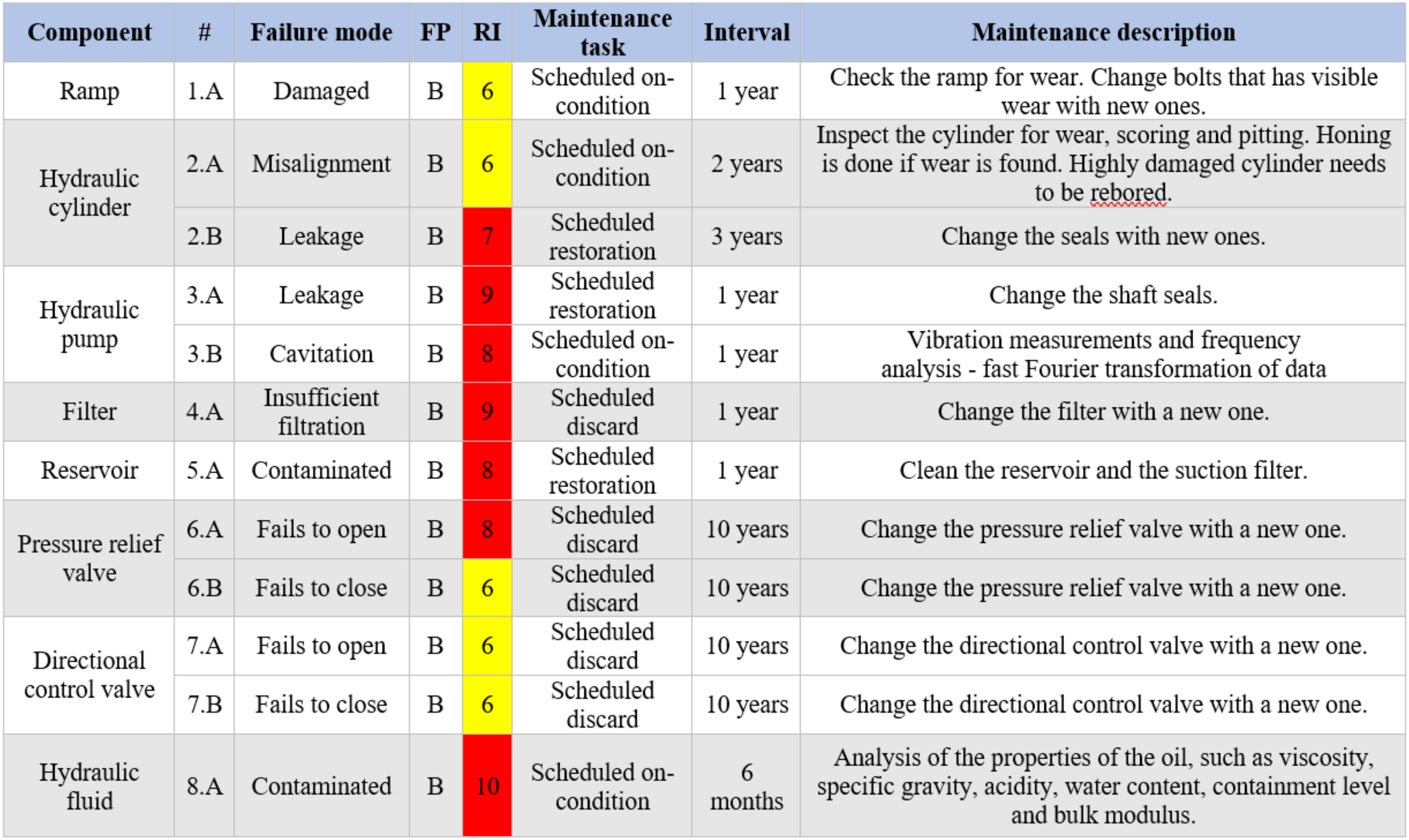
Loss of reputation will, as mentioned above, be a major part of the costs for the system. For situations where passengers may be on board and are unable to get off due to the mooring system, has been given a level 3 when it comes to loss of reputation. Failure modes that will only affect the systems lifetime and performance is given level 1. These are failure modes which the passengers will not notice at first, but may notice as the ferry deteriorates faster than expected. Failure modes which are noticeable to the passengers, for example failure modes that leads to vibration, are assigned to level 2.

A new ramp is assumed to cost 10 000 NOK. No information was found here, so this is pure guesswork. For the spare parts it is assumed that a failure modes that has deteriorated the system will cause that a whole new component is needed.

The most important component in the system is the hydraulic fluid, as it will flow through the whole system. Therefore the system will not be healthier than the hydraulic fluid.

Table 6.8: Expense items for cost calculation of mooring system

FM	Spare part costs	Loss of Reputation class	Injury costs	Hours available
1.A	10 000	3	0	439
2.A	8 000	1	0	57
2.B	8 000	1	0	37
3.A	4 000	3	0	417
3.B	4 000	2	0	54
4.A	100	1	0	40
5.A	1000	1	0	41
6.A	800	1	0	40
6.B	800	3	0	376
7.A	2000	3	0	396
7.B	2000	3	0	396
8.A	1000	2	0	33



Component	#	Failure mode	FP	RI	Maintenance task	Interval	Maintenance description
Ramp	1.A	Damaged	B	6	Scheduled on-condition	1 year	Check the ramp for wear. Change bolts that has visible wear with new ones.
Hydraulic cylinder	2.A	Misalignment	B	6	Scheduled on-condition	2 years	Inspect the cylinder for wear, scoring and pitting. Honing is done if wear is found. Highly damaged cylinder needs to be rebored.
	2.B	Leakage	B	7	Scheduled restoration	3 years	Change the seals with new ones.
Hydraulic pump	3.A	Leakage	B	9	Scheduled restoration	1 year	Change the shaft seals.
	3.B	Cavitation	B	8	Scheduled on-condition	1 year	Vibration measurements and frequency analysis - fast Fourier transformation of data
Filter	4.A	Insufficient filtration	B	9	Scheduled discard	1 year	Change the filter with a new one.
Reservoir	5.A	Contaminated	B	8	Scheduled restoration	1 year	Clean the reservoir and the suction filter.
Pressure relief valve	6.A	Fails to open	B	8	Scheduled discard	10 years	Change the pressure relief valve with a new one.
	6.B	Fails to close	B	6	Scheduled discard	10 years	Change the pressure relief valve with a new one.
Directional control valve	7.A	Fails to open	B	6	Scheduled discard	10 years	Change the directional control valve with a new one.
	7.B	Fails to close	B	6	Scheduled discard	10 years	Change the directional control valve with a new one.
Hydraulic fluid	8.A	Contaminated	B	10	Scheduled on-condition	6 months	Analysis of the properties of the oil, such as viscosity, specific gravity, acidity, water content, containment level and bulk modulus.

Figure 6.44: MTA for mooring system

6.9 Communication and visibility system

6.9.1 Functions

The primary and secondary functions for the system are shown in the functional hierarchy in Figure 6.45.

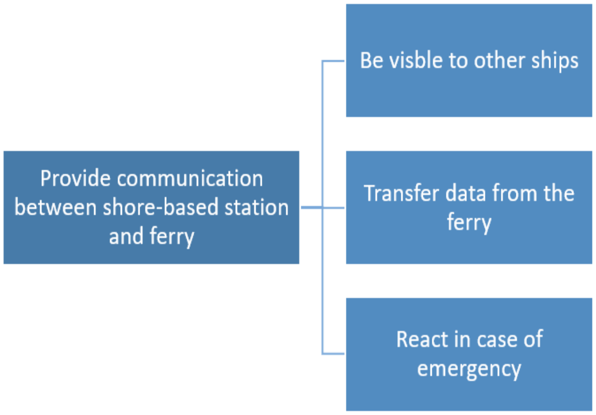


Figure 6.45: Functional hierarchy for the communication and visibility system

This is the system that shall provide the communication from the ferry to the shore-based station.

6.9.2 Functional Failures

The functional failures for the communication and visibility system are listed below.

1. Not visible to other ships
2. No transfer of data from the ferry
3. Unable to communicate with the passengers
4. Unable to stop the ferry

The first functional failure is a violation to the regulations [86]. While the next one implies that the shore-based station is not updated with information from the ferry. This is information about the speed, heading, position, but also information about the components that are monitored. The third functional failure is due to a failure in the two-way radio. The ferry is equipped with an emergency stop button, which will stop the ferry and hold the position through dynamic positioning (DP).

6.9.3 FMECA

The analysis has been performed on the component level, and the components are as follows:

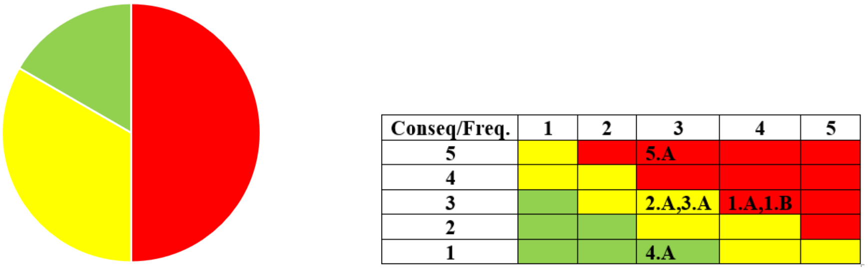
- To-way radio
- Modem
- Router
- Lanterns
- Emergency stop button

Figure 6.47 and 6.48 shows the analysis done for the system.

A total of six failure modes were found relevant for the system. These are based on the function for the components.The MTBF's for the components has the following sources: to-way radio [87], modem and router [88], lanterns [89], emergency stop button [90]. Modem and router are assumed to have the same MTBF, since relevant data for router were not found.

One of the failure modes were evaluated to be hidden, the one for the emergency stop button. Which is a component that will only be used during emergencies. All the failure modes except one are assigned to failure pattern F. The criticality for the failure modes for the two-way radio which has the purpose to let the passengers communicate with the shore-based station, is evaluated to be three both for safety, asset and availability. If a situation arise where the passengers needs to get in touch with the shore-based station and is not able to do so, it may have severe consequences. It is assumed that the passengers will only get in touch if an emergency situation occurs. Such a situation will also affect the reputation of the ferry, and passengers may see it as a false security. Breakdown of modem and router is evaluated as the same when it comes to criticality. The failure modes causes that the shore-based station is not updated. This is an evident failure, and due to the short crossing time the ferry will not be affected by the failure for long.

A failure to the emergency stop button causes a situation where either the passengers or the shore-based station has seen a danger, but can not take action. This can lead to damage both on passengers and asset. Figure 6.46(a) shows the risk index given to the system, while Figure 6.46(b) shows the risk matrix. From the figures it is clear that three of the failure modes are in the unacceptable area, while two in the ALARP-area and one in the acceptable area.



Conseq/Freq.	1	2	3	4	5
5	🟨	🟥	🟥 5.A	🟥	🟥
4	🟨	🟨	🟥	🟥	🟥
3	🟩	🟨	🟨 2.A,3.A	🟥 1.A,1.B	🟥
2	🟩	🟩	🟨	🟨	🟥
1	🟩	🟩	🟩 4.A	🟨	🟨

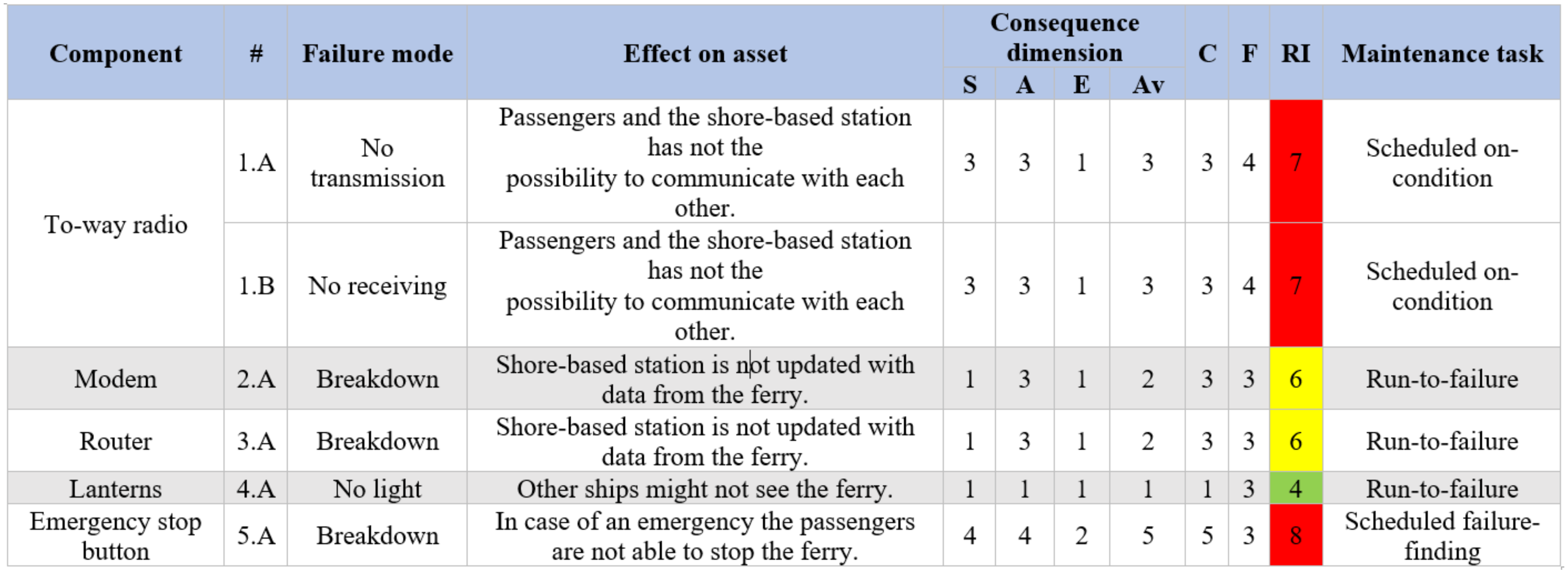
(a) Risk index for communication and visibility system

(b) Risk matrix for commutation and visibility system

Figure 6.46: Summary of risk index for communication and visibility system

Component	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
To-way radio	Transmit and receive communication with land	1.A	No transmission	Flat battery Antenna failure Electrical malfunction	F	E	59 000 h
		1.B	No receiving	Flat battery Antenna failure Electrical malfunction	F	E	59 000 h
Modem	Change data form digital to electrical	2.A	Breakdown	Electrical malfunction	F	E	250 000 h
Router	Send electrical signals to shore-based station	3.A	Breakdown	Electrical malfunction	F	E	250 000 h
Lanterns	Be visible to other ships	4.A	No light	Light bulb failure	A	E	100 000 h
Emergency stop button	Stop all the systems onboard immediately when being pushed	5.A	Breakdown	Electrical malfunction	F	H	1 250 000 h

Figure 6.47: FMECA for communication and visibility system, part 1

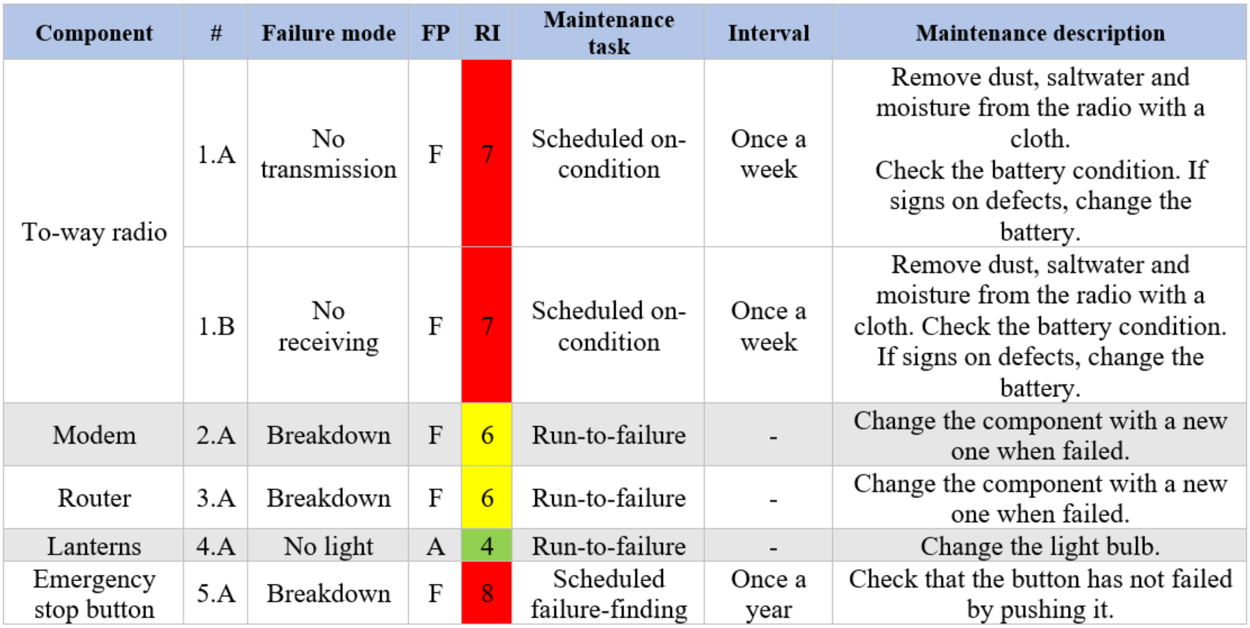


Component	#	Failure mode	Effect on asset	Consequence dimension				C	F	RI	Maintenance task
				S	A	E	Av				
To-way radio	1.A	No transmission	Passengers and the shore-based station has not the possibility to communicate with each other.	3	3	1	3	3	4	7	Scheduled on-condition
	1.B	No receiving	Passengers and the shore-based station has not the possibility to communicate with each other.	3	3	1	3	3	4	7	Scheduled on-condition
Modem	2.A	Breakdown	Shore-based station is not updated with data from the ferry.	1	3	1	2	3	3	6	Run-to-failure
Router	3.A	Breakdown	Shore-based station is not updated with data from the ferry.	1	3	1	2	3	3	6	Run-to-failure
Lanterns	4.A	No light	Other ships might not see the ferry.	1	1	1	1	1	3	4	Run-to-failure
Emergency stop button	5.A	Breakdown	In case of an emergency the passengers are not able to stop the ferry.	4	4	2	5	5	3	8	Scheduled failure-finding

Figure 6.48: FMECA for communication and visibility system, part 2

6.9.4 Maintenance Task Analysis

The MTA performed for the system is shown in Figure 6.49. Three of of the failure modes are assigned to run-to-failure, these are the ones that are not in the unacceptable area and where safety or environment is not affected. The failure modes in the unacceptable area are all assigned to preventive maintenance. For the radio this implies scheduled on-condition, where the batteries are checked. In addition to this dust are removed from the device. The emergency stop button is assigned to scheduled failure-finding once a year, where it will be checked that the devices is still operable.



Component	#	Failure mode	FP	RI	Maintenance task	Interval	Maintenance description
To-way radio	1.A	No transmission	F	7	Scheduled on-condition	Once a week	Remove dust, saltwater and moisture from the radio with a cloth. Check the battery condition. If signs on defects, change the battery.
	1.B	No receiving	F	7	Scheduled on-condition	Once a week	Remove dust, saltwater and moisture from the radio with a cloth. Check the battery condition. If signs on defects, change the battery.
Modem	2.A	Breakdown	F	6	Run-to-failure	-	Change the component with a new one when failed.
Router	3.A	Breakdown	F	6	Run-to-failure	-	Change the component with a new one when failed.
Lanterns	4.A	No light	A	4	Run-to-failure	-	Change the light bulb.
Emergency stop button	5.A	Breakdown	F	8	Scheduled failure-finding	Once a year	Check that the button has not failed by pushing it.

Figure 6.49: MTA for communication and visibility system

6.10 Passenger comfort system

6.10.1 Functions

The functional hierarchy for the system can be seen in Figure 6.50.

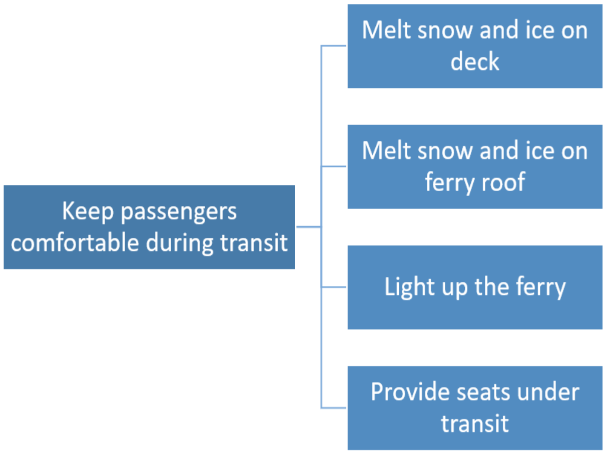


Figure 6.50: Functional hierarchy for the passenger comfort system

The main purpose of the system is to keep the passengers comfortable, which includes the secondary functions provided in the functional hierarchy.

6.10.2 Functional Failures

The functional failures that has been identified for the passenger comfort system are listed below.

1. Passengers not comfortable during transit
2. Snow and/or ice at the deck
3. Snow and/or ice on ferry roof
4. No light

The first functional failure is a total failure of the system. While the second and third is due to failure of the self-regulating heating cables. Where the third functional failure, snow and/or ice on ferry roof, may cause severe consequences as the ferry's center of gravity will change and may make it unstable. The last functional failure causes a situation where it is dark on board, this will only be noticeable at the evening/night in the winter season. When passengers are not comfortable anymore is a subjective opinion, so performance standard is not applicable here.

6.10.3 FMECA

The components analyzed in the FMECA are as follows:

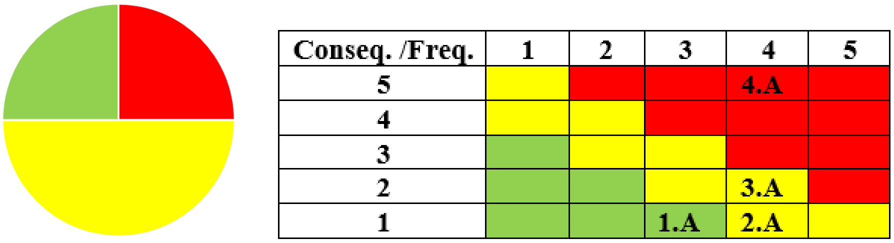
- Chairs/benches
- Lights
- Self-regulating heating cables

The self-regulating heating cables will be mounted on both the roof and the deck. The worksheet from the analysis can be seen in Figure 6.52 and 6.53.

Four failure modes were found relevant for the system. Failure modes for the self-regulating heating cables are based on the manufacturer's manual [91], while the others are based on the functions of the components. The failure modes for the self-regulating heating cables are evaluated to be hidden, while the others are evident. MTBF for chairs/benches were evaluated to not be relevant, thus a frequency class was assumed. For the remaining components the following sources were used for MTBF: lights [92], self-regulating heating cables [93]

The failure mode destroyed chairs/benches has been assessed to have no impact on the asset. Consequently it has been assessed with low criticality in all four categories, and ends up in the green area in the risk matrix. Similarly for the failure modes for the light, no serious impact on the asset. A failure to the self-regulating heating cables on deck may affect the safety for the passengers, as it may get slippery. The last failure mode may have much more severe consequences. As told this may lead to a change in the centre of gravity for the ferry, which makes it unstable. This can result in a tip over, which will have severe consequences for the passengers, asset and especially the reputation.

Figure 6.51(a) shows the risk index for the passenger comfort system, while Figure 6.51(b) shows the risk matrix. From the two figures it is clear that only one failure mode is in the unacceptable area, failure to the self-regulating heating cables on roof.

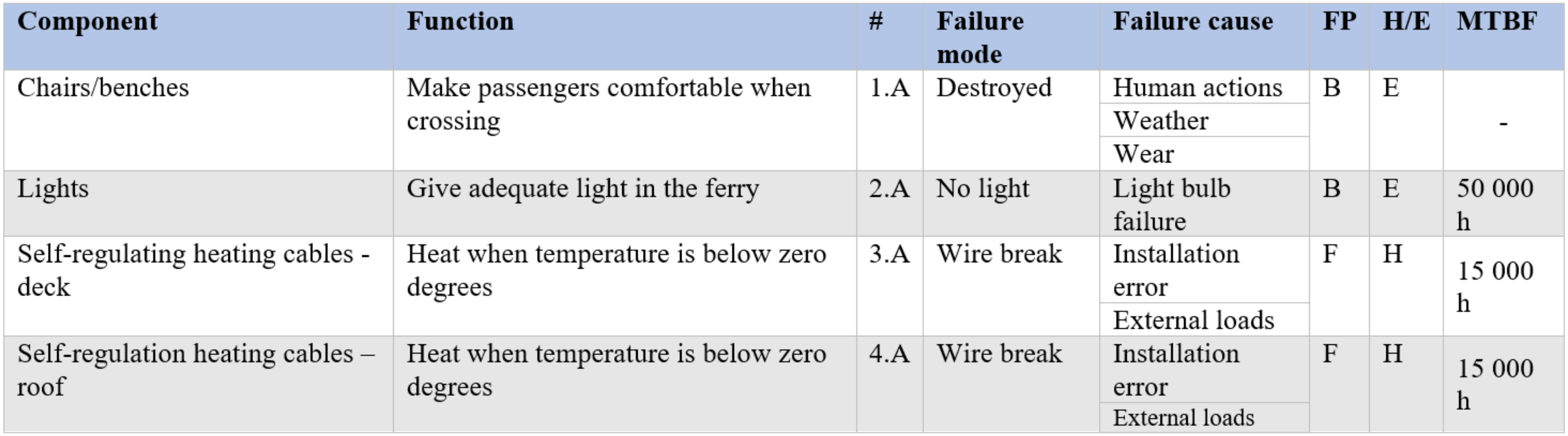


Conseq. /Freq.	1	2	3	4	5
5	🟨	🟥	🟥	🟥 4.A	🟥
4	🟨	🟨	🟥	🟥	🟥
3	🟩	🟨	🟨	🟥	🟥
2	🟩	🟩	🟨	🟨 3.A	🟥
1	🟩	🟩	🟩 1.A	🟨 2.A	🟨

(a) Risk index for passenger comfort system

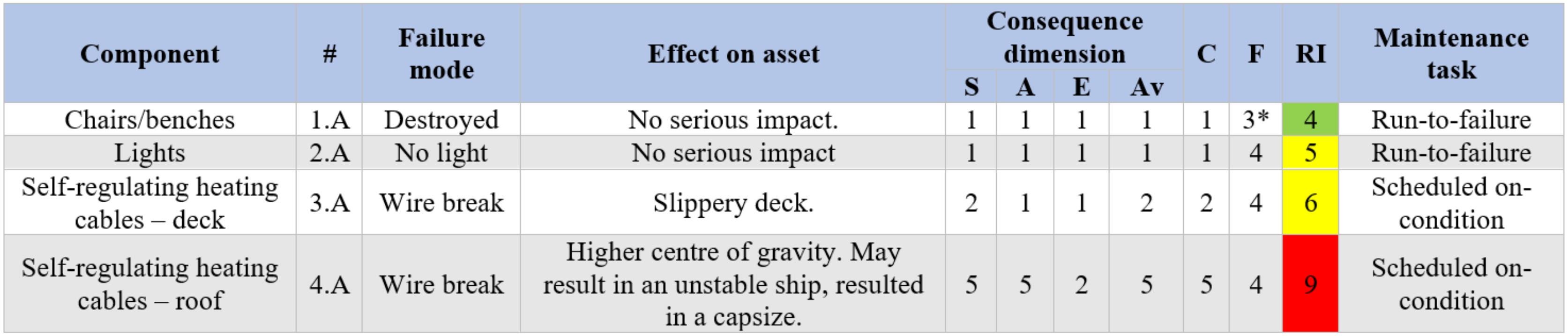
(b) Risk matrix for passenger comfort system

Figure 6.51: Summary of risk index for passenger comfort system



Component	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
Chairs/benches	Make passengers comfortable when crossing	1.A	Destroyed	Human actions Weather Wear	B	E	-
Lights	Give adequate light in the ferry	2.A	No light	Light bulb failure	B	E	50 000 h
Self-regulating heating cables - deck	Heat when temperature is below zero degrees	3.A	Wire break	Installation error External loads	F	H	15 000 h
Self-regulation heating cables – roof	Heat when temperature is below zero degrees	4.A	Wire break	Installation error External loads	F	H	15 000 h

Figure 6.52: FMECA for passenger comfort system, part 1

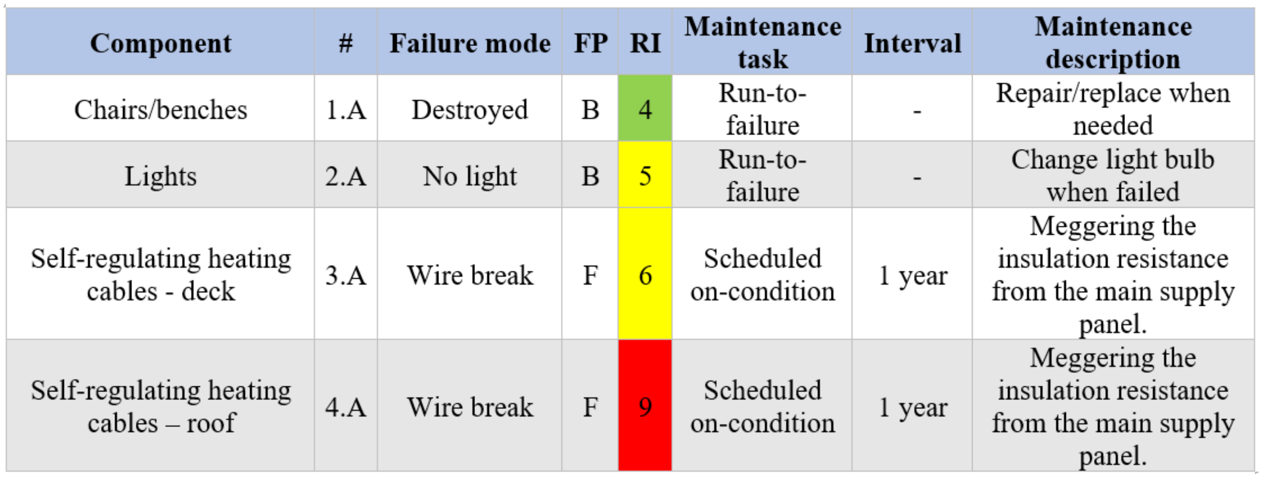


Component	#	Failure mode	Effect on asset	Consequence dimension				C	F	RI	Maintenance task
				S	A	E	Av				
Chairs/benches	1.A	Destroyed	No serious impact.	1	1	1	1	1	3*	4	Run-to-failure
Lights	2.A	No light	No serious impact	1	1	1	1	1	4	5	Run-to-failure
Self-regulating heating cables – deck	3.A	Wire break	Slippery deck.	2	1	1	2	2	4	6	Scheduled on-condition
Self-regulating heating cables – roof	4.A	Wire break	Higher centre of gravity. May result in an unstable ship, resulted in a capsize.	5	5	2	5	5	4	9	Scheduled on-condition

Figure 6.53: FMECA for passenger comfort system, part 2

6.10.4 Maintenance Task Analysis

Figure 6.54 shows the MTA done for the system. Two failure modes are assigned to run-to-failure, because any preventive maintenance will not be technically feasible nor cost effective for the two. The failures regarding the self-regulating heating cables are assigned to scheduled on-condition. A failure to the ones on the roof is in the unacceptable area, and a hidden failure. The preventive task is based on the advice from the manufacturer [91].



Component	#	Failure mode	FP	RI	Maintenance task	Interval	Maintenance description
Chairs/benches	1.A	Destroyed	B	4	Run-to-failure	-	Repair/replace when needed
Lights	2.A	No light	B	5	Run-to-failure	-	Change light bulb when failed
Self-regulating heating cables - deck	3.A	Wire break	F	6	Scheduled on-condition	1 year	Meggering the insulation resistance from the main supply panel.
Self-regulating heating cables – roof	4.A	Wire break	F	9	Scheduled on-condition	1 year	Meggering the insulation resistance from the main supply panel.

Figure 6.54: MTA for passenger comfort system

6.11 Quay system

6.11.1 Functions

The primary function for the quay system is to facilitate the ferry. This includes the secondary functions such as charging the battery packages, call on the ferry when the demand button is pushed, keep the quay free from ice and snow and connect ferry with land. This is all summarized in the functional hierarchy shown in Figure 6.55.

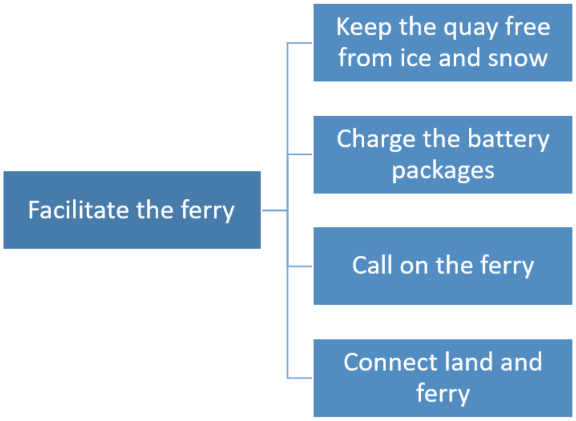


Figure 6.55: Functional hierarchy for the quay system

6.11.2 Functional Failures

The functional failures found relevant for the quay system are listed below.

1. Ice and snow at quay
2. No charging of batteries
3. Unable to call on the ferry
4. No connection between land and ferry

The first functional failure is caused by a failure of the self-regulating heating cables. The quay will still be usable, but may cause irritation for the passengers. The second functional failure is due to a failure in the charger. How the charger should be designed is not decided yet. The failure will cause unavailability for the ferry, since it will eventually be out of power. Next is the failure where the ferry will not come to quay when the demand button is pushed. The final functional failure is caused by a malfunction to the gangway or the quay structure, which connects the land and ferry.

6.11.3 FMECA

The components analyzed in the FMECA are the following:

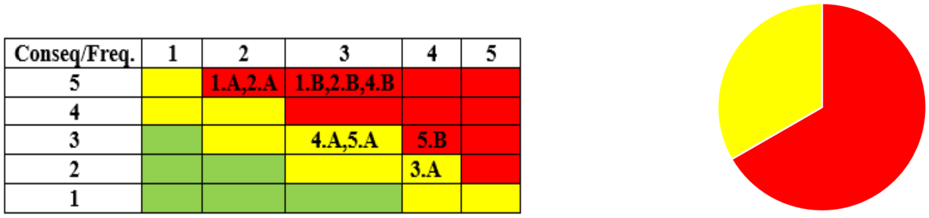
- Quay
- Gangway
- Self-regulating heating cables
- Charger
- Demand button

Figure 6.57 and 6.58 shows the analysis performed.

The failure modes are developed using the functions for the different components, and the project thesis [30]. Some of the information about the components and failure modes were not available, hence some assumptions were done. This is applicable to the quay, gangway and the failure mode ferry does not reply to demand button. It is assumed that the quay and gangway will be made out of steel, and will have a MTBF of 10 years. Failure mode 5.B is assumed to have a frequency category of four, which implies a one to ten failure within 10 years. Nine failure modes were considered relevant for further analysis. Out of these nine three were evaluated to be hidden. These are the failure modes considering the self-regulating heating cables and the charger.

The criticality of each failure mode has been assessed according to the tables presented before. The four first failure modes, 1.A, 1.B, 2.A, 2.B, result in that passengers can not use the ferry. 1.A and 2.A has been evaluated equal, and 1.B and 2.B likewise. A failure that comes from wear has been evaluated to be more critical than one that comes from human actions, as wear will degrade over time and suddenly tear, which can happen when there are passengers present. A situation that is caused by human actions are most likely to happen when other passengers are not present, even tough if they were they would see what's going on. The most critical failure mode is overcharging by the charger. This can cause thermal runaway in the batteries, which may generate more heat and eventually lead to fire. A fire is classified as a 5 when it comes to consequences. A situation where the ferry does not reply on the demand button is not sever to either safety or environment. The ferry will not longer fulfill its requirements, and passengers may get annoyed.

Figure 6.56(a) shows the risk index for the system, while Figure 6.56(b) shows the distribution of risk index. From the figures it is clear that most of the failure modes are in the unacceptable area, while none in the acceptable. There is a combination of high frequency class and high consequence class.



Conseq/Freq.	1	2	3	4	5
5	🟨	🟥 1.A,2.A	🟥 1.B,2.B,4.B	🟥	🟥
4	🟨	🟨	🟥	🟥	🟥
3	🟩	🟨	🟨 4.A,5.A	🟥 5.B	🟥
2	🟩	🟩	🟨	🟨 3.A	🟥
1	🟩	🟩	🟩	🟨	🟨

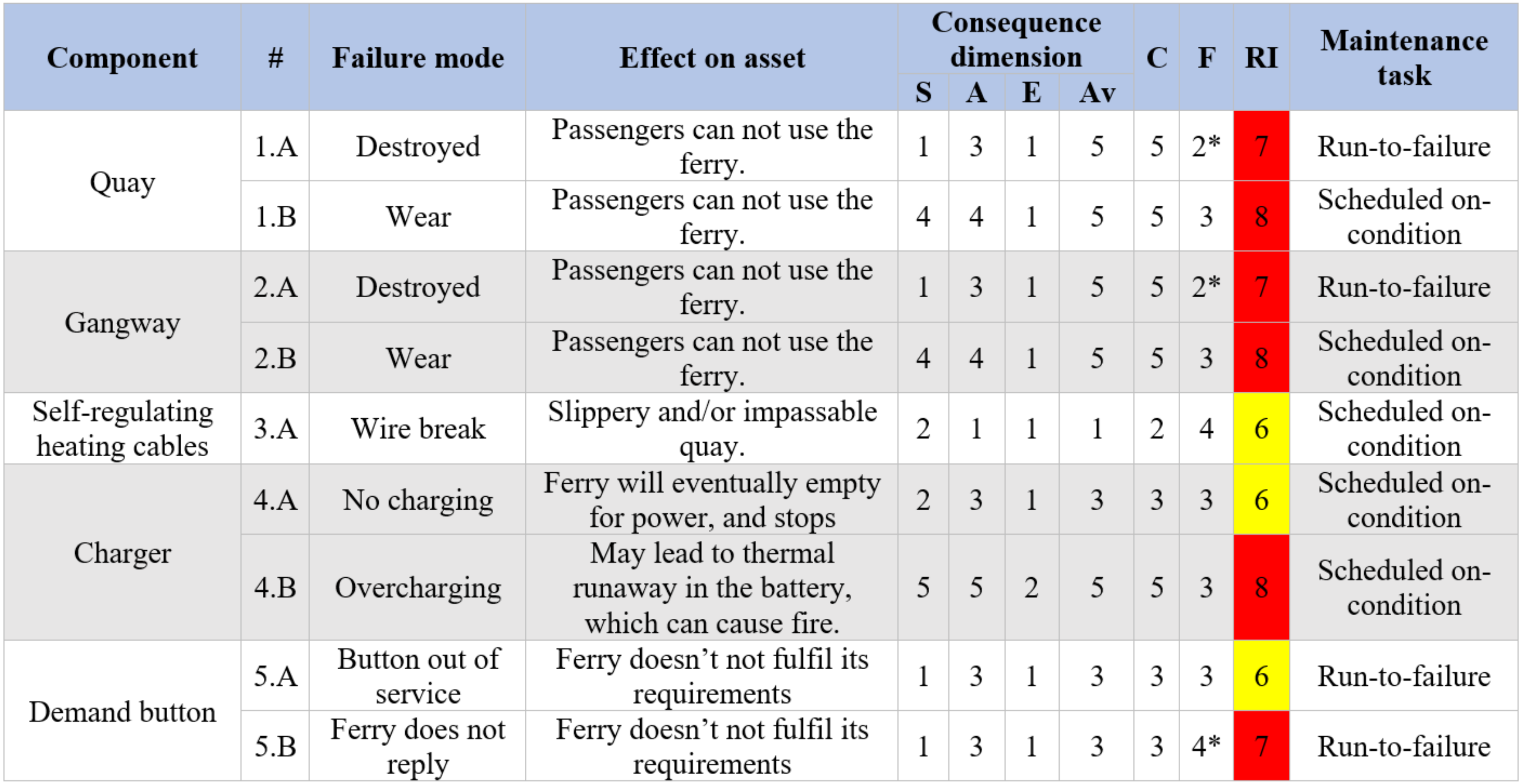
(a) Risk matrix for quay system

(b) Risk index - Quay system

Figure 6.56: Summary of risk index for quay system

Component	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
Quay	Docking space for the ferry	1.A	Destroyed	Human actions	E	E	-
				Weather			
		1.B	Wear	Corrosion	B	E	> 10 years
Gangway	Connect land and quay	2.A	Destroyed	Human actions	E	E	-
				Weather			
		2.B	Wear	Corrosion	B	E	> 10 years
Self-regulating heating cables	Heat when temperature is below zero degrees	3.A	Wire break	Installation error	F	H	15 000 h
				External load			
Charger	Give adequate power to the batteries	4.A	No charging	Electrical malfunction	F	H	2 000 000 h
		4.B	Overcharging	Electrical malfunction	F	H	2 000 000 h
Demand button	Call on the ferry when the button is pushed	5.A	Button out of service	Electrical malfunction	A	E	1 000 000 h
				Wear			
		5.B	Ferry does not reply	Signal failure	F	E	-

Figure 6.57: FMECA for quay system, part 1



Component	#	Failure mode	Effect on asset	Consequence dimension				C	F	RI	Maintenance task
				S	A	E	Av				
Quay	1.A	Destroyed	Passengers can not use the ferry.	1	3	1	5	5	2*	7	Run-to-failure
	1.B	Wear	Passengers can not use the ferry.	4	4	1	5	5	3	8	Scheduled on-condition
Gangway	2.A	Destroyed	Passengers can not use the ferry.	1	3	1	5	5	2*	7	Run-to-failure
	2.B	Wear	Passengers can not use the ferry.	4	4	1	5	5	3	8	Scheduled on-condition
Self-regulating heating cables	3.A	Wire break	Slippery and/or impassable quay.	2	1	1	1	2	4	6	Scheduled on-condition
Charger	4.A	No charging	Ferry will eventually empty for power, and stops	2	3	1	3	3	3	6	Scheduled on-condition
	4.B	Overcharging	May lead to thermal runaway in the battery, which can cause fire.	5	5	2	5	5	3	8	Scheduled on-condition
Demand button	5.A	Button out of service	Ferry doesn't not fulfil its requirements	1	3	1	3	3	3	6	Run-to-failure
	5.B	Ferry does not reply	Ferry doesn't not fulfil its requirements	1	3	1	3	3	4*	7	Run-to-failure

Figure 6.58: FMECA for quay system, part 2

6.11.4 Maintenance Task Analysis

The MTA is shown in Figure 6.59. Four failure modes has been assigned to run-to-failure task. This is failure modes which are not critical for safety and environment. Vandalism on the quay and gangway is not applicable for preventive maintenance, it is not technically feasible without doing 24 hours surveillance of the place. The rest of the failure modes are assigned to scheduled on-condition. The scheduled on-condition for quay and gangway comprises of checking for corrosion and spots without paint.

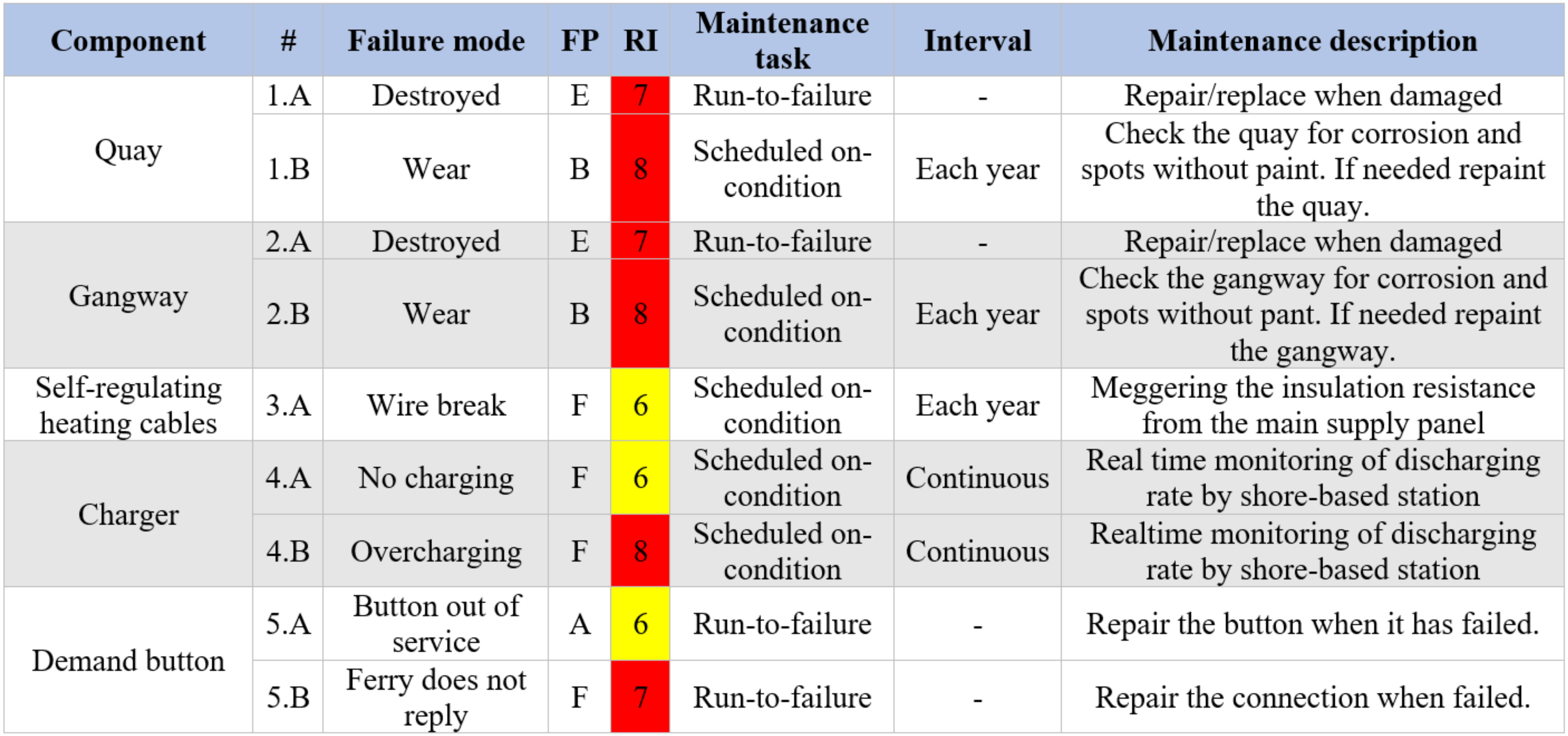
The self-regulating heating cables for the passenger comfort system was decided to be real time monitored. This is also the case for the heating cables at quay. Here it is assumed that the extra costs for monitoring one more heating cable will not be high. Since the failure mode is hidden, run-to-failure is not applicable here.

The charger may cause a severe situation if it leads to overcharging of the battery packages. The component is therefore assigned to scheduled on-condition maintenance where the task is real time monitoring by the shore-based station. The shore-based station will have control over the charging rate. Run-to-failure for the demand button is applicable since the failure mode is evident, and not critical to safety or environment. Due to the high MTBF this will also be the most cost effective.

The numbers used in calculation of the hours available for preventive maintenance are shown in Table 6.9. The table includes only the loss of reputation costs and injury costs, since spare part cost and duration of repair are uncertain numbers. Even tough these would not affected the analysis much, since the numbers would be small compared to reputation loss and injury costs.

Table 6.9: Expense items for cost calculations for quay system

FM	Loss of Reputation class	Injury costs	Hours available
1.A	3	Insignificant	408
1.B	3	Severe injury	43188
2.A	3	Insignificant	408
2.B	3	Severe injury	43188
3.A	1	Slight injury	1147
4.A	3	Slight injury	1527
4.B	5	Fatality	58281
5.A	2	Insignificant	18
5.B	2	Insignificant	18



Component	#	Failure mode	FP	RI	Maintenance task	Interval	Maintenance description
Quay	1.A	Destroyed	E	7	Run-to-failure	-	Repair/replace when damaged
	1.B	Wear	B	8	Scheduled on-condition	Each year	Check the quay for corrosion and spots without paint. If needed repaint the quay.
Gangway	2.A	Destroyed	E	7	Run-to-failure	-	Repair/replace when damaged
	2.B	Wear	B	8	Scheduled on-condition	Each year	Check the gangway for corrosion and spots without pant. If needed repaint the gangway.
Self-regulating heating cables	3.A	Wire break	F	6	Scheduled on-condition	Each year	Meggering the insulation resistance from the main supply panel
Charger	4.A	No charging	F	6	Scheduled on-condition	Continuous	Real time monitoring of discharging rate by shore-based station
	4.B	Overcharging	F	8	Scheduled on-condition	Continuous	Realtime monitoring of discharging rate by shore-based station
Demand button	5.A	Button out of service	A	6	Run-to-failure	-	Repair the button when it has failed.
	5.B	Ferry does not reply	F	7	Run-to-failure	-	Repair the connection when failed.

Figure 6.59: MTA for quay system

6.12 Passenger registration system

6.12.1 Function

The passenger registration system's primary function is to keep the number of passengers in the ferry below 12 at all time. The identified secondary functions are illustrated in Figure 6.60.

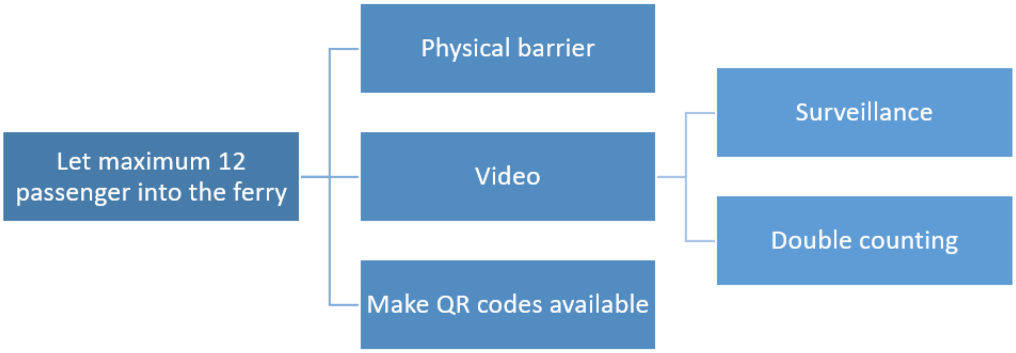


Figure 6.60: Illustration of the primary and secondary functions of the passenger registration system

The physical barrier into the ferry is the swing gates. This will hinder passengers to get on without being counted. The video function will work as a backup for the physical barrier. To get into the ferry through the gates, QR codes are needed. These can be generated from the QR dispenser or an app. The QR codes will also work as a ticket if that is the purpose.

6.12.2 Functional Failures

The functional failures identified for the system are listed below.

- No physical barrier
- No surveillance
- No double counting
- QR codes not available

The first functional failure is due to a failure to the gates, where the gate is open at all times. This makes it possible to have more passengers on board than what is permitted. The second functional failure involves failure to the cameras, which is the same as for functional failure three. The last functional failure is due to failures with the app or the QR dispenser. These two components are covering two different groups of passengers.

6.12.3 FMECA

The components analyzed in the FMECA for the passenger registration system are as follows:

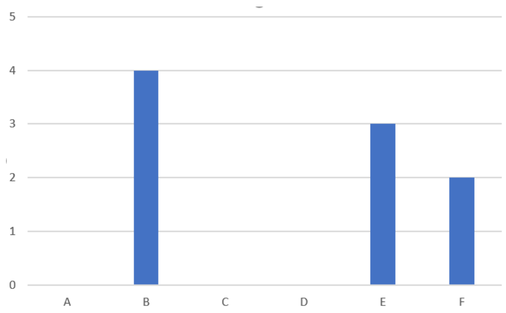
- App
- QR dispenser
- QR reader
- System gates
- Cameras

The worksheets for the system can be seen in Figure 6.62 and 6.63.

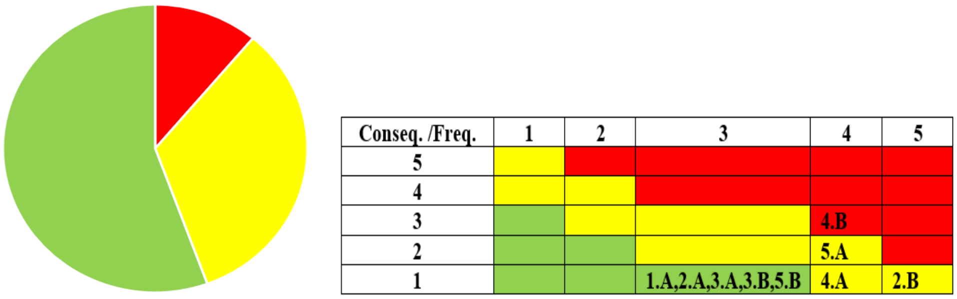
The failure modes and causes for the system are adapted from the project thesis [30] and are developed using the functions from the technical report [38]. The sources for MTBF for the components are as follows: QR dispenser [94], QR reader [95], system gates [96], cameras [60]. A total of 9 failure modes were found relevant for the system. Where all of them are evaluated to be evident. It is assumed that the shore-based station will access the surveillance and the double counting.

A situation where the passengers are hindered to get on the ferry is assessed as a non critical situation. The situation will not lead to any extensive risk to safety, environment or asset. The only failure mode which has the potential to cause any harm is the one where the gates do not close. A critical situation can arise when it is more than 12 passengers on board the ferry. Here it is assumed that the physical barrier will work as intended. Situations where passengers jumps over the gates are solved by having a secondary counting system, the ferry will not leave the quay if the camera counts more than twelve passengers.

Figure 6.61(a) shows the distribution of failure patterns for the system. The figure shows that four of the failure modes has been assigned to failure pattern B, age related failures. This is due to the fact that the failure modes are caused by wear and tear, they comes related to the usage of the component. Two of the failure modes are assigned to failure pattern E, random. These two failure modes has bugs in algorithm as failure cause. Figure 6.61(b) summarizes the risk indexes given to the failure modes. Figure 6.61(c) shows the risk matrix. The figures shows that most of the failure modes area in the acceptable are, and only one in the unacceptable. Five of the nine failure modes has been assigned to consequence category one.



(a) Distribution of failure pattern for passenger registration system

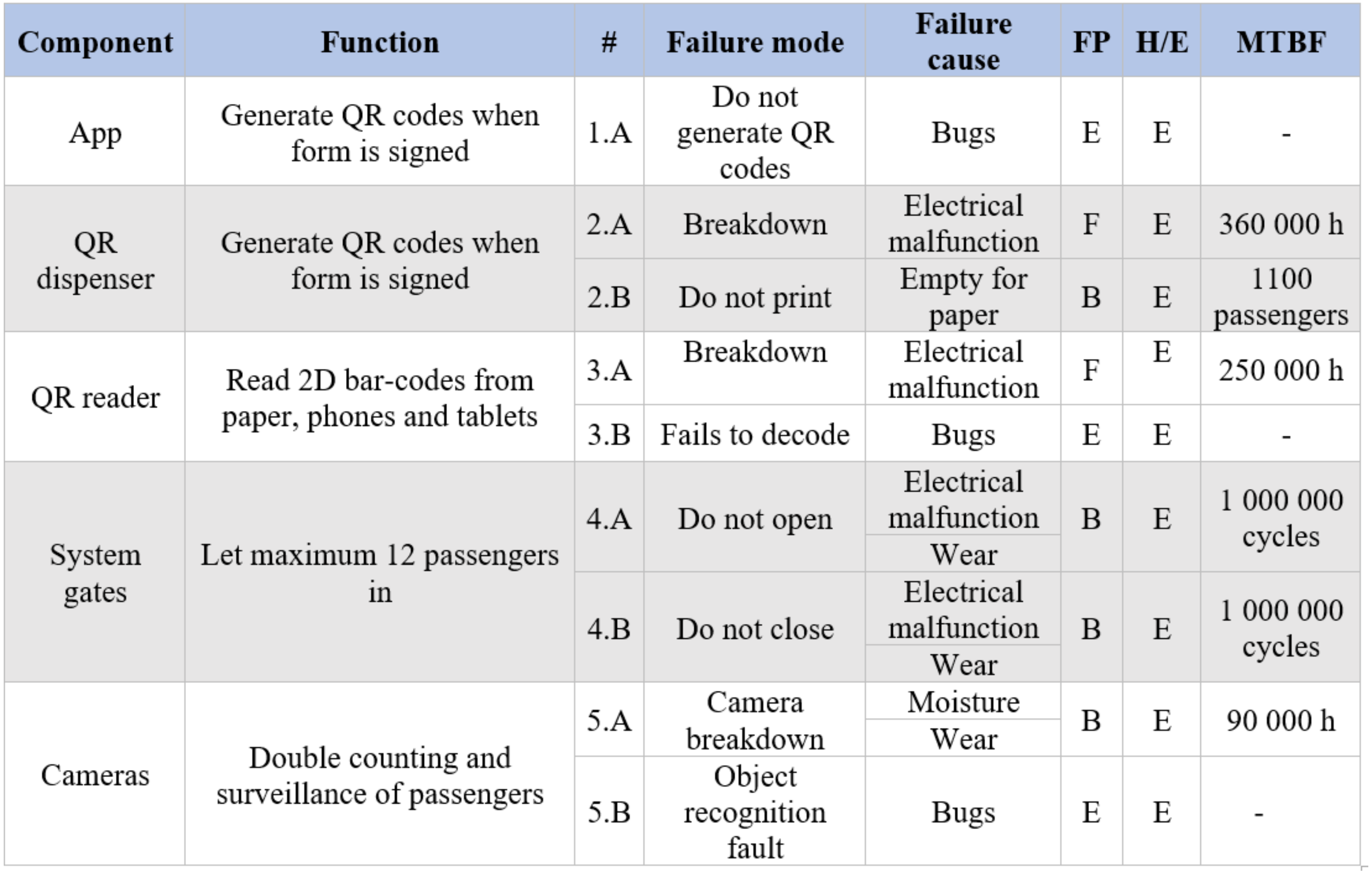


Conseq. /Freq.	1	2	3	4	5
5	🟨	🟥	🟥	🟥	🟥
4	🟨	🟨	🟥	🟥	🟥
3	🟩	🟨	🟨	🟥 4.B	🟥
2	🟩	🟩	🟨	🟨 5.A	🟥
1	🟩	🟩	🟩 1.A,2.A,3.A,3.B,5.B	🟨 4.A	🟨 2.B

(b) Risk index - Passenger registration system

(c) Risk matrix - Passenger registration system

Figure 6.61: Summary of FMECA for passenger registration system



Component	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
App	Generate QR codes when form is signed	1.A	Do not generate QR codes	Bugs	E	E	-
QR dispenser	Generate QR codes when form is signed	2.A	Breakdown	Electrical malfunction	F	E	360 000 h
		2.B	Do not print	Empty for paper	B	E	1100 passengers
QR reader	Read 2D bar-codes from paper, phones and tablets	3.A	Breakdown	Electrical malfunction	F	E	250 000 h
		3.B	Fails to decode	Bugs	E	E	-
System gates	Let maximum 12 passengers in	4.A	Do not open	Electrical malfunction Wear	B	E	1 000 000 cycles
		4.B	Do not close	Electrical malfunction Wear	B	E	1 000 000 cycles
Cameras	Double counting and surveillance of passengers	5.A	Camera breakdown	Moisture Wear	B	E	90 000 h
		5.B	Object recognition fault	Bugs	E	E	-

Figure 6.62: FMECA worksheet for passenger registration system, part 1

Component	#	Failure mode	Effect on asset	Consequence dimension				C	F	RI	Maintenance task
				S	A	E	Av				
App	1.A	Do not generate QR codes	No serious effect on the asset.	1	1	1	1	1	3	4	Run-to-failure
QR dispenser	2.A	Breakdown	Only passenger with app can go on board the ferry	1	2	1	2	2	3	5	Run-to-failure
	2.B	Do not print	Only passenger with app can go on board the ferry	1	2	1	1	2	5	6	Scheduled restoration
QR reader	3.A	Breakdown	No passengers on-board the ferry	1	2	1	2	2	3	5	Run-to-failure
	3.B	Fails to decode	No passengers on-board the ferry	1	2	1	2	2	3	5	Run-to-failure
System gates	4.A	Do not open	No passenger on board the ferry	1	2	1	2	2	4	6	Scheduled discard
	4.B	Do not close	No restriction of passengers to board the ferry. Given a failure to the double counting this can have severe consequences.	3	4	1	5	5	4	9	Scheduled discard
Cameras	5.A	Camera breakdown	No double-counting of passengers, and no surveillance.	1	2	1	2	2	3	5	Run-to-failure
	5.B	Object recognition fault	No double-counting of passengers.	1	1	1	2	2	3	5	Run-to-failure

Figure 6.63: FMECA worksheet for passenger registration system, part 2

6.12.4 Maintenance Task Analysis

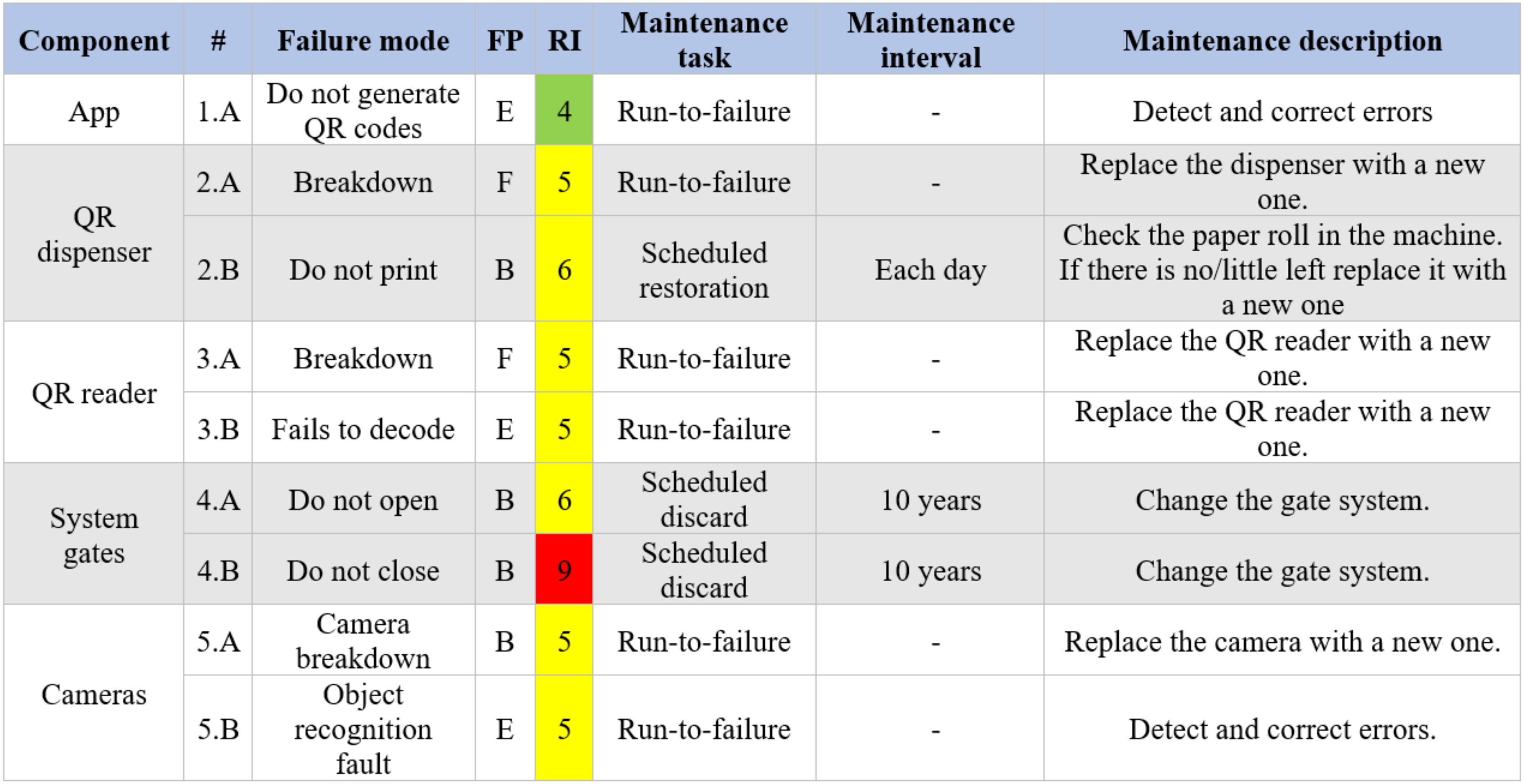
The MTA for the system can be seen in Figure 6.64. This figure shows the assigned maintenance task for each failure mode, in addition to the maintenance interval and the description of the task.

Six of the failure modes are assigned with the task run-to-failure. This is applicable since they are evident failure modes which does not affect the safety, environment or the operability of the ferry. Also the run-to-failure task is the most cost effective for these six failure modes. Hours available to do preventive maintenance in the ones assigned with run-to-failure, ranges from 4 to 28. The assumptions for the cost calculation can be seen in Table 6.10. In addition, the expense items shown in the table are loss of income and duration of repair, which is included in the calculation of hours available.

Failure mode 2.B, 4.A and 4.B has been assigned with preventive maintenance. For 2.B the task is to change the paper in the QR dispenser each day. Here a scheduled discard has been chosen over scheduled on-condition. It is given that the machine can hold tickets for 1100 passengers at once, which implies that with a maximum traffic load all day the tickets lasts for 1.3 days. Here scheduled on-condition could also be applicable, but this would lead to that the personnel had to check the dispenser several times a day, which will not be cost-effective. The systems gates should be replaced with new ones every 10th year. Here run to failure was not applicable since the gates affected the safety on-board. The gates has MTBF of 1 000 000 cycles, and following the passenger profile this will give 10.5 years.

Table 6.10: Expense items for cost calculation of passenger registration system

FM	Spare part	Reputation level	Injury	Hours available
1.A	-	1	Insignificant	4
2.A	2500	1	Insignificant	13
2.B	100	1	Insignificant	2
3.A	6300	2	Insignificant	28
3.B	6300	2	Insignificant	28
4.A	24000	2	Insignificant	62
4.B	24000	2	Severe injury	19 000
5.A	3995	0	Insignificant	11
5.B	3995	0	Insignificant	11



Component	#	Failure mode	FP	RI	Maintenance task	Maintenance interval	Maintenance description
App	1.A	Do not generate QR codes	E	4	Run-to-failure	-	Detect and correct errors
QR dispenser	2.A	Breakdown	F	5	Run-to-failure	-	Replace the dispenser with a new one.
	2.B	Do not print	B	6	Scheduled restoration	Each day	Check the paper roll in the machine. If there is no/little left replace it with a new one
QR reader	3.A	Breakdown	F	5	Run-to-failure	-	Replace the QR reader with a new one.
	3.B	Fails to decode	E	5	Run-to-failure	-	Replace the QR reader with a new one.
System gates	4.A	Do not open	B	6	Scheduled discard	10 years	Change the gate system.
	4.B	Do not close	B	9	Scheduled discard	10 years	Change the gate system.
Cameras	5.A	Camera breakdown	B	5	Run-to-failure	-	Replace the camera with a new one.
	5.B	Object recognition fault	E	5	Run-to-failure	-	Detect and correct errors.

Figure 6.64: MTA for passenger registrations system

6.13 Structural integrity

6.13.1 Functions

The primary function for the hull is to keep the ferry floating. In addition to this there a some secondary functions, which are listed below.

- Be able to dock
- Be able to manoeuvre
- Be able to reach a given velocity

The two last function will in addition to the hull depend on the propulsion system.

6.13.2 Functional failures

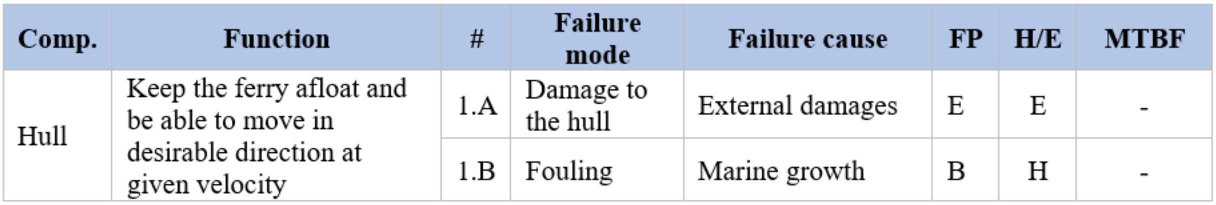
The functional failures that are considered relevant for further analysis has been stated below.

1. Insufficient maneuvering
2. Insufficient reach of velocity

In addition to these are the one where the ferry is unable to dock due to insufficient hull. This is considered as a design issue, and is not analyzed further.

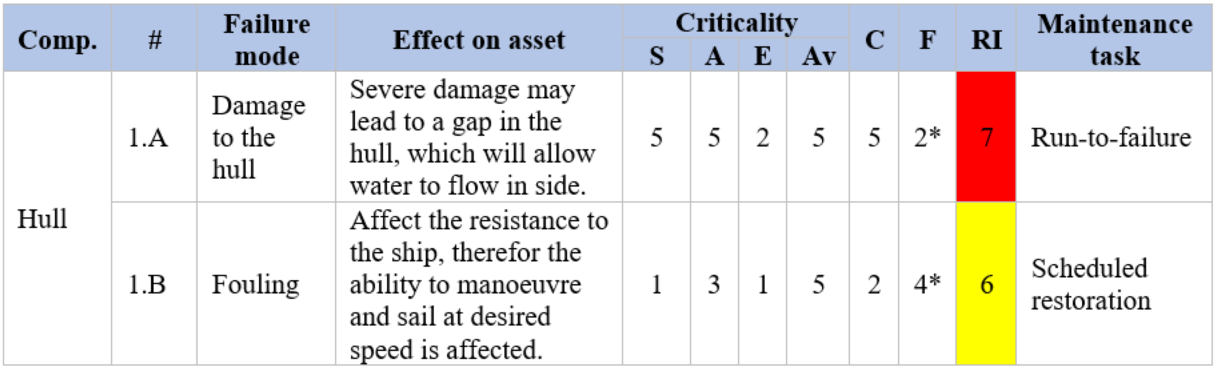
6.13.3 FMECA

One component is analyzed in this FMECA, namely the hull. The worksheet can be seen in Figure 6.65 and 6.66. The failure modes are based on the function statement, and none relevant MTBF were found, but a frequency class for each has been assumed. Damages to the hull has been evaluated to happen rarely, while marine growth will happen more often.



Comp.	Function	#	Failure mode	Failure cause	FP	H/E	MTBF
Hull	Keep the ferry afloat and be able to move in desirable direction at given velocity	1.A	Damage to the hull	External damages	E	E	-
		1.B	Fouling	Marine growth	B	H	-

Figure 6.65: FMECA for structural integrity, part 1

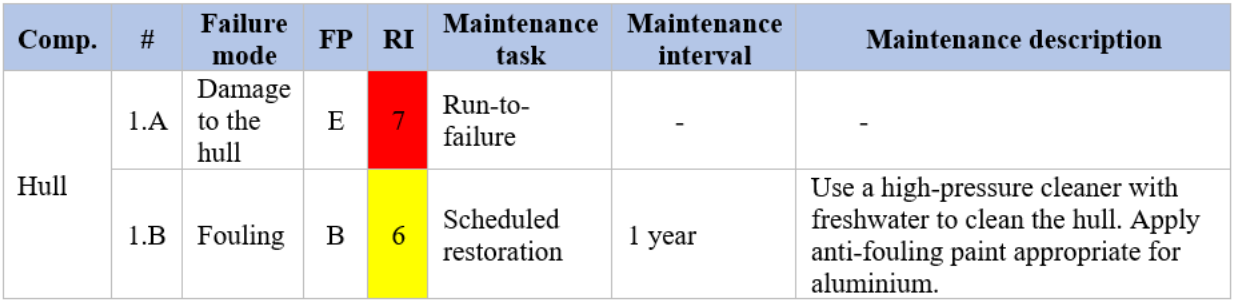


Comp.	#	Failure mode	Effect on asset	Criticality				C	F	RI	Maintenance task
				S	A	E	Av				
Hull	1.A	Damage to the hull	Severe damage may lead to a gap in the hull, which will allow water to flow in side.	5	5	2	5	5	2*	7	Run-to-failure
	1.B	Fouling	Affect the resistance to the ship, therefor the ability to manoeuvre and sail at desired speed is affected.	1	3	1	5	2	4*	6	Scheduled restoration

Figure 6.66: FMECA for structural integrity, part 2

6.13.4 Maintenance task analysis

The maintenance task analysis performed is shown in Figure 6.67. For failure mode 1.A no preventive maintenance is technically feasible, therefore run-to-failure has been chosen. In addition, this failure mode is assumed to happen rarely, and to be evident. Failure mode 1.B has been assigned to scheduled restoration with an interval of one year. The task is to repaint the hull with anti-fouling.



Comp.	#	Failure mode	FP	RI	Maintenance task	Maintenance interval	Maintenance description
Hull	1.A	Damage to the hull	E	7	Run-to-failure	-	-
	1.B	Fouling	B	6	Scheduled restoration	1 year	Use a high-pressure cleaner with freshwater to clean the hull. Apply anti-fouling paint appropriate for aluminium.

Figure 6.67: MTA for structural integrity

Chapter 7

Results and Discussion

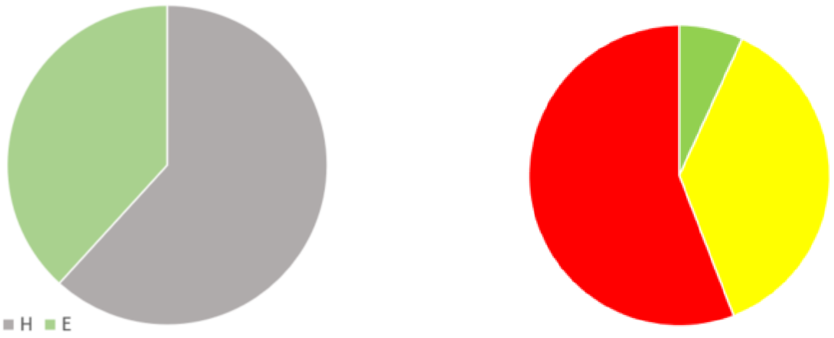
This chapter will firstly summarize the results obtained from the analysis done in Chapter 6. Followed by a discussion of the analysis that has been performed.

7.1 Results

Figure 7.1 shows the split between hidden and evident among all the failure modes for the systems and the split in risk index. The figure shows that most of the failure modes are hidden, which is a result of the unmanned situation. The figure also shows that most of the failure modes are in the unacceptable area, which is a consequence of the conservative analysis, this is discussed further in the next section.

Figure 7.2 shows how the distribution of maintenance tasks are for the autonomous ferry. From the figure it is clear that most of the failure modes are subjected to some sort of preventive maintenance, where the largest share has been assigned to scheduled on-condition. In fact only 19.6% of the failure modes has been assigned to run-to-failure. The high amount of preventive maintenance is a consequences of the hidden failure modes together with their high RI.

The analysis has shown that the most critical systems for the ferry is the propulsion system, navigation system, anti-collision system and battery cooling system. These systems are the most critical in terms of failure modes in the unacceptable area, safety and negative effects. Negative effects also includes loss of reputation, which is an important aspect for the autonomous passenger ferry. The results has been grouped into maintenance packages, which can be seen in Appendix .6. The different maintenance tasks for the systems are grouped by the interval. The maintenance task analysis implies that the ferry should be taken up from the water once a year, so necessary maintenance can be done. The tasks that must be done at land are marked with yellow in the maintenance packages. The packages does not include who is performing the task and the complexity level. This is due to insufficient information about how this should be organized. It is not known if there will be any maintenance personnel in addition to the personnel at the shore-based station. This is something that has to be evaluated before the concept is in operation, as maintenance is important to preserve the safety for the passenger on board.



(a) Split between hidden and evident for all systems

(b) Split between acceptable, ALARP and unacceptable for all systems

Figure 7.1: Summary of results from the analysis for all the systems

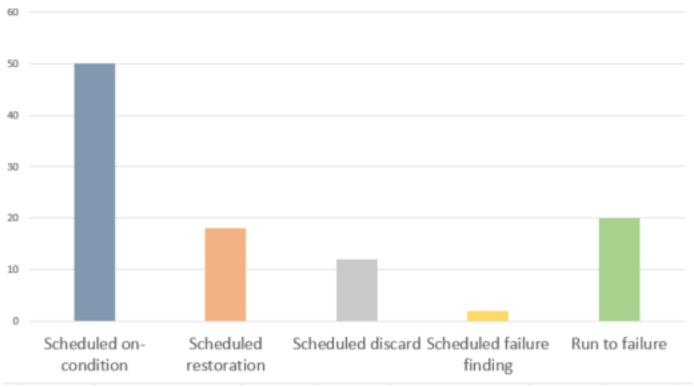


Figure 7.2: Distribution of maintenance tasks for the ferry

7.2 Discussion

The results from the RCM analysis shows that over 80 % of the maintenance tasks are preventive maintenance. This can be a consequence of the autonomous and unmanned concept. As there will be no crew present on the ferry, many of the failure modes will be hidden. Hidden failure modes is not appropriate for a run-to-failure task, therefore preventive maintenance has been chosen. Furthermore it is important for the concept that the passengers can rely on it. Rely that the ferry is safe and in operation. Several occasions where the ferry is out of service may cause that the passengers will stop using it.

As mentioned, reputation is crucial for the ferry. In these technology-driven days bad experiences and situations spreads like wildfire. Two recently examples of this is the

Facebook - Cambridge Analytic data scandal and the presumable pollution in Brazil by Hydro [97] [98]. Not all PR is good PR. In addition to affect the passengers behaviour and thoughts about the autonomous ferry, an unfortunate situation may also affect the development of the regulations, where a setback may happen. When the development of the regulation is affected the future use of the technology is most likely to be affected too. Consequently it is extra crucial to have a reliable asset, where unfortunate situations are avoided.

In this thesis the loss of reputation is measured by peoples reaction. The costs attached to each reputation class is based on the investment costs. This is not the whole picture as even more resources are used on the ferry. Much of the resources has been used for the development of the concept, in addition to the actual investment costs. All this implies that the loss of reputation should be even higher than the numbers used in this thesis. This again will affect the whole costs associated with run-to-failure, and consequently the preventive maintenance task will be even more cost effective.

FTA has been performed for two systems. The navigation- and anti-collision system. Both of the top events were failure of the respectively systems. The analysis showed a relative low probability of failure, with $5.9e^{-}5$ for the navigation system and $2.4e^{-}5$ for the anti-collision system. The low probability is affected by the redundancy in the systems, in addition to the reliable components. One may ask when the probability for failure is low enough. Even though the probability is low, an event of failure in the system may happen. If the situation occurs, the consequences may be severe. To have a more reliable result from the analysis, more accurate inputs should be used. This means more accurate failing data and more accurate repair times. In despite of the uncertainty about the numbers used in the analysis, the FTA shows how the system may fail. Which components in the systems are the most critical. This can be a pointer when it comes to selection of maintenance tasks.

To calculate the cost of run-to-failure for a failure mode, repair time must be known. This is a parameter that can be affected by several factors such as weather, experience of the worker and availability of spare parts. The repair times in this analysis has been excluded due to the uncertainty. To evaluate the repair time for the control algorithms were the most challenging, and since the ferry will be unavailable during repair, the time has a great impact on loss of income. Advice from Professor Roger Skjetne [99] were seeked; repair for control algorithms might take from hours to days depending on the type of failure. The most advanced one is if the philosophy behind the algorithm is fundamentaly wrong. To prevent such a situation, testing of the algorithms is crucial.

Some of the components has been given the maintenance task real time monitoring via the shore-based station. The sensors that are needed to transfer such information from the ferry to the shore-based station is not taken into account in the analysis. These sensors may also fail, and need some sort of maintenance. The sensors came into the analysis at a late stage of the thesis, which would made the work load to large to start the analysis over again. One may argue that the continuous monitoring of the navigational sensor is not cost effective. However this task has been chosen. Here it is assumed that extra monitoring of components by the shore-based station will not significantly increase the costs, since there will already be personnel on the station. The task is also chosen due to the importance of reputation and the lack of information about the sensors.

As mentioned earlier, there will be a shore-based station monitoring the ferry. This implies that there at all time must be a person on work when the ferry is operating, which will greatly affect the operating costs of the ferry. It will also affect the operating time for the ferry, as it is not realistic nor cost effective to have a person on work at the shore-based station 24/7. Another issue regarding the operating time is the weather condition. People may want to take the ferry even tough the weather is harsh, but when it is too harsh? In the thesis it is assumed a all year round operating time, but this may not be realistic.

Safety for the passenger is a crucial element for the concept. One can distinguish between the actual safety for the passengers and the perceived safety. For a new concept which is unmanned, the perceived safety for the passengers may feel low, even though the ferry is safe. In such situation one should evaluated measures which increases the perceived safety. Such measures may be the two-way radio, the emergency stop button and the life jackets.

Systems which uses data derived from multiple information sources applies sensor fusion [100]. This is applicable for the ferry, which gathers information from several sensors. These systems are expected to have a numbers of benefits compared to the use of single sensors [100]. To have a well working system the sensor must work well together. This must be taken into account when the components are chosen. The sensors will also affect the design of the control algorithms. All this makes it clear that just to change a component with another will cause changes.

The analysis that has been performed is conservative when it comes to the evaluation of the criticality of the failure modes. This is obtained in two ways. Firstly the risk matrix used is conservative, where the acceptable area of risk is narrow. Secondly the worst case of consequences dimensions is used for the consequences category. This implies that a five in unavailability will be evaluated to the same as five in safety, which is set to be fatality. One may argue that the safety is the most important, hence the consequences dimension may be weighted. This is not done in this analysis, however since the worst case is always chosen the other consequence dimensions will be included too. It is chosen to do a conservative analysis, as the concept is new and reputation will be crucial.

To be conservative is also important if the method should be applied to a general autonomous ship. The autonomous passenger ferry analyzed in this thesis will not be far from land, therefore maintenance would not have been done at sea anyway. For bigger ships this is another case. Today maintenance is performed continuously at sea, which can not be done for a unmanned ship. Here parallels to the aviation industry can be drawn, where maintenance has to be done when the plane is at ground. The maintenance of airplanes includes pre-flight checks, post flight inspection and scheduled maintenance [101]. In addition, is the monitoring of the key components [101]. If a fault occurs in the air it may have severe consequence, both for safety and reputation. This will most likely be the situation for a unmanned ship at sea as well, especially a passenger ship. This again shows the importance to be conservative.

In the analysis it is assumed that only one failure mode happens at one time. This does not reflect the reality, where several failure modes can happen at the same time. This may be a result of coincident, or spin-off effects. For some of the systems these spin-off effects will be noticeable. For example the mooring system, where a contaminated hydraulic fluid will speed up the failure modes to the rest of the components. As the maintenance plan gets implemented this is important to have in mind.

The maintenance plan proposed in this analysis will only make a framework for the actual plan. Failure modes with causes has to be updated as they are discovered. In addition to the plan is the implementation. Here are the workers important, they have to communicate well in addition to have the sufficient experience and knowledge.

7.2.1 Evaluation of the RCM procedure

The procedure used in this thesis is, as mentioned before, the one from John Moubray [3] which is based on the SAE JA 1011 [4] standard.

The way the functions for the systems are used helps in understanding the systems. One should have sufficient information about the system analyzed, to achieve a good analysis. The analysis is thorough, and small components are included. This may result in an excessive use of resources.

The criticality assessment evaluates the effects on safety, environment, asset and unavailability. This is affected by the authors opinions, and experience is an important matter here. The fact that it is subjective may result in erroneous decision both when it comes to effects, RI and maintenance task.

When the RCM method is performed, follow up of the maintenance plan should be done and new potential functional failures should be registered as soon as they appear.

7.2.2 Limitations

RCM focuses on what the asset does rather than the outcome [3]. This causes that the asset and system should be well known, there must be a good understanding of the functions. As a consequence of this the asset should be well documented, what are the systems on board, which components are installed, what is the performance standard for each component or system. For this project such information has not been available. The design of the ferry and the systems are mainly based on the master thesis *Design of a Small Autonomous Passenger Ferry* [37], however much information is insufficient. Therefore some parts of the systems has been designed as the analysis has been done. Here information from the project manager, internet and other written sources has been. As a consequence of this, parts of the systems may be insufficient designed, some system may miss components or functions that should be included. In addition to more information about the systems, more information and history of failure data and pattern for the components are needed. This also include repair time.

A new concept such as this has very little information available, which causes uncertainty in the analysis. For example in the master thesis *Design of a Small Autonomous Passenger Ferry* [37], it was stated that the ferry should have a emergency stop button. If this button is being pushed the ferry would stop. In early stages of this thesis it was believed that this button would only stop the ferry, with no further action. As this is a ferry and ferries does not have breaks this sounded like a bad idea, since the ferry would just continue forward. This was not the case, a DP system should hold the ferry's position when the button were pushed. A separate DP system is not analyzed for the ferry.

When it comes to the failure modes for the propulsion system, the fact that there are two independent systems are not taken into account. This is due to simplicity in the analysis, but also the fact that it is not known if it possible for one pod drive to take over for the other. If this is the case one has a redundant system and the effects will not be as severe as evaluated in this analysis.

The analysis have not take situation where people may tamper or steal the ferry into account. Since the ferry is unmanned this may be situations which would occur. Cyber attack are not considered either.

Chapter 8

Conclusion

The objectives for this thesis is to use and adapt the RCM method to the autonomous passenger ferry, where the outcome is a maintenance plan. In addition, make recommendations of what data that needs to be registered to improve the maintenance plan. To achieve this, the focus of the analysis has been on the whole concept, which includes all the systems on board and at quay.

Over 100 failure modes has been analyzed in this thesis. Where most of them are evaluated to be hidden failure modes, which is an effect of the unmanned situation. The analysis performed is conservative, with a narrow acceptable area for risk index. Over 50% of the failure modes are in the unacceptable area, consequently many of the maintenance tasks assigned are preventive maintenance. It is proposed to have real time monitoring via the shore-based station for the components which are crucial for the ferry, such as the control algorithms and the navigational sensors. Only 19.6% of the failure modes are assigned to run-to-failure. These are components and systems that are not critical for the asset.

The analysis has shown that the most critical systems for the ferry is the propulsion system, navigation system, anti-collision system and battery cooling system. These systems are the most critical in terms of failure modes in the unacceptable area, safety and negative effects. Negative effects also includes loss of reputation, which is an important aspect for the autonomous passenger ferry.

The RCM analysis has shown how important reputation is for the concept. Not only will a bad reputation affect the ferry it self, it may also affect the development of regulation and further use of the technology

The thesis has been challenging, as there is little to no information about the concept and previously maintenance on autonomous passenger ferries. Hence it has been interesting to be a part of such new technology, that may have huge impact on the future.

Chapter 9

Recommendations and further work

9.1 Recommendations

The objectives for the thesis includes to do recommendations when it comes to failure and maintenance data that needs to be registered.

Firstly all failure modes occurring in the system shall be recorded and included in the maintenance plan. As it will make the plan more thorough, this includes failure pattern and failure rate. It is most important to include the failure modes for the most critical system, such as navigation system, anti-collision system, propulsion system and battery cooling system.

When it comes to maintenance data the actual time of repairing should be recorded. This makes the cost calculation more accurate. Also deviation when it comes to maintenance should be included. These deviation could be that the availability of the components are not sufficient, extra spare parts are needed or the maintenance interval is insufficient.

9.2 Further work

The project of the autonomous passenger ferry is not realized yet, but it will be. As more information about the systems on board becomes available, the analysis should be updated. The performance requirements for each components should be gathered, as the failure modes will be more accurate. This again will affect the maintenance.

By the time of writing this master thesis the anti-collision system was not yet finished. Followed by this the analysis should be updated when more information becomes available. Another uncertain system is the electric power system. As the author does not have sufficient knowledge about the components, functions and what is needed. This systems should be sufficiently designed and analyzed.

As more information will become available, the maintenance packages should be updated with a more detailed description together with what tools are needed and whom is performing the maintenance. One should also look at the shore-based station's part in the concept. Will it still be cost effective?

The passenger ferry will most likely be tested thoroughly. This gives a good opportunity to look at wear and tear of the components and systems, which systems are not sufficiently designed, are redundancy needed and what components are critical.

The maintenance plan suggested in this thesis is only a framework for the actual plan. Before the plan can be implemented, one should know who is performing the maintenance, and what knowledge and expertise they should have.

The thesis has not included failure modes which deals with sabotage, vandalism or cyber attacks. As this may have a significant impact on the asset, one should include it.

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Appendices

.1 Decision tree

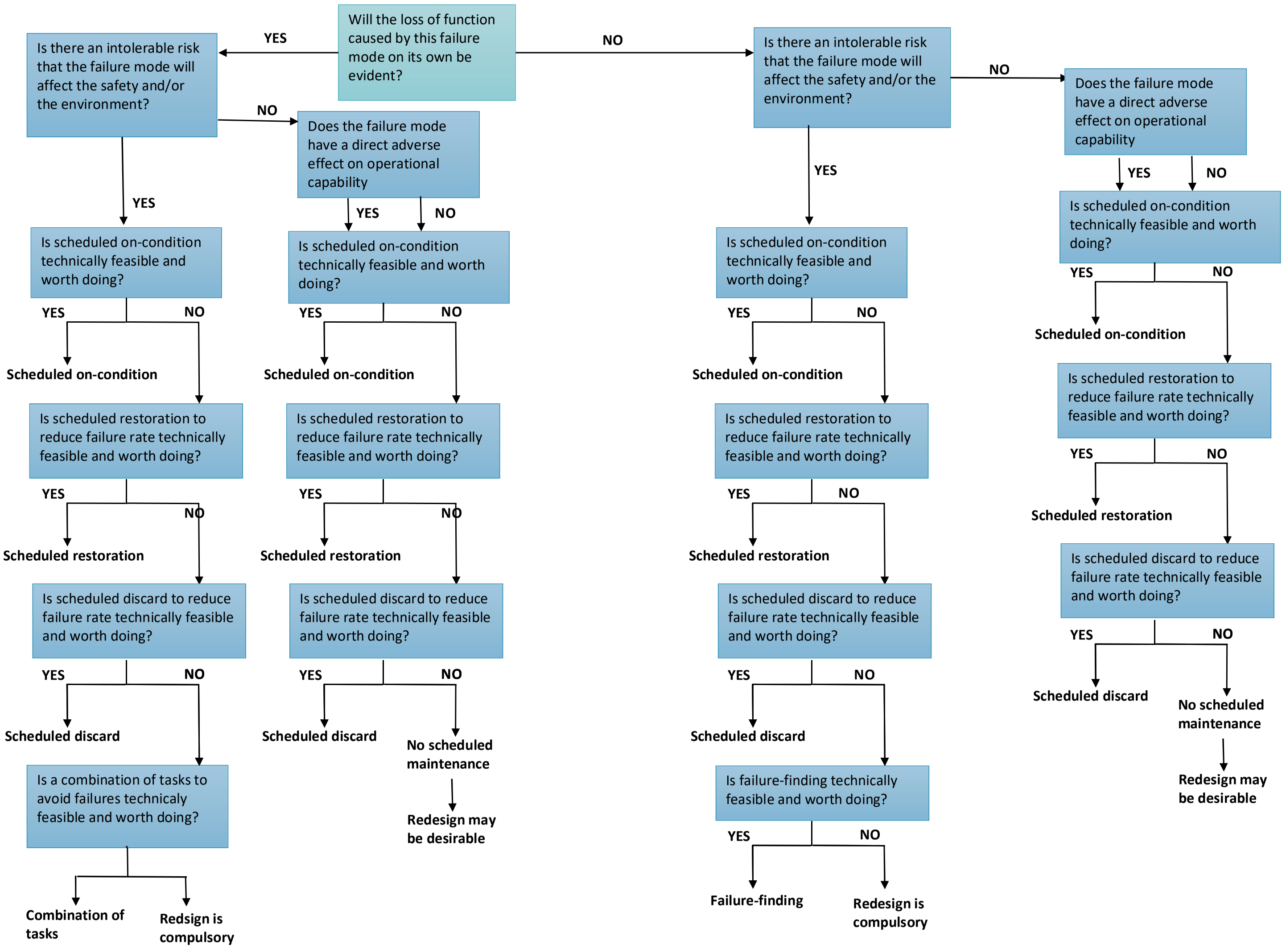
Technically feasibility

Scheduled on-condition: Is there a possiblity to define a clear potential failure condition?
Is the P-F interval reasonably consistent?
Is is practical to monitor the item at intervals less than the P-F interval?
Is the interval long enough for action to be take to avoid or minimize consequneces?

Scheduled restoration: Is there an age where the conditional probability of failures increases?
What is this age?
Do most of the items survive until this age?
Will the task restore the initial capability of the asset?

Scheduled discard: Is there an age where the conditional probability of failures increases? Do most of the items survive until this age?

Failure-finding:
Is there a possbility to do the task without increasing the risk of multiple failure? Is it practical to do the task at the required interval?



.2 Weather data

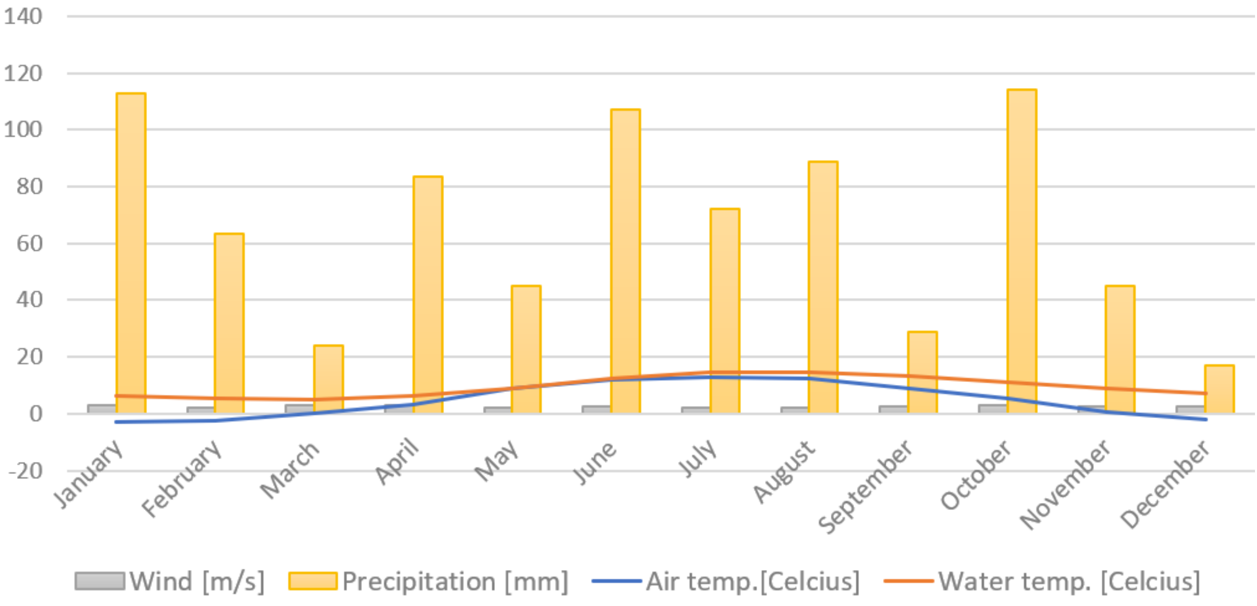


Figure 1: Average weather data for Trondheim in 2017

.3 Passenger profile

The passenger profile has been used to calculate an average number of passengers per trip. Here it is assumed that the ferry will operate 10 hours all year round. It is also assumed that there will be skepticism among the passengers in the beginning. The passenger profile is made by take the time at the day into account. There will be more passengers at afternoon and evening than in the morning.

Hour	08:00						
Trip nr.	1	2	3	4	5	6	7
Numbers of passengers	2	0	2	4	0	1	0
Hour	09:00						
Trip nr.	1	2	3	4	5	6	7
Numbers of passengers	4	3	0	2	2	5	4
Hour	10:00						
Trip nr.	1	2	3	4	5	6	7
Numbers of passengers	5	3	0	1	5	0	0
Hour	11:00						
Trip nr.	1	2	3	4	5	6	7
Numbers of passengers	3	3	5	1	0	2	0
Hour	12:00						
Trip nr.	1	2	3	4	5	6	7
Numbers of passengers	6	3	3	6	5	0	2
Hour	13:00						
Trip nr.	1	2	3	4	5	6	7
Numbers of passengers	1	0	0	2	2	0	4
Hour	14:00						
Trip nr.	1	2	3	4	5	6	7
Numbers of passengers	0	0	4	4	3	2	0
Hour	15:00						
Trip nr.	1	2	3	4	5	6	7
Numbers of passengers	2	2	6	9	5	4	2
Hour	16:00						
Trip nr.	1	2	3	4	5	6	7
Numbers of passengers	0	4	0	2	6	4	4
Hour	17:00						
Trip nr.	1	2	3	4	5	6	7
Numbers of passengers	6	4	8	10	12	12	6
Hour	18:00						
Trip nr.	1	2	3	4	5	6	7
Numbers of passengers	6	6	7	5	10	5	8
Average	3.7 passengers/trip						

Table 1: Passenger profile

.4 Sources for spare part costs

Component	Source
Embedded computer	[102]
IMU	[103]
Radio link	[104]
Camera	[105]
IR	[106]
Lidar	[107]
Radar	[108]
Podded propulsion	[109]
Battery modules	[37]
Electrical cables	[110]
Distribution board	[111]
Bilge pump	[112]
Non return valve	[113]
Circulation pump	[114]
Temperature sensor	[115]
Pressure sensor	[115]
Temperature regulating valve	[116]
Hydraulic cylinder	[117]
Pressure relief valve	[118]
Two-way radio	[119]
Modem	[120]
Router	[121]
Lanterns	[122]
Self-regulating heating cables	[123]
QR dispenser	[124]
QR reader	[125]
System gates	[38]
Hull	[37]

.5 Maintenance cost calculations

.5.1 Electric power system

FM	Spare part costs	Loss of Reputation level	Injury costs	Hours available
1. A	305 000	3	Minor	2105
1.B	305 000	5	Fatality	58 850
2.A	1100	3	Minor	1174
3.A	50	3	Insignificant	14
3.B	700	3	Minor	1173

.5.2 Bilge system

FM	Spare part costs	Loss of Reputation level	Injury costs	Hours available
1.A	1100	1	Insignificant	4
1.B	1100	1	Insignificant	4
1.C	1100	1	Insignificant	4
2.A	300	1	Insignificant	2
2.B	300	3	Major	20165

.5.3 Battery cooling system

FM	Spare part costs	Loss of Reputation level	Injury costs	Hours available
1.A	8 000*	5	Fatality	58294
1.B	8 000*	5	Fatality	58294
2.A	3300	1	Insignificant	6
2.B	3300	1	Insignificant	6
3.A	50	1	Insignificant	0.1
4.A	50	1	Insignificant	0.1
5.A	2000	5	Fatality	58285
5.B	2000	5	Fatality	58285

.5.4 Safety system

Due to the importance of the safety system, both in light of following regulations and for the consequences. No cost analysis has been performed.

.5.5 Communication and visibility system

FM	Spare part costs	Loss of Reputation level	Injury costs	Hours available
1.A	2400	3	Major	20 144
1.B	2400	3	Major	20 144
2.A	700	1	Insignificant	6
3.A	1500	1	Insignificant	7
4.A	100*	1	Insignificant	0.2
5.A	2000*	5	Severe	44 684

.5.6 Passenger comfort system

FM	Spare part costs	Loss of Reputation level	Injury costs	Hours available
1.A	-	0	0	0
2.A	500*	0	0	0.9
3.A	3500	2	Minor	1166
4.A	3500	2	Fatality	58 288

.5.7 Structural integrity

FM	Spare part costs	Loss of Reputation level	Injury costs	Hours available
1.A	300 000	5	Fatality	58840
1.B	300 000	2	Insignificant	604

.6 Maintenance packages

Interval	Task	Description
Continuous	Scheduled on-condition of: - embedded computer - Guidance system - Control system - IMU - GNSS - Radio link - IR - Lidar - Radar - Control algorithm - Electronic box for propulsions system - Battery modules	Real time monitoring of the components via the shore-based station. The algorithms include online updates.
Each day	Scheduled restoration of embedded computer	Connect all the cables properly in the device.
	Scheduled restoration of distribution board	Wipe the panel for moisture.
	Scheduled on-condition of external fire extinguisher	Check that the fire extinguisher is present. Check the pressure of the tank and turn it upside down to prevent clogging.
	Scheduled restoration of QR dispenser	Replace the paper roll in the machine.
Each week	Scheduled restoration of IMU	Disconnect from power supply, computer and antenna. Wipe the case with a damp cloth and mild detergent
	Scheduled on-condition of Novec 1230 facility	Inspect the pressure in the tanks.
	Scheduled on-condition of life jackets	Check that all of the jackets are present
	Scheduled on-condition of life buoy	Check that the buoy is present
	Scheduled on-condition of to-ay radio	Remove dust, saltwater and moisture from the radio with a cloth. Check the battery condition. If signs of defects, change the battery.
10 days	Scheduled on-condition of attachment bolt in the radar	Inspect the bolts. Correct/tighten if needed.
2 weeks	Scheduled on-condition of camera for anti-collision system	Check the focus of the camera. If deviations are found, recalibrate the camera.
1 month	Scheduled on-condition of camera for anti-collision system	Examine all cables for signs of damages, and check that they are securely connected.
	Scheduled on-condition for IR	Ensure proper cable separation and shore video cable

	Scheduled failure finding of fire alarm	Check that the alarm is working by triggering it.
3 months	Scheduled restoration of radar	Wipe the antenna clean with freshwater moisture cloth
	Scheduled on-condition of radar	Check the bolts for tightness and corrosion, replace any corroded bolts and coating new bolts with anticorrosion sealant. Check the scanner drive motor brushed. Change if needed.
6 months	Scheduled on-condition of lidar	Check that the optical window is still intact. If not, replace it.
	Scheduled on-condition of cables in propulsion system	Check the connections and cables for wear. Change if needed.
	Scheduled on-condition of battery cables	Check the connections and cables for wear. Change if needed.
	Scheduled on-condition of hydraulic fluid	Analysis of the properties of the oil, such as viscosity, specific gravity, acidity, water content, containment level and bulk modulus
1 year	Scheduled restoration of propeller	Change zinc anodes
	Scheduled on-condition of propeller	Inspect the propellers for cavitation erosion damage. If severe damages are found, change the propellers.
	Scheduled on-condition of gear shaft	Inspect the shaft If misalignment is found, align it.
	Scheduled on-condition of motor	Vibration measurements to check for faults.
	Scheduled on-condition of bilge pumps	Check that nothing is hindering the float switch. Also check the pumps for cracks, replace if found.
	Scheduled restoration of bilge pumps	Clean the filter.
	Scheduled restoration of non-return valve in bilge system	Clean the valves.
	Scheduled on-condition of non-return valve	Remove cover and O ring. Clean and inspect the ball for damage and examine the sating are. Repair if needed.
	Scheduled on-condition of Novec 1230 facility	Annual control by certified personnel.
	Scheduled on-condition of life jackets	Check the life jackets for wear and tear. If any is found replace the jacket.
	Scheduled restoration of life buoy	Wipe the buoy and make sure the reflexes are visible.
	Scheduled on-condition of mooring ramp	Check the ramp for wear. Change the bolts if there are visual wear.

	Scheduled restoration of hydraulic pump	Change the shaft seals.
	Scheduled on-condition of hydraulic pump	Vibration measurements and frequency analysis. Fast Fouier Transformation.
	Scheduled discard of filter in mooring system	Change the filter with a new one.
	Scheduled restoration of reservoir in hydraulic system	Clean the reservoir and the suction filter.
	Scheduled failure-finding of emergency stop button	Check that the button is till working.
	Scheduled on-condition of self-regulating heating cables on ferry deck and roof, and on quay.	Meggering the insultation resistance from the main supply panel
	Scheduled on-condition of quay	Check the quay for corrosion and spots without paint. If need repaint the quay.
	Scheduled on-condition of gangway.	Check the gangway for corrosion and spots without paint. If need repaint the gangway.
	Scheduled restoration of hull	Use high-pressure cleaner with freshwater to clean the hull. Apply anti-fouling appropriate for aluminium
2 years	Scheduled discard of seals in propulsion system	Change the seals with new ones.
	Scheduled on-condition of hydraulic cylinder	Inspect the cylinder for wear, scoring and pitting. Honing is done if wear is found. Highly damaged cylinder needs to be rebored.
3 years	Scheduled on-condition of circulation in battery cooling system	Visually inspect the pump for leaks. If leaking is found replace the pump with a new one.
	Scheduled restoration of circulation pump	Check the pump for fouling by opening it up. If fouling has occurred, change it with a new one
	Scheduled restoration of hydraulic cylinder	Change the seals with new ones.
5 years	Scheduled restoration of battery modules for both propulsion and electrical power system	Change the battery cells.
	Scheduled on-condition of pipes in battery cooling system	Check the pipes for leaks by adding UV sensitive additive and use a hand hold inspection lamp
	Scheduled restoration of pipes in battery cooling system	Flush the pipes with high-pressure cleaner

	Scheduled discard of temperature control	Change the component with a new one.
	Scheduled discard of pressure control	Change the component with a new one.
	Scheduled discard of temperature regulating valve	Change the component with a new one.
	Scheduled restoration of external fire extinguisher	Send in for inspection.
10 years	Scheduled discard of pressure relief valve	Change the component with a new one.
	Scheduled discard of directional control valve	Change the component with a new one.
	Scheduled discard of systems gates	Change the gates with new ones.