Tampereen yliopisto

Antti Johansson

APPLICATION OF FMEA METHOD IN DETAILED ASSESSMENT PHASE OF SHIPS' CRITICAL SYSTEMS

Master of Science Thesis
Faculty of Engineering and Natural Sciences
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ABSTRACT

Antti Johansson: Application of FMEA method in detailed assessment phase of ships' critical systems
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Failure mode and effects analysis (FMEA) is a systematic method of analysis that has a well-established position in traditional reliability analyses. The objective of the FMEA is to assess and identify potential failures of system components as well as to assess the effects of failures on the system, and to propose countermeasures to prevent adverse effects. Due to the universal nature of the FMEA, it is possible to tailor and apply it in different ways depending on the objectives. The FMEA has a wide popularity and different interpretations, practices and standards of procedure.

The suitability of the FMEA is well managed at the equipment and system levels, where potential failure modes are generally known and the task is to analyse their effects on system operation. Today, passenger ship systems are extensive and complex, so *the International Maritime Organization* (IMO) has suggested a desire to apply the FMEA methodology to ship systems as well. This Master's Thesis examines the applicability of the FMEA in a detailed assessment phase, in which the ship's critical systems are analysed. The purpose of the detailed assessment phase is to ensure and guarantee that the systems in the event of a fire or flooding comply with *SOLAS* (Safety of Life at Sea) regulations. These regulations are also known as *Safe Return to Port* (SRtP). The SRtP regulations impose operational requirements on the systems to allow a ship to return safely to the nearest port in the event of an emergency.

The case company of this thesis has its own approach for the FMEA method. The research problem was to find out whether the FMEA method proposed by the IMO is suitable for the detailed assessment phase and whether the method corresponds to the way the case company performs the analysis. The aim of the research was to deepen the understanding of how the FMEA method could be applied to ship systems in the SRtP context. The SRtP regulations are goal-based in nature, so they do not provide guidelines on the FMEA method and no previous research has been conducted on the subject. Another objective of the research was to improve detailed assessment phase for the case company by proposing how the information obtained from the literature could be applied in the case company.

The thesis was carried out as a qualitative case study for the case company's FMEA in the detailed assessment phase. The research methods used were literature review, thematic interview and content analysis. With the help of the literature, the theoretical framework of the research was formed, which provided the basis for the main concepts of the research and the FMEA methodology. In the empirical part of the work, the initial situation was investigated with internal documents of the case company and by performing an example exercise in order to get a practical picture of the assessment process. Thematic interviews were aimed at experts to gain more in-depth information. The content analysis condensed the research data and found out the interviewees views on the FMEA, challenges and development ideas.

As a result of the empirical part, it became clear that the FMEA of the case company is a simplified version, in which the failure concept is treated binary 1 (up/intact) or 0 (down/affected). due to the compliance of the regulations and the qualitative nature of the analysis process, a criticality analysis based on casualty scenarios was not considered necessary. The case company's FMEA table was finalised by improving its failure effect review as a local and end response. Further research and development would be to utilise a relational database throughout the process model, which would help reduce the amount of manual work. This study deepened the understanding of the FMEA method in SRtP ship systems

Keywords: Safe Return to Port, SRtP, failure mode and effects analysis, FMEA, passenger ship

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

TIIVISTELMÄ

Antti Johansson: FMEA-menetelmän soveltuvuus alusten kriittisten järjestelmien yksityiskohtaisessa arviointivaiheessa
Diplomityö, 79 sivua, 15 liitesivua
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Vika- ja vaikutusanalyysi (VVA) on systemaattinen analyysimenetelmä, jolla on vakiintunut asema perinteisissä luotettavuusanalyyseissä. VVA:n tavoitteena on arvioida ja tunnistaa järjestelmän komponenttien potentiaaliset vikaantumistavat sekä arvioida vikaantumisen vaikutuksia järjestelmään ja ehdottaa vastatoimenpiteitä haitallisten vaikutusten estämiseksi. VVA:n yleispätevän luonteensa ansiosta sitä on mahdollista räätälöidä ja soveltaa eri tavoin tavoitteista riippuen. VVA:n laaja suosio ja erilaiset käyttötavat ovat johtaneet useisiin erilaisiin menettelyä koskeviin tulkintoihin, käytäntöihin ja standardien syntyyn.

VVA:n soveltuvuutta hallitaan hyvin laite- ja järjestelmätasoilla, joilla mahdolliset vikaantumistavat yleensä tunnetaan ja tehtävänä on analysoida niiden vaikutuksia järjestelmän toimintaan. Nykyään matkustajalaivojen järjestelmät ovat laajoja ja kompleksisia, jolloin SOLAS-säännöt (Safe of Life at Sea) ovat ehdottaneet halun soveltaa VVA metodologiaa myös laivan järjestelmiin. Diplomityössä tutkitaan VVA:n soveltuvuutta yksityiskohtaisessa arviointivaiheessa, jossa analysoidaan laivan kriittisiä järjestelmiä. Yksityiskohtaisen arviointivaiheen tarkoituksena on varmistua ja taata, että järjestelmät palo- tai vuoto-onnettomuudessa täyttävät näissä tilanteissa SOLAS-säännöt. Kyseiset säännöt tunnetaan myös nimellä *Safe Return to Port* (SRtP) -säännöt. SRtP-säännöt asettaa järjestelmille toimintakykyvaatimuksia, jotta laiva voisi palata turvallisesti lähimmäiselle satamalle hätätilanteen sattuessa.

Tämän diplomityön kohdeyrityksellä on oma VVA-menetelmän lähestymistapa, jolla se analysoi kriittisiä järjestelmiä. Tutkimusongelmana oli selvittää, soveltuuko *Kansainvälisen merenkulkujärjestön* (IMO) ehdottama VVA-menetelmä yksityiskohtaiseen arviointiin ja vastaako menetelmä kohdeyrityksen tapaa tehdä analyysia. Tutkimuksen tavoitteena oli syventää ymmärrystä siitä, miten VVA-menetelmää voitaisiin soveltaa laivan järjestelmiin SRtP-kontekstissa. SRtP-säännöt ovat luonteeltaan tavoitepohjaisia, jolloin ne eivät anna neuvoa VVA-menetelmästä eikä aikaisempaa tutkimusta aiheesta ole tehty. Toisena tutkimuksen tavoitteena oli kehittää kohdeyrityksen yksityiskohtaista arviointivaihetta ehdottamalla, miten kirjallisuudesta saatua tietoa voitaisiin soveltaa kohdeyrityksessä.

Diplomityö toteutettiin kvalitatiivisena tapaustutkimuksena. Tutkimustapauksena oli kohdeyrityksen VVA-menetelmä yksityiskohtaisessa arviointivaiheessa. Käytetyt tutkimusmenetelmät olivat kirjallisuuskatsaus, teemahaastattelu ja sisällönanalyysi. Kirjallisuuskatsauksen avulla muodostettiin tutkimuksen teoreettinen viitekehys, joka antoi perustan tutkimuksen pääkäsitteille ja VVA metodologialle. Työn empiirisessä osuudessa lähtötilanne selvitettiin kohdeyrityksen sisäisillä dokumenteilla ja suorittamalla esimerkkiharjoitus palovesipumpulla, jotta arviointiprosessista saatiin käytännön kuva. Teemahaastattelut oli kohdistettu asiantuntijoihin syvemmän tiedon saamiseksi. Sisällönanalyysilla tiivistettiin aineistoa ja selvitettiin haastateltavien näkemyksiä prosessista, haasteista ja kehitysideoista.

Empiirisen osuuden tuloksena selvisi, että kohdeyrityksen VVA on suoraviivaisempi versio, jossa vikaantumiskonseptia käsitellään binäärisesti 1:nä (ylhäällä/toimii) tai 0:na (alhaalla/toimimaton). Sääntöjen noudattamisen ja analyysiprosessin kvalitatiivisen luonteen vuoksi kriittisyysanalyysia vaurioskenaarioiden pohjalta ei koettu tarpeelliseksi. Kohdeyrityksen FMEA-taulukkoa päädyttiin parantamalla sen vikavaikutus tarkastelua paikallisena ja loppu vasteena. Lisätutkimus ja kehitysehdotus olisi relaatiotietokannan hyödyntäminen koko prosessimallissa, joka auttaisi vähentämään manuaalisen työn määrää. Tutkimuksella syvennettiin käsitystä FMEA-menetelmän käyttöönotosta SRtP-laivojen järjestelmissä.

Avainsanat: Safe Return to Port, SRtP, vika- ja vaikutusanalyysi, FMEA, matkustajalaiva

Tämän julkaisun alkuperäisyys on tarkastettu Turnitin OriginalityCheck –ohjelmalla.

PREFACE

This master’s thesis has been completed with a stipend from the University of Tampere Foundation on the topic received from Deltamarin Ltd’s machine department. Researching the detailed assessment phase as part of a larger process has been challenging but ultimately rewarding. Along the way, there have been twists and turns where I have weighed my own views on several occasions. The opportunity provided by the work to get to know the SRtP process and its challenges has been quite an interesting and educational experience. However, I am proud to be finally at this writing stage as finishing this project feels evermore rewarding.

I would like to extend my sincere thanks to my supervisor M.Sc. Miia Kauntola for the guidance, feedback and patience throughout this journey. Big thanks for the colleagues in Deltamarin for interviews during this project. Thanks to my closest friends who have been interested in the progress of my thesis as they provided me energy to keep on writing. Special thanks to Rachel Turola for proofreading and giving grammar advice.

Finally, the sincerest thank you to my parents for their support and encouragement during my thesis and studies.

Tampere, 09.05.2022

Antti Johansson

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ABBREVIATIONS AND DEFINITIONS

Class	Classification society: a body, exercising technical supervision over shipbuilding and navigation, and establishing technical and safety standards to ensure the seaworthiness of vessels.
Critical system	Essential Systems identified in the overall assessment phase that are affected by a fire or flooding casualty.
DNV	Det Norske Veritas is a classification society formerly known as DNV GL
Essential system	All systems, or sections of systems, in spaces not directly affected by flooding or fire casualty that need to remain operational by SOLAS regulations.
FMEA	Failure mode and effects analysis
FMECA	Failure mode, effects, and criticality analysis
Flag Administration	The maritime department or agency of a flag State's government responsible for enhancing the implementation of international agreements and national regulations on vessels entitled to sail the State's flag.
FTA	Fault tree analysis
HVAC	Heating, ventilation, and air-conditioning is the technology of indoor and vehicular environmental comfort.
IMO	International Maritime Organization
IEC	International Electrotechnical Commission
I/O	Input/output
MFZ	Main fire zone
MSC	Maritime Safety Committee (commission within IMO)
OEA	Orderly Evacuation and Abandonment
RBD	Reliability Block Diagram
RPN	Risk Priority Number
SOLAS	International convention for the Safety of Life at Sea. A set of regulations for maritime safety of vessels.
SRtP	Safe Return to Port

1. INTRODUCTION

1.1 Research background

The International Convention for Safety of Life at Sea (**SOLAS**) has existed since 1914 when it was first introduced due to the RMS Titanic accident in 1912. The rules are continuously developing to reflect the industry's enhanced capabilities when it comes to safety on the seas. The Maritime Safety Committee (**MSC**) of the International Maritime Organization (**IMO**) adopted a set of amendments of SOLAS at its 82nd session in 2006 (MSC 2006). These amendments are referred to as *Safe Return to Port* (**SRtP**) regulations that disclose the minimum requirements a ship and its equipment must meet in order to make sailing at sea as safe as possible. The reason for this regulation was to replace and update prevailing SOLAS regulations that could not meet the challenges of new passenger ship designs. The aim of these regulations was to switch the emphasis more on preventing casualties from occurring, and to enhance the survivability of the ships. SRtP regulations are applicable to new passenger ships having keel laid on or after the 1st of July 2010, and having at least 120 m in length, or having at least three main vertical zones. (Huttunen & Baarman 2011; IMO 2006)

To fulfil the intentions of the SRtP regulations, the requirements are achieved through more redundant and segregated system arrangements, providing increased robustness and fault tolerance. Prior to installations, an SRtP assessment should be performed. It is a structured analysis of the possible consequences of predefined fire or flooding casualty on the essential systems, covering all possible scenarios within the casualty threshold. (DNV GL 2019a)

The assessment of essential systems is performed based on casualty scenarios, connections/dependencies between various systems and functions. This requires complex and time consuming analyses due to the extent of the systems, system connections and numerous casualty scenarios that need to be considered in order to ensure regulation compliance. The author's case company, Deltamarin Ltd, has solved the issue for the overall assessment part, but the detailed assessment is still a laborious task due to the spreadsheet approach (Puranen 2014). Here, the overall assessment describes the functionality of all essential systems in predefined casualties. A detailed assessment is required once an essential system is identified in the overall assessment phase as a critical system due to operability concerns. (IMO 2006)

This thesis explores applicability of *failure mode and effects analysis* (**FMEA**) method in SRtP detailed assessment phase. The output of this thesis is to provide more information on the use of FMEA in marine engineering.

1.2 Research problem, objectives and scope

The research problem of this thesis is to determine whether the FMEA method proposed by the International Maritime Organization is suitable for the detailed assessment and whether that method corresponds to the way the case company performs the analysis. At the moment of doing this thesis, there are no scientific articles nor are there any specific guidelines related to the detailed assessment of ships' critical systems by applying the FMEA method.

The research objective is to deepen the understanding of the applicability of the FMEA method in the SRtP context by describing its suitability and benefits. The goal-based nature of the SRtP regulations set goals and criterions, but do not specify how they will be achieved. Therefore, this study contributes to research FMEA in SRtP context by introducing one way to apply FMEA in the detailed assessment phase. Another objective is to give answers how to improve the current FMEA approach for the case company. The case company's current approach involves a lot of manual work, making it tedious. Therefore, it is prone to errors which can add up because of changes and overlapping work in documentation. Moreover, each employee has their own way of doing the analysis procedure, so it needs clarification in that part. The idea is to suggest suitable solutions for the case company's current approach. In order to achieve the research objectives, the research subject is the case company's FMEA approach to the detailed assessment phase. In this way, the problems of the current situation can be identified and improved.

The scope of the research is the basic and detail design phase of the shipbuilding process, in which the assessment of ship systems is performed. This research is focused on the detailed assessment part although the overall assessment is also included as it is necessary part of the assessment procedure. In this research, the analysis and assessment are based on likelihood rather than probability which is a statistical number. To avoid confusion, the analysis term will be used in the context of methods and the assessment term in the systems SRtP assessment process. The reader should bear in mind that SRtP systems are briefly discussed at a certain category level to keep the whole topic perceptible. The study deals partially with the shipbuilding design process to see the impact of the detailed assessment on the whole.

This thesis is not part of a project assignment, and the intention was not to produce an analysis tool, but to do a preliminary study on the subject. On the basis of the topic, conclusions would be drawn about the usefulness of the method and it will be determined whether it is worthwhile to continue the research or development of the method.

1.3 Research questions and methods

The objectives and research questions determine the chosen research methods and approach. The main research question of the thesis is:

- How should the FMEA method be applied to the detailed assessment phase to achieve its objectives?

The main research question is divided into three sub-questions, which deal with the topics covered in the main research question in more detail:

1. What are the analysis steps and requirements of the detailed assessment phase?
2. How does the case company's FMEA approach differ from the typical System FMEA?
3. What are the challenges and problems of the detailed assessment phase?

A case study has been chosen as the research strategy for the thesis. The research problem and questions are answered by using qualitative research methods, which in this research include a literature review, a thematic interview, and content analysis. The literature review creates theoretical framework, and the thematic interview provides the main data for this research. Content analysis is used to analyse the qualitative data. Written materials from the case company have been used as background information for the research case.

The research sub-questions are answered through a literature review and analysis of empirical data as shown in Figure 1. The first research sub-question is to clarify what steps and requirements are involved in the detailed assessment phase. The first research sub-question is answered by literature review of the SRtP and collecting information from the case company. The second research sub-question is answered with thematic interview to see interviewees' perspective and feedback if the case company's FMEA corresponds to the System FMEA that is recommended by the IMO. The content analysis is used in the third research sub-question to find out different challenges and problems that often occur in the detailed assessment phase. The purpose of the third research question is to suggest development measures for the case company's FMEA approach. A glimpse of the results is shown in Figure 1.

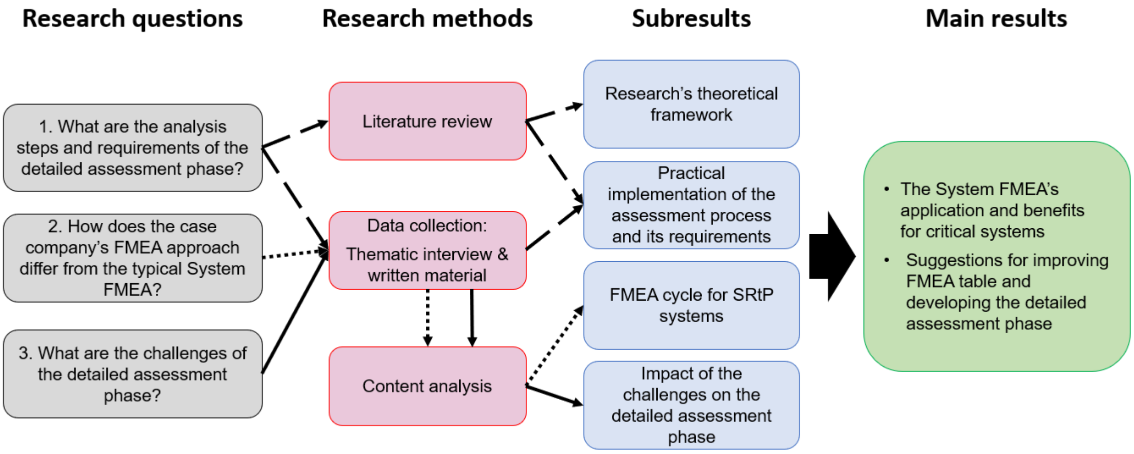

Figure 1. *Method path.*

In Figure 1, the literature review starts with the regulations that lay the foundation for why the detailed assessment of critical systems is done in the first place. After that, the literature review of the FMEA standard is to provide the best practices for implementing the FMEA method. The basis of literature reviews are regulations, guidelines by Classification Societies and the FMEA standard of IEC 60812 (International Electrotechnical Commission). This thesis deals with the theory related to reliability and safety engineering because the interpretation of the standard and guidelines would be difficult without the theory knowledge. Some literature review is done on recent research articles related to the reliability analysis of ship systems. Below is a brief description of the research methods.

Data collection method used in this thesis is the thematic interview. The thematic interview is one degree more structured than an open-ended interview, as the topics prepared on the basis of previous research and familiarisation with the topic are the same for all interviewees, although they move flexibly without a strict path (Saaranen-Kauppinen & Puusniekka 2006). Thematic interviews are intended for SRtP systems engineers to obtain deeper understanding of the detailed assessment of critical systems. Written materials were used as a basis for the case study, interview questions, and comparison with theory. Written materials are the case company's internal instructions and worksheets. Content analysis was then used to analyse written form of data.

Content analysis provides means of compacting the text format data and finding repetitive patterns. Content analysis, like other text analyses, proceeds as follows: Create a coding diagram, code text, calculate frequencies or percentages, perform hypothesis testing (Järvinen & Järvinen 2018, p. 65). More about implementation of research methods can be found in chapter 4.

This research focus was on exploring the FMEA methodology and its application. It does not provide generalisable knowledge due to its single case study nature. On the other hand, the results primarily serve the case company. Stakeholders can also benefit from this.

1.4 Report structure

The overall structure of this report takes the form of six chapters, including this first chapter, which is an introduction to the research. The report follows a typical IMRaD structure (Introduction, Methods, Results, and Discussion). This report is written with British English writing conventions. Like any thesis, this research begins with a literature review, which forms a theoretical framework.

Chapter 2 is first part of the literature review. It introduces the regulations and requirements of SOLAS “Safe Return to Port” regulations that set the basis for understanding certain concepts and measures for achieving safer passenger ships. Chapter 3 is the second and last part of the literature review that covers the FMEA methodology, which goes through the FMEA at a general level and is then followed by System FMEA procedure.

Chapter 4 describes and justifies the methodological choice for this research. It also introduces how the research was executed.

Chapter 5 presents the empirical results of the research. The data collected and created during the research are in the appendices of the report.

Chapter 6 is a discussion and conclusion chapter where the results are evaluated. The sixth chapter answers research questions and reflects on the success of the research. Moreover, suggestions for further research are introduced.

2. FOUNDATIONS OF SAFER SHIP DESIGN

The *Safe Return to Port* is design criteria issued by the Maritime Safety Committee of the IMO to improve the safety of passengers in the event of a casualty. A casualty can be a fire limited to one or more spaces bounded by A-class bulkheads and decks at a time, or a flooding bounded by watertight bulkheads and decks. Safety is enhanced by setting functional requirements for the ship's essential systems which must be met up to a certain damage threshold. Once the threshold is exceeded in fire casualties, then at least the most important systems need to be in operation to allow passengers to be evacuated safely and quickly. The SRtP regulations are goal-based in nature, which do not take a position on the method of implementation but on the final result. (IMO 2006, DNV GL 2019)

The starting chapter is a short description of the International Maritime Organization and the SOLAS convention. The following chapter introduces the SRtP regulations in their entirety to clarify the background to the research topic. The chapter 2.3 is a description of the design of the essential systems for the purpose of complying with the rules. Providing this information, the reader understands the design impact placed on ship systems design and the notation **SRtP** that covers the scope of the SOLAS regulations for *Safe Return to Port* and *Orderly Evacuation and abandonment* (OEA) concepts.

2.1 Bureaucracy of international maritime conventions

The International Maritime Organization is a United Nations organization established in 1948 whose responsibility is maritime safety, security and prevention of maritime emissions. Thus, IMO is the global standard-setting for the safety, security and environmental performance of international shipping. The organization is also empowered to deal with administrative and legal matters related to these purposes. IMO's organizational structure consists of Assembly, Council and main committees. IMO has 174 member states and three associate members. (IMO 2021b)

The assembly has the highest decision-making power in the IMO. The Assembly comprises all the member states of the IMO and is convened every two years. Whereas the council acts as the governing body between the sessions. The Council oversees the work of the organization, acting as a substitute for the meeting on matters other than making recommendation to member states on safety and emission prevention issues. Most of the work of the organization is carried out by the five main committees of the

IMO. The first one is Marine Safety committee, or MSC, which is responsible for matters relating to maritime safety. Whereas the Maritime Environment Protection Committee (MEPC) is responsible for matters relating to the reduction of maritime emissions. The Legal Committee (LC) is responsible for legal affairs. The Technical Co-operation Committee is responsible for the technical area of either the reference or the executor actor in these cases. The final one, the Facilitation Committee (FC) is an auxiliary body of the council. It facilitates the work of the IMO by eliminating unnecessary formalities and bureaucracy in international shipping. In addition, the MSC and MEPC are assisted in their work by a number of sub-committees that are presented in Figure 2. (IMO 2021b)

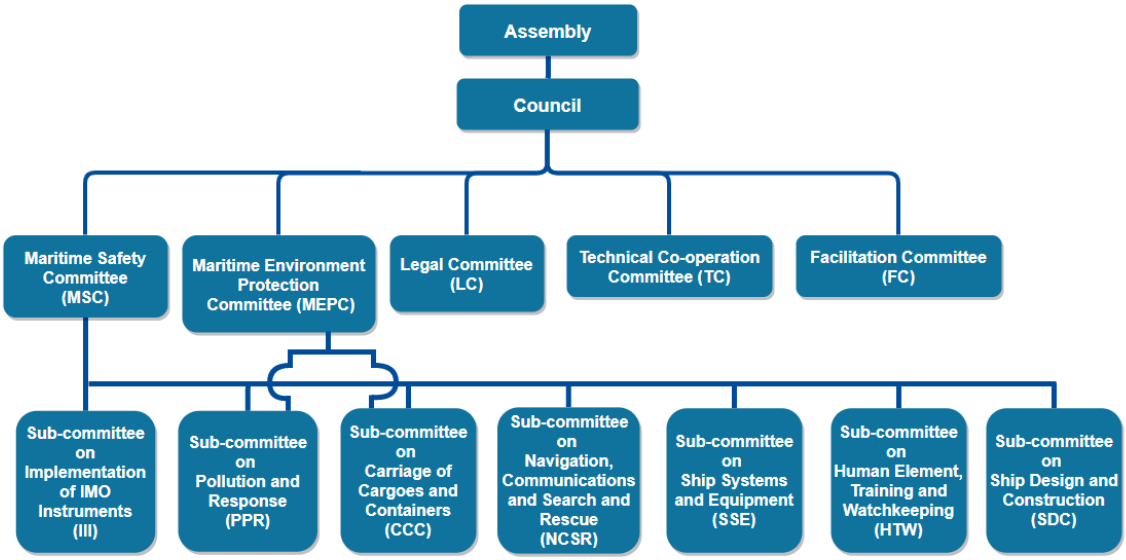

Figure 2. *Organizational structure of IMO.*

The IMO's first task was to adopt an updated version of the International Convention for the Safety of Life at Sea – SOLAS is the most important of all treaties dealing with maritime safety and is overseen by the IMO – and this was achieved in 1960 (IMO 2021b). It was a big step forward in modernising the rules and keeping up with technological developments. The IMO adopted a fifth version of SOLAS in 1974. This incorporated an amendment adopted to the 1960 Convention as well as other changes, including an improved amendment procedure under which amendments adopted by the MSC would enter into force on predetermined date unless they were objected to by a specific number of states. The 1974 Convention has since been regularly updated and modified to take account of technical advances and changes in the industry. The Convention in force today is sometimes referred to as **SOLAS, 1974, as amended**. (IMO 2021b; Vassalos et al. 2010) Figure 3 illustrates risks being managed in SOLAS.

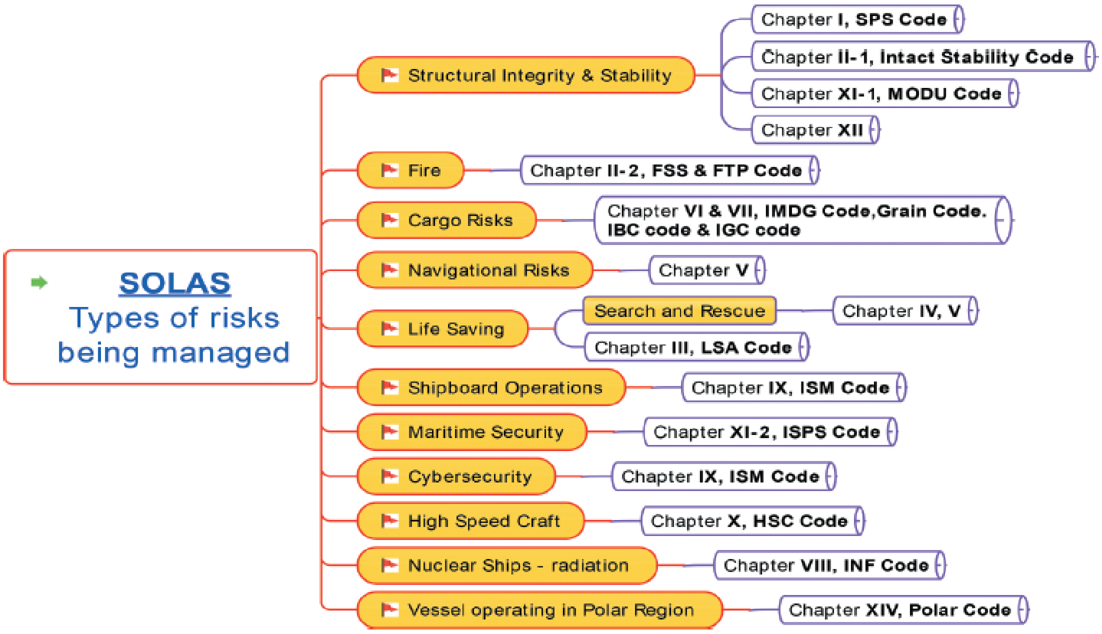

Figure 3. *Classification of risks being managed in SOLAS and chapters mitigating the primary risks (Joseph & Dalaklis 2021).*

SOLAS regulations define various standards and rules for naval architecture. It should be noted that all SOLAS regulations are not valid to every single type of vessel. Depending on the type, certain regulations have to be put into force – SOLAS is not a requirement for inland waterway vessels, whilst SOLAS is required for vessels navigating in international waters. On the other hand, warships, naval auxiliaries and other non-commercial ships owned and operated by the Contracting Government are excluded. (IMO 2009)

2.2 SRtP regulations framework

From a report of the Maritime Safety Committee on its 72nd session, the Secretary-General of the IMO set up a Working Group on safety of large passenger vessels (MSC 2000). The Secretary-General's concern came to prominence when prevailing Conventions duly addressed all the safety aspects of the operation of large passenger vessels. Due to the 1990's cruise ship accidents, entailed new improved regulations to mitigate the risk of flooding and fire accidents (Louis et al. 2002, p. 94-95; Papanikolaou 2009, p. 24). Thus, future passenger ships should be designed for improved survivability based on the time-honoured principle that the ship itself is the best lifeboat. The *Safe Return to Port* is the latest set of regulatory improvements, it has now been over 10 years since its original inception. (MSC 2000; MSC 2006)

Safe Return to Port is a very crucial concept introduced by amendments to SOLAS 1974 via the MSC resolution 216(82) in 2006. SOLAS regulations II-1/8-1, II-2/21 and II-2/22 are collectively referred to as the Safe Return to Port regulations or shortly SRtP regulations. Furthermore, the primary IMO guidance document, *Interim Explanatory Notes of MSC.1/Circular 1369,* includes the operational aspects of the regulations. It is stated in regulation II-1/2.5 that SRtP regulations are valid for passenger ships constructed on or after 1 July 2010 having a length of 120 m or more, or having three or more main vertical zones. (IMO 2006)

Regulation II-2/21 provides requirements regarding casualty thresholds, safe areas and safe return to port. The purpose of this regulation is to establish design criteria for a ship safe return to port under its own propulsion after a fire casualty that does not exceed specific casualty threshold. Moreover, it also provides functional requirements and performance standards for safe areas that take care of passengers' safety during the return to port voyage. (SOLAS: II-2/21)

Regulation II-1/8-1 provides requirements regarding system capabilities and operational information after a flooding casualty. Specifically, a passenger ship shall be designed so that the systems specified in regulation II-2/21.4 remain operational when the ship is subject to flooding of any single watertight compartment. (SOLAS: II-1/8-1)

The **casualty threshold** is the basis for the use of design rules. It is describing criteria for the amount or extent of damage that a ship is able to withstand and is still capable of returning to port safely. The casualty threshold for fire damage is defined in the regulation 21 as: the loss of the space of fire origin up to the nearest "A" class boundaries if the space of origin is protected by a fixed fire-extinguishing system. If the space is not protected, then the fire spreads to the adjacent spaces up to nearest "A" class boundaries. (SOLAS: II-2/21) "A" class boundaries are divisions formed by non-combustible bulkheads and/or decks constructed of steel, or equivalent material, that prevents the passage of smoke and flames of a one-hour standard fire test (IMO 2009). "A" class bulkheads and decks are insulated with non-combustible materials so that if either side is exposed to a standard fire test, after 60 minutes, the average temperature on the unexposed side will not rise more than 139°C above the initial temperature. Furthermore, the temperature at any point on the unexposed side, including any joint, should not increase by more than 180°C above the initial temperature. The time duration for which the bulkhead complies with this, governs its class:

"A-60"	60 min
"A-30"	30 min

“A-15”   15 min

“A-0”   0 min

In accordance with MSC.1/Circ. 1369 Interpretation 7, only the adjacent spaces within the same main vertical zone need to be considered and the casualty threshold includes spaces one deck upwards. Therefore, a fire is not intended to spread downwards but only to upper decks (Figure 4). If the fire exceeds the threshold, then OEA of the ship is to be performed. The casualty threshold for flooding damage is considered as one watertight compartment. If any watertight compartment or less is lost, then the casualty threshold is not exceeded (SOLAS: II-1/8-1).

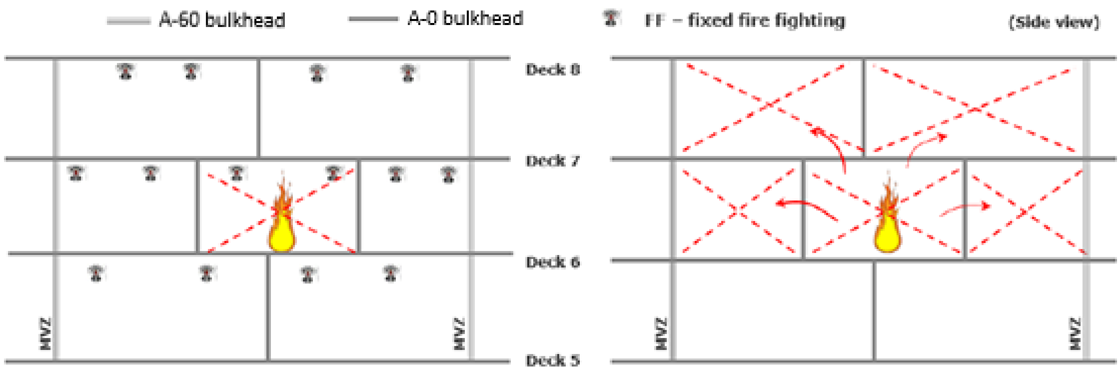

Figure 4. *Fire casualty threshold: a) Fire in a protected space; b) Fire in a non-protected space (DNV GL 2020).*

It is noteworthy that the casualty threshold is a technical design criterion. Therefore, exceeding casualty threshold does not automatically mean evacuation of the ship. On the other hand, damage within the casualty threshold does not mean that the ship could not or should not be evacuated. In real situations, the decisions to start evacuating a ship is made by the ship’s captain and crew. (Ilus 2011, p. 5) If the casualty is within the casualty threshold, then the essential systems shall be designed to enable recovery of the intended functionality after any fire or flooding casualty within one hour (IMO 2006).

When fire or flooding damage is within the prescribed casualty threshold, the ship shall be capable of returning to port while providing a safe area. In order to execute this safe voyage to nearest port, the following systems shall remain operational in the remaining part of the ship not affected by fire or flooding (SOLAS: II-2/21 & II-1/8-1):

1. Propulsion;
2. Steering and steering-control systems;
3. Navigational systems;
4. Systems for fill, transfer and service of fuel oil;
5. Internal communications;

6. External communications;
7. Fire main system;
8. Fixed fire-extinguishing systems;
9. Fire and smoke detection system;
10. Bilge and ballast pumping system;
11. Power-operated watertight and semi-watertight doors;
12. Safe Area services;
13. Flooding detection systems;
14. Other systems determined by the Flag Administration to be vital to damage control efforts.

As mentioned above, **safe areas** are ship zones in which passengers and crew must stay after a damage not exceeding the casualty threshold and during the return of the ship to port. Safe areas shall generally be internal spaces. The use of an external space as a safe area may be allowed by the Flag Administration on the basis of any restriction due to the area of operation and relevant expected environmental conditions. The safe areas shall provide all occupants with the following basic services to ensure that the health of passengers and crew is maintained:

- restrooms and potable water & food;
- shelter from the weather;
- lighting and HVAC (heating, ventilation, and air-conditioning).

One thing that is not listed is an alternate space for the medical care. Such a space should be arranged in addition to the primary hospital that is located in a different fire zone and is easily accessible. There needs to be additional attention to HVAC in that the ventilation must be designed in a way which reduces the risk of smoke and hot gases from entering the safe area. The temperature in internal safe areas needs to be in the range of 10 to 30 Celsius. Also, safe areas must have means of access to life-saving appliances, considering the possibility of a loss of a complete main vertical zone that may not be available for internal transit. (SOLAS: II-2/21; Interpretation 47)

Regulation 22 provides design criteria for systems required to remain operational for supporting the **orderly evacuation and abandonment** of a ship in case the casualty exceeds the defined threshold (SOLAS: II-2/22). In these circumstances, the casualty can be considered to involve an entire main vertical zone. As a result, the following systems shall be arranged and segregated in such a way they remain operational:

1. Fire main;
2. Internal communications (in support of fire-fighting as required for passenger and crew notification and evacuation);

3. Means of external communications;
4. Bilge systems for removal of fire-fighting water;
5. Emergency lighting (escape routes, assembly stations, embarkation stations);
6. Guidance systems for evacuation.

The systems listed above shall be capable of operation for at least 3 hours based on the assumption that there is no damage outside the unserviceable main vertical zone. These systems are not required to remain operational within the unserviceable main vertical zones. (SOLAS: II-2/22) The casualty procedure is illustrated in Figure 5.

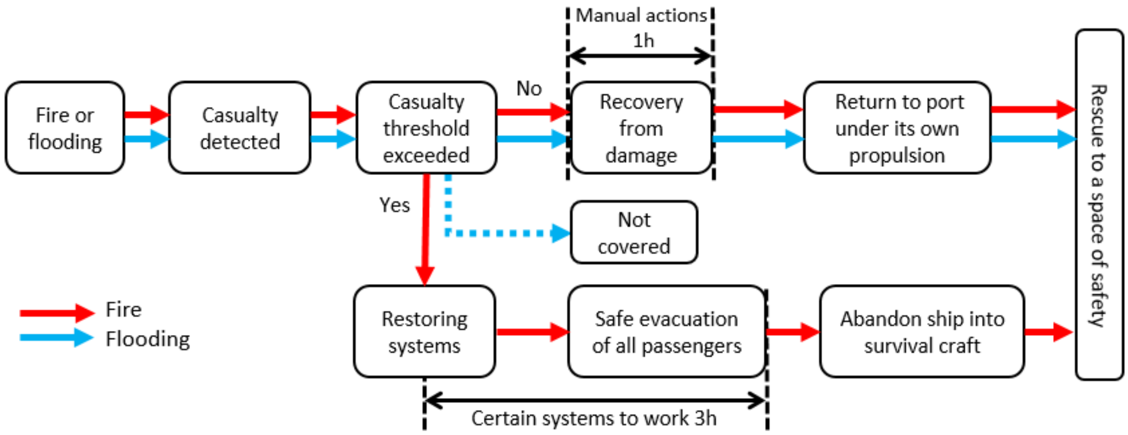

Figure 5. *Schematic of the course of the SRtP situation.*

In this thesis, the main parts of the regulation text are presented. Therefore, further information is found in the regulation text (IMO 2006). It needs to be noted that the SRtP regulations are generally given as a goal-based standard, giving functional as well as performance requirements to the capabilities of the systems deemed necessary to enable safe voyage to port after a casualty or to support orderly evacuation if the situation demands so. Basically, goal-based implies that the goals and functional requirements are formulated as long standing requirements without reference to specific technology or ways on how the goals should be achieved (Papanikolaou 2009, p. 97). The goal-based structure is presented in Figure 6.

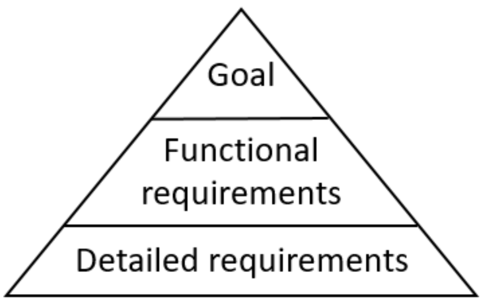

Figure 6. *Goal-based structure of SRtP regulations.*

In Figure 6 the detailed requirements cover functional and performance requirements that are supported by detailed rules and guidance notes. These rules provide a set of generally acceptable solutions to meet the goals, either in part or in whole. (DNV GL 2019a & 2019b) The primary guidance document MSC.1/Circ.1369 gives allowance for operational procedures to meet the intentions of SRtP by accepting and by the restoration of system capabilities in the event of a casualty. The next subchapter reviews the varying design approaches and the documentation phases to achieve SRtP goals.

2.3 Design intent for ship systems

The goal in ship design practice nowadays is to deliver a ship that meets the expectations defined by the owner's operational or functional requirements while complying with the statutory rules and regulations as well as ensuring that the construction process stays within a budget and schedule (Papanikolaou 2009, p. 20). Due to the fact that the Safe Return to Port regulations are deterministic in their design, it is therefore open to different interpretations. This creates ongoing dialogue between owners, shipyard/designers and classification societies creating inconsistency in methods and practices within the industry. Compliance checks are the responsibility of a Flag Administration; however, part of the work is delegated to a classification society (Papanikolaou 2009, p. 159).

The role of a classification society is to exercise technical supervision over shipbuilding and navigation, and to establish technical and safety standards to ensure the seaworthiness of vessels. They are non-governmental organizations and Det Norske Veritas (**DNV,** formerly DNV GL between years 2013-2021) is one of the major classification societies in the marine and offshore industry. DNV is an autonomous and independent foundation with the objectives of safeguarding life, property and the environment, at sea and onshore. As stated in DNV (2012), it undertakes classification, certification, and other verification and consultancy services relating to quality of ships, offshore units and installations, and onshore industries worldwide, and carries out research in relation to these functions. The guidelines from DNV have provided a lot of detailed information for chapter 2.

The design criteria given by SRtP regulations is implemented via guidelines of MSC.1/Circ.1369 and DNV. These guidelines aim to clarify the regulations so that there is less room for speculation and all stakeholders involved know the boundaries within they act. In the following subchapters systems design and assessment as well as documentation phases for SRtP requirements are described.

2.3.1 Systems design against a casualty

As stated in DNV GL (2019) the objective is to ensure that the required systems are designed and arranged with adequate redundancy segregation so that any casualty will have very limited impact beyond the boundaries of the casualty threshold. The essential systems can then be restored in all relevant spaces outside the loss space due to fire or flooding incident. Therefore, SRtP regulations need to be taken into account from the very beginning of the design process – this is discussed more deeply in subchapter 2.3.3. In order to fulfil requirements for essential systems to remain operational, the SRtP regulation provides five possible approaches (IMO 2006; DNV GL 2019a):

- **Separation**: to place various components of a generic system inside different space, delimited by A-class boundaries or different watertight compartments.
- **Duplication**: to carry out a specific service by using two smaller elements, rather than a single bigger one.
- **Redundancy**: to provide at least two identical elements, each capable of ensuring the full service requested by a single component - generally, one element is active while other is on standby (DNV 2012, p. 8-9).
- **Protection**: to use special materials able to protect pipes, components, or vital parts of a system, which could be damaged**.**
- Combination of the above

However, in order to choose the best design approach possible, there needs to be an understanding of how each essential system works in casualty scenarios. These systems can be split into four different categories based on their operating principles. The following categories are:

1. Duplicated systems
2. Systems with a general service across the ship
3. Safe area systems
4. Orderly evacuation and abandonment systems

Category 1 systems that provide propulsion, steering and navigation for instance shall be arranged to ensure simultaneous availability after a casualty that may occur in any compartment. These systems are naturally arranged with duplication/redundancy, a system ‘A’ and ‘B’, each system located within separate A-class spaces dedicated for either system A or B. This means that all components, from main mechanical components to necessary power supplies, shall be arranged and located in the dedicated zones (i.e. casualty thresholds). Therefore, the general arrangement of the ship with a clear definition of which zones and compartments that are dedicated for the redundant systems shall be made at an early phase, and the design and arrangement of all relevant systems shall be made in accordance with the zone definition. (DNV GL 2019a, p.18-19)

Category 2 systems with a general service across the ship, such as bilge systems or fire detections, are inconvenient for duplication since the systems may serve any space on board making duplication systems A and B insufficient because any casualty in one space will impair the continued service in any other space. This requires different design principles to be applied. These systems must remain available in all spaces not subject to damage. This is a quite strict requirement and demands highly redundant and segregated systems. However, DNV has its SRtP class notation for the systems in this category that grant less stringent acceptance criteria for what can be considered operational. (DNV GL 2019a, p. 19)

Category 3 systems are safe area systems that are listed in chapter 2.2. Depending on the number of persons on board, the simpler solution is to provide two safe areas located in different main vertical zones: forward and aft. All the safe area systems are arranged so that the systems are supported within the zone, and have the possibility to isolate from the neighbouring zone. In this way, the general design approach may be equivalent to the category 1 systems where the general requirement is that either one of the safe areas remain operational after any casualty on board. (DNV GL 2019a, p. 20)

Category 4 systems are for orderly evacuation and abandonment scenario. These systems require adequate protection for cables and pipes. This is because if the main vertical zone is lost then the systems listed in SOLAS II-2/22 need to remain operational in all other main vertical zones to support the evacuation. As a result, specified systems shall be designed in such a way that any casualty in one main vertical zone does not impair the continued service for three hours in the other main vertical zones. (DNV GL 2019a, p. 20)

The implications of the chosen design approach can be quite significant as shown in Figure 7. It is strongly recommended that this aspect is considered carefully in the early project phases and that the chosen approach is agreed upon between the owner and the yard. This subchapter has introduced the different design approaches against casualty for a system to remain operable. The next chapter addresses the assessment of systems as it is a very laborious process where each fire or flooding scenario is analysed system by system.

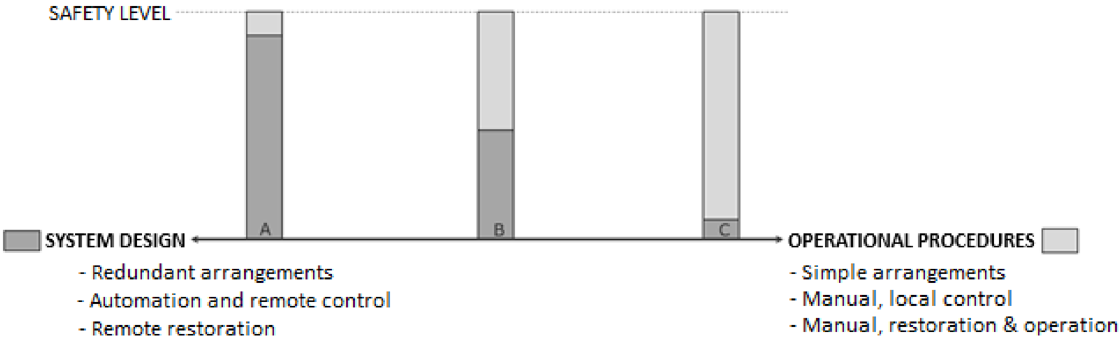

Figure 7. *Design approaches. Option A has more costly design solutions with limited operational impact. Option B has cheaper design solutions with higher operational impact. (Modified from DNV GL 2019a)*

2.3.2 Assessment of ship systems capabilities

Assessment of systems is a two-step process designed to determine the level of survival of systems from the requirements placed on them. The process flow is illustrated in Figure 8. This is the most laborious part of complying with the Safe Return to Port regulations. When performing the assessment, it should be based on structured methods and a system-by-system-based approach is recommended. This system-based approach will outline potential weaknesses but requires holistic understanding of the ship's systems. Thus, it needs information on how systems are coupled into essential systems and auxiliary systems. (IMO 2006)

In the first phase, a comprehensive system assessment is carried out, reviewing all essential systems. This **overall assessment** is a systematic study of each essential system to demonstrate their capability to remain operational after a fire or flooding casualty. Manual actions by the crew to maintain the operability of the systems are permitted, provided that they are planned and defined in advance. In addition, the flag administration of the ship must give its approval to any manual operation. Instructions for all manual operations must be found, as well as the required tools. All the systems that do not pass the first phase of assessment, are classified as critical systems. If no critical system has been identified during the first phase, the overall assessment is considered acceptable without the need for further analysis. (IMO 2006)

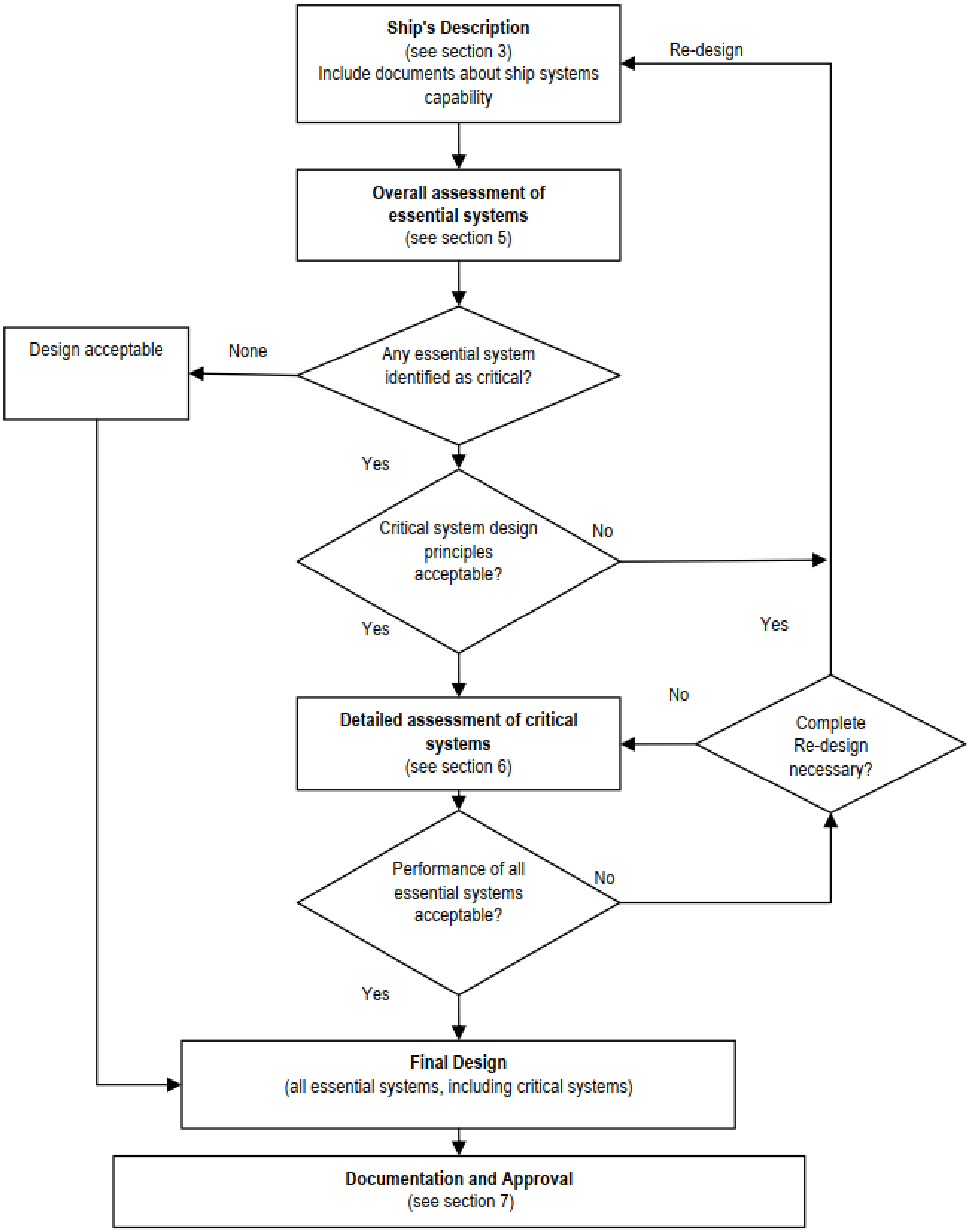

Figure 8. *Assessment of SRtP systems capabilities process flowchart (IMO 2006).*

The next phase of the process is the **detailed assessment** of critical systems. During the detailed assessment, each critical system must be described as how the system will be restored to operation. Quantitative analysis can be carried out as a part of the detailed assessment of all critical systems. This might mean performing fire risk within a space that is supported by fire engineering analysis or fire testing, as appropriate. A failure mode and effects analyses of a system might be included, and for flooding incidents the possibility of flooding of a particular compartment can be evaluated with a detailed analysis.

It is noteworthy in the assessment that the regulations do not provide a guideline for the numbers used in the assessment and the performance requirements of the systems. Nonetheless, if the system's capability cannot be ascertained for all casualty situations that do not exceed the casualty threshold, then the design must be changed and a new assessment must be carried out. (IMO 2006)

2.3.3 Phases of design approval

In the design of ship systems, it is possible to use different design criteria to achieve the design requirements set for the ship. The selected design requirements must be well documented in order for the systems to be approved. Here, the process of verification of the ship's design, with respect to SRtP requirements, is detailed in MSC.1/Circ. 1369, and is primarily intended to be performed with a system-based approach. Documentation required for such assessment should be carried out in a way that the following information is acquired, documented and delivered to the Classification Society and the owner. In Figure 9 is a holistic presentation of SRtP documentation phases from the perspective of the design office. The documentation is based on design phases, Interim Explanatory Notes and other reports. (Puranen 2014, DNV GL 2019a, IMO 2006)

When a new project starts, shipowner's requirements are the most important input. A prerequisite and starting point for this assessment is that the shipowner has defined the operating patterns of the ship, for example maximum area of operation, routes and upper limit on the number of passengers. All of the system capabilities built into the ship will depend on the operating patterns. (DNV GL 2019a, IMO 2006)

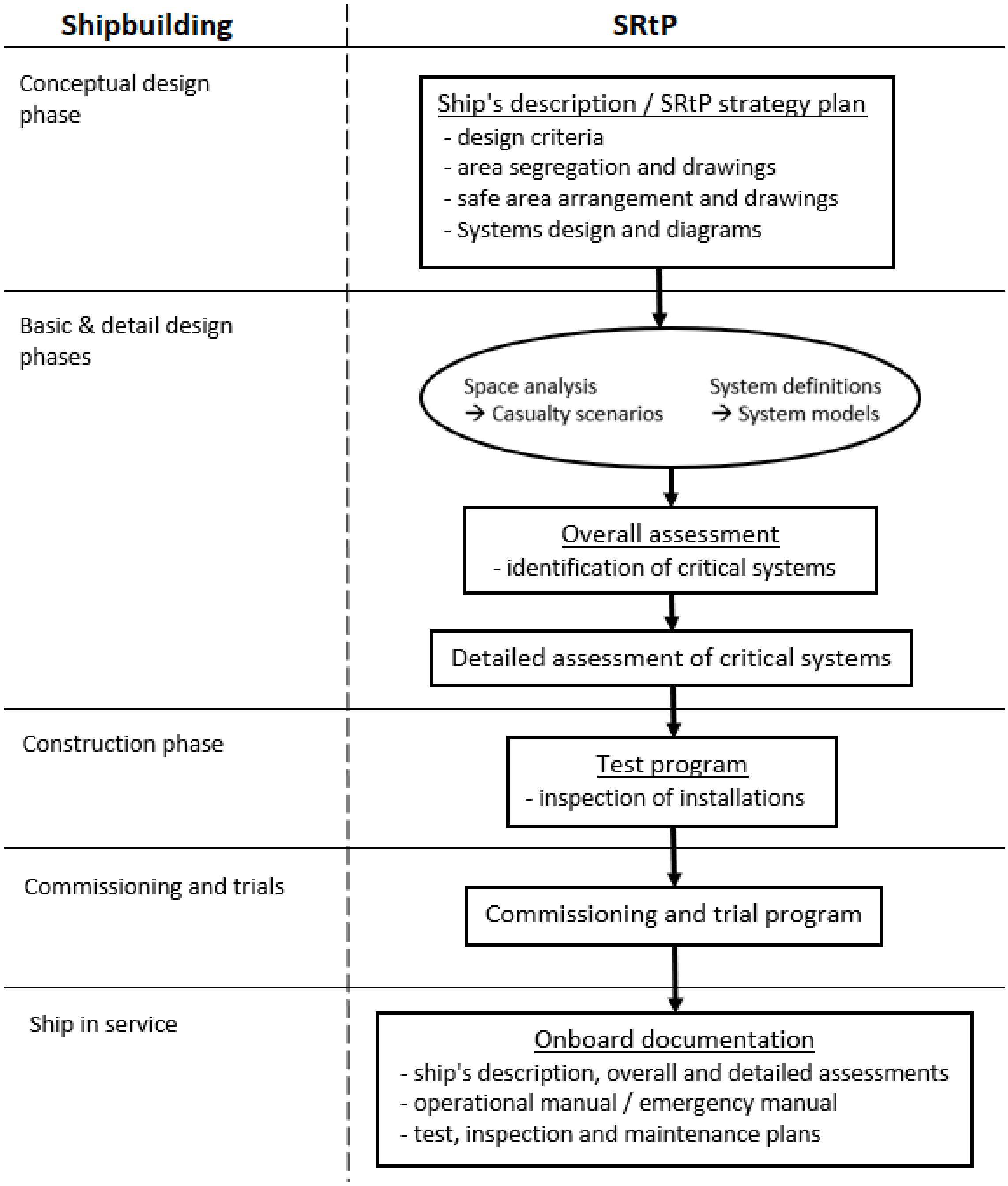

Figure 9. *The role of SRtP documentation requirements in different stages of shipbuilding (Modified from Puranen 2014).*

The operating pattern(s) should be included in the **conceptual design phase**. In this first phase, the ship's description along SRtP strategy plan should be provided to the Flag Administration. The main goal of the ship's conceptual design phase is to design a ship that meets the owner's requirements and is also economically viable for the shipyard. At this stage of the design project, relatively large decisions are being made about the ship's SRtP characteristics. Therefore, the conceptual design phase documentation should at least include:

- **Design criteria** to be applied for essential systems to achieve compliance (e.g. separation, duplication, redundancy, protection, or a combination of the above).
- **Area segregation** and drawings, which show basic layout of the ship with necessary information (such as drawings describing A-class boundaries, watertight boundaries, spaces protected by fixed fire-extinguishing systems etc.).
- **Safe area** arrangement and explanatory drawings.
- **System design** describing the features and locations of essential systems in outline.

The ship description and SRtP strategy plan are therefore the top SRtP document because it defines the basic design intent and operational criteria for the project. Thereby, covering entire SRtP regulations and design philosophy. (Baarman 2012; Bureau Veritas 2016; DNV GL 2019a; IMO 2006).

The second phase is a systems assessment. The capabilities of the essential systems shall be analysed and documented in a report. Here, the **basic and detail design phase** starts with creating casualty scenarios based on the A-class bulkheads and watertight subdivision. As a result, the system design becomes more detailed. This allows the system models to be utilised in the overall and detailed assessment. It needs to be noted that the detail design of the individual systems affected by the SRtP regulations should not be done before the design philosophies are developed. When all relevant information of spaces and systems is available, the overall assessment can be made. (DNV GL 2019a; Baarman 2012; IMO 2006)

Once the overall assessment is concluded, the results define the need for a possible detailed assessment. Here, a detailed assessment must be performed for each system whose functionality could be affected after a damage. Therefore, the detailed assessment of these critical systems should contain the following information:

- Remaining functionality of the system
- Details of any manual action providing the required ship systems functionality
- Details of any operational solution forming part of the design criteria

The assessment and the report serve different purposes, both as part of the verification of the actual detail design and also as a key document for the preparation of operational procedures. The assessment is based on the detail drawings and documentation of the actual design, and it is necessary to identify clearly on what basis the assessment is done. (DNV GL 2019a; IMO 2006)

The **construction phase** consists of a test programme which should include methods of testing, and test facilities provided, where applicable. At this stage, it is important to verify that the as-built arrangements and systems meet the design and verify that the required capability following a damage scenario is available. After the actual installation, the test shall be performed. If there is a difference between the installations and design, the functionality of the system is revised, and the assessment process is to be redone. The worst-case scenario is to do reinstallations. This implies a continuous cross check activity. The test programme is also carried out in the **commission and trials** phase where systems functionalities under certain conditions are verified during quay and sea trials. (Bureau Veritas 2016; DNV GL 2019a; IMO 2006)

Lastly **ship in service** includes documentation for onboard. The onboard documentation is generally the full set of design documentation and, in addition, the SRtP operational manual and maintenance manual. Onboard personnel need to perform manual actions to return certain systems to working order following a casualty within the threshold. These operational manuals need to be made so that any manual actions identified can be completed within the required time of one-hour (Lloyd's Register Group Limited 2014, p. 4). Even if the SRtP regulations are design criteria, the consequences of each casualty and corrective actions for them are planned and reported for possible use onboard. The onboard documentation as a package consists mostly of documents that are part of the approval scope. Thus, the onboard documentation in itself is not subject to approval by the Classification Society. The onboard documentation is also intended to be the design basis for future modifications and refurbishments so that eventual changes to the system arrangements, or casualty thresholds, do not impair the robustness or system capabilities. In Figure 10 is presented the timeline of the SRtP documents. (DNV GL 2019a; IMO 2006)

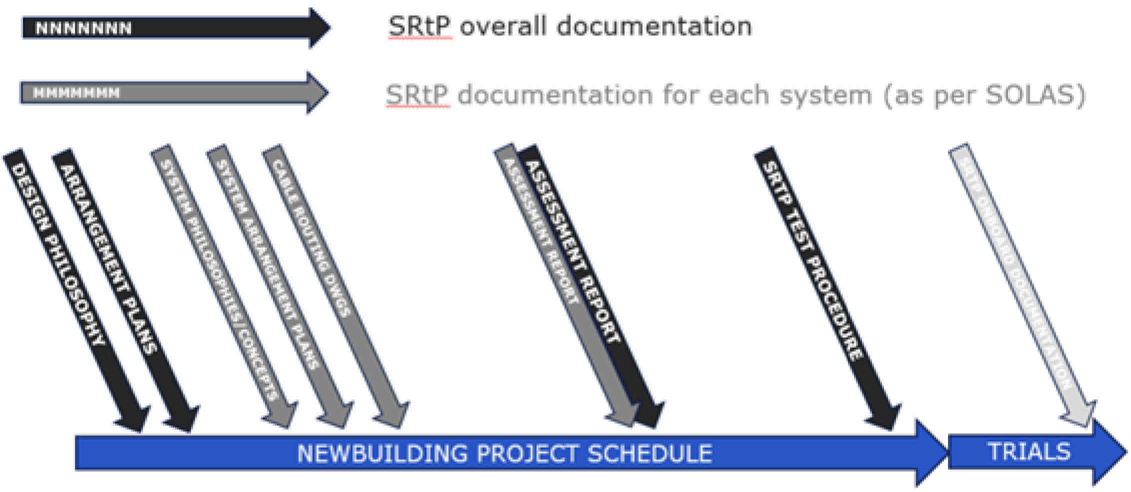

Figure 10. *SRtP documentation flow and sequence (DNV GL 2019a).*

3. FAILURE MODE AND EFFECTS ANALYSIS

Safety can be shortly described as the state of protection from the hazards of natural forces and human errors. As in terrestrial facilities, safety is one of the most important issues in ships. Sames (referenced Papanikolaou 2009, p. 3) stated that risk is used to measure the safety performance. In the SRtP the assessment is normally a very complex exercise. Thus, a wide variety of different methods and tools are used, such as the manual desktop analysis of drawings to modern computerised models and simulators. The methods and tools mentioned above utilise a certain hazard identification technique. There are various techniques available depending on the case, the purpose and the level of the design knowledge available – HAZID, FMEA, SWIFT, HAZOP etcetera (Papanikolaou 2009, p. 29).

Technical systems typically consist of several subsystems and components which, due to their interaction, enable the performance of the functions assigned to them. Maintaining these functions requires the identification, assessment and management of the technical risks associated with them. This chapter is a literature review for exploring the FMEA methodology. It is recommended by the IMO that the failure mode and effects analysis is utilised for critical systems functionality in accordance with standard IEC 60812 and/or resolution MSC.36(63), annex 4. The latter is used as context for FMEA applicability for vessels.

3.1 Purpose and objectives of FMEA

Failure mode and effects analysis is a systematic and structured risk assessment method of evaluating a system or a process to identify the ways in which it might potentially fail. The purpose of this analysis method is to find possible faults as well as hazards due to operational errors and measures to prevent these. (SFS 2018) FMEA discipline was originally developed in the United States Military in the late 1940's. In the 1960s, the National Aeronautics and Space Administration (NASA) was the first, outside the military, to adopt FMEA application during their Apollo missions. Afterwards, the automobile industry has strongly utilised FMEA techniques, and it was introduced in all industries, including the maritime industry. FMEA has been introduced by many industries and organizations, and is therefore applicable to hardwares, softwares, processes, human action, and their interfaces, in any combination. (Jeon et al. 2020; Russomanno et al. 1994; Papanikolaou 2009, p. 198; Spreafico et al. 2017)

The primary objective of FMEA is to identify and eliminate weaknesses before the product gets into the hands of the customer. FMEA may also include identifying the causes of failure modes. (SFS 2018) When performed effectively, FMEAs can contribute to improved designs for products and processes. This leads to higher reliability, better quality, increased safety, enhanced customer satisfaction and reduced costs. (Carlson 2012, p. 25) Regarding failure modes, the terms associated with them are defined in the paragraph below for clarity.

The failure mode is defined as the effect by which a failure is observed on the failed item. The definition of failure is the termination of the ability of an item to perform a required function. Failure is an event, whereas fault is a state. (DNV 2012, p. 8) Depending on the definition of failure established by the analysis team, failure modes may include:

- failure to perform a function within defined limits,
- inadequate or poor performance of the function,
- intermittent performance of a function,
- and/or performing an unintended or undesired function.

Once the failure mode is known, the failure effects can be determined. Failure effect is the consequence of a failure mode in the scenario defined for the analysis. The same failure effect might be caused by one or more failure modes of one or more elements of a system. The failure modes are discovered through testing and brainstorming as part of the development process. (SFS 2018; Carlson 2012)

Failure modes may be prioritised according to their importance. The prioritisation can be based on a ranking of the severity alone, or this can be combined with other measures of importance. When failure is prioritised, the process is referred to as failure mode, effects and criticality analysis (FMECA). In IEC 60812, FMECA is included in the term FMEA. Nonetheless, FMEA is great for analysing the effect of single failures. Needless to say, it is not suitable for analysing and handling situations where more than one failure exists at the same time. It should be pointed out that the FMEA should be implemented in a manner that is consistent with any legislation that is actually within the scope of the FMEA, or the type of risks associated with it. (SFS 2018)

The term system is often used in this thesis because it is the subject of this FMEA research. The FMEA is suitable for use at various stages of the system life cycle, from early design review to operational development. Systems are often comprised of elements that may each be individually considered. In FMEA a system is broken down into elements (Figure 11). The definition of element according to IEC 60812 is: “level of sub-division of a system, item or process hierarchy at which failure modes are to be identified". In practice, FMEAs are worksheets that should be the guide to the development of a complete set of actions that will reduce risks associated with the system, subsystem, and component to an acceptable level. (SFS 2018; Carlson 2012)

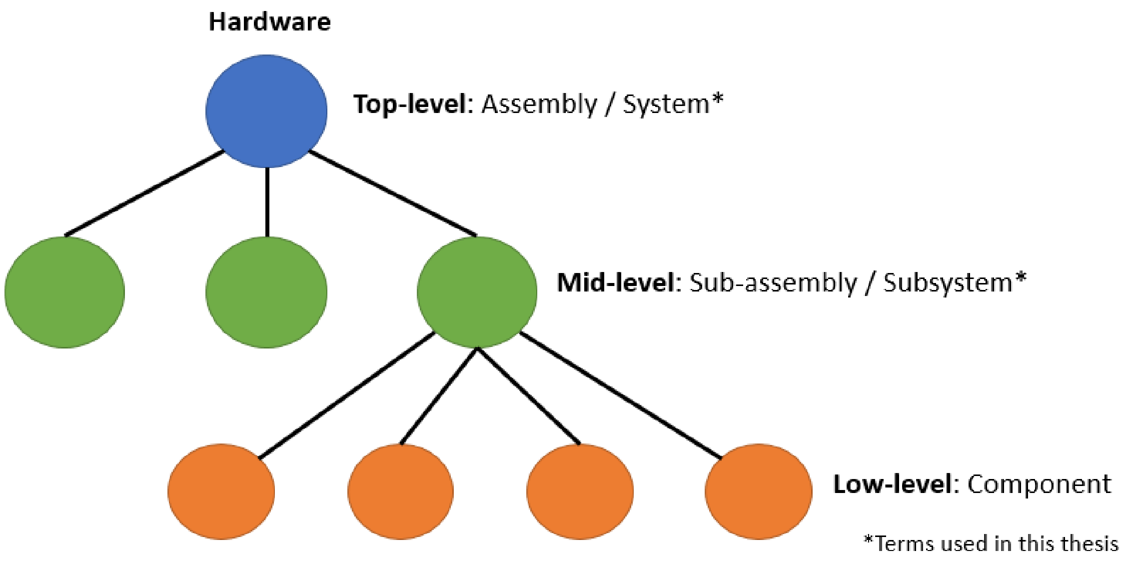

Figure 11. *Levels of hierarchy for hardware.*

The following chapter introduces a criticality analysis method as part of the FMEA. The SRtP regulations' main purpose is to make passenger ships safer if a casualty occurs and safety deals with consequences of failure (Ram & Davim 2017). Therefore, criticality analysis method needs to be introduced and scrutinised properly.

3.2 Criticality analysis in decision-making

The FMEA analysis can be extended with a criticality analysis that assesses at least two risk factors for the effects of the failure mode. The criticality analysis seeks to determine the significance or criticality of each failure mode – compared to the proper operation and performance of the system – and to determine the impact on the reliability and safety of the process in question. Criticality analysis normally measures the severity of the effect with at least one other characteristic of a failure mode. (SFS 2018)

By adding a criticality analysis, it enables prioritisation of the failure modes for potential treatment. In this way, FMEA analysts can assign the limited resources to the highest risk elements. Criticality analysis greatly enhances the benefit of the effect analysis, as it can be used to identify an element whose closer inspection can eliminate a particular hazard, reduce the likelihood of a failure, or reduce the damage caused by a failure. It is recommended that the criticality analysis be performed in more detail on a newly designed system with an unknown reliability history. Such a system should be addressed in a bottom-up approach. (SFS 2018; Carlson 2012)

A bottom-up approach means that the starting point to the analysis is for elements at the lowest level of the hierarchy relevant to the objectives. There is also a top-down approach where the starting point to the analysis is the top- or mid-levels in the hierarchy and the causes for the failure modes limited to the failure of the elements in the next lower level(s). (SFS 2018)

3.3 Measurement scales for criticality parameters

The method for criticality analysis can vary between projects, even within the same organization although a consistent approach to criticality analysis is beneficial. Before one may perform criticality analysis, the measurements for criticality parameters need to be defined. The choice of criticality levels requires careful and considered decisions. Criticality levels can be based on, for example, personal injury or financial loss due to an operation. A higher criticality value means more urgent corrective action. Determining the mutual importance, i.e. prioritising them, is the basic idea of the analysis. Criticality parameters can be measured qualitatively, quantitatively or semi-quantitatively. The following definitions for the measurements are from IEC 60812 (SFS 2018):

- Criticality parameters might be expressed **qualitatively** using descriptive categories, ordered by degree. For example, ‘minor’, ‘major’ or ‘catastrophic’ (for severity of effect); or ‘frequent’, ‘occasional’ or ‘remote’ (for the likelihood of the failure mode occurring). Qualitative scales might be useful when detailed information is unavailable, or the item is insufficiently defined to enable relevant quantitative data to be applied.

- Criticality parameters might be expressed **quantitatively** using empirical or other data in the form of a failure rate or probability of failure, and quantifiable consequences such as the economic or financial cost of failure. Ratio scales are established to match the relevant range of data with specified units.

- When data only allows descriptive or order of magnitude estimates to be made, then criticality parameters might be expressed using ordinal rating scales, sometimes called ranking scales. If numerical labels are associated with ordinal ranks of likelihood and severity, or bands of failure rates and financial cost ranges, the approach is sometimes referred to as **semi-quantitative**.

In traditional FMEA analyses, every failure mode is assigned a risk priority number (RPN) (Liu 2016). A risk priority number is a numerical ranking of the risk of each potential failure mode. The RPN is calculated as the product of the severity (*S*), occurrence (*O*) and detectability (*D*). That is,

$$RPN = S \times O \times D, \tag{1}$$

where *S* is the seriousness of the failure, *O* is the probability or frequency of the failure, and *D* is the ability to detect the failure before the impact of the effect is realised. If detectability is omitted, RPN is calculated directly from severity and occurrence. Then the value is called the critical number. (Carlson 2012; SFS 2018) Importance of these three parameters in the FMEA is briefly explained below:

- **Severity** is the FMEA rating scale that shows the seriousness of the effect of the failure, not the severity of the failure mode itself. It is evaluated from the end user's point of view directly at and near it. The value refers only to the effects of the failure. (Carlson 2012; SFS 2018) Particularly important is to identify and understand single-point failures that are high severity problems. A single-point failure occurs where failure of a single component results in complete failure of the entire system (Carlson 2012).
- **Occurrence** is the FMEA rating scale that shows the probability or frequency of the failure. The occurrence ranking has a relative meaning rather than an absolute value and is determined without regard to the severity or likelihood of detection. (SFS 2018) In FMEA language, redundant design can reduce the occurrence of system failure and reduce system severity to a safe level (Carlson 2012).
- **Detectability** is the ability to detect the failure before the impact of the effect is realised. Just like previous scales, detection is a relative ranking within the scope of the specific FMEA and is determined without regard to the severity or likelihood of occurrence. The higher the value, the less likely it is to detect a failure before its effects. Some practitioners avoid detection scale entirely because of concerns about the validity of this type of risk. Instead, they focus on severity and occurrence. (SFS 2018)

The scale of RPN depends on the scales of the values used for it. Generally, the criticality parameters *S*, *O* and *D* are scaled and calculated by experts with an integer number from 1 to 10. Thus, the RPN can scale from 1 to 1000. However, these scales can be adapted to better suit the application if the FMEA team so decides. An example of an integer number ranking system for the criticality parameter of severity is provided in Table 1.

The values for S, O and D should be determined according to a guideline table that displays a verbal explanation for each value. This contributes to the consistency of the analysis. These guideline tables should also be prepared with a view to the subject to be analysed, and there is no universal basis for them. The goal of the FMEA practitioners is to reduce the RPN; the higher the risk of severe impact, the more the FMEA process will seek to reduce it before product release or re-release through corrective actions. Because of the corrective actions, RPNs should be recalculated to see whether the risks have gone down and to check the efficiency of the corrective precaution for each failure mode. (Carlson 2012, Liu 2016)

Table 1. Traditional ratings for severity of a failure mode (Liu 2016).

Rating	Effect	Severity of effect
10	Hazardous without warning	Highest severity ranking of a failure mode, occurring without warning, and consequence is hazardous
9	Hazardous with warning	Higher severity ranking of a failure mode, occurring with warning, and consequence is hazardous
8	Very high	Operation of system or product is broken down without compromising safe
7	High	Operation of system or product may be continued, but performance of system or product is affected
6	Moderate	Operation of system or product is continued, and performance of system or product is degraded
5	Low	Performance of system or product is affected seriously, and the maintenance is needed
4	Very low	Performance of system or product is less affected, and the maintenance may not be needed
3	Minor	System performance and satisfaction with minor effect
2	Very minor	System performance and satisfaction with slight effect
1	None	No effect

It needs to be pointed out that the RPN number can only be used to compare failures under investigation with each other, and the number has no other meaning. For example, the results of previous FMEA analysis cannot be compared in terms of risk priority values. (Stamatis 2003) The main disadvantages are presented next.

The conventional RPN method is not a perfect measure of risk. It has been broadly criticised in the literature as having many inherent deficiencies, which affects its effectiveness and limits its actual applications (Bashan 2020). The main limitations of RPN are as follows:

1) subjectivity of RPN because its parameters are difficult to be exactly evaluated due to their subjective judgement on a 10-point scale basis. Therefore, placing the RPN threshold value for primary failure can be difficult because of the different opinions.

2) The mathematical formula for calculating RPN is debatable and lacks a complete scientific basis.
3) There are holes in the scale (i.e. RPN is not a continuous scale due to the ordinal scale).
4) The RPN has many duplicate numbers. For example, 60 can be formed from 24 different combinations of *O*, *S*, and *D*.
5) The relative importance among *O*, *S*, and *D* is not considered. For instance, an extreme case of a failure mode with a very high severity by itself should have a higher priority for corrective action despite RPN number.

For comprehensive reviews on the drawbacks of the RPN, one can refer to Liu's Appendix (2016, p. 215-219).

The IEC 60812 standard presents four other criticality analysis methods that only combine measures for the parameters: likelihood of failure, the consequences of failure, and the detectability of the failure. The RPN was one of the methods. The rest are the criticality matrix, the criticality plot and the alternative risk priority number. Each of these methods described, including RPN, are general and should be tailored for the application in order to be meaningful to the context. (SFS 2018)

3.4 Types of FMEAs

Depending on the object to be analyst, FMEA can be applied to services, softwares, systems, product design and processes (SFS 2018). Unless otherwise noted, hereinafter the term target refers to a service, software, system, product design or process. The target under consideration can be approached with different types of FMEA. Several types of FMEA have been mentioned in the literature and each has a different way of dealing with the target (Carlson 2012, SFS 2018 Stamatis 2003, Yang & Basem 2009). The different FMEAs are related to each other but can also be performed independently. Each of them focuses on the different phases of a target over time, see Figure 12. (Stamatis 2003)

The FMEA can generally be classified as either a product FMEA or process FMEA depending upon the application (Haapanen & Helminen 2002). Some resources refer to a product FMEA as a Design FMEA. It is mentioned by Haapanen and Helminen (2002, p. 13) that:

"Some sources refer to a design and a process FMEA instead of a product and a process FMEA, however, both FMEA types focus on design – design of the product or design of the process – and therefore latter terminology is used in the text."

Nonetheless, three FMEA types are introduced here: Design FMEA, Process FMEA and System FMEA. The first two mentioned are the most common types of FMEA found in literature, while System FMEA is the most suitable for detailed assessment.

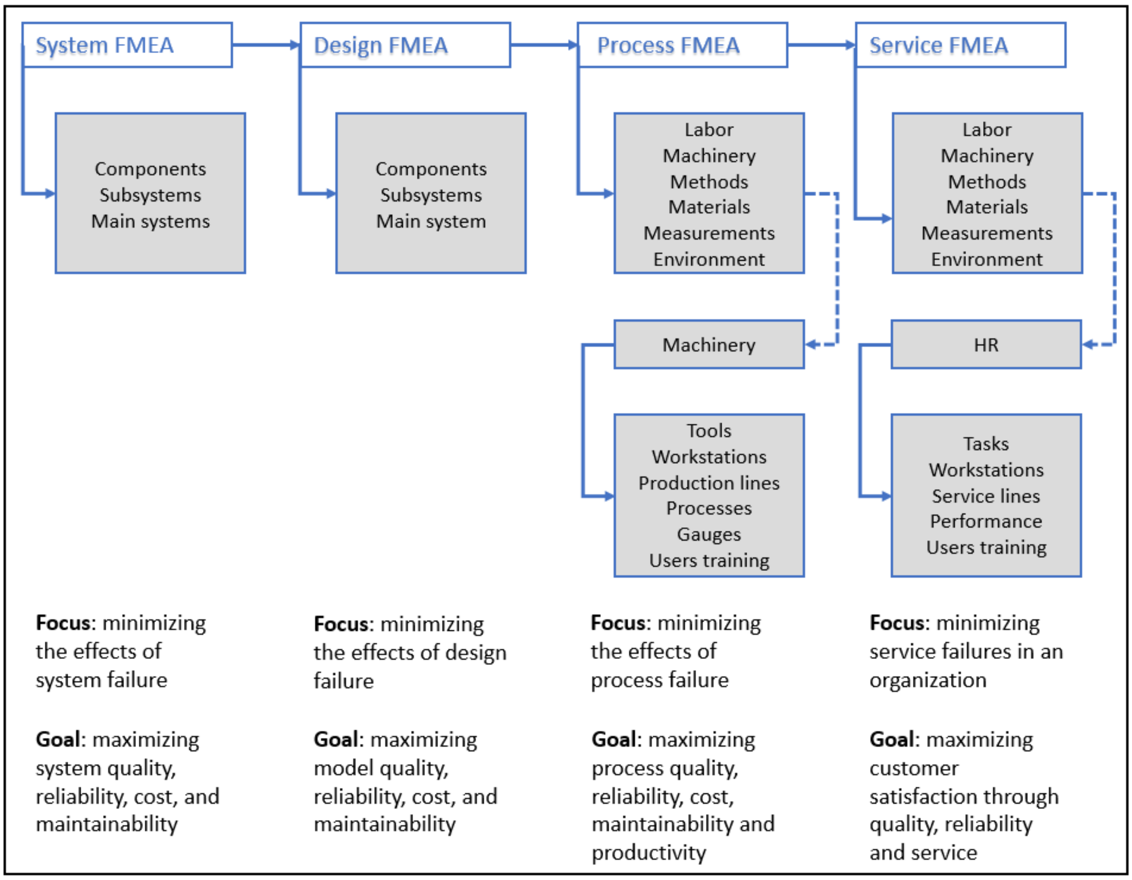

Figure 12. *Descriptions of FMEA types (Modified from Stamatis 2003).*

Design FMEA (DFMEA) focuses on product design, typically at the subsystem or component level. The focus is on design-deficiencies, with emphasis on improving the design and ensuring product operation is safe and reliable during the useful life of the equipment. The scope of DFMEA includes the subsystem and component itself, as well as the interfaces between adjacent components. DFMEA usually assumes the product will be manufactured according to specifications. (Carlson 2012) design FMEA looks at the design solutions and is one of the most efficient analysis techniques for it (Adila & Rahul 2020, p. 3; SFS 2018).

Process FMEA (PFMEA) focuses on the manufacturing or assembly process, emphasizing how the manufacturing process can be improved to ensure that a product is built to design requirements in a safe manner, with minimal downtime, scrap and rework. The scope of PFMEA can include manufacturing and assembly operations, shipping, incoming parts, transporting of materials, storage, conveyors, tool maintenance, and labelling. (Carlson 2012)

System FMEA is the highest-level analysis of an entire system, made up of various subsystems. The focus is on system-related deficiencies, including system safety, system integration, interfaces or interactions between subsystems or with other systems, interactions with the surrounding environment, human interaction, service and other issues that could cause the overall system not to work as intended. In System FMEA, the focus is on functions and relationships that are unique to the system as a whole. In other words, they do not exist at lower levels of hierarchy as failure modes are associated with interfaces and interactions in addition to considering single-point failures. Some practitioners separate human interaction and service into their own respective FMEAs. (Carlson 2012)

The form of FMEA used in this thesis falls under System FMEA. It is commonly used in the concept and design phase (Carlson 2012). Often, the System FMEA evaluates the operation and functions between the elements of the system and the chances of their failure. Stamatis (2003) presents the outputs and strengths of System FMEA in his book as follows:

Outputs:

- List of failure modes sorted by RPN
- List of system functions to detect a fault
- A list of measures that can eliminate or reduce these forms of failure

Strengths:

- Helps choose the best way to implement the system
- Helps reduce unnecessary or extra functions
- Helps define the basis for system diagnostic methods
- Improves the likelihood that problem areas will be addressed
- Identify potential system failures and their effect on other systems or subsystems

3.5 FMEA methodology and implementation

The failure mode and effects analysis is a fairly flexible method of risk assessment that is generally well adapted for a wide variety of applications. However, it must be implemented in accordance with certain principles in order to be expected to produce typical, useful and clear results. The following FMEA methodology and steps presented are mainly based on standard *IEC 60812* and *resolution MSC.36(63), annex 4* (SFS 2018; IMO 2020). The standard provides a general basis for methodology, while the annex gives context for how FMEA is applied in systems of high-speed craft vessels. In addition, detailed information has been sought from scientific articles and textbooks.

The FMEA phases are divided into three parts according to the *IEC 60812* standard: Plan the FMEA, perform the analysis and document the analysis (Appendix A). Ten steps are included here in order to perform System FMEA.

3.5.1 Plan the FMEA

The first phase of FMEA can be a separate or part of a higher-level document, such as a project plan or a system engineering management plan. The output of the planning phase is an FMEA plan that describes a tailored, cost-effective application of the FMEA for the particular context. In this case, the context is ship systems.

Step 1 is to define the objectives and scope of analysis for narrowing down the project focus. The FMEA is a specific methodology to evaluate a system for possible ways in which failures can occur. This necessitates a detailed study of the system to be analysed through the use of drawings and equipment manuals. This step is clearly important because the boundaries defined in it provide a basis for the issues to be considered and the approaches that the team will address during the analysis. The FMEA worksheet, which is an important component of FMEA, should be confirmed before performing an FMEA. (SFS 2018, IMO 2020)

A team should be established for carrying out an FMEA. The FMEA is a team-based activity and thus cannot be done by one person. The team should be composed of suitable individuals and that the group is multidisciplinary and willing to participate in the analysis. Each team member must have some knowledge of group behavior, the task at hand, the problem to be discussed, and direct or indirect ownership of the problem. The size of the FMEA team should be 4-8 members for an effective core team focus and efficiency. The FMEA team should be led by someone possessing team facilitation skills or well trained in it. (Carlson 2012, Liu 2016)

Once the team is formed a narrative description of the system and its functional requirements should be drawn up including the following information (IMO 2020):

1) general description of system operation and structure;
2) functional relationship among the system elements;
3) acceptable functional performance limits of the system and its constituent elements in each of the typical operational modes, and
4) system constraints.

The planning stage should include details of the decision criteria and where a criticality analysis is required. This is the method by which criticality is to be established.

3.5.2 Perform the analysis

Step 2 is to understand the system to be analysed. In this step the system needs to be divided into elements, using drawings, schematics and flowcharts to identify components and relations among components (SFS 2018). Making use of the functional block diagram, parameter diagram, and FMEA interface matrix are applicable for System FMEAs (Liu 2016). A hardware approach is used in this thesis because hardware products can be uniquely identified from schematics, drawings, and other engineering and design data.

The team develops block diagrams showing the functional flow sequence of the system, both for the technical understanding of the functions and the operation of the system, and for the subsequent analysis (IMO 2020). The block diagram should contain at least:

1) a breakdown of the system into major subsystems or equipment;
2) all appropriate labelled inputs and outputs and identification numbers by which each sub-system is consistently referenced; and
3) all redundancies, alternative signal paths and other engineering features which provide “fail-safe” measures.

Step 3 includes the identification of failure modes, their causes and effects. Once everyone on the FMEA team understands the system, a series of brainstorming sessions should be conducted to list all the potential failure modes that could affect the system operability and identify the potential effects of the failure, should it occur. (Carlson 2012; Liu 2016; SFS 2018) Prior to failure modes, is identifying functions and performance standards for each element. However, this can be omitted if one is interested in the failure consequences rather than the failure concept.

The FMEA practitioner should be aware of what part of the system is significant and where one should start. The *resolution MSC.36(63), annex 4* suggests a top-down approach, but that recommendation is for high-speed crafts (IMO 2020). Bottom-up would be preferable to ensure a system level functionality and reliability (SFS 2018).

Step 4 is to evaluate each failure effect. The consequence of a failure mode on the operation, function, or status of a system is called a failure effect. Failure effects on a specific subsystem or element under consideration are called *local failure effects.* The evaluation of local failure effects will help to determine the effectiveness of any redundant equipment or corrective action at that system level. In certain instances, there may not be a local effect beyond the failure mode itself. The impact of a subsystem or element failure on the system output is called an *end effect*. End effects should be evaluated, and their severity classified in accordance with the following categories (Table 2): minor, critical, major/hazardous and catastrophic.

Table 2. Severity ratings as outlined in IMCA M 166 (Jeon 2020).

Classification	Degree	Description
1	Minor	Functional failure of machinery and process components without the effects of injury, damage, or contamination.
2	Critical	Failure without severe damage, contamination, or injury to the system.
3	Major	Critical damage to the system, including the possibility of injury or minor contamination.
4	Catastrophic	Failure causing total system loss with high possibility of fatal injury or large contamination.

If the end effect of a failure is classified as hazardous or catastrophic, back-up equipment is usually required to prevent or minimise such an effect. For hazardous failure effects corrective operational procedures may be accepted. (IMO 2020)

Once the failure effects have been evaluated, there is **step 5** that includes detection methods and controls for failure modes. Detection methods are for an incipient failure, whereas controls are design features that have the ability to prevent or reduce the likelihood of the failure mode or modify its effect (SFS 2018).

Depending on the scope of the FMEA, **step 6** is corrective measures for those failure modes requiring treatment that should be identified, evaluated and documented. In some cases, only treatments that are immediately obvious are documented as part of the FMEA. The reasons for recommending any potential treatment are based on the decision criteria agreed in the FMEA plan and should be documented. (SFS 2018)

Step 7 is assessing the probability of failures causing hazardous or catastrophic effects if corrective measures or redundancy as described in preceding paragraphs are not provided for any failure. Therefore, the probability of occurrence of such failure should meet certain criteria of acceptance where catastrophic effect is extremely improbable or frequent failure mode does not exceed minor effects. (IMO 2020)

3.5.3 Document the analysis

Step 8 is to document the analysis. It is helpful to perform FMEA on worksheets. The worksheet should be organised to first display the highest system level and then proceed down through decreasing system levels. (IMO 2020) An example of a worksheet is shown in Appendix B.

Step 9 includes a test program to prove the conclusions of FMEA. Because this thesis' scope is detailed assessment, the inspections and testing phase are out of this scope (see Figure 9, p. 19). Therefore, it is not discussed further in this thesis.

Step 10 is the FMEA report. The report consists of a detailed recording of the aforementioned steps and summary of the analysis, which includes a brief description of the method of analysis and the assumptions made, as well as the basic starting points. In addition, it lists the following: recommendations for service personnel and operators, and failures that have led to serious consequences. (IMO 2020) Also this step is out of this thesis scope.

It is good practice to revisit the analysis to check whether other failure modes have merged. It is vital to follow up each recommended action to ensure completion to the satisfaction of the FMEA team so that risk is eliminated or mitigated to an acceptable level. Otherwise, the FMEA analysis has been pointless. If the recommended changes are done but not recorded, the company may be legally vulnerable. On the other hand, if the recommended changes are not done, then the risk is not reduced to an acceptable level. (Carlson 2012)

In summary, the answers are searched in the FMEA through an iterative analysis process, for which the main phases are shown in Figure 13. The analysis process starts from the identification of the scope of the system and the functions the FMEA is to be applied on. After the subject for the FMEA is confirmed, the next step is to identify the potential failure modes in a gradual way. There exist many different worksheets to support the documentation of FMEA overall. In the following phases the effects and causes of potential failures are determined. The so-called cause and effect diagrams can be used to help in these phases, although the FMEA steps do not include a method for a full causal analysis (SFS 2018, p. 25). The last part is to document the process and take actions to reduce the risks due to the identified failure modes.

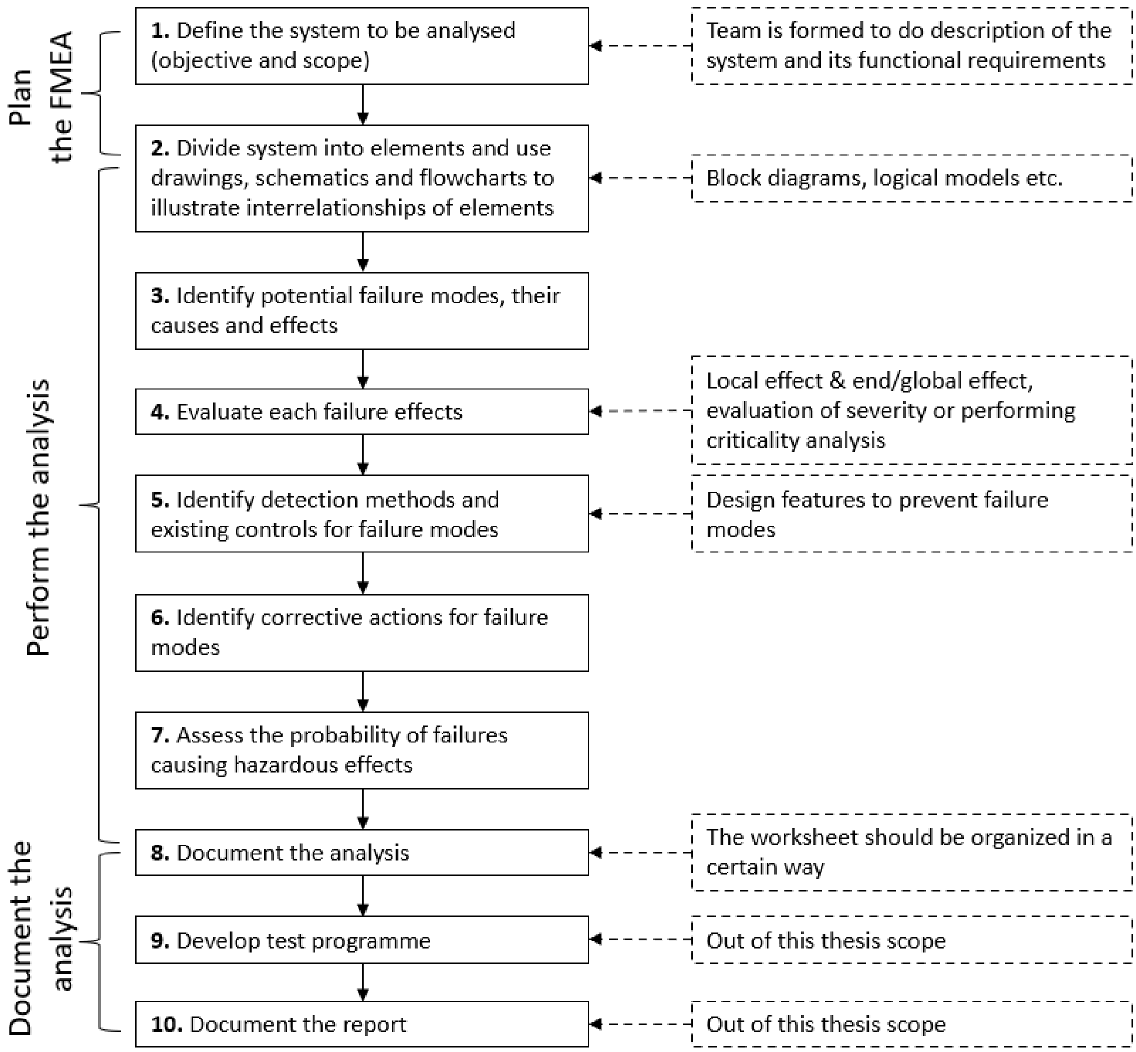

Figure 13. *Main steps for System FMEA (Modified from SFS 2018 with IMO HSC code, annex 4).*

3.6 Software support for FMEA method

Utilising FMEA can be very difficult and laborious in complex systems with many functions and consisting of several components, as there is a lot of detailed information (Carlson 2012). Spreafico et al. (2017) have said that in many cases FMEA is perceived as time-consuming, boring and expensive. For this reason, it is convenient to use software to ease some of the manual procedures. This should be considered in the SRtP process as there is a lot of information that needs to be handled. Using a good relational database software is an essential part for an effective FMEA program in any company. According to Carlson (2012) the important characteristics to consider in the selection of FMEA software from analysis standpoint are:

1. Basic FMEA functionality
2. Time savings

3. Easily generated reports and charts
4. Import functionality
5. Seamless linkage to other processes
6. Simultaneous access for multiple users
7. Relational database

For novices, the software should be easy to adopt, and the interface should be intuitive. The user should be able to modify the FMEA worksheet and its text fields with one or two clicks. Good FMEA software can reduce time by providing instant retrieval of past FMEAs and the transfer of FMEA data to and from other applications. In addition, FMEA software should easily import system hierarchies (Bill of Materials) in order to avoid unnecessary data entry. FMEAs can benefit from other quality and reliability processes. Therefore, FMEA software should support these linkages in a seamless manner. Potential linkage to reliability tools includes reliability block diagram and fault tree analysis. Lastly, when working in a company with multiple FMEA users, the database should be easily accessible to different users simultaneously. (Carlson 2012)

Carlson (2012) has questioned why a spreadsheet software is not enough because they are “two dimensional” with a limited and inefficient ability to access other information. Carlson mentions that the best FMEA programs require immediate and efficient access to all past FMEAs, as well as a database of field failures, test regimens, and many other sources of information. Carlson argues that even spreadsheet macros do not come close to the power of a relational database.

It should be noted that good FMEA software should not only utilise relational databases, but also have an FMEA worksheet that looks and acts similar to spreadsheet software. The technical definition of a relational database is (Carlson 2012): “[A] computer database in which all data is stored in relations, which (to the user) are tables with rows and columns. Each table is composed of records and each record is identified by a field (attribute) containing a unique value. Every table shares at least one field with another table in ‘one-to-one’, or ‘many-to-many’ relationships. These relationships allow database users to access the data in almost an unlimited number of ways, and to combine the tables as building blocks to create complex and very large databases.” As Carlson (2012) has pointed out that, regardless of the software selected for FMEAs, users should evaluate the FMEA software from a rational set of criteria and base the selection on their own unique needs.

4. RESEARCH METHODOLOGY

This chapter discusses the research methodology. The research methodology refers to the theory of how research is conducted and what phenomena or assumptions underlie research. The purpose of the methodology is to guide the data collection and its analysis by aiming for an objective description of reality. This chapter deals with the implementation of research, defining the ways and means by which research information is obtained, compiled and justified. The chapter is divided into describing research background and need (4.1), choosing the research strategy and approach (4.2), and research methods (4.3).

4.1 Baseline for the research

The research has been carried out for a case company that provides ship design, offshore engineering and construction support services for marine and offshore industries worldwide. The case company is a ship design office whose services cover the entire life cycle of a project from concept designs to deployment conversions. The context of this research is on the SRtP regulations and its compliance that set challenges for ship design. A ship’s essential systems need to be redundant or their operation in an emergency situation needs to be secured in other ways. Seeing as the SRtP regulations are fairly new, it involves an innovative approach, excellent teamwork, modern tools and the application of best practices.

The role of the case company in complying with the SRtP regulations is to act as the shipyard’s design office (I1). The engineers involved in SRtP-related design and documentation are more or less labelled as SRtP people and participate in projects as if they are an organization within an organization (I2). At the moment, the case company has a dozen of SRtP people and then there are internal and external subcontractors that are used as needed. The case company is constantly developing its working methods and the development of their analysis software is underway and the finished part is already being used. Further development of the analysis software focuses on the detailed assessment. The aim would be to reduce the time spent on these analyses and to facilitate data updates. (I1)

The interest of this research is the case company’s own FMEA approach, which they refer to as the *FMEA table* for critical systems. Due to the fact that there is no previous research on FMEA in SRtP-related analyses, this thesis is a preliminary study on the

FMEA's applicability and how the case company's FMEA approach corresponds with the System FMEA type. The above is the research problem with two research objectives. The first research objective is to deepen the understanding of the applicability of the FMEA method in the detailed assessment phase by describing its suitability and benefits. The second research objective is to give answers on how to improve the current FMEA approach for the case company.

In order to achieve the research objectives, the research phenomenon is the detailed assessment phase for critical systems. The theory behind the phenomenon is the FMEA. The first phase is to clarify how the case company does the detailed assessment. Then, the case company's FMEA approach is to be analysed by reflecting it to the System FMEA. After that, the challenges occurring in the detailed assessment are to be identified. On the basis of these phases, a synthesis is made to develop the case company's analysis method. In this research, the developments will only remain at the suggestion level.

4.2 Research strategy and approach

A qualitative case study was chosen as the research strategy because this is a preliminary study to explore the applicability of the FMEA method and its benefits in the context of SRtP. The qualitative research emphasises a holistic, in-depth understanding of the research case and an interpretation of the phenomenon. The advantage of the research is its flexibility, which makes it particularly well suited to research topics that have been studied relatively little in the past. (Saaranen-Kauppinen & Puusniekka 2009, p. 43-44) For this thesis, the qualitative research is used to improving an existing approach and the case study's purpose is to understand the phenomenon with a specified segment instead of larger entity. The research case for this thesis is the case company's detailed assessment phase which is part of an assessment process. The assessment process is a core stage of the SRtP process. Essential here is that the research case under investigation forms some kind of whole (Saaranen-Kauppinen & Puusniekka 2009, p. 44).

Yin (1994, p. 13, 79) defines a case study as an empirical study in which the boundaries of the phenomenon and context under study are not clear, and the research data from multiple data sources are typically used. The case study research can be roughly divided into two types: extensive or intensive. An extensive case study seeks out common feature's, general models, and new theoretical ideas and concepts through the comparison of multiple cases. Whereas an intensive case study aims at a frequent description, interpretation and understanding of a unique and therefore theoretically interesting case. The goal of an intensive case study is to produce contextualised information about a case. (Eriksson & Koistinen 2014, p. 17-20) This thesis is an intensive case study, as the aim is to produce a diverse description of the single case study. The research data and knowledge for this case study has been collected from several sources and they are qualitative data.

The choice of research approach determines how new research knowledge is to be created. The meaning of research approach is to describe the relationship between the research data and the theory. An abductive approach was used in this research where the analysis of the research data is not directly based on theory, but connections to it are observable. (Saaranen-Kauppinen & Puusniekka 2009, p. 15) The abduction is great choice for this thesis research problem as it allows the author to be open and sensitive to the data while also allowing for the use of pre-existing theories (Flick 2018, p. 5). More of abductive approach in subchapter 4.3.4.

It should be pointed out that case studies have been criticised for not being able to produce generalisations. One or a few cases cannot be statistically generalised and are not the purpose of a case study. (Eriksson & Koistinen 2014, p. 37-38) The purpose of this intensive case study is to provide a comprehensive description of a single case study, rather than to describe multiple cases in a broad way and to seek generalisations.

4.3 Methods of data collection and analysis

A characteristic of qualitative research is that it is always empirical, meaning it is based on data collection and its analysis. A key part of empirical research is the research material acquired by the author of the research. This may consist of, for example, texts, discussions, interviews, observation diaries or pictures. (Tietoarkisto 2021) Methods typical for qualitative research have been used in this study. The applied research methods include a literature review, a thematic interview and content analysis.

4.3.1 Literature review

The literature review is the part of the research that reviews previous research and scientific literature related to the research topics. The literature review compiles the results of previous studies, which serve as a basis for new results. (Tietoarkisto 2021) The literature review was chosen as one of the research methods because it provides a theoretical framework for the research and some theoretical benefits for the case company's FMEA approach.

When starting a research process, the researcher must decide what position the theory has in that research. For this research abductive approach, the theory's role is to provide explanations and confirmations for findings made from the data. The FMEA provides theory for the analyses of critical system whereas the rules of SRtP regulations set boundaries and approaches for the FMEA. The theoretical framework is illustrated in Figure 14. This research is supported by showing that the work is based on established ideas. The aim of the theoretical framework is to guide data analysis and use theory as basis for interpreting the results.

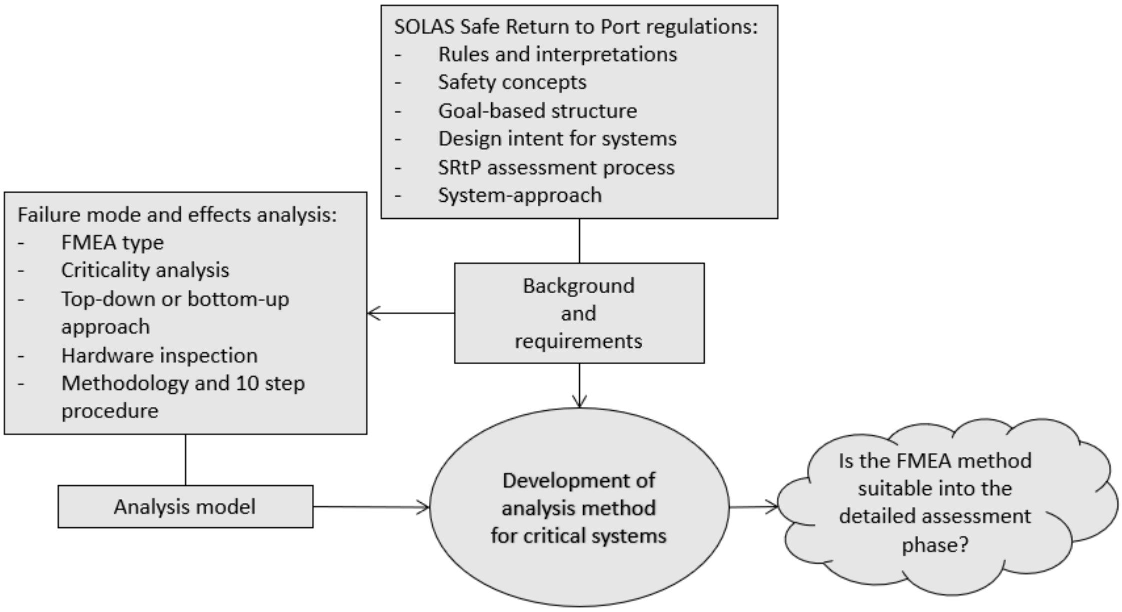

Figure 14. *Theoretical framework.*

The theoretical part of this thesis consists of a literature review, which deals with the SOLAS regulations for Safe Return to Port and IEC 60812 standard for failure mode and effects analysis. The main sources were obtained from the case company because they were not publicly available or free. The literature review was conducted as a systematic search when it was initially intended to search previous research information. The search for information started with the listing of the research topic's key concepts. The key concepts used in the information search were **Safe Return to Port**, **SRtP**, **failure mode and effects analysis**, **FMEA** and **reliability engineering.** They formed a set of keywords to search databases. The main database used in the study was the Andor search service, which includes printed and electronic books and journals acquired by the Tampere University Library, as well as theses from the university. In addition, the research service has an extensive collection of international articles and other publications. The sources from the Andor were peer-reviewed scientific articles on FMEA and reliability engineering. Moreover, individual books, websites and studies from outside the aforementioned database have been utilised as supplementary sources.

4.3.2 Thematic interview

Data for this research were collected using a thematic interview and gathering written materials from the case company. The thematic interview was the main data collection method to gather deeper information about how the case company utilises their FMEA table for detailed assessment of critical systems. The purpose is to describe phenomena from the perspective of experts and thus to understand the subjects' own perceptions. Interviewing as a research method was seen as suitable as it is powerful way to get information from other people due to its interactive nature. In this research, a semi structured thematic interview was selected which is based on pre-planned topics and related questions. The thematic interview emphasises the interviewer's professionalism, interaction skills and knowledge of the topic, as the progress of the interview is determined by the dialogue between the interviewer and the interviewee without a strongl guiding formula. The interview questions should be set according to the research problem and research objectives. The content of the theoretical framework has been utilised in the interviews when considering themes and questions. (Hirsjärvi & Hurme 2011, Saaranen-Kauppinen & Puusniekka 2009)

The choice of the thematic interview was also supported by the fact that the researcher examined the perspective in a largely unexplored area, highlighting the importance of the interviewees' personal views and experiences. A structured interview would not have highlighted these perspectives and an open interview would have required the author to have solid experience in implementation and data analysis.

Mixing research questions and interview questions is a common problem, especially for inexperienced researchers. The research questions and the interview questions are closely related, but they are not one and the same thing. Thus, the interview questions should be worded in such a way that they can be used to answer research questions. There are many different types of questions that can be used in the interviews, which are presented below.

The interview questions can be classified in three ways (Ovaska et al. 2005):

- open – closed,
- primary – secondary and
- neutral – leading.

Open questions, as the name implies, allow the interviewee to answer the question freely in their own words. Open questions were used a lot in the interview process, because it provided information that might not otherwise have been asked. At times, the questions had to be explained, easily making it a closed question. The closed question ended up being bipolar, meaning that the question has an answer option. There was also a need to ask highly closed questions where the answer options had been provided. The closed questions also do not explain why the interviewee thinks the way she/he does. (Ovaska et al. 2005, p. 46)

For that reason, secondary questions were asked to clarify the issues that have already been raised and to gather additional information from the interviewee. Secondary questions can be open or closed questions. The purpose of primary questions, as the name implies, is to gather information about what the interviewer wants to find out in the interview. Neutral questions were appropriate when it came to knowing the challenges and problems related to detailed assessment. Neutral questions allow the interviewee to answer freely without introduction or pressure from the interviewer to answer in a certain way. (Ovaska et al. 2005, p. 46-47)

Before the interviews, the author went through **written materials** to get familiar with the case company's FMEA approach. Getting acquainted with written material means obtaining information from written sources. Those sources are the case company's documents. Documents can include letters, memos, agendas, system diagrams, presentations, follow-up reports, etc. (Järvinen & Järvinen 2018, p. 155) In this thesis, the documents were analysis worksheets of detailed assessment and presentations related to how the case company does the SRtP assessment process. The documents provided good topics for the development theme.

4.3.3 Conduct of thematic interviews

A total of four thematic interviews were conducted. The individuals selected were engineers who take care of the compliance with the SRtP rules in projects. Interviews were conducted and recorded through a business communication platform called Microsoft Teams. For each recording, consent was sought and granted. Interview discussions were transcribed by using word processing software called Microsoft Word. To supplement the interviews, written material from the case company about the "FMEA table" (example in Appendix M) was used as background material. The FMEA table was searched for questions related to the purposes of its columns.

Information on the interviews is summarised in Table 3 and information on other written material used in the study can be found in Appendix C. To protect the anonymity of the interviewees, their names and titles are not mentioned in Table 3. All the interviewees are from the case company. The interviewees' experience on SRtP varied from two to more than ten years.

Table 3. Conducted research interviews.

Interviewee	Date	Duration
I1	13.10.2021	43 min
I2	19.10.2021	1 h 41 min
I3	19.10.2021	1 h
I4	21.10.2021	1 h 26 min

At the beginning of the thesis, the interviewees had not been decided completely in advance, because the perception of the phenomenon changed and became more precise as the study progressed. Thus, the persons with the best knowledge of the subject were selected for the interview. The interview concentrated on the interviewee's own experience, the big picture of assessment process and its challenges as well as future outlook. The first interview served as a pre-interview to gather an overview of the SRtP process. After that, the first and also second interviewee suggested who else should be interviewed. The Interview questions progress from general issues to specific ones. Some of the information obtained through the interviews was used to form interview questions for the next interviewee. As a result, the durations of the interviews varied widely. The most important interviews were the last two, as they provided detailed and practical information on how the detailed assessment phase is done. It was also affected by the fact that the questions were more specific due to previous interviews. In other words, data collection and its analysis were an iterative process. It should be noted that during the data collection, the researcher improved as an interviewer, which naturally streamlined the interviews.

Because the aim of the interviews was to produce a comprehensive description of the research case, the themes and preliminary questions were sent to the interviewees in advance. This way, the interviewees were able to give more specific and better answers. Thematic interviews were conducted semi-structured and in Finnish language. The topics of the interviews can be found in Appendix D. The structure of the interview for the semi-structured thematic interview was typically modified somewhat according to each interviewee (Hirsjärvi & Hurme 2011, p. 48). The interview process is illustrated in Figure 15.

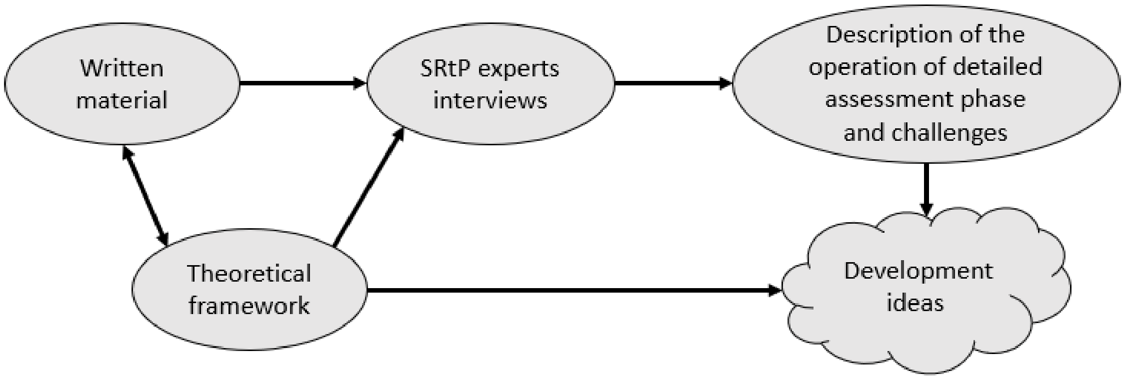

Figure 15. *Interview process.*

However, the following themes were repeated from one interview to another:

- Person’s educational background and role in the case company
- SRtP as a discipline
- Development of the detailed assessment phase and challenges
- Analysis tool
- free word

Under each theme, there were more general questions and some of these were more specific sub-questions if the upper-level question did not receive sufficient discussion. The body of the interview served more as an initiator and support of the discussion than as a facilitator of the interview, and the interviewees were also allowed to bring new perspectives to the discussion. Some of the themes were repeated from one interview to another, but the form and order of the questions varied as the discussion progressed.

At the beginning of the interviews, the individuals talked about their own background and role. The interviewees’ role to some extent influenced the layout of the questions as the interview progressed. At the end, the interviewees were given the opportunity to freely bring up new perspectives or supplement something previously discussed.

4.3.4 Data processing and content analysis

There is no general formula for analysing qualitative data (Saaranen-Kauppinen & Puusniekka 2009, p.73-74). In the context of empirical research, analysis can be a careful reading, arrangement, breakdown of structures, or structuring and reflection of data. The research problem and strategy provide some boundary conditions for how well the data and material should be approached (Saaranen-Kauppinen & Puusniekka 2009, p. 93). The objectives of the data analysis can be roughly divided into three parts: 1) the extensive data must be organised in some way into a coherent whole; 2) the data must be analysed; 3) the findings and conclusions obtained in the analysis must be interpreted. This means giving some meaning to the findings of the data, providing explanations and understanding, building connections between them and drawing conclusions. (Eriksson & Koistinen 2014, p. 9 & 33)

The data analysis was an ongoing process and dialogue between data and theory. The data processing phase was constantly guided by the research problem: what the data tells about the phenomenon of interest. The written materials were used to form a preliminary understanding of the research case by outlining the whole assessment process from start to finish.

To enable analysis of the thematic interviews, all the interview discussions were recorded, later on listened multiple times and finally transcribed covering the most relevant parts of the discussions. The focus of the interview transcript was on the substance, what the interviewee says rather than how he or she says. Then the interview transcript was analysed via content analysis.

The qualitative data analysis method used was content analysis**.** Content analysis can be used to systematically analyse almost any document that has been edited into written form. It aims to describe the phenomenon under study in a concise and general way. However, it is important to remember that the analysis only serves as a basis for drawing conclusions from the data. (Saaranen-Kauppinen & Puusniekka 2009, p. 97) The content analysis was chosen as the research method because it can reorganise and condense data as well as form concepts and themes.

The starting point for the analyses was coding that was conducted in order to analyse the data more efficiently. The coding technique is used to identify patterns and organise the text. Relevant words, sentences or sections were labelled and categorised. Relevancy was based on repetition, matter of surprise, the stress placed on the importance of the matter by the interviewer, or the appearance of the matter in the theoretical framework. The codes were taken under the themes of theoretical framework or the codes generated themes that were then analysed. Direct citations have been used to illustrate the findings, so sentence structures have been somewhat clarified in the transcript to ensure readability. The role of the abductive approach should be considered when doing the data analysis.

The content analysis of qualitative research can be divided into three categories: data-based, theory-driven, and theory-based analysis. The aim of **the data-based** analysis is to interpret the data as free from previous observations, data and theories about the phenomenon under study. In practice, it is almost impossible to make such objective and pure interpretations, as the findings are influenced by, for example, the research methods and concepts used. This research's content analysis is mainly theory-driven as the research approach is abductive. **The theory-driven** analysis is not directly based on a particular theory, but the theory serves as an aid in doing the analysis and previous knowledge partially guides the analysis. The purpose is not to test the theory in practice but to open up new possibilities for interpreting the data on the basis of previous knowledge. The data collection can be relatively free-form, but the results are mirrored to the theory presented in the theoretical part of the research. In **theory-based** analysis, the theory guides the analysis from the beginning. Based on the theory, certain things are searched for in the data, or the meanings and concepts that emerge from the data are compared with the already existing knowledge or theoretical model. (Saaranen-Kauppinen & Puusniekka 2009) In a sense, to solve the research problem, this research has theory-based features.

The theory-based of this research is that the detailed assessment of critical system is considered according to the System FMEA model. The starting point is to look at how the case company's FMEA table can be described using this theory model. However, typical hypotheses of theory-based research are not set in this research. As is often the case in theory-based research, the theoretical model is applied in a new context. The three categories of FMEA methodology (plan the FMEA, perform the analysis, and document the analysis) are now used to describe the analysis of critical systems.

The FMEA methodology in the literature and in IEC 60812 standard is not an ambiguous theoretical model whose functionality could be directly tested in the detailed assessment phase. Rather, it, together with the SRtP regulations, forms the frame of reference that guides the analysis of the research data. In addition, the data is not forced into the form of the FMEA theory to be tested, but new categories related to the phenomenon under study can be created according to the themes that emerge from it. In practice, based on the data, critical systems do not tend to be described according to certain FMEA methodologies. Thus, additional features are to be brought to light. In this sense, the data analysis method of research is very largely theory-driven. (Saaranen-Kauppinen & Puusniekka 2009) The results obtained from analysing the data are described in the next chapter.

5. RESULTS FROM THE CASE COMPANY

The fifth chapter of the report presents the empirical results of the research. The empirical research is divided into three parts. In each part, general observations were made about the experience of the research case's example exercise and/or on the feedback of interviewees. The research case is the case company's FMEA approach to the detailed assessment phase and the exercise example has been used to familiarise the author with the research case. First, the case company's detailed assessment phase is explored by mapping out the main steps and requirements. Next, the FMEA approach of the case company was analysed by reflecting it to the System FMEA procedure. The System FMEA procedure address topics of planning, performing and documenting. Then the challenges of the detailed assessment phase are covered.

The purpose of the results section is to present the findings in light of the research objectives and research questions. The research questions have guided the analysis of the interview data and thus the presentation of the results is also structured according to the research questions.

5.1 Mapping of the research case

The empirical part of the study was started by mapping the main steps and requirements of the research case. The objective was to identify and describe the steps and requirements of the research case, which focus was on assessing failure modes. This was done first by the literature review on the phenomenon to gain understanding of the topic. Then the case company's detailed assessment phase was mapped mainly with the help of written materials (see Appendix C). Thematic interviews were used to supplement the author's views. The mapping resulted in a current state description of the assessment process which is visualised as a flow chart (Figure 16).

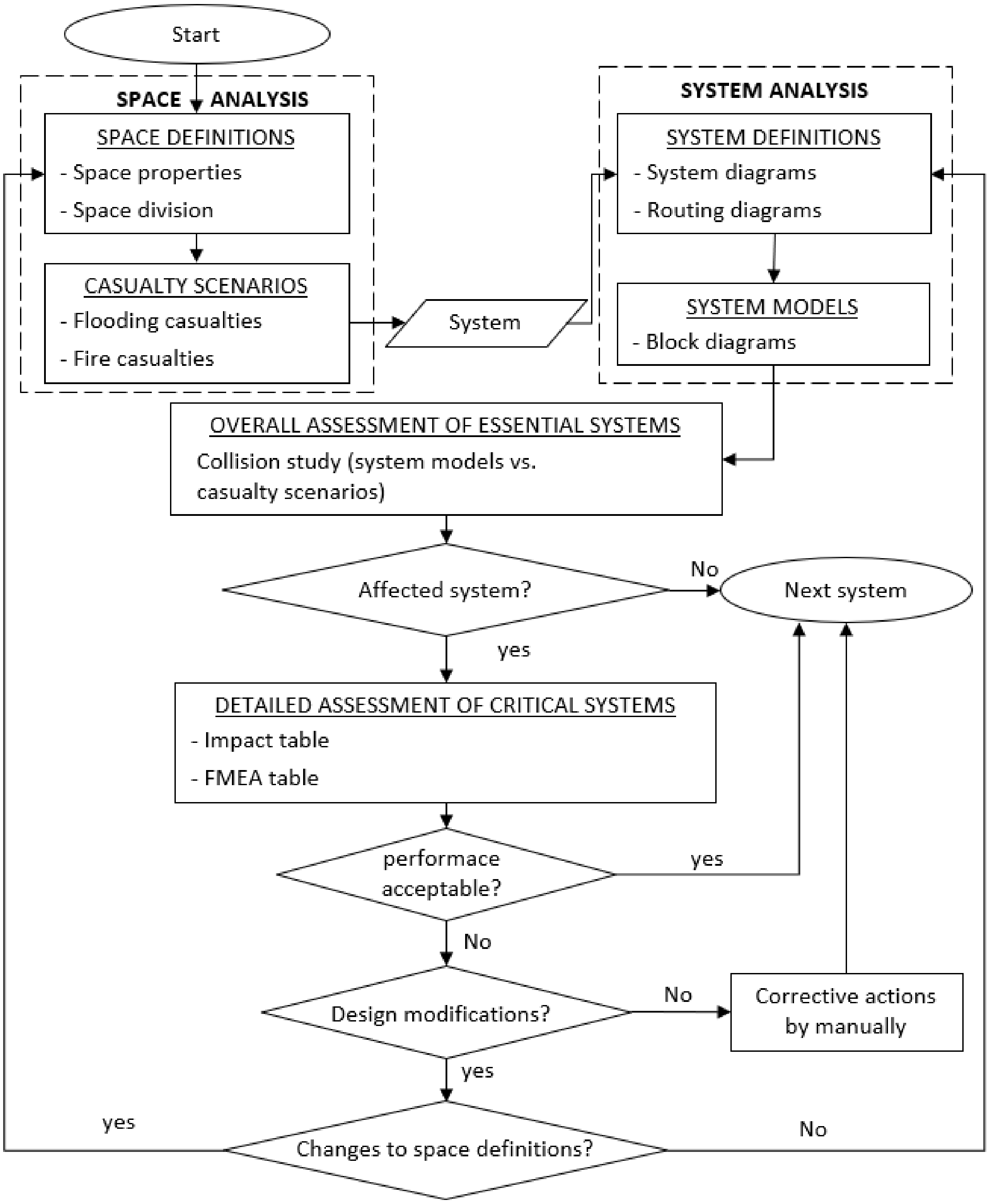

Figure 16. *Flow chart of assessment process.*

The research case is divided into two phases:

- First phase (chapter 5.1.1) defines the steps and requirements of the overall assessment phase which includes collision study. The documents and results of this phase will be utilised in the second part.

- Second phase (chapter 5.1.2) defines the steps and requirements of the detailed assessment phase which includes the concerning results of the collision study and the FMEA table.

Ideally, one person is responsible for one system in the whole SRtP process (see Figure 9, p. 19). Within an individual system, the process progresses step by step. (I1, I2) Since direct observation was not possible to perform due to the pandemic, the author's observations of the research case are based on his own experience of an exercise. The exercise example was a fire water pump. The fire water pump is a subsystem of the fire main and is a category 1 system (see p. 14-15). Contrary to the practices of the case company, the exercise example was done manually from start to finish so that the author gained an understanding of the main steps. The fire water pump's documents are attached to this research report (Appendices E-M). The appendices' tables were made with MS Excel and the diagrams with AutoCAD.

5.1.1 Steps and requirements for the collision study

At the time of the research, the case company uses an in-house browser-based analysis software that it has developed to generate the results into table form (I1, I2, I3, I4). In this overall assessment phase, the case company performs a number of collision studies with their analysis tool to identify where the casualty scenarios and the system coincide. This collision study demonstrates the operability or inoperability of a system by examining its signal flow. The signal means inputs/outputs (I/O) states that can be either 0 (down/affected) or 1 (up/working). The collision study provides a holistic view of system function as it is carried out as a scenario-based analysis (I4). Therefore, different documents covering the information of system and ship spaces are required. To perform this collision study, prerequisites are space analysis and system analysis.

Space analysis

The first step is space analysis that involves space definitions and casualty scenarios. In this step list of single casualty scenarios and their possible propagation to other spaces are analysed. The casualty scenarios are based on space definitions from the ship's premises, and the space definitions determine the location of the ship's spaces and their properties. A brief example of what space analysis documents contains is described in the following paragraphs, starting off with space definitions.

Space information for the vessel of this exercise example is shown in Appendix E. This exercise example has three decks with four main fire zones (**MFZ**). The MFZ4 is horizontal main fire zone that is shown in Appendix F. Only fire casualties are included here, so space of fire origin is indicated in column 5 of space properties. Some of the spaces are outfitted with a fixed fire-extinguishing system to prevent fire spreading to adjacent spaces as it is required or seen necessary. Space division with A-60 boundaries of main fire zones are shown in thick red lines in Appendix F. In Appendix F, the first profile is a side profile of the decks and rest of the profiles are deck profiles from third deck to first deck. The routing diagram shown in Appendix F is part of the system analysis and should not be confused as part of the space analysis. The space division and routing diagram is done separately but here they are combined to reduce the appendices of this thesis.

Casualty scenarios for fire and flooding scenarios are defined separately and they need to be done once unless the design of general arrangement changes. This exercise example includes 33 casualty scenarios (Appendix G). The casualty scenarios serve as the basis for each assessment process because the casualty scenarios are same for all SRtP systems in one project. In the next step, the system topology and models are then taken into account.

System analysis

The next step is system analysis that provides detailed information about the system's design by including a system principle diagram, routing diagram and block diagram. The system principle diagram is made of subsystems describing the operating principle of the subsystem and the elements that belong to the subsystem. The signal flow of any system is easier to examine on the top-level once they are divided into subsystems (I4). The system principle diagram serves as a basis for the block diagram where logical interrelations of elements, referred as the blocks, are shown with AND or OR functions. The routing diagram displays the layout of the subsystem with all the blocks in their correct locations. The precise position of the block is not necessary to be defined; selecting the correct A-class space is sufficient (I4).

For this exercise example, the fire main is already divided into a subsystem of the fire water pump (Appendix H). The fire water pump has two power supplies, one of which must always be on (Appendix I). Water is always required and it comes from sea chest, which is located in same room as the pump itself (Appendix F). Isolation valve for this subsystem is located in deck above, safe from casualty scenarios. Once the subsystem has been modelled on sufficient level, then comes the collision study.

Collision study

The overall assessment culminates to collision study, where the interest is only in the consequences of a casualty to the subsystem's blocks belonging to the space or spaces

(I1, I2, I3, I4). This implies that the results are either 0 or 1. Thus, the analysis can be accelerated when there is no need to analyse the effects of the casualty in more detail. Typically, the block’s attribute information is given as a space number (I4) (see Appendix F for space numbers). The collision study is performed separately for each casualty scenario. Blocks with attribute information of one space or more are in some way present in the affected space are highlighted with yellow colour as affected. The results of the exercise example are in Appendix J. There were 9 casualty scenarios where the fire water pumping system was affected. These scenarios are then further analysed the in detailed assessment phase.

Unlike this exercise example, the collision study is a continuous iteration until equilibrium state is achieved. The equilibrium state means that the signal flow does not change after iterating overall assessment multiple times to achieve signal to all subsystems that are under the scope of SRtP. Once the equilibrium state is achieved and there are still blocks affected by casualty scenarios, then detailed assessment is required. The assessment process continues in the detailed assessment phase where the affected blocks are examined in detail as the signal flow in the subsystem is compromised and might possibly affect the system as well as other systems as they are connected to each other in some way (I4).

5.1.2 Steps and requirements for FMEA

The detailed assessment phase consists of impact table and FMEA table. These two tables should be made simultaneously.

The impact table identifies and lists all different failure modes from the results of the overall assessment. For instance, the exercise example has nine casualty scenarios where the subsystem is identified as critical (Appendix K). The failure modes are prioritised by choosing the most crucial block or input by creating event numbers. Each event number has a case number that should be derived from the event number. The event number is the block’s failure and the case number is the block’s state from the failure. An event may include more than one case due to a fire or flooding scenario, for instance, a block that is water resistant cable will be affected by a fire casualty but in a flooding casualty it will remain operable. In each case number, the affected part of the subsystem is described briefly without going into technicalities. After that, possible corrections of failure modes are done. The impact table finalises the collision study after which all casualties from impact table is exported to FMEA table for the right cases as a system-based form (I4).

The FMEA table defines the failure modes and provide restoring actions, where necessary. The first column of FMEA table lists the documents from the previous analysis phase (see Appendix L). The second column is the system scope, which only includes one subsystem in this demonstration. Columns three and five were created in the impact table. In this exercise, each event only has one case. The failure mode is listed in column four and it is described same way as in the impact table except the main failure is marked in brackets. The *Response* (column 7 & 8) is a description of the effect of the failure. It may include restoring actions or a redundancy description. In this exercise example, the first three events have redundancy response. Therefore, the design complies with the system requirements in those scenarios. Same with the fourth event except the response is a design enhancement of a fire-resistant cable. The fifth event means that the space affected in those scenarios have blocks 3, 4, 5 and 6 down. However, the most important block is the pump itself. No restoring actions are required in these scenarios, meaning there is another subsystem that checks the regulation compliancy. Even if there were restoring actions required, it would not include specific information as there is separate document for it. The last column *Verification method* is to define inspection and testing items so that the assessment, design and installation is consistent with each other. But this information is taken into the next phase of SRtP process, which is not part of the research case anymore.

This mapping was of only one company's assessment process and FMEA is used to summarise the collision study results. The case company has interesting way of doing the assessment process but it is not unique, as some companies have same approach due to shared projects (I2). On the other hand, the interviews revealed that some companies do not report their results in FMEA format (I2 & I3). In general, the analyses of other companies are simplified when it comes to the detailed assessment phase as their results do not show the entire analysis cycle (I2). In addition, other companies may rely on a ready-made analysis software where the collision study in these are based on the data contained in the 3D model from the ship (I2). However, the information of other companies was not up to date. Anyhow, the result of this chapter is utilised in the next chapter, where the case company's FMEA table will be analysed in more detail.

5.2 Analysis of the case company's FMEA approach

The failure mode and effects analysis can be tailored and applied in different ways depending on the objectives. Here, the applicability of the case company's FMEA is compared according to existing System FMEA model to see if the activities are similar at all. In subchapter 3.4.3, the figure of System FMEA procedure will be used for comparison reference. Thematic interviews with the case company's SRtP experts were conducted in order to get their view and perspective on the FMEA methodology. Content analysis is done on interview answers and on the case company's written materials. The content analysis of written materials was based on the interviewees' feedback and comments.

All the interviews were analysed with three focus areas: planning the FMEA (5.2.1), performing the analysis (5.2.2) and documenting the FMEA (5.2.3). These three areas are analysed in their own chapter in order to gain a deeper understanding of the topics separately. In Figure 17, is the result of case company's approach for their FMEA.

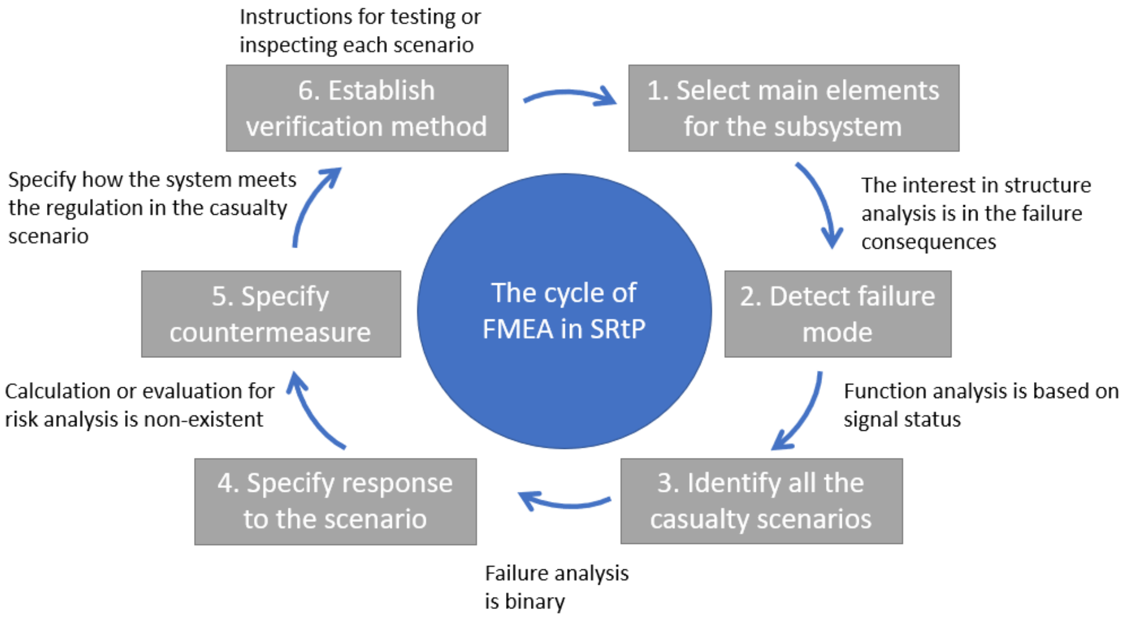

Figure 17. *The FMEA cycle for SRtP.*

5.2.1 Planning the FMEA

The planning of the case company's FMEA approach was evaluated on the discussion around questions related to objective and scope of the system analysis. Questions around these topics generated more discussion and that is also analysed below.

The first question to this area was how the interviewees perceived SRtP as an engineering field. They replied that it is systems engineering with reliability as main theme (I2), reliability engineering (I3), or systems engineering/multidiscipline (I4). The explanation for their answers followed the same pattern; the purpose is to understand how different engineering disciplines interact. The main theme here is reliability engineering, but the reliability side of SRtP was not seen as a typical reliability engineering as it is not technical due to the casualty scenarios involved in these systems' spaces. Since SRtP is goal-based in nature, the purpose of designers is to respond unequivocally to the message of the rule. The following quote describes the multidiscipline nature of SRtP well:

"The thing that makes this non-typical technical is that these casualty scenarios are associated with these spaces. In most case, they do not go very deep into the internal functions of the system component, but it is then the connections and locations between the various components with which to are played with here." (I2)

In analysing systems operability, the causes of failure are always known and these are the fire or flooding casualty. When asked interviewees if they are interested in the consequences of failure or the concept of failure, the answer was always on the consequences of failure. On the other hand, the concept of failure is included, but it is straightforward (I4). Straightforwardness means that the failure mode is either intact or affected (I1, I2, I3, I4). In this way, the compliance check is achieved much faster. The consequences of failure were reported as follows:

"-- we're not interested in awful lot of what's going on inside that damaged device. But whether it is affected at all or not. Then we go much higher to look at that thing. And we are interested in where some things are routed or where they are placed" (I2)

"-- basically, so that if a space is damaged (fire or flooding) and there is a device in that space, then that device is always damaged. We are not going to assess or analyse what the probability of damage to that device is or so on." (I3)

Defining failure is not always black and white. Although a component is immediately assumed to be affected when exposed to fire or flooding casualty, there may be mitigating circumstances (I1, I4). A component that has been affected by casualty may actually be intact due to these mitigating improvements that are indicated in system definitions (I1, I4). In other words, in the concept phase of a ship project, these casualty scenarios are prepared by designing the system to be redundant and/or fire-resistant. More on countermeasures in the Chapter 5.2.2.

The interviewees pointed out that the objective of the FMEA is to provide guidance on the deployment of ship systems, i.e. whether something needs to be tested or inspected. Therefore, a quantitative and in-depth analysis is not required from the FMEA (I1, I2, I3, I4). Thus, the FMEA table contains only relevant information and serves more efficiently for ship deployment (I4). The following quote illustrates the purpose of the FMEA:

"It served the very purpose of getting some sort of quick summary of if we have a failure mode or casualty situation then what are the scenarios where it occurs -- when a failure mode comes in so we need to do something to get rid of it." (I2)

The FMEA table is used in a way to express the results of the collision study, which is scenario-based, in a system-based format (I4). The documents utilised in the detailed assessment are the same as in typical System FMEA for illustrating interrelationships of elements, such as block diagrams. The analysis and the decision criteria are just narrow in SRtP, and the arguments are presented in Chapter 5.2.2. This also reflects to the teamwork as FMEAs are team-based activity.

The first two interviewees were asked about teamwork and the designers doing the SRtP process. In an ideal situation one person analyses one system, but this does not always occur in each project. This is due to resourcing as there is not that many experts in SRtP (I1). An individual may have to manage multiple systems that are similar in terms of technology (I2). But co-operation happens between different discipline departments because each system has interfaces with other systems. The designers are found within the case company and in the subsidiary and there can be subcontractors as well. However, the FMEA table is not meant to be teamwork activity and the results are in line with that. This brings a minor problem which is discussed more in Chapter 5.3. It should be noted that projects are being led in Finland and the actual workforce is being acquired elsewhere (I1).

All in all, the planning of FMEA requires a comprehensive understanding of system dependencies. The thing that makes planning the FMEA lighter is that it focuses on the failure consequences rather than failure mechanism. The SRtP is not interested in evaluating a system for possible ways in which failures can occur and for that reason specific hardware documents are not needed. It may seem that the boundary between a collision study and FMEA is blurry, but the case company does not actually perform failure mode analysis with the FMEA rather they express the results of the collision study in an understandable form by using a FMEA worksheet. The next chapter discusses how and why the case company’s FMEA table is filled out in a certain way.

5.2.2 Performing the analysis

The performing the analysis point-of-view was evaluated with questions related to the columns of a FMEA table and the discussions that was generated through these questions. The questions varied from failure modes to countermeasures and everything in between. These questions led to interesting discussions about how FMEA could be performed in the context of SRtP.

First discussion was surrounded around failure modes. One of the interviewees mentioned about the failure modes that when analysing the whole ship, the systems should be divided into suitable system groups in order to comply with the rules. This interviewee referred to the fact that in the analysis of systems' operability there is no interest in mechanical failure but in whether or not the system is available (I4). Also, the failure modes are not always specified because they are damage-specific (I1). As a result, the way the failure modes are defined in detailed assessment is polarised. This means that the system is either affected or not (I1, I2, I3, I4). The failure mode identification is not intended to be brainstormed and the different ways in which the system could failure in a casualty scenario are not meant to be thought out. It does not add value to compliance with the rules (I2, I3, I4). However, the interviews revealed that there is room for improvement in the prioritisation of failure modes, as there is a lot of variation between designers. More about its issues in chapter 5.3.2

When asked about the interviewees opinion on using function column in their FMEA table, half of them said that it could be considered (I3, I4). The additional information it could provide to an inspector during the verification of the system was mentioned as a benefit. The problem was that how function column could be scaled to other subsystems as some subsystems are easier to be defined and others not (I3). In addition, the failure causes are external events that are fire, flooding or even loss of MFZ scenario and these scenarios imply different system requirements that needs to be taken in account (I4). But the specific reason why function column is not included in the FMEA table is that it is not the result of the analysis. Thus, it is information that has no use for the table because it is initial data (I2). The role of function in SRtP is described in the following quotes:

"- - the rules provide the systems with functional requirements that are tried to be analysed and demonstrate or verify that they are met. Sometimes it can be difficult to define the functional requirements for individual subsystems when they are part of a larger whole." (I3)

"- - we have at an earlier stage demands demolished. What it means in the functional level is that if the rule requirements are this, then what is it in our system when it is configured, then what does it mean in the functional sense. Again, that usually means being available or not available." (I4)

As can be seen from the second comment's last sentence, the reasoning in the process is binary. Due to this binary reasoning throughout the assessment process and interest only in failure consequences, the description of failure mode is generic rather than detailed description of failure mechanism. However, in detailed assessment the operability of systems is specified in different column, which is discussed below.

The discussion shifted to evaluating failure effects. It was mentioned that the evaluation of the failure effect is almost non-existent in their FMEA (I3, I4). The main reason for this was that the most essential of assessment process is to demonstrate compliance with the rules. In their current failure effect column (response column), the focus is on subsystem's response and how the failure effect is seen on the mid- or top-level of the system hierarchy (I2). Thus, the interest is only in the state of the subsystem that is indicated through the signal flow. Typically, in FMEA the impact of a subsystem on top-level hierarchy is evaluated and their severity classified. One of the interviewees mentioned that there might have been evaluation included in some of their earlier development version of FMEA, but it has been omitted. The interviewee did not specify or could not remember what the evaluation included. The discussion led to whether their FMEA should be qualitative or quantitative analysis.

The interviewees agreed that the qualitative analysis of casualty scenarios is enough. Two of the interviewees mentioned that in certain situations it might be possible to perform a quantitative analysis. But all the interviewees emphasised that it is difficult to obtain truthful data for the figures in the quantitative analysis, and that numerical values do not provide any additional benefit. Moreover, getting failure information from an equipment manufacturer is almost impossible to get because the manufacturers want to keep failure data to themselves (I2). There was brief discussion about the probabilities between a fire and flooding casualty (I1, I2). A fire casualty was considered common and there can be many causes for the fire. In addition, a fire casualty does more damage than a flooding casualty (I1, I2). But one of the interviewees emphasised that the realization of fire and flooding casualty depends very much on what is in the space. From an analytical point of view, it is easier to start with the regulations and assume that both fire and flooding are equivalent in terms of probability and severity (I1, I2, I3). An opinion was also asked about expressing the analysis qualitatively using descriptive categories - ordered by degree (see Table 2, p.33). It was seen that a certain kind of breakdown or procedure could be made for their FMEA table (I1, I2). According to the interviewees, this could be considered but the use of descriptive categories would lead to contradictions, as interpretations are subjective (I3). The following quote describes the problems of using descriptive categories:

"Determining severity is very subjective, but it would be good to indicate, for example minor = intact and catastrophic = affected. -- what is the difference between the critical and major? If we have a designer in some analysis and the designer writes severity is major and classification checks it and wonders why you have major damage. -- you can

do the whole FMEA so that you have all the failure modes very low. You just subjectively state that it is extremely unlikely that we will have a fire." (I3)

On the same note, the interviewees were asked about using criticality analysis in their FMEA. They had differing opinions on using criticality analysis in their FMEA as some was for it and some against it. The idea of using criticality analysis that is based on casualty scenarios with likelihood and severity parameter could bring some value by specifying the actual outcome of the casualty scenario. Shipowners in particular would be interested in this result, but it should be expressed in relation to other scenarios and not in absolute terms (I2). Problems with the use of criticality analysis were seen as the unambiguous definition of parameters and their application should be system-independent.

Lastly, identifying actions to mitigate or eliminate the failure mode from happening was discussed little. The interviewees mentioned that redundancies, protections and manual actions are the treatment options for failure modes (I1, I4). It was pointed out that early on in the project, they have a certain hierarchy to look for solutions for a casualty scenario (I4), and these solutions are meant to be indicated in the response column (I2). Aforementioned redundancy and protection treatments are controls rather than actions that needs to be implemented after FMEA results are available. Instead, the manual action is a countermeasure for restoring the operability of the system that takes place during operation. A separate plan for executing manual actions is managed outside the FMEA table. These treatments are only brief statements as they are not the main objective of FMEA table. During the interview it emerged that the design modifications are identified and described in impact tables instead in FMEA tables (I4).

Overall, the qualitative analysis for expressing conclusions in their FMEA worksheet is effective and unambiguous due to the binary reasoning. The major difference between their FMEA and System FMEA is that the case company's FMEA does not have RPN and/or criticality analysis. Therefore, the output is not same as System FMEA. Then again, the goal-based nature of SRtP regulations does not require quantitative analysis or any parameters for assessing the failures and their effects. Interviewees stated that their FMEA approach was not perfect, but it is at least more thorough than their competitors.

5.2.3 Documenting the analysis

Documenting the analysis was the third aspect that was discussed briefly with some of the interviewees. The documentation aspect was addressed more through benchmarking perspective because the FMEA was limited to worksheets.

Interviewees were asked about how other companies do the FMEA and, to their knowledge, other companies do not even use the FMEA worksheet (I2, I3). This refers to how the results are reported. Other things were also mentioned about the companies, such as variation in practices (I1, I3) and the assessment process being lighter (I1, I2). According to the interviewees, the analysis of the case company is more thorough, where one can easily see the main stages of the analysis (I1, I2, I3). The following quote describes how the case company's detailed assessment is more informative due to FMEA tables:

"If we are interested in what different failure modes there are in general and what kind of stuff we need to be prepared to do there on board. It can be found from that table (FMEA) pretty quickly." (I2)

Also, the practicality of the printed FMEA table is interesting to mention. The reason behind it was that the FMEA is used for inspection and testing, and the size of the FMEA table is essential for it to be readable. The FMEA table is printed out on A3 paper and the columns and text should fit on the paper so that it is readable (I2).

Questions about the test programme was left out of this scope as it is not part of the detailed assessment, but it is taken into account at a later stage in the SRtP process. However, the case company's documentation generated discussion about the challenges occurring in the documentation of FMEA. Further discussion of the challenges found in the FMEA and other challenges related to the current detailed assessment phase are presented in the next chapter.

5.3 Difficulties of the current process

The challenges in the current detailed assessment phase led to interesting discussions. The purpose was to find out what the challenges in the detailed assessment phase are and whether the theoretical framework can be provided to help these issues. The identified challenges in the detailed assessment phase are divided into the following categories in Table 4:

- SRtP systems
- Data management
- SRtP regulations

Table 4. Identified challenges.

Challenges	Interviewee
SRtP systems	
Extensive systems	I4, I3, I1
Complex connections between systems	I4, I3, I1
Design changes	I4, I3, I2, I1
SRtP design and boundaries	I2, I3
Data management	
Lack of efficacy in database	I1, I2, I3
Standardization of the FMEA table	I1, I2, I3, I4
SRtP regulations	
Different opinions on the regulations	I1, I3, I4
Rules divided into different sources	I4
Understanding SRtP process	I1, I2, I4

First, the challenges associated with critical systems were investigated. Then challenges in data management are presented, as the main challenges are in that category. Also, the SRtP regulations generated some discussion due to fact that the regulations are goal-based in nature and thus complying it is not unambiguous. In this results' report, the term SRtP system is used rather than critical system because the problems of the challenges extended beyond the detailed assessment phase. That is why this subchapter has a process included in the headline.

5.3.1 SRtP systems

The set of questions for SRtP systems was to find out what challenges the SRtP systems might bring to the detailed assessment phase. The most repeating answer related to SRtP systems were that some of the systems are extensive, and systems have complex connections to other systems. Managing extensive systems was not seen as cumbersome but made the analysis more laborious due to all the casualty scenarios that needs to take into account and how each system is connected to other systems. As a result, the extensive systems make root cause finding challenging (I4). Root causes are eventually founded, but it was described as a time consuming process to update those with their manual routines (I1, I3, I4). On top of that, there is a big difference between the systems in terms of workload as some systems are extensive or simple, and have different requirements (I1, I2). Therefore, the thing that made the workload difficult and challenging was complex interdependencies between systems (I2, I3, I4). Some of the interviewees stressed that it is important to understand how each system is connected to other systems so that the operability of systems can be ensured during a casualty scenario. One interviewee put it:

“The greatest challenge for systems is, in my opinion, these signal connections. From the initial iteration to elsewhere and how things (systems) interact in that ship’s environment with each other. ” (I4)

As far as complex connections are concerned, the impact of it was discussed in depth. Interviewees were asked if there are any changes in the design of the systems afterwards and what kind of chain reaction it may cause when the systems have these connections. They responded that typically the most design changes happen in the routing of pipes or cables during construction phase. Also, devices can change places. In particular, in the initial iteration of power plant, electric power distribution and fuel oil systems were seen as problematic as these systems are needed to achieve equilibrium state. Some of the interviewees referred to these three systems as the “holy trinity” (I2, I3, I4) as the output signal affects rest of the SRtP systems and can result in a domino effect if the signal flow is not in balance. The following quote illustrates the importance of understanding the interdependencies of systems:

“This is the holy trinity from which analyses begin. If major changes take place there in such a way that the statuses of our electrical switchboards change drastically, for example, it could also mean significant changes to the systems that depend on that main switchboard.” (I3)

The interviewees described the impact of design changes to the assessment process in various ways. Basically, the worst case scenario would lead to having to restart the whole assessment process for numerous systems (I1 ,I2, I3, I4). On the other end, even a small design change can have a big impact on the results of the analysis, but it does not necessarily affect compliance (I1, I2). Interviewees said that updating the detailed assessment phase is tedious due to their manual routines and the designers might not welcome the outcome. However, the iteration of the process is being developed with the aim of getting rid of manual routines.

One of the interviewees mentioned that the challenge of SRtP systems depends on how much effort has been put into the SRtP design. If the premise is bad, then the designs affect the whole assessment process as the signal flow can not achieve equilibrium state and thus the compliance of SRtP regulations is not met. It was also mentioned that errors may occur when modelling complex systems (I3). One of the interviewees described a bad starting point for the SRtP design as follows:

“In that case, we simply have designs that make it impossible or difficult to get them in a condition that would meet the rule. It’s a hell of a miss if it is noticed at this point when

we start… A collision study has been carried out and now FMEA is being done. It is a sign that it has gone far too far with the problem without addressing it." (I2)

In the previous quote, the interviewee went on to say that the function scope boundaries of different system groups and even a single system group causes confusion and clarification between people. As a result of this communication problem, there can be more than one person doing the same thing or between two systems something could be left out. The interviewee underlined that this needs improvement.

All in all, it seemed that the SRtP systems can be challenging to manage but it is not a problem. Improvements could be made in communication by being active. The key is to understand the connections between the systems in order to achieve equilibrium for signal flow. One of the main findings were the fact that in worst case scenario the holy trinity (power plant, electric power distribution and fuel oil systems) can theoretically result in having to reissue the documents completely and the pressure is placed on these designers doing it. This led to data management as it generated an interesting discussion about improving the case company's detailed assessment phase.

5.3.2 Data management

The biggest challenge turned out to be data management. All the interviewees mentioned that there is room for improvements in their analysis procedure. Especially in standardising the FMEA table. But the most important challenge was solving the data management to work efficiently. It was their number one priority as most of the issues stem from manual work.

The interviewees were asked how the detailed assessment phase could be improved and a variety of perspectives were expressed. Currently, the main development work is being done in the detailed assessment phase with the aim of reducing the workload that goes in these analyses and to facilitate the updating of documents. Thus, the solutions for these challenges were mostly related to improving the in-house analysis software. The second interviewee had no previous user experience on the analysis software but he mentioned that the challenge is to keep the information up to date when design changes occur. These design changes cause problems in managing the analysis (I1, I3) as the FMEA table is more or less done manually. One of the problems was seen re-entering the data multiple times in different places during the whole SRtP document process (I3). This leads easily to typos, contradictions and eventually inaccurate analysis results. One of the interviewees described the practical problem of entering the data in following manner:

“Here, too, this column six (FMEA table) is manually written. That information is picked up from somewhere else and then that information is taken back to somewhere else. Things like this should be in the database so you don’t have to manually type in a series of numbers in Excel. The danger of typo then is considerable. On the other hand, it makes the inspection process cumbersome.” (I3)

It was hoped that the data would be entered once into the SRtP document set. In addition, the first interviewee longed for relief in updating the data, which would ease the inspection process by comparing the analysis results to see the impact of the change. As a result, the in-house analysis software is not efficient in the database and could be improved with relational database.

Concerns were expressed about the FMEA table also. The interviewees mentioned the need to develop a common way to reconcile the outcome of the work. The problem was that the FMEA table is dependent on the designer. The challenge was how it would be possible to decompress the block diagram data into columns of 2nd, 3rd and 4th of the FMEA table, as filling it in so far depends on the designer’s interpretation (I2). In practice, this challenge means how to export collision study’s results to FMEA table in a common way. The problem was set out to be solved by understanding how failure modes are prioritised in their FMEA table.

The interviewees were asked about if their analysis approach for prioritising failure modes was based on either top-down or bottom-up approach. The interviewees could not say whether it was top-down or bottom-up because there is no clear approach for it (I2, I3, I4). There is no systematic way of prioritising common cause failure that is caused by the external event and each system is approached in different way.

“I would say top-down, but is there a clear approach to that. The FMEA is conducted one subsystem at a time and thus it may have the appearance of the designer so I’m not sure if there is clear… There may not be a uniform practice for it. That may be system-specific, depending on what is done in it.” (I3)

The interviewees’ way of prioritising failure modes was based on the selection of the most important component for the operation of the system from the failure combinations of scenarios and the second most important component of the remaining scenarios, etc. The following quote is an example of prioritising failure modes of the fire water pump (Appendix I):

“-- if the pump is being analysed, then when that… That pump could be the most important. When the pump is gone, then nothing happens and they are all picked from the scenarios. Then there may be something else left for us after that. We have that sea

chest or the pipeline coming there alone may be. Let's take it -- and there may be left scenarios where the main switchboard one is down. That would be the failure modes for this (subsystem)." (I4)

However, not everyone prioritises failure modes (I4). Moreover, it was mentioned that the AND-function causes variation in prioritising failure modes as the components in the block diagram might be same and thus equal in value (I4). A sudden solution to this was not found from the theoretical framework and the biggest issue was finding a prioritising technique that would be applicable for any system. As the third interviewee said, such a technique would require internal development work.

The type of problem in the previous paragraph was related to standardisation of the FMEA table, which requires other improvements in order to reduce variability. One interviewee said that conducting the analysis is exact but how it is presented is subjective (I3). The first two interviewees mentioned that the 8th column of FMEA table needed improvement. The 8th column is *Response* and it should indicate two things: 1) the response of the subsystem in question to the failure and 2) the possible ways in which the situation can be improved or circumvented so that it is compliant. This was seen more as a shortcoming than a problem. This could be easily solved by splitting the column into local and end effect as demonstrated in Appendix M. The rest of the interviewees agreed that this would add value to the FMEA table. One interviewee argued that defining the end effect would not be applicable on systems where the output signal branches to other systems (I4). Nonetheless, improving the eight column assists inspectors in conducting checks on board as the 8th and 9th columns are meant to be information sources for their test programs (I2).

A recurrent thing amongst interviewees was that the whole process is time consuming. The case company is trying to solve the problem by programming the FMEA table to work as interface and it would be standardised so that the designer does not have to make interpretations (I4). It was not specified how this could be achieved, but programming the FMEA table was set to be number one priority. The latest improvement that was mentioned was utilisation of computer multitasking for reducing manual work. However, multitasking has so far reduced a very small proportion of the workload by concatenating data entry. There are still challenge in the iteration of signal flow in the collision study by automating it with computer multitasking. There was also brief discussion about utilising relational database. The concept of relational database was seen as useful for managing data (I3), but the problems of a new software were how it would integrate with their software, is it easy to adopt and is it affordable.

The results in this subchapter indicate that the level of automation of design change data needs to be increased to avoid human errors in documentation updates. Currently, the in-house analysis software consists of some manual work that cause risks to the assessment process. Albeit the analysis software has reduced a lot of manual work for the assessment process, one improvement for it could be utilisation of relational database for managing data throughout the SRtP process. Also, the recognition of prioritisation needs to be considered in a new way in the future if the FMEA table is to be standardised. At the moment, there is not a systematic way of doing the prioritisation and this causes variation in the FMEA tables as the interpretations are not mutual between analysts. The next subchapter moves on to discuss the SRtP regulations.

5.3.3 SRtP regulations

In the final part of the interview, interviewees were asked about challenges related to SRtP in general and how they see it changing in the future. These questions surfaced mainly in relation to the SRtP regulations, as the interviewees often implicitly mentioned in their responses that the interpretation of the regulations is an important factor in compliance. The challenges surrounded in SRtP regulations was mainly the interpretation of the rules as they are goal-based and Classification Societies interpretates them in different ways. All of the interviewees preferred that the analysis of systems operability should remain qualitative in the future. Surprisingly, the SRtP regulations did not cause any challenges for the analysis or at least the interviewees did not mention it.

A common view amongst interviewees (I1, I3, I4) was that there are varying opinions on the SRtP regulations. The interviewees mentioned that combining different rules and interpretations were challenging as each Classification Society has a different interpretation of the SRtP regulations. It should be pointed out that the interviewees did not make a clear distinction between the regulations and the rules, but judging from the context, regulations and rules are used almost interchangeably to refer to SOLAS and MSC documents for SRtP (i.e. SOLAS regulations II-1/8-1, II-2/21, II-2/22 and Interim Explanatory Notes of MSC.1/Circular 1369). Interestingly, the fourth interviewee mentioned that these rules, overseen by IMO, are divided into different sources that need to be combined and thus combining these documents can be challenging. Especially when Classification Societies have their own interpretations of the rules that may slightly change how the SRtP regulations are complied in each project (I1, I3, I4). As one interviewee said:

"Different Classification Societies have different interpretation of the rules, meaning that in different projects we cannot directly assume that something is like this because it was the case in another project. And besides, within Classification Societies, interpretations vary and evolve. The biggest challenge is that you can never be completely sure how those rules will be interpreted in a project this time around." (I1)

One of the interviewees emphasised the interpretations of the rules at the individual level, as everyone has slightly different interpretations and also unwritten things that may be interpreted differently in projects. This is also complicated by the fact that the employees of the Classification Society may change and thus new opinions will be formed. Although the interpretation of the SRtP is cumbersome, it is manageable with a project-specific document that brings together the topics agreed upon in the project (I1, I3, I4). Regarding individuals, there is shortage of expertise in SRtP knowledge and skills.

The internalisation of SRtP regulations and its process was one challenge that was repeated in the responses of the first and second interviewees. This was an interesting finding as this affects project(s) because the main bottle neck and the decisive factor is the designer responsible for the design and analysis. The assessment process binds work hours and this requires qualified and efficient employees. Due to the fact that there is scarcity of SRtP experts, new entrants need to be trained. The challenging part of teaching SRtP to new designers or anyone, is understanding how everything comes in together in the SRtP process. One interviewee mentioned that teaching SRtP is paradoxical, as teaching it would require for an inexperienced engineer to have previous practical experience of it.

"I don't know if it's a paradoxical thing that explaining a thing like this for the first time so that the other person internalises it. Then it would almost require, when done successfully, that the person has had time to go through this process once. That is, you have to teach the other a thing that the other has already done." (I2)

This led to the next question. The interviewees were asked how they see the SRtP regulations changing in the future because the regulations are currently ambiguous. The answer was that the regulations will be supplemented (I1, I3, I4). Interviewees talked about how classification societies will narrow down the interpretation of SRtP regulations, as they are open to a wide range of different interpretations. By narrowing down interpretations of the regulations, it will benefit all stakeholders by saving time.

"-- it's much easier for all parties that everybody knows how much SRtP will cost when everybody knows in more detail what it entails. Then you know how to prepare for or not to be surprised during the project from different interpretations" (I4)

Interviewees did not see or mentioned possible changes for methods. The current qualitative analysis was seen as a good practice and was not seen to change in quantitative direction. Quantitative analysis was not an excluded option in the future, but the comments of each interviewee gave the impression that the implementation of the quantitative analysis is unlikely.

Based on these results, there are gaps in interpretation in achieving SRtP goals. This then affects individuals and thus stakeholders. Clarifying the regulations would reduce the scope for interpretation, allowing the project to run more smoothly. Currently the interpretation of the regulations can be time consuming and especially challenging when a new or inexperienced person is involved in a project. Clarifying the regulations and bringing in tacit information would make ships even safer.

6. DISCUSSION AND CONCLUSION

In this chapter, the research results are given meaning by evaluating and interpreting them. The starting point for this chapter is to answer the research sub-questions by interpreting the results and their implications. After that is evaluation of the reliability and limitations for the results. Finally, some remarks are made on further research regarding the research subject. Due to the nature of this research, the remarks are addressed to the case company of this research.

6.1 Conclusions of key findings

The thesis is a preliminary study, researching and elucidating the use of the FMEA method in the context of Safe Return to Port and possibly to develop the current analysis process for the case company through the FMEA. The research problem was to determine whether the FMEA method proposed by the International Maritime Organization is suitable for detailed assessment of critical systems and whether that method corresponds to the way the case company performs the analysis. The qualitative methodology was pertinent for this thesis to understand the detailed assessment phase and promote development ideas. The literature review formed a theoretical framework for the detailed assessment phase, where critical systems should be analysed using the System FMEA model. After that a case study was used to make a comprehensive description of the case company's assessment process, which focused on the detailed assessment phase. The theoretical framework and empirical description are used to draw conclusions and deepen the understanding of the applicability of the FMEA method in the SRtP context. The main research question in the thesis was:

How should the FMEA method be applied to the detailed assessment phase to achieve its objectives?

The answer to the main research question was sought using three research sub-questions. Through the research sub-questions, the analysis process of the research case was comprehensively mapped and analysed. In addition, development ideas were formed for the case company, where the FMEA theory could complement. The first research sub-question was:

1. What are the analysis steps and requirements of the detailed assessment phase?

This research sub-question was crucial for understanding how the case company performs the detailed assessment phase, so that further research could be conducted.

The result provided a flow chart of the assessment process (Figure 16, p. 48). In short, the assessment process is done during the detail design of a ship project and its purpose is to ensure that the design of systems complies with the regulations.

It became clear that the assessment process is complex, extensive and iterative, with an analysis based on collision study and the final results are shown in FMEA tabular format. The detailed assessment phase is preceded by an overall assessment phase in which the collision study is performed. Contrary to the IMO's recommendation of system-based approach (IMO 2006), the collision study is a scenario-based approach consists of space analysis and system analysis. In this scenario-based approach the interest is in signal flow between systems, subsystems and elements. This approach is performed in qualitative means and the approach was seen as a more holistic analysis. The signal flows that are affected are then further analysed in the detailed assessment phase where the scenario-based results are specified.

An interesting finding was that the assessment process requires the use of many tools, making the process error-prone. But the most important finding of mapping the research case was that the actual analysis for critical systems is not conducted with FMEA. Surprisingly, FMEA's worksheet is used to translate the scenario-based results in system-based form. This finding was unexpected and suggests that conclusions of the assessment results is easier to assimilate by presenting them in an FMEA worksheet.

Above all, the empirical results provided a new insight into the detailed assessment phase, as the interviews revealed that few companies are unaware of the content of the detailed assessment phase. The likely explanation for why companies have not provided a more detailed insight to this phase is entirely due to the desire to keep their procedure a business secret. The results therefore need to be interpreted with caution as it only includes necessary information and certain design tools were excluded from the research case. Despite this caution, the flow chart can be enhanced by specifying it, for example, adding some checkpoints for documents or refine the steps for a particular system.

Nevertheless, the empirical results were not fully consistent with the FMEA methodology, which is the next research question:

2. How does the case company's FMEA approach differ from the typical System FMEA?

The theoretical framework of the research made it possible to compare empirical data with established theory. Specifying the FMEA methodology, from a systems perspective in the literature review, provided an essential basis to analyse the FMEA table of the case company. The comparison resulted in an extensive analysis covering the three phases of the IEC 60812 standard: plan the FMEA, perform the analysis and document the analysis.

The significant difference in the first phase was that there is interest in the consequences of failure in the analysis and it is straightforward. This finding was not surprising as the failure causes are known and determining the failure mechanism in a fire or flooding scenario does not matter for completing the compliance check. Instead, the data suggests that the outcome of failure mechanism is defined binary as either affected or not affected. In this way, the concept of failure is taken into account, except it is simplified. Moreover, it makes the FMEA procedure faster as the scope of the analysis is complex and vast. However, the main objective is not to make the analysis fast but to provide guidance on the deployment of ship systems for testing and inspection.

In the second phase, it was identified that the effects of the failure are not analysed in more detail here. The most significant difference between the FMEA table and the System FMEA is that no criticality analysis is performed. It is possible to add a criticality analysis to the current FMEA table, where the parameters are the likelihood of casualty and its severity. But this research has shown that obtaining quantitative information would be difficult or almost impossible to obtain reliably. For qualitative criticality analysis, it ended up being too subjective and inconsistent to scale to other systems. One of the criticisms of any FMEA is that it is subjective or relative to its application (Carlson 2012, Liu 2016). The absence of a criticality analysis technique can be explained by the fact that each failure mode is treated as equal instead of being prioritised.

Finally, the documentation of an FMEA table is unusual compared to System FMEA or any other FMEA worksheet due to the interest in consequence of failure. Therefore, the columns may appear confusing to outsiders if they are not familiar with the context. However, the most important thing in this FMEA table is to show that the system under analysis meets the requirements as well as provides information for testing and inspection. It can be concluded from the data that the worksheet of an FMEA table is understandable and shows the main stages of assessment. The weaknesses of FMEA table and the detailed assessment phase are concluded in the third research sub-question:

3. What are the challenges and problems of the detailed assessment phase?

The purpose of this research sub-question was to supplement the FMEA of the case company with the System FMEA obtained from the literature. The second research sub-question was answered with interviews. The challenges were sought from an application and efficiency perspective. The application of FMEA in SRtP formed two categories, namely SRtP systems and SRtP regulations. The efficiency of FMEA procedure formed a category of data management. The challenges and problems in these categories were used to identify their effects and then to consider ideas for improvement. Most of the challenges and problems extended beyond the detailed assessment phase.

In the end, the challenges that caused the most problems were in data management as it affects the entire SRtP process. The case company does not have an effective way of performing the iteration for the assessment process meaning that all updates and iteration are done manually. Also, the current databases were seen as ineffective as data is handled through a common database. This is hampered by the fact that the detailed assessment's documents have dozens of pages if not hundreds and a manual approach can most likely result in human error. Although a minor change or mistake in the analysis might not impact the compliance check, there is a risk that the whole assessment process would need to be redone if something crucial is not taken into account from early on. The solution for manual routines is being sought out from computer multitasking but the current obstacle for automating the detailed assessment is to find a uniform and systematic way of completing the FMEA table. Unfortunately, this research has been unable to demonstrate and solve the case company's analysis approach for prioritising failure modes. The standardisation of the FMEA table would require more internal research in order to find variation and reoccurring patterns between designers. Besides implementing and developing computer multitasking, the case company could utilise a relational database for efficient data management throughout SRtP process.

Improvements could be made to the case company's FMEA table by adding local and end effect columns to illustrate the failure mode's response on the mid- and top-level of the system hierarchy. Even though this is incremental improvement, this will lead to a more informative FMEA table. If the rules become quantitative, the use of criticality analysis in a detailed assessment phase would be helpful to determine the critical system's true status in a casualty scenario. The criticality analysis would be based on a casualty's probability and its severity.

There were some challenges with SRtP systems as well as SRtP regulations and rules. The challenges and problems in these two categories are not exactly problems that require urgent attention rather they are slight issues for experienced designer. On the question of improving the detailed assessment phase, this study found that some of the challenges of the SRtP manifest at the individual level. Especially when there are inexperienced people involved in a project. The problems were that various interpretations and views on solutions slow down the progress of the project and, above all, become expensive. Certain Classification Societies intend to clarify the rules in order to minimise room for interpretation. Even if the rules become clear, the problem is still finding competent engineers that understand the bigger picture of the outcome of SRtP design. Even teaching and explaining the SRtP process is not an easy task as it involves paradox where the inexperienced person needs to have practical experience in order to understand the bigger picture. One solution to such a problem is to make the teaching materials more practical rather than explain the SRtP process at a general and abstract level. No real solution to this was found during the research, but utilising some diagram would be a great way to promote the internalization of the SRtP process.

Conclusion on the applicability of the FMEA method

Taken together, these results suggest that the case company's FMEA is lighter version of the standard FMEA in terms of presenting the analysis. The implementation of the FMEA method in the detailed assessment phase should be done from a safety perspective which deals with consequences of failure. The case company's implementation for the FMEA method in the context of the SRtP is to conclude the collision studies in the FMEA form to provide the information for ship system deployments when something needs to be tested or inspected. The benefit of this practice is that the results are easier to read in the FMEA format.

But in the analysis sense, the FMEA method is not suitable for analysing single-point failures that the fire and flooding scenario can pose on the SRtP systems. Based on the empirical results, an analysis based on the FMEA method would be laborious and, above all subjective. The author hoped that the criticality analysis could have brought additional value to the current detailed assessment approach but the parameters of criticality analysis were not scalable and it is difficult to define clearly for each system. Reflecting on the chapter 3, it can be stated that the FMEA method is not exact science. The methodology of FMEA is very flexible and it can be applied to any failure type regardless of the target. The FMEA method is great for eliminating or mitigating failure modes but not for checking that the initial design of systems complies with the rules/regulations.

6.2 Evaluation of the research

There were some limitations in conducting this research that are important to be aware of when evaluating the research. Factors related to the validity and reliability of the study can be considered as constraints. Validity refers to the competency of a research; whether it is thorough, whether the results obtained, and whether the conclusions reached are "correct" (Saaranen-Kauppinen & Puusniekka 2009). This is a particular challenge faced in qualitative research. This thesis deals with whether the research succeeds in describing risk analysis in the context of SRtP and the applicability of the FMEA to it. There are two validity-related concepts, namely external and internal validity. External validity is related to the generalizability of the interpretation outside the research, and internal validity to the internal logic and consistency of the interpretation made. In addition to validity, an essential criterion for evaluating research is reliability. Reliability means that the results obtained by the research method are reproducible and not random (Ovaska et al. 2005).

Limitations on the external validity of the research include the number of research cases, the nature of the case study and the fundamentals of the SRtP regulations. This is an intensive case study focusing on a single research case. The research case is limited to one industry, in which case the results cannot be directly generalised to the FMEA of other industries. The FMEA for detailed assessment should not be generalised to other System FMEA applications as the SRtP regulations set certain goals and requirements. As mentioned in the FMEA standard, the FMEA should be tailored for the application in order to be meaningful in relation to the context and objectives of the analysis (SFS 2018, p. 15). The author has been aware of the limitation of the generalizability of results since the beginning of the thesis. The goal was to produce a rich description of the detailed assessment phase and to analyse the case company's FMEA table for critical systems. Based on the research objectives, the qualitative case study as a research strategy is a justified choice.

The challenging and constraining part of this research was the uniqueness of the field. The SRtP as a whole is fairly new in marine engineering and its literature is scarce and open to interpretation. Thus, linking reliability concepts and practical concepts was challenging. Moreover, no previous research on the topic has been conducted, so it was not possible to compare empirical results with previous research knowledge. As a result, implementing SRtP rules involves pioneering work. It was important at the outset to become familiar with concepts of the SRtP regulations and the FMEA methodology, and to highlight the enormous versatility and vastness involved in defining them. Thus, the formation of a scientific argument for a relatively new research topic using multiple research fields is warranted. In terms of the theoretical part, the reliability of the results can be considered satisfactory in terms of the sources used, as the source material consists of mainly the SRtP regulations and its supplements that are commonly used in projects, as well as one significant standard. On the other hand, the reliability of the literature review is undermined by the fact that the main sources are not publicly available. It is possible that not all of the possible significant publications in the subject area have been discovered.

Limitations affecting the reliability and internal validity of the research include the subjectivity of the author's interpretations, the data collection and analysis methods used in relation to FMEA theory, and the selection of interviewees. A single researcher and subjective interpretations may limit the reliability of a study compared to a study conducted by multiple researchers. To improve reliability, the author has sought to carefully describe the choices made to conduct the research, such as research strategy, data collection and analysis.

The research has been made as reliable as possible so that each step of the case study has been carefully documented and explained (Yin 1994, p. 81). The description of the research methods is a good basis for the reliability of the research as it shows that the researcher has done the research. This means that the data has been collected and processed. Description of the research case has been illustrated so that it is easier to parse with an example exercise. In addition, experts have been asked their opinions on the development ideas proposed by the author. Free word was included at the end of the interviews if something needed to be supplemented.

The chosen data collection method of this research was thematic interview. The interviews were supplemented with written materials. The interpretations of thematic interviews were reduced by recording all interviews and then transcribing them. The interviewees were selected as the research progressed and the detailed assessment phase became more precise. The interviewees were allowed to directly propose new suitable interviewees, which alleviated the possible subjectivity related to the selection of the interviewees. The interviews could have been conducted much earlier, allowing the research to progress faster. Furthermore, the reliability of the research could have been improved by interviewing more people. Then again, the homogeneity of the interviewees affected the number of interviewees as each interviewee was employed by the case company. The results could differ if the study had interviewed subcontractors and asked their views on the FMEA approach in the detailed assessment phase. It is likely that there are matters that have not been addressed properly or something may have been left unregistered purely due to lack of experience.

The use of multiple research methods is a way to improve research internal validity. Thus, the triangulation method for data collection would have been useful in order to get valid results. Observation would have been a complementary method to the data collection in addition to the interview. Unfortunately, observation was not possible due to the COVID-19 pandemic. Moreover, the author was not working for the case company during the research, so it prevented project observations. Direct observation would have been most useful for allowing to observe the working methods of other analysts.

Furthermore, benchmarking would have been an ideal addition for this thesis to compare case company's detailed assessment phase to other companies'. Benchmarking could have complemented the research by looking for the best practices from other companies. Furthermore, benchmarking would have added more reliability and validity. Conducting a benchmarking in the future would be useful for the development of the case company's analysis software. Lastly, group interviews would have been also useful in terms of development, because then the ideas and arguments could have been refined much further than in the individual thematic interview.

6.3 Significance of the results

The main contributions of this research are that it offers a good basis for more in-depth and broader investigation on the topic as well as identified key issues concerning the FMEA method's implications in the SRtP context. As the industry and rules are evolving and experiences are collected, it is considered natural that practices and methods will be expanded. Since the SRtP regulations are relatively new, the first objective was to clarify how the detailed assessment phase can be achieved practically and thereby complement the SRtP's goal-based structure. With the help of the results and developments ideas presented in this thesis, the case company is able to start evolving some of their on-going processes of contributing to the improvement of the FMEA table.

This qualitative case study offers valuable insights of implementing and improving the System FMEA for SRtP ships and thus it can act as guidance in the future if the regulations' goal-based structure requires quantitative approach. This research can be used as a basis for examining similar themes in another company's FMEA approach or used as benchmarking. In addition, it will be easier to address the challenges of research in the future, as some of the problem areas were identified during this research process.

On the other hand, the study worked well in opening a new perspective to look at the use of FMEA in SRtP ship systems. It would be interesting to quantitatively study the impact of casualty scenarios and its progress in a ship, as the results of this research do not explain their occurrence. This would provide a more accurate understanding of the behavior of the fire or flooding casualty, allowing the captain and crew to make a more realistic decision to resolve the emergency situation. At the moment, their decision is based on their intuition and experience. It is hoped that this research will contribute to a deeper understanding of FMEA implementation in SRtP passenger ships. The study will have impact on how the future FMEA table will assess failure effects on local and end levels.

6.4 Recommendations for further research

The first research objective was achieved, but the second research objective raised more research and development topics that will require further research in the future. Further research topics have been considered from the perspective of developing the case company's analysis software. The original purpose was to study the FMEA method and also an FMEA-based software. The FMEA software was to promote new ideas and techniques to improve the SRtP documentation management for the case company. During the research, the author was wearing two hats in this case study: 1) an engineer and 2) a researcher. The attitude of the engineer is result oriented and cooperative. Whereas the attitude of researcher is to question and challenge. Where the engineer will promote the use of a proposed method or technique, the researcher needs to question its validity. Balancing with these two roles was not easy. In the scope of this thesis, the main emphasis was on the FMEA method.

Consequently, the study and use of FMEA-based software was left out as it did not fit for this research strategy and the software theory was based on a relational data model. However, the FMEA-based software utilises a relational database which can reduce manual work by entering data once. But the software cannot perform collision studies, which is essential in the performance of the assessment process. Therefore, research on the underlying theory behind relational databases is recommended. This would solve the current problems related to manual work if it can be integrated with the case company's analysis software. Another thing related to the relational database is how it would integrate. It is also worth keeping up with the latest technology developments of data storage and analysis. There are different solutions on the market for data storage and its management, so understanding their operation is important when choosing a suitable product. Another interesting research topic would be to study Boolean functions, so that the analysis software could express systems connections and functions as Boolean variables. At the moment, they are expressed as reliability block diagrams. Boolean functions could bring a systematic solution for prioritising failure modes in the FMEA table in a coherent way. The case company could move forward by researching the topics related to data management.

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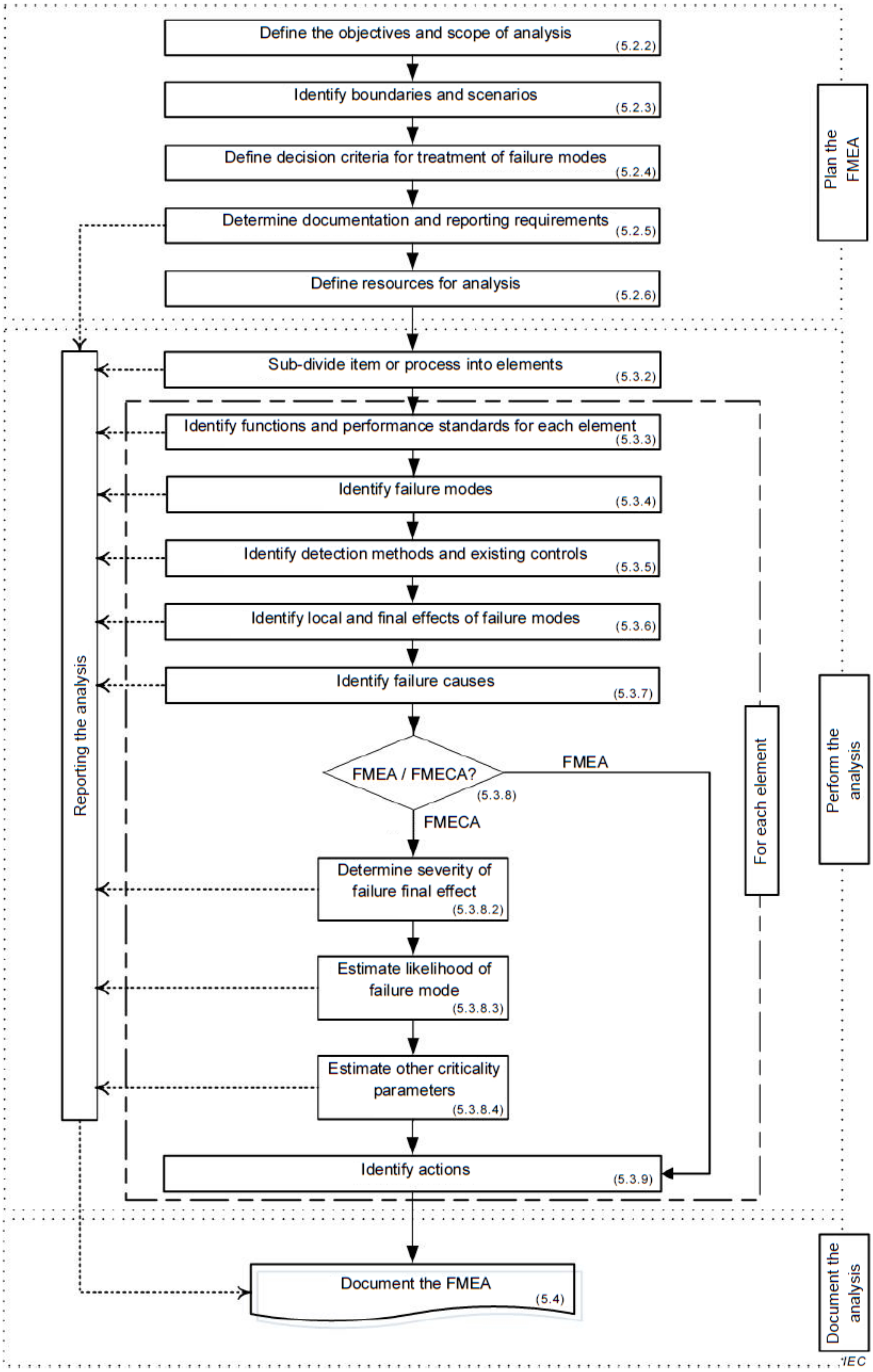
APPENDICES

APPENDIX A: OVERVIEW OF FMEA METHODOLOGY BEFORE TAILORING

The activities shown in this figure should be tailored to the application. Therefore, not all the listed activities always need to be performed.



Numbers in brackets refer to subclauses.

APPENDIX B: SYSTEM FMEA WORKSHEET FOR HIGH-SPEED CRAFTS BY IMO

Name of System				References						
Mode of Operation				System Block Diagrams						
Sheet of Operaton										
Date										
Name of analyst				Drawings						
Equipment name or number	Function	Indent .No.	Failure cause	Failure Effect		Failure Detection	Corrective action	Severity of failure effect	Probability of failure (if applicable)	Remarks
				Local Effect	End Effect					

APPENDIX C: WRITTEN MATERIALS

Documents	Type of file
IMDC2012_Deltamarin_Slides	PDF
2012_0415_Deltamarin_Color	PDF
SRTP_assessment_training_DMCN_03_2021	PDF
FMEA_Example	PDF
Example_241_part_1	PDF
Example_241_part_2	PDF
Example_241_part_3	PDF
SRtP_Part_C_Documentation	PDF
SRTP_life_cycle_process	PDF

APPENDIX D: THEMES OF THE INTERVIEWS

Basic information about the interviewee and SRtP.

1. Interviewee's educational background and job description.
2. Interviewee's experience in SRtP
3. SRtP as a discipline
4. Tools used in SRtP process

SRtP assessment process

1. Teamwork and roles of analysts
2. Common challenges in SRtP process
3. The analysis perspective of detailed assessment
4. Dealing with Critical systems and challenges
5. Thought process in making decisions
6. Utilization of spreadsheet software
7. Shortcomings/problems with spreadsheet software
8. Problems of FMEA table
9. Other companies approach to the assessment process

Development of analysis and future of SRtP

1. Development of analysis for detailed assessment
2. Case company's latest developments
3. SRtP regulations in future

Closing questions

1. Free word
2. Feedback from the interview

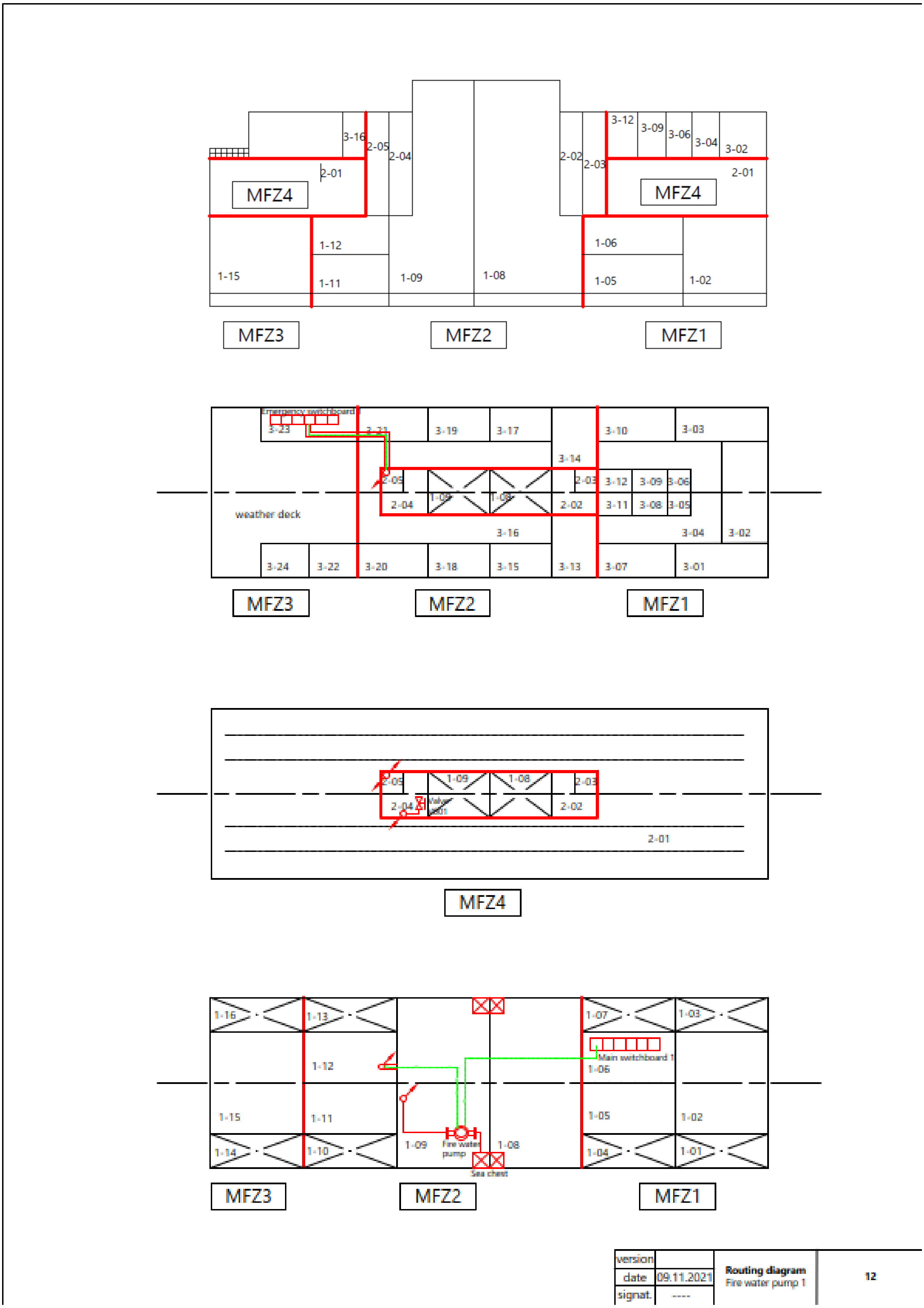
APPENDIX E: SPACE PROPERTIES OF EXERCISE EXAMPLE

1 Deck 1	2 Space number	3 Between decks	4 Space description	5 Space of fire origin	6 FFES required	7 FFES applied
MFZ1	1 - 01	1 - 2	fresh water tank 1S	no	-	-
	1 - 02	1 - 2	pump room 1	yes	no	-
	1 - 03	1 - 2	fresh water tank 1P	no	-	-
	1 - 04	1 - 2	fuel oil tank 1S	no	-	-
	1 - 05	1 - 2	auxiliary equipment room 1	yes	no	yes
	1 - 06	1,5 - 2	switchboard room 1	yes	no	-
	1 - 07	1 - 2	fuel oil tank 1P	no	-	-
MFZ2	1 - 08	1 - 4	main engine room 1	yes	yes	yes
	1 - 09	1 - 4	mainengine room 2	yes	yes	yes
	1 - 10	1 - 2	fuel tank oil tank 2S	no	-	-
	1 - 11	1 - 2	auxiliary equipment room 2	yes	no	yes
	1 - 12	1,5 - 2	switchboard room 2	yes	no	-
	1 - 13	1 - 2	fuel oil tank 2P	no	-	-
MFZ3	1 - 14	1 - 2	fresh water tank 2S	no	-	-
	1 - 15	1 - 2	pump room 2	yes	no	-
	1 - 16	1 - 2	fresh water tank 2P	no	-	-

1 Deck 2	2 Space number	3 Between decks	4 Space description	5 Space of fire origin	6 FFES required	7 FFES applied
MFZ4	2 - 01	2 - 3	trailer deck	yes	yes	yes
MFZ2	2 - 02	2 - 4	piping trunk 1	no	yes	yes
	2 - 03	2 - 4	cabling trunk 1	no	no	no
	2 - 04	2 - 4	piping trunk 2	no	yes	yes
	2 - 05	2 - 4	cabling trunk 2	no	no	no

1 Deck 3	2 Space number	3 Between decks	4 Space description	5 Space of fire origin	6 FFES required	7 FFES applied
MFZ1	3 - 01	3 - 4	accommodation	yes	yes	yes
	3 - 02	3 - 4	accommodation	yes	yes	yes
	3 - 03	3 - 4	accommodation	yes	yes	yes
	3 - 04	3 - 4	corridor	yes	yes	yes
	3 - 05	3 - 4	locker	yes	yes	yes
	3 - 06	3 - 4	locker	yes	yes	yes
	3 - 07	3 - 4	accommodation	yes	yes	yes
	3 - 08	3 - 4	locker	yes	yes	yes
	3 - 09	3 - 4	locker	yes	yes	yes
	3 - 10	3 - 4	ac room	yes	no	-
	3 - 11	3 - 4	equipment room	yes	no	yes
	3 - 12	3 - 4	equipment room	yes	no	-
MFZ2	3 - 13	3 - 4	corridor	yes	yes	yes
	3 - 14	3 - 4	corridor	yes	yes	yes
	3 - 15	3 - 4	day room	yes	yes	yes
	3 - 16	3 - 4	corridor	yes	yes	yes
	3 - 17	3 - 4	laundry	yes	yes	yes
	3 - 18	3 - 4	mess	yes	yes	yes
	3 - 19	3 - 4	shower	yes	no	-
	3 - 20	3 - 4	pantry	yes	yes	yes
	3 - 21	3 - 4	ac room	yes	no	-
MFZ3	3 - 22	3 - 4	store room	yes	yes	yes
	3 - 23	3 - 4	emergency generator room	yes	yes	yes
	3 - 24	3 - 4	deck store	yes	yes	yes

APPENDIX F: SPACE DIVISION AND ROUTING DIAGRAM OF EXERCISE EXAMPLE



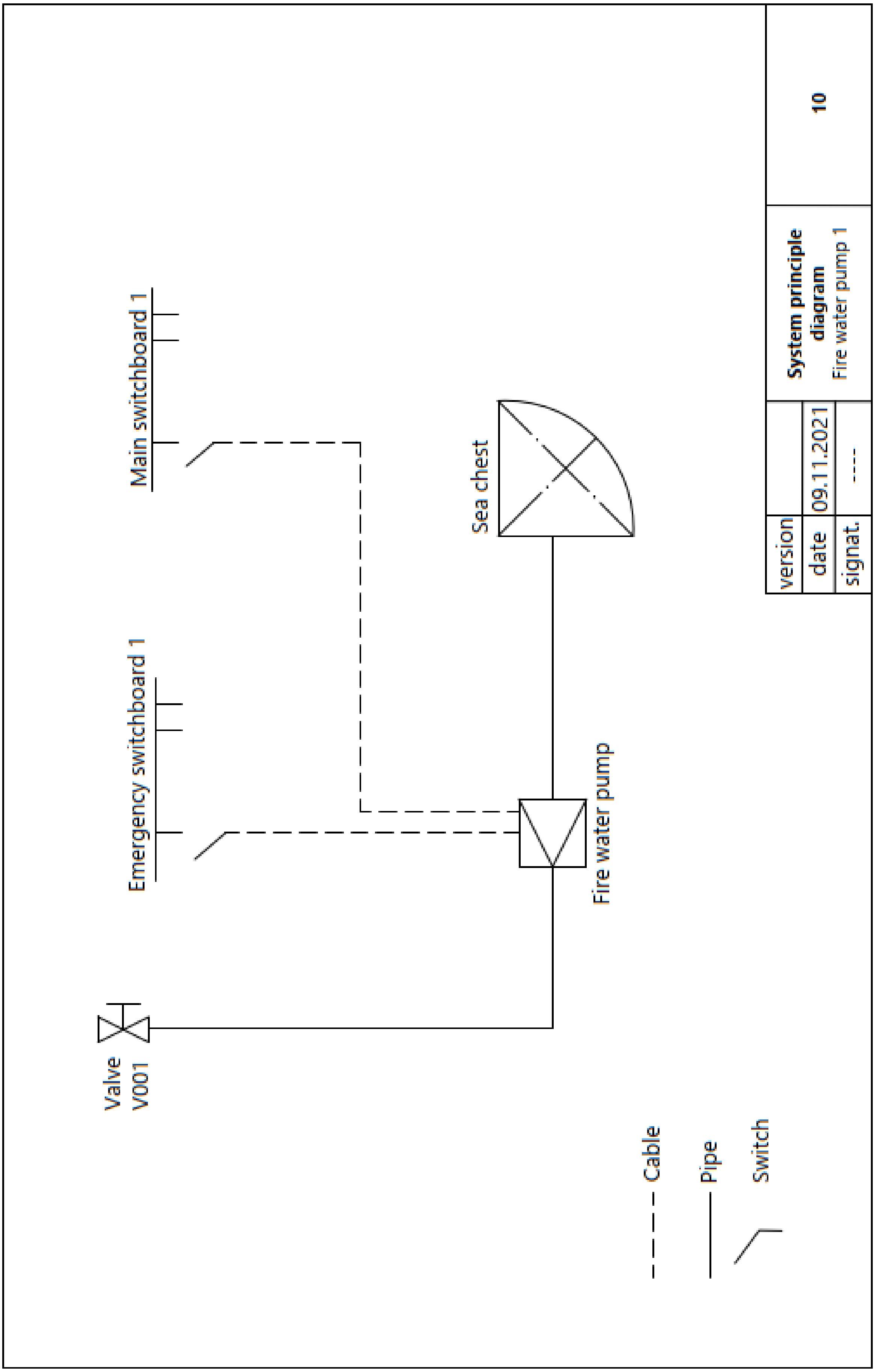
APPENDIX G: CASUALTY SCENARIOS OF EXERCISE EXAMPLE

Page 1(2)

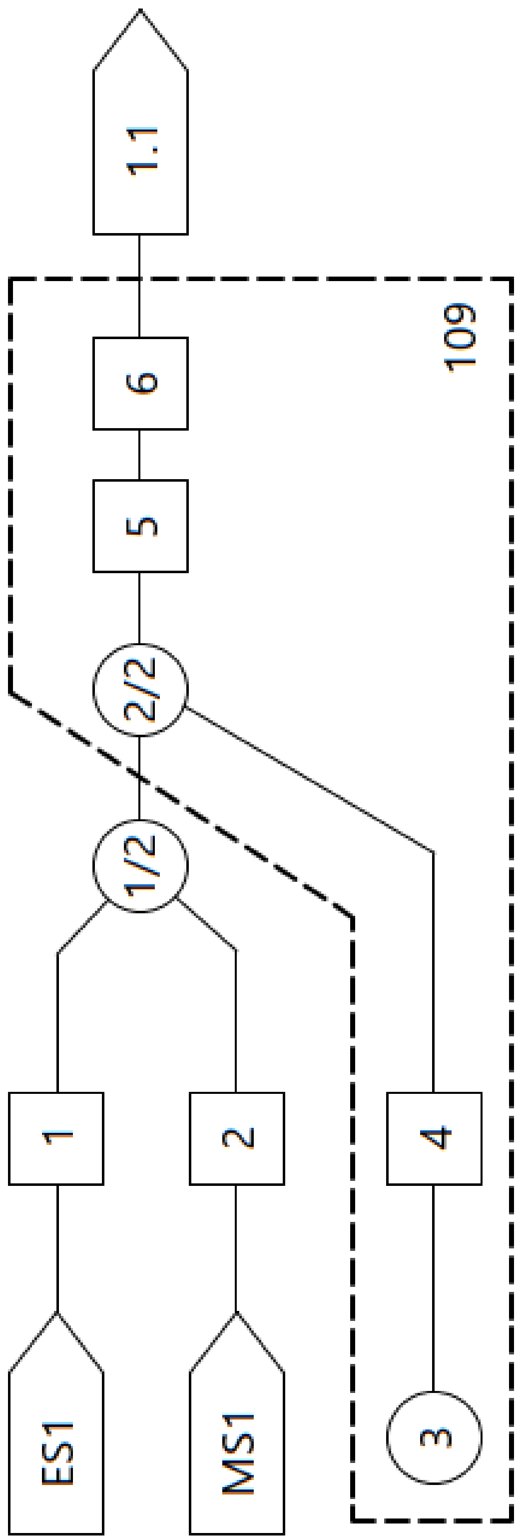
1	2	3	4	5
row number		space of fire origin		adjacent spaces affected by fire
1	1 - 02	pump room 1	1 - 01 1 - 03 1 - 05 1 - 06	fresh water tank 1S fresh water tank 1P auxiliary adjacent room 1 switchboard room 1
2	1 - 05	auxiliary equipment room 1	n / a	
3	1 - 06	switchboard room 1	1 - 02 1 - 05 1 - 07 2 - 03	pump room 1 auxiliary equipment room 1 fuel oil tank 1P cabling trunk 1
4	1 - 08	main engine room 1	n / a	
5	1 - 09	main engine room 2	n / a	
6	1 - 11	auxiliary equipment room 2	n / a	
7	1 - 12	switchboard room 2	1 - 09 1 - 11 1 - 13 2 - 05	main engine room 2 auxiliary equipment room 2 fuel oil trunk 2P cabling trunk 2
8	1 - 15	pump room 2	1 - 14 1 - 16	fresh water tank 2S fresh water tank 2P
9	2- 01	trailer deck	n / a	
10	3 - 01	accommodation	n / a	
11	3 - 02	accommodation	n / a	
12	3 - 03	accommodation	n / a	
13	3 - 04	corridor	n / a	
14	3 - 05	locker	n / a	
15	3 - 06	locker	n / a	
16	3 - 07	accommodation	n / a	
17	3 - 08	locker	n / a	

1	2	3	4	5
row number		space of fire origin		adjacent spaces affected by fire
18	3 - 09	locker	n / a	
19	3 - 10	ac room	3 - 03 3 - 04	accommodation corridor
20	3 - 11	equipment room	n / a	
21	3 - 12	equipment room	3 - 04 3 - 09 3 - 11	corridor locker equipment room
22	3 - 13	corridor	n / a	
23	3 - 14	corridor	n / a	
24	3 - 15	day room	n / a	
25	3 - 16	corridor	n / a	
26	3 - 17	laundry	n / a	
27	3 - 18	mess	n / a	
28	3 - 19	shower	3 - 16 3 - 17 3 - 21	corridor laundry ac room
29	3 - 20	pantry	n / a	
30	3 - 21	ac room	3 - 16 3 - 19	corridor shower
31	3 - 22	store room	n / a	
32	3 - 23	emergency generator room	n / a	
33	3 - 24	deck store	n / a	

APPENDIX H: SYSTEM PRINCIPLE DIAGRAM OF EXERCISE EXAMPLE



APPENDIX I: BLOCK DIAGRAM OF EXERCISE EXAMPLE



ES1 = power supply from emergency switchboard 1

MS1 = power supply from main switchboard 1

1 = cable route from ES1 to fire water pump 1 (fire-resistant cable)

2 = cable route from MS1 to fire water pump 1

3 = sea chest

4 = pipeline from sea chest to fire water pump 1

5 = fire water pump 1

6 = pipeline from fire water pump 1 to isolation valve V001

109 = main engine room 2

1.1 = output state of fire water pump 1

version		**Block diagram**	11
date	09.11.2021	Fire water pump 1	
signat.	----		

APPENDIX J: OVERALL ASSESSMENT RESULTS

The yellow cells are indications of impact damage to element.

13

1/2

Fire water pump 1

row number	Input ES1	Input MS1	Block 3	Block 1						Block 2		
1	1	0	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
2	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
3	1	0	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
4	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
5	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
6	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
7	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
8	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
9	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
10	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
11	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
12	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
13	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
14	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
15	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
16	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
17	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
18	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
19	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
20	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
21	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
22	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
23	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
24	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
25	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
26	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
27	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
28	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
29	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
30	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
31	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09
32	0	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-06	1-08	1-09
33	1	1	1-09	3-23	3-21	3-16	2-05	1-12	1-09	1-07	1-08	1-09

Fire water pump 1

row number	Block 4	Block 5	Block 6		Output 1.1
1	1-09	1-09	1-09	2-04	1
2	1-09	1-09	1-09	2-04	1
3	1-09	1-09	1-09	2-04	1
4	1-09	1-09	1-09	2-04	1
5	1-09	1-09	1-09	2-04	0
6	1-09	1-09	1-09	2-04	1
7	1-09	1-09	1-09	2-04	0
8	1-09	1-09	1-09	2-04	1
9	1-09	1-09	1-09	2-04	1
10	1-09	1-09	1-09	2-04	1
11	1-09	1-09	1-09	2-04	1
12	1-09	1-09	1-09	2-04	1
13	1-09	1-09	1-09	2-04	1
14	1-09	1-09	1-09	2-04	1
15	1-09	1-09	1-09	2-04	1
16	1-09	1-09	1-09	2-04	1
17	1-09	1-09	1-09	2-04	1
18	1-09	1-09	1-09	2-04	1
19	1-09	1-09	1-09	2-04	1
20	1-09	1-09	1-09	2-04	1
21	1-09	1-09	1-09	2-04	1
22	1-09	1-09	1-09	2-04	1
23	1-09	1-09	1-09	2-04	1
24	1-09	1-09	1-09	2-04	1
25	1-09	1-09	1-09	2-04	1
26	1-09	1-09	1-09	2-04	1
27	1-09	1-09	1-09	2-04	1
28	1-09	1-09	1-09	2-04	1
29	1-09	1-09	1-09	2-04	1
30	1-09	1-09	1-09	2-04	1
31	1-09	1-09	1-09	2-04	1
32	1-09	1-09	1-09	2-04	1
33	1-09	1-09	1-09	2-04	1

APPENDIX K: CASUALTY IMPACT TABLE FOR EXERCISE EXAMPLE

The yellow cells are indications of impact damage to element. The status 1* in block 1 means that it is not affected due to fire-resistant protection. Event numbers are not shown here directly, but they are numbered according to columns of the elements (Input ES1 = 1-11, …, Block 109 = 1-15).

Fire water pump 1 | 14-500

row number	Input ES1	Input MS1	Block 2	Block 1	Block 109	Output 1.1	Case number	Assessment result for output 1.1	Input ES1	Input MS1	Block 2	Block 1	Block 109	Output 1.1
1	1	0	0	1	1	1	1-12.1	Main switchboard 1 down.	1	0	0	1	1	1
3	1	0	0	1	1	1	1-12.1	Main switchboard 1 down.	1	0	0	1	1	1
4	1	1	0	1	1	1	1-13.1	Cable from MS1 to fire water pump affected.	1	1	0	1	1	1
5	1	1	0	0	0	0	1-15.1	Main engine room 2 affected.	1	1	0	0	0	0
7	1	1	0	0	0	0	1-15.1	Main engine room 2 affected.	1	1	0	0	0	0
25	1	1	1	0	1	1	1-14.1	Cable from ES1 to fire water pump affected.	1	1	1	1*	1	1
28	1	1	1	0	1	1	1-14.1	Cable from ES1 to fire water pump affected.	1	1	1	1*	1	1
30	1	1	1	0	1	1	1-14.1	Cable from ES1 to fire water pump affected.	1	1	1	1*	1	1
32	0	1	1	0	1	1	1-11.1	Emergency switchboard 1 down.	0	1	1	0	1	1

APPENDIX L: FMEA TABLE FOR EXERCISE EXAMPLE

Fire water pump 15

1	2	3	4	5	6	7	8	9
Document references	System scope	Event n:o	Primary event, failure or failed item	case n:o	Involved scenarios		Response	Verification method
10 11 12 13 14-500	Subsystem 1.1 Fire water pump 1	1-11	Emergency switchboard 1 down. (Input ES1)	1-11.1	32	R	Power supply will be supplied by MS1.	Testing of pump with power supply from ES1 down.
		1-12	Main switchboard 1 down. (Input MS1)	1-12.1	1, 3	R	Power supply will be supplied by ES1.	Testing of pump with power supply from MS1 down. Inspection of cable route from MS1 to fire pump.
		1-13	Cable route from MS1 to fire water pump affected. (Block 2)	1-13.1	4	R	Power supply will be supplied by ES1.	Inspection of cable route. Testing of pump with power supply from MS1 down.
		1-14	Cable route from ES1 to fire water pump affected. (Block 1)	1-14.1	25, 28, 30	D	Fire-resistant cable remain intact.	Inspection of cable route and cable type.
		1-15	Main engine room 2 affected. (Block 109: includes blocks 3, 4, 5, 6)	1-15.1	5, 7	-	Pump down	Inspection of fire water pump 1 location. Inspection of sea chest location. Inspection of pipe route from sea chest to fire water pump 1. Inspection of pipeline from fire water pump 1 to isolation valve V001.

APPENDIX M: FMEA TABLE WITH LOCAL AND END EFFECT COLUMNS

Fire water pump 15

1	2	3	4	5	6	7	8	9	10
Document references	System scope	Event n:o	Primary event, failure or failed item	case n:o	Involved scenarios	Consequence			Verification method
							Local response	End response	
10 11 12 13 14-500	Subsystem 1.1 Fire water pump 1	1-11	Emergency switchboard 1 down. (Input ES1)	1-11.1	32	R	Subsystem does not receive electricity	Subsystem 1.1 operable due to MS1 electricity supply.	Testing of pump with power supply from ES1 down.
		1-12	Main switchboard 1 down. (Input MS1)	1-12.1	1, 3	R	Subsystem does not receive electricity	Subsystem 1.1 operable due to ES1 electricity supply.	Testing of pump with power supply from MS1 down. Inspection of cable route from MS1 to fire pump.
		1-13	Cable route from MS1 to fire water pump affected. (Block 2)	1-13.1	4	R	Subsystem does not receive electricity	Subsystem 1.1 operable due to MS1 electricity supply.	Inspection of cable route. Testing of pump with power supply from MS1 down.
		1-14	Cable route from ES1 to fire water pump affected. (Block 1)	1-14.1	25, 28, 30	D	subsystem receives electricity due to fire-resistant cable	Subsystem 1.1 remains intact and operable	Inspection of cable route and cable type.
		1-15	Main engine room 2 affected. (Block 109: includes blocks 3, 4, 5, 6)	1-15.1	5, 7	-	Subsystem down due to fire water pump failure.	System remains operable due to other subsystem	Inspection of fire water pump 1 location. Inspection of sea chest location. Inspection of pipe route from sea chest to fire water pump 1. Inspection of pipeline from fire water pump 1 to isolation valve V001.