Panagiota Savvidou

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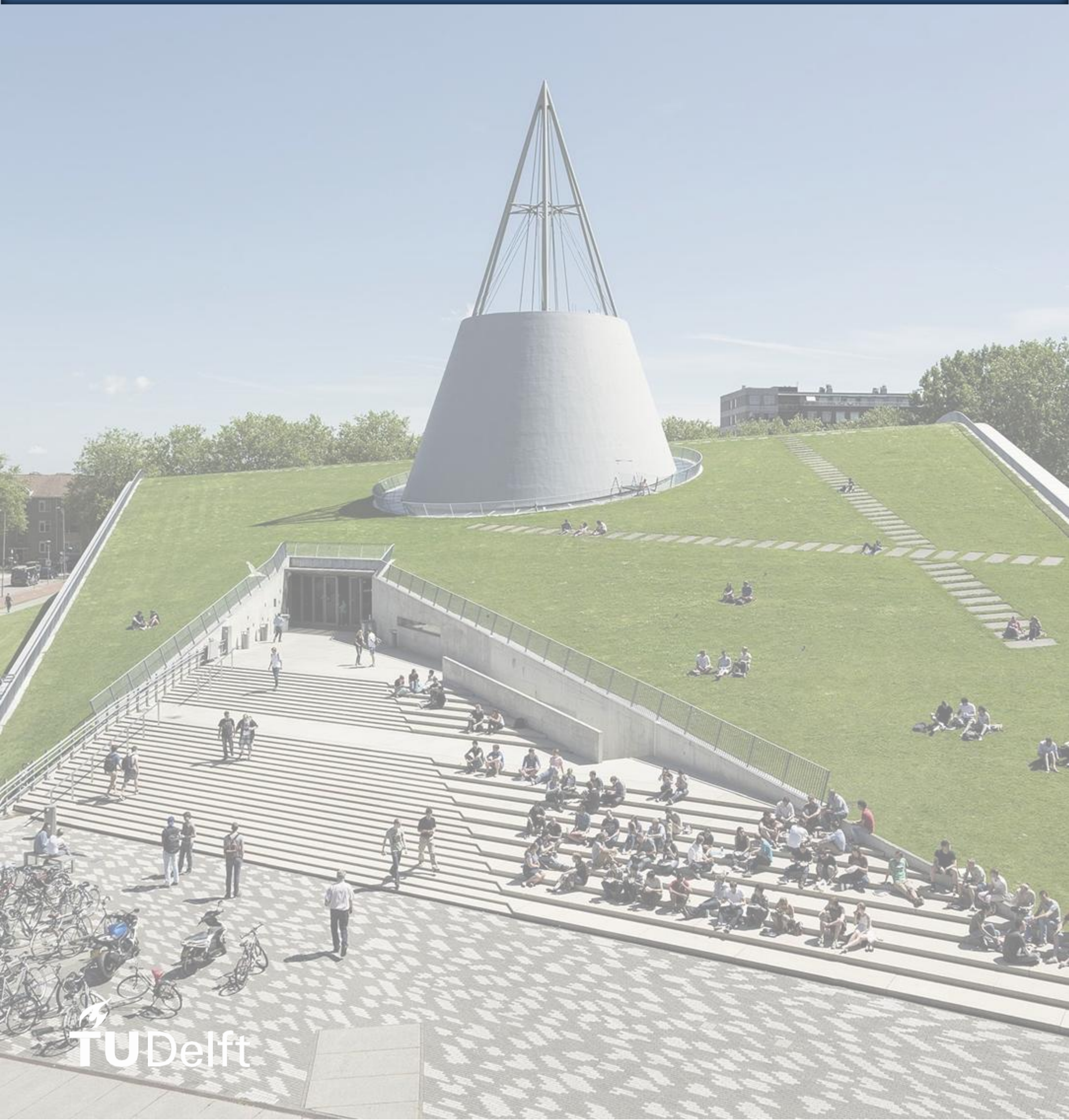

Risk Assessment of Downtime in Ship Operations

By

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Preface

This thesis project has not only solidified my fascination with complex systems engineering but has also allowed me to understand, at a deeper level, what a complex system is and how it can be managed as a socio-technical system. It was during this research endeavor that my interest in the maritime world grew. During my time in the MSc Complex System Engineering and Management programme, I studied how to design, integrate, and manage complex socio-technical systems, fundamentally concerning transport and logistics and beyond. Then I pursued the integration of the human and technical aspects to gain insights into reducing downtime and improving safety at sea.

This report is structured into seven sections, each of which contributes to bridging the identified research gap and builds upon the previous one to guide the reader step by step towards the study's objectives. Qualitative tools and approaches, such as the socio-technical system perspective, are used in combination with and complement established risk assessment methodologies to investigate the inspection and maintenance operational practices in oil tankers. Considering both human and technical aspects, as well as the interactions that arise between them during operations, the study aims to mitigate ship operational downtime. A structured methodological approach that contains sequential steps culminates in the integration of Failure Mode, Effects, and Criticality Analysis, and Functional Resonance Analysis Method. This framework stands out as a means to identify opportunities for improvement and ultimately reduce downtime in ship operations using a socio-technical modeling approach. I hope that this effort, which deepened my appreciation and love for the research process, contributes even a small brick to the scientific community and the maritime industry.

Acknowledgments

"No one is an island, entire of itself; every one of us is a piece of the continent, a part of the main."

— John Donne

First and foremost, I deeply thank my parents, Sofia and Peter. They have infused me with a lifelong curiosity, taught me to dare, to strive for my goals and dreams, to believe in myself and that I can succeed through effort and patience, and offered me the opportunity to live this journey. To my sister, Helen, who gives me strength while moving forward and flourishing together in this life. To my partner in life, Gabriel, for his patience during long writing, the relief and fresh air that balanced work, and the unwavering confidence. To my friends for their never-ending support and the much-needed opportunities to unwind and let the pressure of work melt away, and to the new friends I met in the Netherlands during my studies, who enriched this journey and made the challenges more enjoyable.

I am deeply grateful to my supervisor, Dr. Ming Yang, and my thesis advisor, Dr. Ir. Yue Shang, for the inspiration, their valuable guidance, support, invaluable feedback sessions, and the opportunity they gave me to conduct this thesis project. My thanks extend to the chair of my thesis committee, Pr. Dr. Jafar Rezaei, who provided an impartial third perspective, reviewed my work and offered his researcher's insight to ensure objectivity and rigor in this study. I aspire to embody the same qualities in my future career. Additionally, I would like to thank the industry partners for their experience-based operational insights and the dataset, both were essential and crucial for the completion of this study. As my last word, I am sincerely thankful to the entire TU Delft community and the teaching team that led the courses. They provided an inspiring environment, the tools, expert guidance, and knowledge that have greatly influenced this work.

I hope this research contributes to more efficient ship operations, more sustainable supply chains, and stands as a stepping stone for further development and future research.

Nothing in life is to be feared. It is only to be understood. Now is the time to understand more, so that we may fear less.

— Marie Curie

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Abstract

Global maritime transportation facilitates more than 80% of world trade; therefore, the reliability of ships is inextricably linked to global supply chains. Inefficient inspection and maintenance practices can trigger failures, which in turn increase operating costs. These failures can account for up to 35% of total expenses and cause downtime that cascades through logistic networks.

Consequently, unplanned equipment and machinery failures that occur on a vessel can disrupt the ship's overall operation and lead to delays, higher transport costs, and wider societal impacts, most notably supply shortages and elevated environmental risks. To avoid these domino effects, ship operators must understand the most common failure mechanisms and their underlying causes. Thus, systematic risk identification is a starting point for any strategy that aims to mitigate operational downtime.

Existing literature on risk identification in ship inspection and maintenance operations largely focuses on technical and engineering solutions. In order to address this gap, this research adopts the socio-technical system (STS) approach to identify improvement opportunities for inspection and maintenance activities, ultimately mitigating operational downtime. A two-stage Failure Mode Effects and Criticality Analysis (FMECA) is conducted to determine the fundamental failure mechanism in oil tankers and the most critical system, based on industry inspection reports. The Functional Resonance Analysis Method (FRAM) is used to deep dive into that failure. Semi-structured expert interviews and operational data serve as a means of identifying performance variability scenarios across human, organizational, and environmental contexts, within the ship operational process. Finally, the integration of the FMECA and FRAM assists in evaluating suggested control measures based on their effect on ship availability.

Corrosion in the steam supply subsystem arises as the leading operational downtime driver. Personnel competence, equipment availability, inspection areas accessibility, and time constraints are the key factors that create performance variability in the operational process. Hinging upon the FRAM models, which qualitatively visualize the propagation of these variability scenarios, control measures are developed based on a Hierarchy of Controls (HoC) - As Low As Reasonably Practicable (ALARP) framework.

Next steps should begin with a pilot on a single ship subsystem that is highly critical, and a high-resolution failure and downtime dataset. Virtual tests are advised to be conducted before the actual deployment of the identified control measures.

Keywords: Ship Availability, Downtime, STS, FRAM, FMECA, Ship Operations, Inspection, Maintenance

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Nomenclature

Abbreviation	Definition
ABM	Agent-Based Modeling
ALARP	As Low As Reasonably Practicable
ANN	Artificial Neural Networks
CBM	Condition-based maintenance
COT	Cargo Oil Tank
DRN	Downtime Risk Number
DT	Downtime
DWT	Deadweight Tonnage
FM	Failure Mode
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode Effects and Criticality Analysis
FRAM	Functional Resonance Analysis Method
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Study
HoC	Hierarchy of Controls
HSI	Human-system interaction
KPI	Key Performance Indicator
LNG	Liquefied Natural Gas
NDT	Non-destructive testing
OEM	Original Equipment Manufacturer
RBI	Risk-based Inspection
PPE	Personal Protective Equipment
RPN	Risk Priority Number
RQ	Research Question
STAMP	System-Theoretic Accident Model and Processes
STS	Socio-technical system
WBT	Water Ballast Tank

1 Introduction

1.1 Background

The maritime industry is paramount in the contemporary, competitive, demanding, and globalized world. Maritime transport stands of utmost significance for global trade, facilitating over 80% of international merchandise movement by volume [1]. Moreover, maritime trade is projected to rise by over 2% between 2024 and 2028 [2].

The progress in the growth of the global fleet from 2001 to 2013 is impressive. While the year 2012 was the peak of the largest period of ship construction ever documented, since 2001, the global fleet had more than doubled, reaching 1.63 billion deadweight tons by January 2013 [3]. Maintenance activities can represent 25–35% of an operator's direct operating expenses, at the same time that other cost pressures have led to additional increases in maintenance budgets. As a result, operators are looking for ways to reduce maintenance costs to remain profitable [4].

Disruptions in ship availability, whether resulting from unplanned breakdowns or scheduled maintenance, can cause cascading effects throughout global supply chains, significantly affecting industries and consumers. Unscheduled downtime, in particular, can lead to delays in the delivery of critical goods, escalating transportation costs, and placing additional strain on maritime logistics networks. These disruptions have wider societal impacts, such as increased consumer prices and the potential for supply shortages, as evidenced during recent global supply chain disruptions [1] [5].

Increasing the effectiveness and efficiency of ship operations to enhance ship availability is highly beneficial. To achieve this, risk identification activities may be applied to maintenance and inspection operations. Hinging upon this approach, this research is developed on the risk assessment of downtime in ship operations.

Figure 1.1: Risk assessment of downtime in ship operations (Image generated by OpenAI's DALL-E, 2024)[6]

1.2 Research Problem

1.2.1 Situational Overview

A ship is divided into four different systems of grouped components: fore end, cargo area, aft end, and machinery space [7]. The integrity and functionality of the vessel's systems and components stand out as of paramount importance for the effectiveness and efficiency of the ship's maintenance and inspection operation processes.

Each system is broken down into subsystems; in this way, the ship is decomposed into the physical zones that make up the vessel [7]. Therefore, a ship can be categorized as a complex system, characterized by a multitude of subsystems and diverse interrelationships among them, which collectively enhance the system's intricacy [8]. While the number of these subsystems and their interconnections increases, comprehending the system as a whole and modeling its behavior becomes extremely challenging and almost impossible [9].

In ship maintenance and inspection processes, numerous stakeholders and actors are involved [10] [11]. These stakeholders include the ship owner(s), managers, crew, builders or repair yards, classification societies, insurers, charterers, flag, and port states [10]. Each of these groups of actors has an interest in the ship's safe operation and maintenance [10]. Additionally, during a hazard identification inspection, it is essential to identify skilled and qualified personnel to carry out the inspection process effectively [12].

Considering the context of complex socio-technical systems, these systems combine physical and technical components with networks of mutually reliant actors [8]. These systems are viewed from two distinct perspectives:

- the systems perspective, which is grounded in hard systems engineering
- and the actor perspective, rooted in the social sciences. [8]

These perspectives are interconnected, influencing each other significantly [8]. Such large-scale systems typically comprise numerous smaller subsystems [13]. If any one subsystem fails to operate correctly or as initially planned, this will likely adversely affect the functioning of the entire system. Often, these subsystems may exhibit conflicting functions and depend on each other in complex ways [13].

From the actor's perspective, decision-making involves numerous stakeholders with diverse, sometimes conflicting interests. In a ship, the actor perspective also includes the interactions between humans and machines. This refers to the point where communication and physical interaction occur between an individual operator or onboard personnel and a specific ship component [14]. Collaboration among these actors is crucial, however, it is not always guaranteed [8]. Their interdependent relationships necessitate collective effort to address issues [9]. This interdependence forms what is known as a "policy network" or an "issue network", where no single actor can resolve problems independently [8]. The choices made by stakeholders involved in the design and management of ships have a significant impact on asset performance and the safety and operational efficiency of maritime activities [14].

An example of human-machine interaction within ship operations is the maintenance process involving the removal and reconnection of a pump from a separation system. A critical task during pre-maintenance is the draining and purging of lines, where operators interact with the system's valves and control mechanisms to ensure proper isolation and functionality [15].

The proposed hypothesis argues that by modeling inspection and maintenance operations from these distinct perspectives, it may be possible to improve their effectiveness. This approach could generate insights or implementations that contribute to greater efficiency in these processes, ultimately helping to mitigate ship operational downtime. Complex behaviors that arise from interactions within ship systems and their environment underscore the need for a socio-technical approach in ship maintenance and inspection, which can better address this complexity [16]. Moreover, identifying the factors that influence ship availability is a practical necessity. Both unexpected breakdowns and scheduled maintenance are key factors that influence maritime operations. In addressing these factors, this study will focus on the first risk assessment step, as detailed below, to systematically identify improvement options.

A risk assessment is commonly used to support the decision-making process [17]. This procedure involves collecting data and integrating information to build an understanding of the risks faced and consists of five steps:

1. identification of the various risks associated with a project or operation.
2. determination of the likelihood and potential consequences of each identified risk
3. evaluation of the level of each risk by considering its consequences
4. identification of possible treatments for the risks and exploration of opportunities for improvement to mitigate these risks effectively
5. documentation of all the steps taken, the findings, and the measures planned or implemented. [17]

1.2.2 Problem Statement

Ship maintenance and inspection operations ensure safety, reliability, and operational efficiency. The complexity of modern ships is characterized by interdependent systems; however, there are significant challenges in maintaining their integrity and functionality. These systems involve numerous subsystems with intricate interrelationships, making it difficult to model their behavior as a whole.

In addition to the technical complexity, ship operations are influenced by a wide array of stakeholders, each with distinct roles and interests. This diversity of actors, combined with the interactions between human and technical components, forms a socio-technical system where decision-making and operations can be prone to variability and inefficiency. The challenge lies in managing these interactions effectively to ensure smooth maintenance and inspection processes and reduce operational downtime.

A tangible instance of inefficient inspection and maintenance operational process was the 2022 collapse and subsequent sinking of the oil tanker Prestige off the coast of Galicia, Spain [18]. The single-hull vessel fractured in two after a submerged, corrosion-thinned part of its hull collapsed under cyclic wave loading. Routine visual inspections had been unable to identify extensive internal corrosion in the amidships plating, and without ultrasonic thickness gauging or smart-pigging of ballast tanks, a fatigue crack in a corroded weld toe grew until failure. The spill of approximately 63.000 tons of fuel oil contaminated hundreds of kilometers of coastline, closed down fisheries and ports for months, and cost over €1.5 billion in cleanup and compensation costs. The particular example serves as a lesson to recognize that unreliable operational processes on board ships can have far-reaching financial, environmental, and social impacts, though it should be noted that classification society rules, inspection means, and technologies have evolved significantly since then.

This research proposes a socio-technical model representing the ship maintenance and inspection operations, postulating that such an integrated approach can significantly enhance the effectiveness and efficiency of the operations by acknowledging and systematically addressing the interrelations between human factors and technical components.

1.3 Research Objectives

The purpose of this study is to model maintenance and inspection from two different perspectives—the system perspective and the actor perspective. By systematically evaluating these perspectives, the study aims to provide insights into mitigating operational downtime and enhancing decision-making in such a complex socio-technical environment. To accomplish the purpose of this study, the following sub-objectives need to be fulfilled:

i) Identify the socio-technical elements involved in maintenance and inspection processes.

ii) Determine the interrelations between the identified socio-technical elements.

iii) Investigate risk management methodologies implemented in the maritime sector and assess their suitability for maintenance and inspection operations.

iv) Identify failure modes within the system.

v) Model the maintenance and inspection operations to identify how failure modes occur and determine the black spots in maintenance and inspection operations that contribute to limited ship availability.

vi) Implement a small scale case to demonstrate the socio-technical modeling approach for the ship inspection and maintenance operations.

1.4 Scope of the Study

The scope of this thesis project is outlined as follows:

i) Ship availability in maritime operations

ii) Socio-technical perspective in inspection and maintenance processes

iii) Improvement options to mitigate the downtime in maintenance and inspection operations

1.5 Research Questions

The research objective of this research is addressed by formulating the following research question:

RQ: ***How can a socio-technical modeling approach to maintenance and inspection activities help to identify opportunities for improvement and ultimately mitigate downtime in ship operations?***

To answer the main research question, the following sub-questions may be addressed:

SRQ1: *What are the key socio-technical elements and their interrelations involved in inspection and maintenance processes?*

SRQ2: *How can the identified elements and their interrelations be modeled from the socio-technical perspective to support inspection and maintenance?*

SRQ3: *In what ways can a socio-technical analysis of inspection and maintenance practices reveal opportunities to improve system reliability and reduce downtime?*

1.6 Link with the CoSEM Programme

This section presents the link to the master programme. During the first academic year, students are taught to approach complex socio-technical systems through design and systems thinking, to get a handle on key concepts in complex systems engineering, and to apply these principles in various real-world cases as well as diagnose the complexity of systems and problems. Furthermore, students are educated on recognizing the role of change, exploring systems from an actor's perspective, assessing decision-making complexities, and evaluating how these complexities affect the potential for responsible interventions or redesign within systems.

This thesis project aligns with the MSc program "Complex Systems Engineering and Management". Complex socio-technical systems integrate technical and physical elements with networks of independent actors [8]. These systems are studied from two distinct perspectives: the systems perspective, built upon hard systems engineering, and the actor viewpoint, which is rooted in social sciences [8]. A ship's operations are processes within a system composed of various subsystems [12]. More specifically, a ship functions as a high-level system made up of different subsystems, such as the fore end, cargo area, aft end, and machinery space [7]. Operators play a crucial role in a system's operation, bringing the human element into the process through human-machine interaction.

Risk identification is an essential aspect in every complex system, serving as a vital tool to improve the system's operational effectiveness and efficiency. Consequently, the ability to optimize system operations and mitigate downtime is a desirable skill for any project team.

2 Theoretical background and Literature Review

This section provides a foundation for understanding the socio-technical context and its implementation in ship and ship operations, such as inspection and maintenance. Socio-technical methodologies are explored. Moreover, the asset management approach focuses on integrating strategic, technical, and operational practices to ensure the efficient, reliable, and sustainable management of maritime assets through structured inspection and maintenance processes. Furthermore, risk management in ship operations is addressed, emphasizing systematic methods to identify and assess potential hazards, while integrating technical and human factors to ensure operational safety and efficiency. Each subsection builds on the other, incorporating literature from essential fields to model maintenance and inspection from the two distinct perspectives, with the ultimate goal of providing insights into mitigating operational downtime and enhancing decision-making in ship inspection and maintenance operations.

2.1 Socio-techncial systems

2.1.1 Definition and Concepts

The Socio-Technical System (STS) has become increasingly popular in contemporary engineering and design. A STS focuses on the relationships between humans, machines, environments, organizational structures, processes, and activities within systems [13]. This approach has been widely adopted by researchers who have expanded their understanding of "joint optimization of the social and technical systems" that entails the interactions among different system components and the relationships between the system and the broader external environment surrounding it [13].

According to Mumford (2006), a STS consists of two interconnected subsystems: the technological subsystem, which consists of not just the equipment, machines, and tools but also the organization of work, and the social subsystem, which includes the individuals and teams involved, alongside the requirements for coordination, control and managing boundaries [19], as depicted in Figure 2.1. Breaking down a system into its individual components for analysis supports the management of the growing complexity of systems that are starting to emerge [13]. A socio-technical system's configuration involves an interplay of people, technologies, and their environment, aimed at achieving certain functions or goals. These systems are characterized by their complex interactions, including a large number of interacting elements, a diversity of components, and the presence of unexpected variability and resilience. Such systems require specific management approaches emphasizing adaptability, robust process design, and continuous monitoring of the gap between intended and actual performance [20].

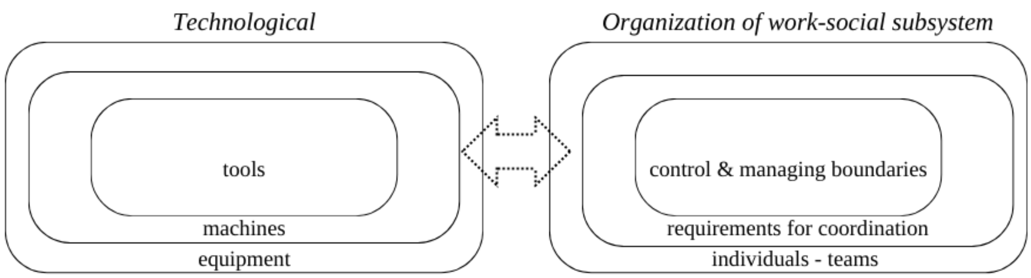

Figure 2.1: Socio-technical system (Information adapted from [19])

Despite the broad utilization of the STS approach across various sectors and fields, different experts and scientists hold varying approaches and theories regarding how these systems should be defined, analyzed, or applied. There is no widespread consensus on these views, emphasizing the diverse interpretations and implementations within the scientific community.

Previous research by Kroes et al. (2006) defines a STS as a hybrid configuration consisting of various intentional and non-intentional elements, such as institutions, human agents, and technical artifacts [9]. This system is characterized by its dual nature, integrating human and machine elements essential for its intended functions. These systems are engineered to include necessary components for achieving specific operational goals, and this often means that human roles and social structures are considered integral parts of the system, not just external factors [9]. At the lowest levels, engineering systems are often viewed as solely technical artifacts, where the system operates without direct human intervention. However, as we move to more complex layers of the system, the role of human agents becomes significantly more crucial. These agents use and operate the technical artifacts and perform various important sub-functions within the intricate network of these artifacts. Beyond mere operation, agents contribute to creating and maintaining essential social, economic, and legal institutions that support the overall system's functionality. Consequently, at higher levels, engineering systems exhibit greater heterogeneity as both the technical and social infrastructures, inclusive of human agents, become integral, essential components for the system's effective operation [9].

Günter Ropohl (1999) introduces the socio-technical system as a framework that analyzes the complex interactions between humans and technology within work environments. The concept emphasizes the reciprocal relationship between humans and machines, aiming to harmonize technical and social conditions to ensure that efficiency and humanity coexist without conflict [21].

Finally, the STS perspective recognizes that the success of a system depends not only on its technological elements but also on the design, behavior, and collaboration of the people involved. The aim is to achieve an optimized balance between the technical tools and processes and the social structures, culture, and practices to enhance functionality, safety, and sustainability while addressing complex societal challenges [22].

2.1.2 Systemic Safety Analysis Methods

Several approaches exist for integrating a socio-technical perspective into ship maintenance and inspection operations. The System-Theoretic Accident Model and Processes (STAMP) and the Functional Resonance Analysis Method (FRAM) are the most widely used and referenced methods. Each of these methods has distinct objectives and scopes, which will be explored in detail in this sub-section.

Nancy Leveson (2004) argues that by utilizing STAMP, challenges posed by modern, complex, socio-technical systems can be addressed. Initially, the STAMP is based on systems theory [23]. At the same time, the framework redefines safety as a control problem, shifting the focus from simply preventing component failures to ensuring the effective enforcement of safety constraints across interactions within a system, including both human and technical components [24]. Hazards are understood as the result of insufficient or failed safety constraints. The framework integrates key concepts such as constraints, control loops, feedback mechanisms, and socio-technical levels of interaction, providing a holistic view of safety [24]. Within STAMP, safety is maintained by imposing and enforcing constraints that prevent hazardous interactions. Systems are modeled as hierarchical structures with feedback loops that promote equilibrium and adaptability. Furthermore, safety is treated as an emergent property arising from system-wide interactions and the ability of the system to adapt to changes effectively [24], [23].

The FRAM is utilized to study complex sociotechnical systems by identifying and analyzing the intricate interdependencies among system functions[25], [26]. A function represents the means required to achieve a specific objective. Broadly speaking, a function refers to the activities or collection of activities necessary to deliver a particular outcome; it describes what individuals or groups need to do to accomplish a defined goal. Functions can also apply to organizational roles, such as the emergency room's purpose of treating patients. In addition, functions may be related to the actions of a technological system, which operates independently or collaboratively with humans [27]. A function's description should typically be a verb or a phrase starting with a verb. According to FRAM, each function is characterized by six aspects: input, output, control, resource, time, and precondition [25]. This method differs from traditional risk management approaches by focusing on how real-time performance variability from prescribed procedures and adjustments made by operators affects the overall safety and functionality of the system [25]. The primary goal of FRAM is not only to understand the specified functions within a system but to explore how these functions interact under various conditions, thus highlighting potential sources of systemic failures or accidents [26]. By adopting a holistic view that recognizes that the sum of the parts of the system is greater than its functions, FRAM provides a framework to improve resilience and safety through a deeper understanding of operational dynamics and their impacts on system performance [25].

To construct a FRAM model, these four essential steps are followed.

1. Identify and depict system functions: define the system's vital functions and describe each function using up to six fundamental characteristics known as aspects, which collectively form the FRAM model.

2. Assess function variability: analyze both the potential and the observed variability in the functions within the model during different realizations.

3. Evaluate functional resonance: examine the likelihood of functional resonance by studying the dependencies and interactions among functions, considering their variability.

4. Formulate management strategies: propose strategies to manage the function variability by either reducing variability that may cause adverse outcomes or by promoting variability that leads to beneficial results. [28]

Based on the analysis of the methods, FRAM is utilized in this project because it offers clarity and the ability to clarify the sequence of resonances -the chain of events- that are triggered by the ongoing interactions between various functions within a system that result in accidents. In contrast, STAMP fails to provide a clear sequence for analysis. In this research project, the precision of the resonance sequence is of paramount importance because it involves analyzing the existing procedures for maintenance and inspection of ship operations.

2.2 Ship Systems Overview

2.2.1 Types and Hierarchical Structure

A ship is not just an individual system but integrated components of larger systems [29]. The hierarchical decomposition of a ship allows engineers to analyze subsystems individually while maintaining their interconnections [29].

Seagoing marine vessels can be categorized into two main groups: transport vessels, which include cargo ships, container ships, and passenger ships, and non-transport vessels, such as fishing boats, service craft like tugs and supply vessels, and warships [30]. The various types of merchant ships, including general cargo ships, container ships, tankers, dry bulk carriers, and passenger ships, have been primarily influenced by the cargo type and the specific trade routes they serve. Additionally, each category of marine vehicle includes different subtypes of ships designed for particular functions [30]. Figure 2.2 illustrates the hull points of an oil tanker.

Figure 2.2: Tanker with labeled hull points (adapted from **Source:** [31])

Furthermore, a ship is organized into three hierarchical levels. At the primary system level, the ship is divided into four major systems: the fore end, cargo area, aft end, and machinery space [7], and these in turn are subdivided into subsystems and components. This thesis focuses specifically on equipment and machinery components of the systems that make up the ship. Equipment refers to the discrete hardware and appliances, such as anchors, chains, mooring lines, and winches [7]. While machinery includes engines, pumps, compressors, boilers, and their foundations, such as the power and utility producing systems [7].

There are four phases within the ship's life cycle: ship design, ship production, ship operation, and decommissioning of the ship. [32].

- Ship design involves parametric optimization and simulation-driven design. This phase incorporates the planning and development of ship design using advanced digital tools
- The ship production phase covers the actual construction of the ship, utilizing digital technologies for efficient production processes.
- Ship operation focuses on the daily operation of the ship, enhanced by digital technologies that monitor performance and support decision-making to optimize operational efficiency.
- Decommissioning is the final phase where the ship is decommissioned and dismantled, or recycled. [32]

The operation phase of a ship, which is the focus of this project, focuses on routine tasks, supported by digital technologies, to ensure efficient performance [30]. Ships function as integrated systems, with the operation phase ensuring subsystem functionality and alignment with life cycle phases. This phase integrates modern technologies and strategies to optimize performance and sustainability [30].

2.2.2 Key Technical Elements and Actors

On a ship, the key actors include Asset Owners, System Integrators, Original Equipment Manufacturers (OEMs), Service Providers, and Logistics Service Providers [33]. Asset owners, such as shipping companies, service providers, or military organizations, are responsible for deploying the ships and initiating maintenance and logistics services [33]. System integrators, such as shipyards, assemble the vessel by integrating components and systems from various OEMs and sometimes handle maintenance [33]. OEMs design and manufacture specific ship components, such as engines, navigation, and communication systems, and may also provide spare parts, tools, and maintenance support [33]. Service providers are third-party organizations specializing in maintenance services, logistics support, or spare parts for specific maritime components, while logistics service providers manage the supply chain for parts and equipment needed for ship maintenance and repairs, often covering a multi-echelon logistics network [33].

The technical elements of a ship contain several key systems essential for its operation and maintenance [33]. The hull forms the main structure and often requires specialized maintenance, particularly during dry-docking periods [33]. It refers to the primary structural framework that forms the shape of the vessel and provides buoyancy [12]. Propulsion systems including engines and propellers, are vital for the ship's movement and undergo both preventive and condition-based maintenance [33]. Proper maintenance of propulsion components is crucial, especially drying planned dry-docking, to ensure continued performance and safety [12]. Navigation and communication equipment, such as radar and communication devices, are sensitive electronic systems that may need repairs through replacement [33]. Additionally, crew welfare and mission-specific equipment are integral, including systems like sewage, air conditioning, and specialized tools or armaments, depending on the ship's purpose [33]. Unique to each ship type, spare parts are crucial for ongoing maintenance, though often subject to obsolescence and stored across multi-level inventories at locations like onboard, harbors, or centralized facilities [33].

2.3 Risk management in Ship Operations

2.3.1 Risk Identification Methods

The maintenance and inspection operation of ships involves several sophisticated methods and tools to ensure the reliability and safety of the vessel. These operations typically incorporate a variety of risk and reliability analysis methods.

Focusing attention on risk management in ship operations, it is essential to define "risk". In the context of this thesis research project, risk refers to the probability and potential consequences of adverse events that may disrupt a ship's mission and lead to downtime.

The objective of risk management is to address risk systematically by assessing, controlling, and determining acceptable thresholds, thereby enabling informed, risk-based decision-making in the execution of ship-related operations such as maintenance and inspections [34].

Broadly speaking, risk management can be approached from two distinct perspectives: bottom-up and top-down.

- In bottom-up approaches, the process begins with the analysis of the simplest components by examining their failure modes and probabilities. This analysis is then incrementally extended to higher levels of complexity, ultimately enabling an estimation of the likelihood and impact of specific failures on the overall system.

- The top-down perspective, in contrast, is effective for the comprehensive design of ship systems. This method begins with an examination of the system as a whole, subsequently breaking it down into progressively smaller components to identify and address the most significant risks requiring control. By systematically reducing these risks, a cumulative balancing effect is achieved, ultimately resulting in an acceptable and uniform level of risk across the design. [34]

Several approaches exist for managing risks in ship operations. Among these FMECA and HAZOP are the most broadly applied methods. Failure Mode and Effects Analysis (FMEA) is among the earliest systematic methodologies developed by reliability engineers in the 1950s for identifying potential failures [35]. This process involves analyzing components, assemblies, and subsystems to determine possible failure modes, their causes, and their effects [35]. When criticality is assigned to the identified effects, the method is referred to as Failure Modes, Effects, and Criticality Analysis (FMECA). It ensures a thorough consideration of all potential failure modes and their impact on system performance while identifying and prioritizing these failures and their consequences [36].

This approach is particularly effective in understanding the interactions between components and potential failures within complex systems. Daya and Lazakis (2023) highlight that FMECA provides a detailed understanding of how equipment, components, and personnel interact, facilitating the management of risk and reliability concerns. In marine systems and ship operations, this methodology is widely utilized to improve reliability and safety by identifying critical failure modes [36].

HAZOP analysis is utilized for identifying potential risks and operational deviations in systems [37]. It is particularly effective in both the design and operational phases, helping to prevent costly modifications and delays [37]. Conducting a HAZOP analysis requires a team of experts and is guided by considerations such as “why,” “when,” “how,” and “where” it should be performed, and “who” should be involved [38]. Additionally, HAZOP aids in identifying new hazards and supports maintenance planning, particularly in scenarios where repairs involve active equipment nearby [38].

In the context of this thesis project, the FMECA methodology has been selected as the risk assessment approach. This choice is justified by its suitability for conducting a hierarchical breakdown of the ship's structure and systems and utilizing the socio-technical approach. By systematically analyzing the ship into its simplest components, FMECA allows for the identification of potential failure modes, their causes, and their effects. This bottom-up approach aligns with the project's objective to thoroughly examine component-level risks.

Furthermore, FMECA is particularly appropriate for the scope and timeline of this research. Its structured framework ensures efficient prioritization of critical failure modes, which are essential for meeting the project's deliverables within the thesis planning. The methodology's focus on detailed component-level analysis complements the need for a practical yet comprehensive approach to risk identification in ship operations, making it a well-suited choice for this study.

2.3.2 Risk in Socio-Technical Context

According to the Merriam-Webster dictionary, risk is defined as: 1. the possibility of loss or injury. 2. someone or something that creates or suggests a hazard [39]. While according to the Chambers dictionary, risk is defined as 1. the chance or possibility of suffering loss, injury, damage, etc, danger. 2. someone or something likely to cause loss, injury, damage, etc. [40]

Based on the definitions, it can be concluded that risk is inherently connected to hazard and damage, and it does not concern only the tangible components but also the human factor. Furthermore, in the industrial sector, managing risks is essential for ethical, regulatory, and financial reasons. The risk management process, tailored to each organization's unique framework, involves several key steps: identifying risks, analyzing them by assessing their potential impacts and likelihood of occurrence, prioritizing and ranking these risks, and formulating a strategy for each. This strategy may include accepting or tolerating the risk, eliminating it, mitigating its effects, transferring it, or distributing it among various stakeholders [41].

In the context of risk management, it is important to address various error types, as they often represent significant sources of hazards. Errors based on skills and rules, such as slips, lapses, and mistakes in following rules, cognitive errors, including incorrect diagnoses and poor decision-making, errors arising from inappropriate actions, violations of established rules, and failures in teamwork or communication [42]. It becomes evident that risk is not only related to machine elements and technical characteristics but also to the human factor, as well as activities and organizational structures.

To conclude, the socio-technical approach is particularly suitable for addressing the multifaceted nature of risks in complex systems. By emphasizing the interplay between technical and social components, this approach facilitates the integration of human factors, organizational structures, and technological elements, ensuring a balanced and adaptive response to potential hazards. This makes the socio-technical approach a valuable tool and a critical perspective for enhancing system resilience, efficiency, and safety.

2.4 Asset Management Approaches

The asset management approach in ship management is a strategy to ensure efficient, cost-effective, and sustainable operation of maritime assets. It integrates strategic, operational, technical, and human resource management. This approach focuses on maintaining asset reliability, optimizing performance, and adapting to evolving industry challenges, ensuring both economic viability and regulatory adherence [43]. Various policies can be implemented to achieve an efficient asset management approach. In this project, the inspection and operation strategy to be modeled and analyzed aligns with the approach currently employed by the collaborating industry partner.

2.4.1 Inspection Strategies

Inspection operation is defined as "the detailed examination of a component" [12], or "a systematic examination to assess the condition" [44] and involves various processes and methodologies to ensure the integrity of a ship structure over time addressing potential risks and degradation [12]. Inspections are performed by various stakeholders, including ship owners, crew, classification societies, and port state authorities, each with a vested interest in ensuring integrity and safety [44].

The inspection process of a ship is a structured approach that prioritizes risk to ensure safety and efficiency. The Risk-Based Inspection (RBI) approach consists of four primary stages: operator evaluation, preparation and planning, inspections and surveys, and review [12].

The inspection begins with operator evaluation, where inspectors assess the feasibility of adopting a risk-based approach by analyzing the operational environment, understanding the ship's lifecycle, and evaluating the potential benefits and limitations of RBI [12]. This evaluation facilitates the determination of the areas that are suitable for risk-based inspection based on factors like operational conditions and historical data [44]. Inspectors then define the scope of the RBI and perform an impact study to evaluate whether implementing an RBI approach is a viable and beneficial strategy for the ship [44].

In that the decision to proceed with an RBI approach is confirmed, the next stage, preparation and planning, is implemented. This phase involves identifying specific areas for inspection based on past inspection records, risk assessments, and criticality analyses, focusing on zones most prone to wear or failure [44]. This process combines risk assessment with an understanding of degradation mechanisms and possible failure consequences, supported by structural analysis, to develop a targeted inspection program for the asset [45]. Each subsystem is divided into zones with clearly defined inspection criteria, such as coating condition, corrosion, deformation, fractures, and cleanliness [12]. During this phase, necessary tools and checklists are prepared to ensure systematic data collection, and an RBI plan is developed. The RBI plan includes assigning risk bands to different areas, defining inspection frequencies, and establishing management protocols to monitor and address identified risks. This plan undergoes a review process for approval before being implemented [12].

The third phase, inspections and surveys, is the execution of the RBI plan. Inspections are conducted in line with the plan, which prioritizes critical structural areas and high-risk zones. Inspectors begin with an overall inspection to understand each component's general condition, followed by close-up visual inspections and detailed examinations of previously identified high-risk areas [44]. Special attention is paid to structural components prone to stress and fatigue [44]. A grading system—typically a traffic light system with green, yellow, and red indicators—is used to classify inspection findings, with green representing satisfactory conditions, yellow indicating moderate issues, and red flagging severe concerns [44]. If significant issues are identified, the operator proceeds to further analysis, and any necessary updates to the RBI plan are made accordingly [12].

The final stage, review, ensures that the inspection findings are systematically integrated into the ship's ongoing maintenance strategy. Data collected during inspections is documented in comprehensive reports, including visual documentation such as photographs and sketches to support the findings. Any anomalies or deviations from expected conditions are listed, and follow-up actions are organized. These inspection results are used to prioritize repairs, adjust inspection frequencies, or identify areas for closer monitoring [12]. This process focuses on risk mitigation, optimizing inspection schedules, and maintaining structural integrity throughout the ship's life cycle.

Ship availability is significantly influenced by inspection and survey-related factors that ensure the system's integrity and operational safety. Periodical classification surveys, such as annual, intermediate, docking, in-water, and special inspections, contribute to maintaining the vessel's condition and detecting failure issues [46]. These surveys are complemented by damage and repair inspections for unplanned incidents and voyage repair surveys for addressing hull, machinery, or equipment issues during operation, provided they are pre-approved and planned in alliance with the classification society. Effective survey planning, execution, and prompt correction of deficiencies are fundamental to maintain ship availability and performance [47].

Damage is often observed in equipment and machinery components, with issues ranging from corrosion, material wastage, mechanical wear, fatigue stresses, and seal or lubrication system degradation [48]–[50].

Ship downtime often results from equipment and machinery degradation caused by various forms of corrosion, such as general corrosion, pitting corrosion, and grooving corrosion, accelerated by the marine environment and inadequate maintenance or protective coatings [51]. Various factors contribute to this problem, as detailed below [49]:

- Material defects and design faults contribute to stress concentrations and subsequent failures.
- Extreme weather conditions, such as temperature, salinity, and moisture, leading to corrosion.
- Operational practices, including mishandling cargo, overloading, or uneven loading, exacerbate stress.
- Wear and tear from regular use, repeated stress cycles, and exposure to harsh conditions further degrade the integrity of the ship.
- Inappropriate inspection, repair, and maintenance of critical areas, along with failure to follow planned surveys, increase these risks, making regular maintenance essential to minimize downtime.

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2.4.2 Maintenance Strategies

The maintenance of ships is a multifaceted, large-scale engineering operation [52]. The quality and scope of ship maintenance are closely related to its reliability [53]. It generally includes processes and strategies to ensure equipment reliability, operational availability, and safety [54]. This operation refers to actions taken to preserve or restore the ship systems' integrity based on inspection findings [44]. Based on the work by Norden et al. (2013), maintenance refers to the collective technical, administrative, and managerial actions performed throughout a unit's life cycle to sustain or reinstate its operational functionality [55]. This includes proactive, preventative measures, repairs, or replacements of defective components [44] [54]. Maintenance is often planned based on the equipment's expected life cycle and the operational needs of the ship, guided by strategies like Reliability-Centered Maintenance (RCM) and Risk-Based Maintenance (RBM) frameworks. These frameworks prioritize tasks by considering failure risks, scheduling maintenance actions according to real-time condition assessments, and leveraging both expert judgment and optimization techniques to enhance efficiency and reliability [54]. Maintenance operations are intended to address anomalies, prepare for dry-docking, and ensure the vessel remains in compliance with safety and classification standards [44].

Maintenance policies vary and include corrective and preventive strategies, as illustrated in Figure 2.3. Corrective maintenance involves repairing equipment after it has failed, while preventive maintenance entails proactive actions like inspections, repairs, or replacements. Predetermined maintenance follows a set schedule or usage criteria, without considering the actual condition of the equipment. In contrast, condition-based maintenance (CBM) uses data from condition monitoring techniques to determine when maintenance actions are needed [55].

CBM offers several benefits over corrective and predetermined strategies. Unlike corrective maintenance, CBM mitigates downtime, labor, and costs associated with failure. While predetermined maintenance can also prevent failures, CBM uniquely reduces the risk of catastrophic failures. It enables inspections to be triggered autonomously, lowering costs and scheduling them based on data analysis. This reduces uncertainty about system performance between inspections. Furthermore, CBM shifts inspection scheduling from predefined intervals to a performance-based approach informed by monitoring data [55].

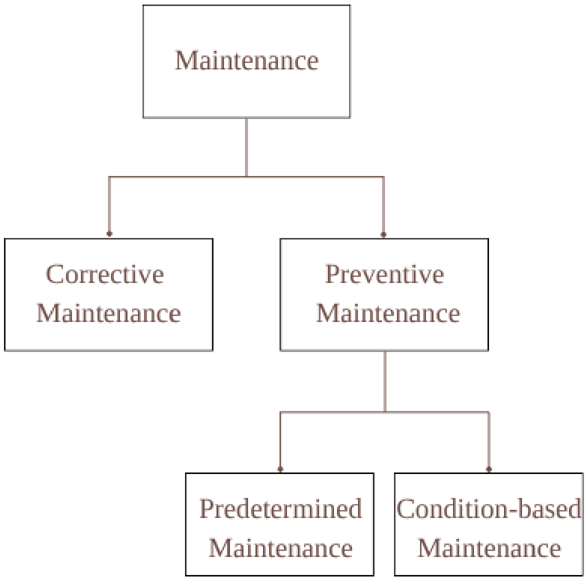

Figure 2.3: Maintenance Policies (Data adapted from [55])

The maintenance operation for a ship, as detailed in the paper by Cullum et al. (2018), involves key stages that aim for the effectiveness and risk-based scheduling of maintenance activities. Initially, a dedicated team must be established, comprising vessel operations managers, engineers, and asset managers, to manage the maintenance framework. Following the scoping phase, where the specific applications and boundaries of the maintenance operation are clearly defined, in order to ensure all necessary information and to address interfacing requirements, such as integration with asset management systems. Next, in the design and testing phase, a data management and analysis system is developed, and an operational trial is conducted to validate that the system functions as expected, utilizing data from both experimental and real ship operations. Afterward, the rework phase establishes system refinements based on trial feedback, optimizing the system design and interface for full operational use. Finally, during the integration phase, a user acceptance test is conducted to confirm that all organizational policies and system elements operate cohesively to provide enhanced maintenance schedules. Continuous improvement is then maintained through periodic reviews, especially after significant operational changes or major maintenance activities such as re-engineering of the vessel, to ensure that the system remains under operational needs [54].

2.5 Failure modes in Ship Equipment

This section examines four primary failure modes in general equipment and machinery of ships: coating degradation, corrosion, deformation, and fatigue-induced cracks, by outlining their assessment and the corresponding inspection and maintenance actions.

Coating refers to the barrier layer applied to surfaces to prevent the steel from seawater, oxygen, other corrosive agents, and maintain integrity [56]. Condition classification has three levels: good, fair, and poor. A good condition coating shows only slight instances of spot rusting, while a fair condition has local coating failures, with rust affecting no more than 20% [47]. Poor coating conditions have greatly deteriorated, affecting more than 20% of the area, or hard scaling covers at least 10% of the surface [47].

Corrosion of shipboard equipment and machinery is the chemical or electrochemical degradation of a metal, whose interaction with its operating environment creates. [57], [58]. Figure 2.4 illustrates the categories of corrosion.

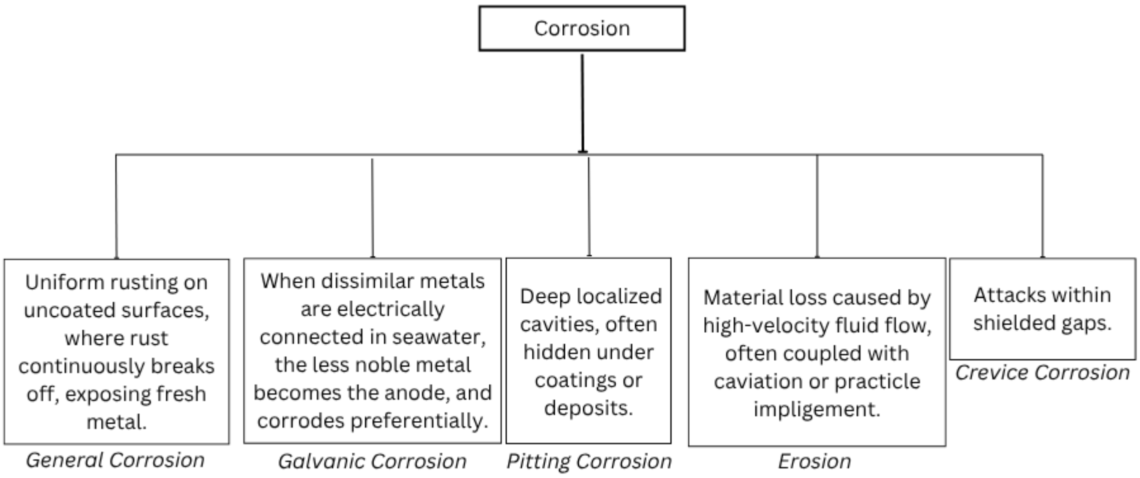

Figure 2.4: Categories of corrosion failure mode (Data adapted from [58])

Minimal corrosion with negligible rusting covering less than 5% shows a good condition, while corrosion is evident, with light rust covering more than 20% of the area or hard scaling on 10% of surfaces, showing a fair condition [59]. The poor condition corresponds to corrosion in more than 30% of the area, with active scale formation and weakening of the material [59].

There is an interrelationship between coating degradation and corrosion intensity. Poor coating maintenance amplifies corrosion, particularly in high-stress areas. Regular coating inspection and maintenance are a proactive measure to control corrosion progression and maintain ship integrity [59].

Deformation is the physical distortion or change in shape, alignment, or dimension of a component due to mechanical loads, thermal stresses, or fatigue [47]. This type of equipment and machinery degradation is important because even small deviations can increase bearing loads and accelerate wear, lead to premature failure, cause leaks or fatigue cracks, and raise the risk for rubbing or seizure [60]. It is assessed based on the extent and type of distortion that occurs due to impact loads, overloading, or fatigue-induced weakening

[49], [61]. In practice, deformation evaluation is categorized into three condition bands. Good condition shows that deviations are within the manufacturer's tolerances and require only visual monitoring and protective coatings. Fair conditions exhibit moderate distortion that warrants close-up inspection and minor fairing or reinforcement to prevent progression. The poor band displays severe deviation that requires urgent repair actions [47], [59].

In the context of a ship's general equipment and machinery, fatigue-induced cracks are microscopic flaws that occur due to repeated cyclic loadings, leading to a visible split in the metal [62]. Fatigue damage is assessed based on the number of millimeters of the crack, and how much it exceeds the minimal detectable length, and the risk level is determined based on the location of the fracture and the severity of the crack [63]. To make maintenance decisions more transparent, cracks are further classified into three risk levels. Low-risk fatigue-induced cracks require routine periodic inspections and no immediate repair actions. The medium risk band increases the frequency of close-up visual inspections and demands temporary mitigation measures. High-risk cracks demand immediate and detailed inspection actions and the essential follow-up repair and replacement treatments [47], [64].

Figures 2.5, 2.6, 2.7, 2.8 illustrate each of the above-mentioned failure modes, frequently detected in shipboard general equipment and machinery, with the corresponding inspection and maintenance actions.

There is a strong interrelationship between coating degradation and corrosion progression, as coatings deteriorate, corrosion accelerates; conversely, active corrosion weakens the remaining paint layers and the primer adhesion [59]. Minor repair actions for these failure modes are done onboard, while major repairs must be done in dry-dock. Furthermore, critical failures may require emergency dry-docking for urgent reinforcement [49], [59], [61], [63].

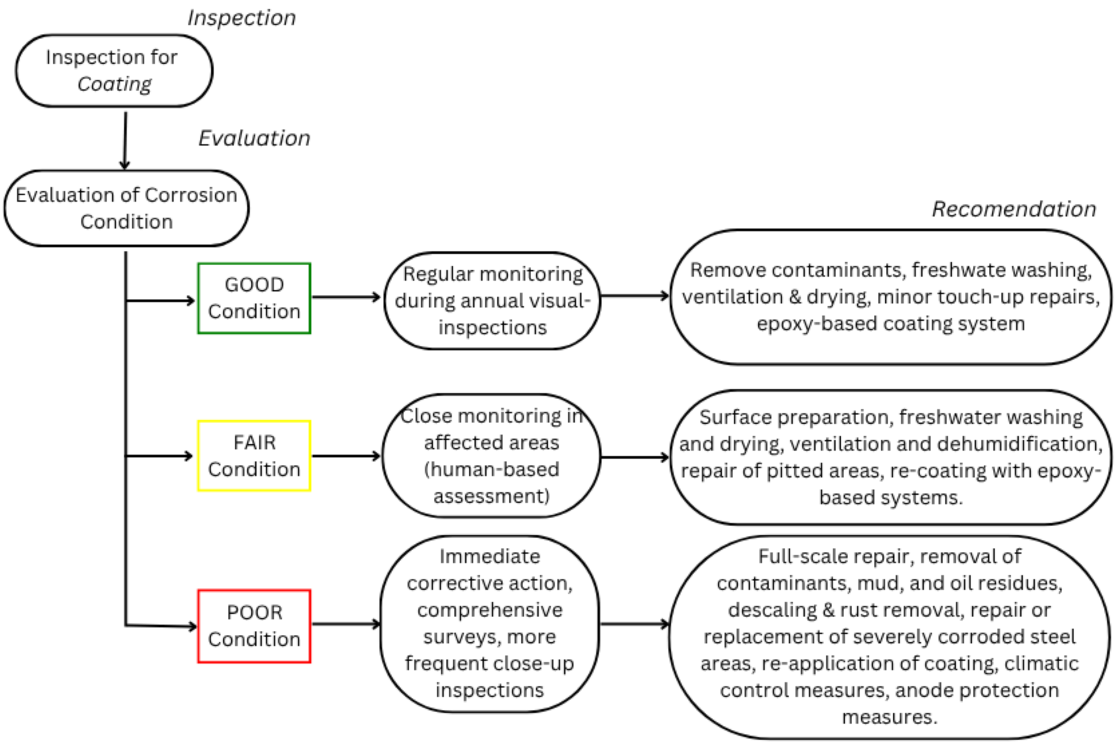

Figure 2.5: Process diagram for coating failure mode (Data adapted from [47], [59], [65]) *Insufficient repair actions, when coating is in poor condition, accelerate higher-risk corrosion bands (Figure 2.6)*

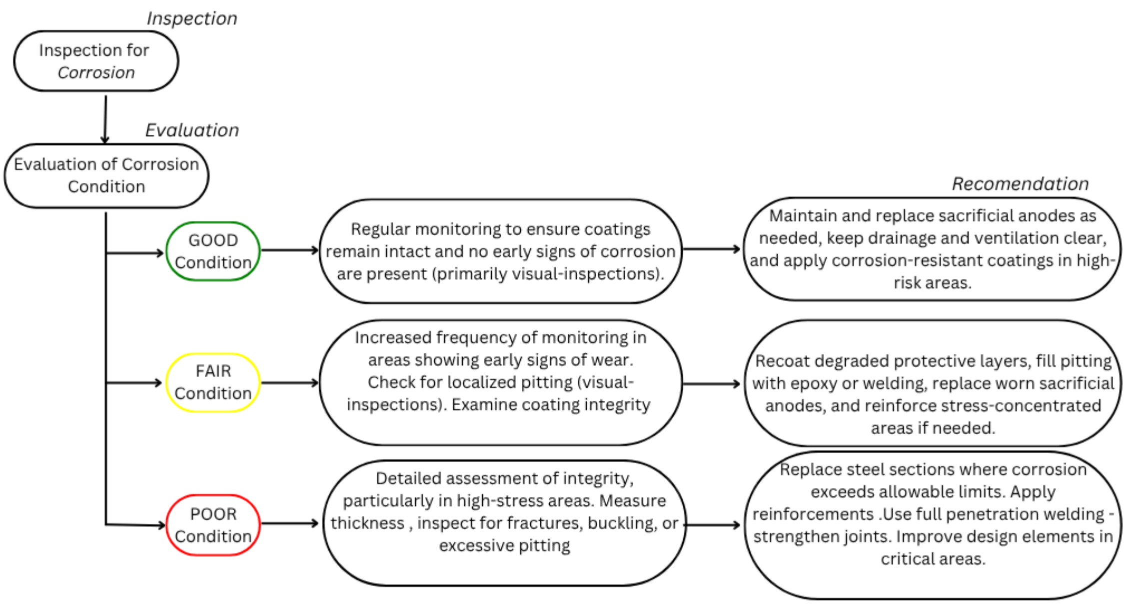

Figure 2.6: Process diagram for corrosion failure mode (Data adapted from [64], [59]) *Active corrosion in the Poor band further degrades coating integrity (Figure 2.6)*

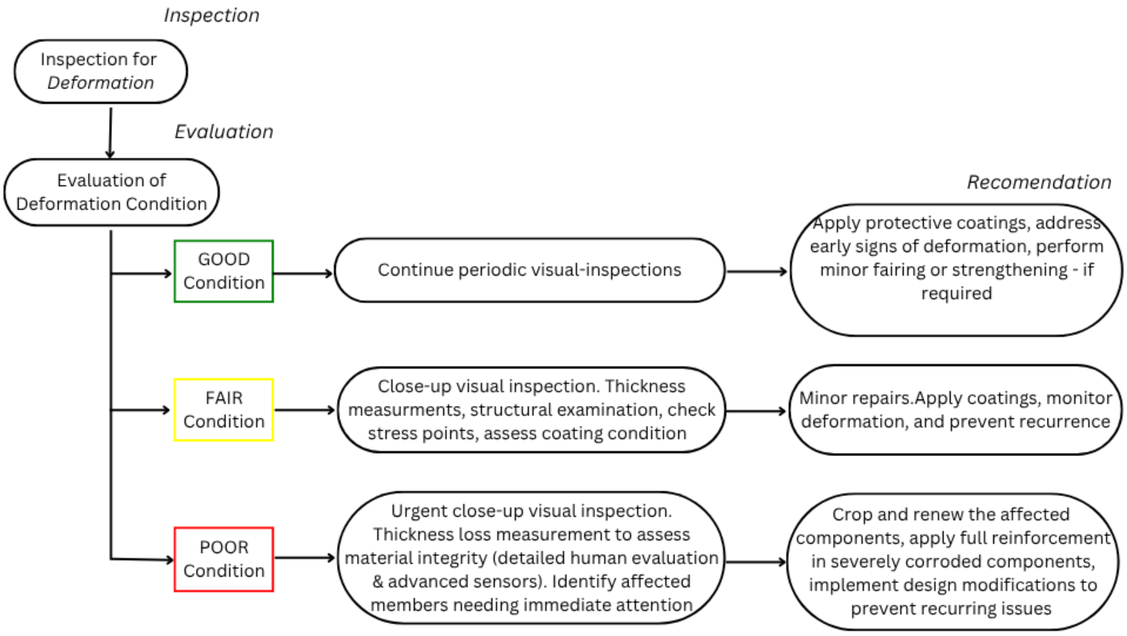

Figure 2.7: Process diagram for deformation failure mode (Data adapted from [47], [59])

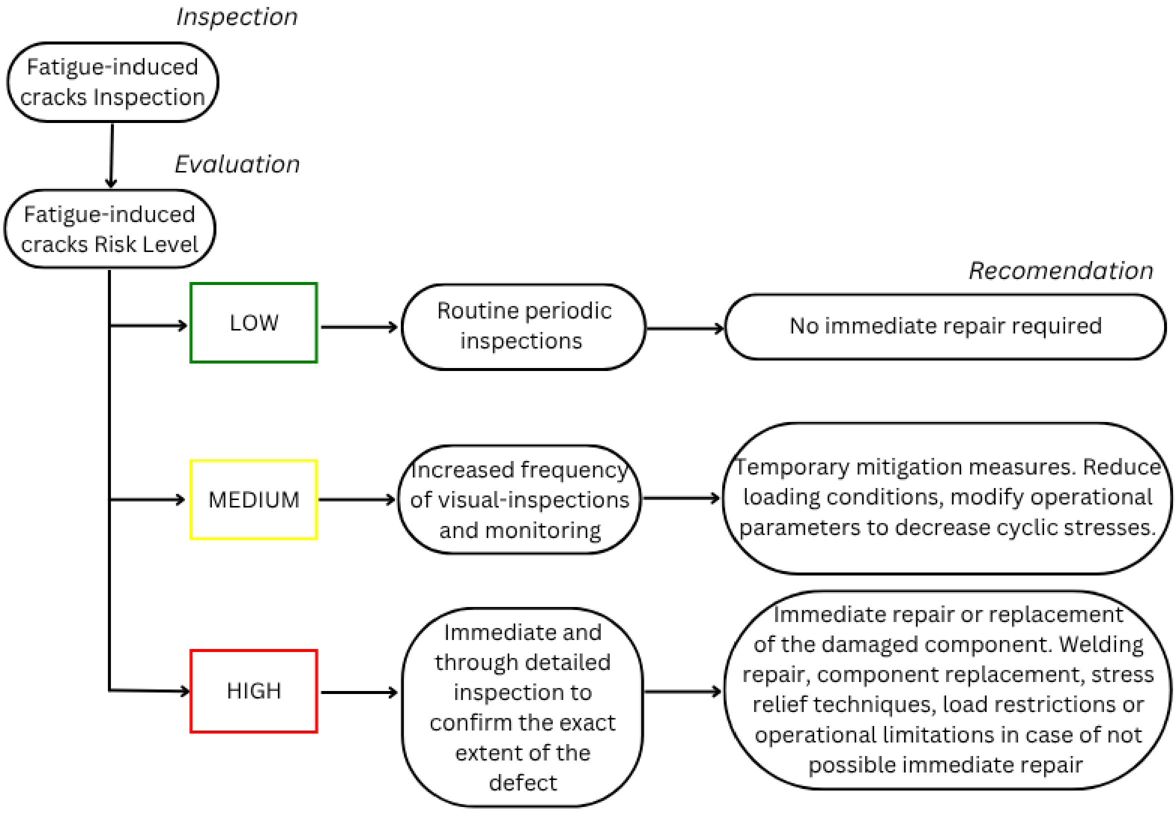

Figure 2.8: Process diagram for fatigue-induced cracks failure mode (Data adapted from [47], [59], [66], [64])

2.6 Selected Vessel Type

The focus of the analysis on this project is on oil tankers. The oil tanker is a self-propelled vessel whose principal design or modification is devoted to the bulk carriage of crude oil or petroleum products. This category encompasses ocean-going tankers, inland tank barges, and combination carriers, vessels that my also be equipped to transport noxious liquid substances, provided that their primary cargo consists of crude oil or petroleum products carried in bulk [67]. If a vessel's class certificate carries the Oil Tanker endorsement, it means its hull and machinery have been built and inspected to meet the society's standards for oil-carrying ships. In the certificate is a detailed cargo manifest that spells out exactly which oils are allowed on board, complete with their maximum densities and temperature limits, and if the ship ever hauls only high flash-point products, the endorsement can be updated to include the phrase "flash point above 60 °C" [68].

A crude-oil tanker is a ship built specifically to haul unrefined petroleum in large volumes. Every aspect of its design, from reinforced hull structures and corrosion-resistant tank coatings to thoughtfully divided cargo compartments, is tailored to accommodate the unique density, viscosity, and chemical characteristics of raw crude oil [69]. A product tanker is a ship built to carry refined petroleum products, lighter than residual fuels such as diesel, gasoline, and kerosene. Its pumps, piping, and tank are all specially designed to handle these clean, lighter oils safely and efficiently [70]. A combination carrier, often called an Oil or Bulk/Ore (OBO) carrier, is a single-deck vessel of double-skin hull and double bottom, plus both lower (hopper) and upper (topside) wing tanks. Its intention is the carriage of oil or dry cargoes in bulk [71].

Major classification societies—such as ABS, DNV, BV, LR, IRClass, and those under IACS, sort oil tankers into size bands based on deadweight tonnage (DWT) listed below in Table 2.1.

Table 2.1: Oil tanker categories with typical DWT ranges & references

Category	**DWT Range (metric t)**	**Notes**	**Source**
Handysize	≤ 50,000	Small product and coastal tankers; can enter most smaller ports.	[72]
Panamax	50,001–80,000	Max. size for pre-Panamax Panama Canal locks.	[72]
Aframax	80,001–120,000	AFRA system standard for medium crude/product trades.	[73]

Category	DWT Range (metric t)	Notes	Source
Suezmax	120,001–200,000	Max. size able to transit Suez Canal in laden condition.	[73]
LR2 (Long Range 2)	80,000–159,999	Often for clean products; overlaps Aframax/VLCC in some societies' product-tanker rules.	[74]
LR1 (Long Range 1)	45,000–79,999	Clean-product tankers for medium-range trades.	[74]
MR (Medium Range)	25,000–44,999	Coastal/regional product tankers.	[74]
GP (General Purpose)	10,000–24,999	Small coastal product tankers; limited range.	[74]
VLCC	200,000–320,000	Very Large Crude Carriers for long-haul crude trades.	[75]
ULCC	$> 320,000$	Ultra Large Crude Carriers—supertankers requiring deep-water terminals.	[75]

2.7 Application of Socio-Technical Systems in Ship Management

This section will examine research in the maritime sector that integrates the socio-technical system into ship management and the assessment of potential failures in the maritime sector. Several studies have explored the integration of socio-technical systems with some specifically focusing attention on ship management, and the evaluation of failure scenarios within the maritime field, as highlighted in Table 2.2.

Table 2.2: Overview of added value in selected literature

Source	**Added Value**
Sultana and Haugen, 2023 [26]	Introduce an extended Functional Resonance Analysis Method (FRAM) for evaluating safety in socio-technical systems, focusing on the adequacy of safety barriers and dynamic variability. An LNG ship-to-ship transfer case study demonstrates its application for identifying safety functions, variability, and resonance effects, offering qualitative and quantitative safety performance insights.
Viran and Mentes, 2024 [76]	This approach focuses on analyzing risks in Vessel Traffic Services (VTS) management using the FRAM. The VTS system in the Turkish Straits, a region known for risky ship passages is examined, while it aims to enhance safety and minimize negative impacts on people, goods, and the environment. The paper demonstrates how FRAM can assess complex socio-technical systems like VTS and provides insights into managing risks in vessel traffic operations.
Vries, 2017 [77]	The study adopts a socio-technical system approach, exploring the interaction between humans, technology, and organizational factors. The FRAM is used to analyze how pilots and VTS operators manage navigational assistance. It describes the work performed by these professionals and the integration of various information sources to ensure safe vessel operations. The research highlights the importance of local knowledge, communication, preparation, and foresight in contributing to safe maritime navigation. It aims to develop a deeper understanding of how the work is performed in the maritime domain to ensure safety.

Source	Added Value
Hirose and Sawaragi, 2020 [78]	The paper addresses the safety of socio-technical systems, emphasizing the challenges of understanding their complexity using traditional safety methods. How variability in system operations, such as supply chain disruptions or changes in operational procedures, can influence safety outcomes. The paper argues that instead of merely analyzing failures (Safety-I), focusing on why systems operate successfully (Safety-II) can improve overall safety management. An extended FRAM model is used to simulate the effect of variability and countermeasures in real-world scenarios, revealing the dynamic relationships between system components and how they impact safety.
Lazakis, Turan, and Aksu, 2010 [11]	The paper explores methods for enhancing the operational reliability of ships through improved maintenance practices. Traditionally, ship maintenance was treated as a necessary financial burden, often not given enough attention for its role in ensuring safety, environmental protection, and transportation quality. The paper proposes a novel predictive maintenance strategy that combines operational data with advanced analytical techniques to reduce downtime and increase the ship's operational capacity. The strategy involves using tools like FMECA and Fault Tree Analysis (FTA) to identify critical components, estimate reliability, prioritize maintenance tasks, and improve system availability. A case study of a Diesel Generator (DG) system aboard a cruise ship demonstrates the application of these methodologies, showing how the reliability of individual components and sub-systems can be assessed and enhanced to improve overall system performance.

Source	Added Value
Lee and Chung, 2018 [79].	This paper presents a new methodology for analyzing human-system interaction (HSI) in the maritime domain, specifically focusing on how the interactions within a crew network impact system safety and contribute to maritime accidents. The paper integrates the FRAM with the concept of HSI to better understand the collaborative dynamics between system functions and human crew members.
Lazakis, Turan, Alkaner, and Olcer, 2009 [80]	The paper focuses on developing an effective ship maintenance strategy based on a risk and criticality approach. It discusses the evolution of maintenance practices in the maritime industry and highlights the importance of reducing operational costs and improving ship reliability through advanced maintenance techniques. Three categories of ship maintenance: corrective, preventive, and predictive are described. Furthermore, FMECA methodology and Fault Tree Analysis are combined to identify critical equipment, estimate failure risks, and calculate the reliability and availability of ship systems.
Daya and Lazakis, 2024 [81]	The paper presents a methodology combining FMECA and Artificial Neural Networks (ANN) to identify critical ship system components and predict performance degradation. Using data from diesel generators on an Offshore Patrol Vessel (OPV), the study highlights mission-critical failures and patterns using FMECA risk prioritization and ANN clustering for anomaly detection. It provides insights into maintenance prioritization, degradation diagnostics, and reliability analysis to improve operational efficiency and reduce downtime. Future work includes enhancing fault classification and supporting maintenance decision-making with advanced analytics.

Source	Added Value
Lazakis, Turan, and Aksu, 2010 [82]	The paper explores how predictive maintenance strategies, including tools such as FMECA, FTA, and importance measures, can improve ship maintenance by enhancing reliability, reducing downtime, and increasing operational safety. It applies these methodologies to the DG system of a cruise ship, identifying critical components such as fuel filters and lube oil systems for prioritized maintenance. The results show significant reliability improvements when dynamic models and spare components are introduced. The study advocates for adopting advanced reliability tools and predictive maintenance practices in the maritime.
Chaowei, Peng, Bo, and Peichang, 2017 [83]	The paper explores the application of Maintenance Progress FMECA (MP-FMECA) to enhance the safety and reliability of ship equipment maintenance. It adapts traditional FMECA to address failures that arise during maintenance, considering factors such as human errors, operational issues, and resource constraints. provides a systematic approach to identifying, assessing, and mitigating potential failures. The study highlights the benefits of this methodology in reducing accidents, improving safety standards, and its potential applicability to other complex equipment systems.

The recorded studies were published between 2009 and 2024. The tool commonly used for analyzing complex systems is FRAM. This methodology assists the understanding of how socio-technical systems operate by focusing on human tasks in collaboration with machines. It also allows for identifying risks that stem from variability in human or machine performance, thus enhancing the system's resilience. Furthermore, FMECA is a methodology used to assess potential failures in a system, examine their impacts, and evaluate the criticality of these failures. This analysis enables the categorization of the risks associated with the system and facilitates taking preventive actions to minimize their effects.

2.7.1 Synthesis of prior studies combining socio-technical models, risk assessment, and ship operations

Based on the information analyzed in the previous sections, it becomes evident that a ship is a complex system composed of numerous interconnected components. Maintenance and inspection processes encompass various tasks, including multiple activities. The effective and safe execution of these processes is highly dependent on human collaboration, which plays a vital role in ensuring the completion of inspection and maintenance operations.

Effectiveness and safety in inspection and maintenance operations within socio-technical systems, such as the ship shape, can be compromised due to the variability of working conditions and human interactions within complex environments. This variability stems from trade-offs between efficiency and thoroughness, deviations from standard operating procedures caused by non-linear interactions. These risks can lead to functional resonance, where minor variations propagate through the system, causing unintended and critical consequences.

Failure Mode, Effect, and Criticality Analysis (FMECA) is an advanced tool used to identify potential system failures, examine their causes and impacts, and evaluate their criticality. It aids in decision-making by prioritizing maintenance activities and optimizing the allocation of resources while enhancing the understanding of system behavior. Its application in complex systems demonstrates its importance in improving safety, reducing operational risks, and boosting overall efficiency. Additionally, the Functional Resonance Analysis Method (FRAM) is recognized as an effective tool for analyzing and visualizing functions in complex systems. As highlighted in Table 2.2, research adopting a socio-technical perspective frequently uses FRAM due to its ability to address unpredictable risks. FRAM complements root cause analysis by examining interactions between elements and identifying performance variability, making it valuable for understanding and mitigating system risks.

2.7.2 Identification of research gap and limitations in existing literature

Existing literature on risk identification in ship maintenance and inspection operations largely focuses on technical and engineering solutions. For instance, condition monitoring and risk assessment methodologies that aim to predict failures and optimize maintenance schedules[84] [85] [86]. However, there is a notable lack of attention to the socio-technical perspective in these processes. Complexities addressed by the interplay among system and actor perspectives may not be fully captured by traditional risk models focused on technical elements alone. This oversight can lead to failures that are not just technical but also organizational and human.

3 Methodology

3.1 Research Design Overview

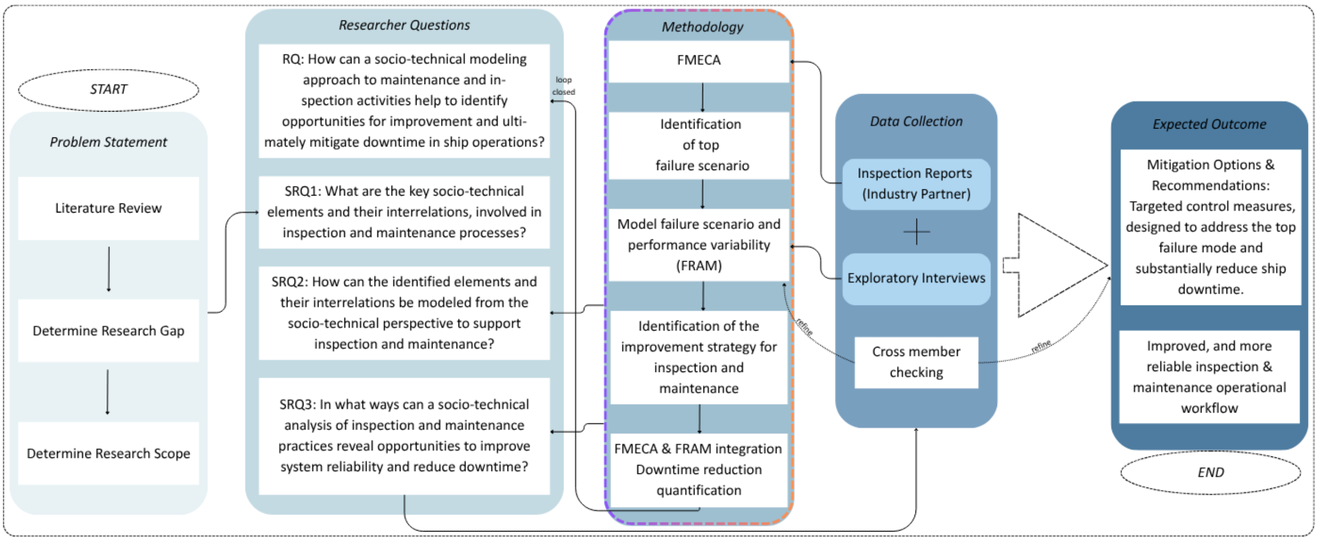

Figure 3.1: Research Flow Diagram

This thesis project aims to identify improvement options, looking at the inspection and maintenance operations from a socio-technical perspective, to ultimately mitigate downtime. A literature review is initially conducted, where the research gap, as well as the research scope of the study, are determined. First, information is gathered on the implementation of a socio-technical system perspective in ship operations, and how ships are operated and maintained, and second, data regarding risk management within the maritime sector and the engineering asset management approach. This comprehensive literature review provides a foundational understanding necessary for continuing to the next step of the research.

A Failure Mode Effect and Criticality Analysis (FMECA) is conducted. Hinging upon data gathered from official industry inspection reports, this analysis aims to identify and rank failure modes within the system, and evaluate their consequences on it [87] [35]. Within this FMECA process, the systems encompassed by the defined boundaries of this study are initially analyzed by breaking them down into fundamental subsystems. This is followed by the identification of equipment and machinery failures that were reported on the organizational inspection documents, during inspection and maintenance operations. Each failure scenario is ranked based on its impact on system performance. A risk priority number (RPN) is then calculated, which is the product of three factors: Severity, Occurrence, and Detection.

$$\text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection} \tag{1}$$

Severity assesses the seriousness of the impact a failure has on the system's operation and availability. Occurrence evaluates how likely it is for the failure to happen. Detection measures the probability of identifying the failure before it has significant consequences. Together, these elements assist in understanding and prioritizing potential risks in the system. All three contributing factors are evaluated on a scale from 1 to 5, while higher RPNs demand more attention [88].

In this study, both the RPN and the Downtime Risk Number (DRN) are calculated to guide prioritization. First, failure modes are ranked by their RPN to identify the single most critical failure mechanism. Only for the top-ranked failure mechanism, the subsystems are further prioritized using the DRN to ensure that downtime impact drives the selection of the most critical system for further analysis.

Thus, to align the risk ranking with the ultimate goal of enhancing ship availability, the DRN is defined [89]–[92]:

$$\text{DRN} = \text{Occurrence} \times \text{Midpoint of Downtime Band} \tag{2}$$

This metric weighs the frequency of a failure by its average downtime time [93]. Midpoints are taken from a clustering of severity against downtime. Failure modes are then re-ranked, and and most critical system with the corresponding failure requiring the most attention is selected for further analysis.

Following the Functional Resonance Analysis Method (FRAM), hinging upon semi-structured exploratory interviews' insights with different industry partners, is applied as a qualitative method to illustrate and analyze the entire inspection and maintenance process.The top failure mode identified in the FMECA is selected for further analysis. Within the FRAM, the entire operational process is modeled to understand how each failure mode occurs, by realizing how performance variability contributes to this failure mode, and acknowledging the contributory factors that lead to these variations.

In more detail, focusing on the interconnections between the actors and the technical elements of the process [94], and enabling the systematic description of the primary functions that shape the operations, the functions involved in the failure scenario are recorded—functions essential for everyday operational performance and system purpose fulfillment. These interactions are identified by documenting the everyday performance during activities, describing each function and its aspects. Each function's aspect relates to another function, creating inputs and outputs. By using specific data, such as the determined failure incidents, the developed model explains how these occurred [95]. This happens by determining whether a variation in a specific function is connected to a contributory factor and analyzing how this variation propagates through the entire process.

In such a way, a small-scale case study is conducted to demonstrate the socio-technical modeling approach for inspection and maintenance operations.

FMECA and FRAM are not isolated tools but complementary methods. While FMECA rates the identified failures, FRAM builds on FMECA by analyzing how performance variability, considering both technical and human aspects, leads to unwanted behaviors. FRAM focuses on understanding the interrelations identified in the socio-technical model, providing qualitative insights into how failure modes arise and spread in complex systems.

Corporate inspection reports and exploratory discussions support the whole analysis by providing deeper insight into real-world operations and processes. Industry experts, due to their experience, provide insights into the operational activities, workflows, and overlooked processes about how tasks vary under different conditions. They identify human, technical, organizational, and environmental factors that impact system performance. Therefore, exploratory interviews facilitate a more accurate mapping of the operational process, ensuring that the model reflects the real complexities and performance variability of the operations.

Through this structured methodological approach, improvement options for inspection and maintenance operational processes are identified, aiming to reduce downtime. The identified failure mode and its contributory factors inform the development of a risk management strategy and targeted interventions. A final enhanced FRAM model serves as a tool to help operators understand and improve the operational performance of the system.

The integration of FMECA and FRAM aims to close the loop of this methodological approach. The targeted interventions are quantitatively evaluated by incorporating DRN components into the FRAM models' functions. In this way, the effectiveness of the suggested interventions is assessed, and ultimately, the downtime in ship inspection and maintenance activities is mitigated through a socio-technical modeling approach.

Finally, cross-member checking, semi-structured feedback sessions with the same industry partners, is an academic tool that contributes to validated and realistic results. By discussing the FRAM model's outputs as well as the proposed risk management strategy with the same industry partners interviewed, the methodological approach and the outcome of the study are firmly anchored in operational reality, thereby enhancing their validity and practical relevance.

Different knowledge domains, such as structural engineering, operational planning, and inspection practice, are represented so that the dataset is gathered for the FMECA analysis, performance variability scenarios are identified and modeled via FRAM, the structured methodological process, and results are validated, and the dataset is gathered for analysis using the FMECA. The participation of experts from different disciplines and specialties is indissolubly connected to the interdisciplinary nature of the research problem as well as the socio-technical approach that is adopted to investigate it.

To provide a clear understanding of how the research process unfolds, Figure 3.1 illustrates the progression of the study.

3.2 FMECA: Risk Identification and Ranking

This subsection performs a Failure Mode Effect and Criticality Analysis to identify and rank failure modes within the ship's general equipment and machinery. It also systematically evaluates vulnerabilities by synthesizing the system's technical knowledge from the literature review with operational insights gathered from inspection reports.

In this analysis, the failure modes dataset was compiled from ship inspection records, including externally commissioned inspection reports and internal assessments. To protect ownership interests, no identifying details of the commissioning organization or the vessels inspected are disclosed. A subset of the records follows established industry inspection protocols (typically referenced in the shipping sector), while the remainder includes routine inspection findings collected through the company's standard sampling procedures. All reports were reviewed to extract failure observations, such as fatigue-induced cracking, localized corrosion, deformation, and coating deterioration, ensuring that only incidents directly related to equipment and machinery integrity were included. By anonymizing the source of the reports, yet maintaining the methodological rigor of each type of inspection, the dataset provides a representative, high-quality basis for FMECA without violating confidentiality restrictions.

Given the scope of this FMECA, the number of failure modes is sufficient to capture the most significant and recurring general equipment and machinery failure mechanisms (e.g., corrosion, coating, deformation, and fatigue-induced cracks) and aligns with the precedent in published FMECAs of ship systems [96], [97].

FMECA protocol builds on well-established guidelines from the academic literature [98]:

- Define the scope and functions: Describe the boundary of the system, and list the components.
- Break down the structure: Create a system - subsystem - component hierarchy.
- Identify failure modes: For each component or function, list how it may fail and list the underlying causes or mechanisms.
- Assess effects and detection: Record how each failure impacts its subsystem and the overall system, and note how (or if) it can be detected.
- Assess frequency and severity: Classify rates and severity
- Prioritize via risk matrix: Plot occurrence against severity to highlight highest-risk (high-rate, high-severity) modes that need attention.
- Suggest mitigation: For the top risks, develop targeted countermeasures. In this specific analysis, a FRAM model is developed to model the propagation of key aspects influencing the operational process of the top failure mode that can be modified to ensure a more efficient inspection and maintenance process.

3.2.1 System Breakdown and Component Selection

Here, the scope of the analysis is delineated and the boundaries of the system under study are established, clearly indicating its intended function and operational environment. Then, a hierarchical decomposition of the system into subsystems and components is introduced to provide the framework within which each identified failure mode is mapped.

IEC 60812:2018 [99] specifies that effective FMECA is not only analyzing identical systems but also selecting failure modes that truly reflect the system under study. This FMECA covers all general equipment and machinery assemblies in the oil tankers' main-deck machinery area, and related failures, such as corrosion, coating, fatigue-induced cracks, and deformation, which oil tankers experience.

Machinery spaces are the catch-all term for any compartment that houses major shipboard equipment. That includes category A engine rooms plus any other space containing propulsion engines, boilers, fuel-oil units, steam or diesel generators, large electrical gear, oil-filling stations, refrigeration or stabilizing equipment, ventilation and air-conditioning plant, and similar machinery, along with the trunks or passageways leading to those areas [100].

A mechanical assembly is " an assembly of linked parts, from which at least one must be movable, with the appropriate actuators, control, and power circuits" [101]. Per classification society rules [63], [101], a mechanical assembly on an oil tanker is responsible for converting and conveying power, whether mechanical, hydraulic, pneumatic or electromechanical into movements and forces needed for deck and machinery tasks (such as ventilation, mooring, anchoring, and cargo handling), all while meeting prescribed safety, redundancy and performance requirements.

Moreover, a piping assembly is a fully integrated network of pipes, valves, flanges, fittings, gaskets, supports, and related hardware that moves liquids or gases, such as cargo, ballast water, fuel, inert gas, steam, or bilge, around the ship. It must be designed, built, and maintained to meet class rules for strength, pressure ratings, materials, testing, and periodic inspection [102], [103].

Table 3.1 lists every system, subsystem, and component where a failure mode is identified. The hierarchy is indented as specified in IEC 60812:2018, moving from system to subsystem to component [99].

Table 3.1: System Breakdown of General Equipment and Machinery Assemblies

System	**Subsystem**	**Component**	**Classification as Mechanical or Piping Assembly**
1.Ventilation, A/C & Heating Systems	Mechanical + G2–G8 Vents (Monkey Island, Steering Gear, Elevator Space)	Mushroom-Type Ventilation Wheels	These wheels are rotating mechanical elements that provide forced ventilation airflow [99], *covered under "mechanical equipment" in the scope.*

System	Subsystem	Component	Classification as Mechanical or Piping Assembly
2.Accommodation Electrical Systems	Bridge Wing Lighting	Conduit Pipe for External Light Cable (Port Bridge Wing)	Although it contains cable, the conduit is a mechanical protective assembly (metal piping) for routing and protecting wiring from mechanical damage, *treated as mechanical equipment.*
3.Deck Piping Systems	FO, DO, CYL, LO, SWG & SLDG Lines	Pipework and manifold connection valves (poop deck – port & stbd)	These are pressure-bearing piping assemblies and valves used for cargo/service oil transfer, and *fall under "piping systems"* per classification-society machinery rules.
4.Anchoring System	Windlass Mechanism	Starboard Windlass Bar Stopper Pin	The stopper pin is a mechanical retaining device in the windlass assembly, classed as part of deck machinery, *(mechanical equipment)*.
5.Inert Gas System	Ballast Tank Control	IG to Ballast Tank Control Valve (No. 2 COT Port)	Control valve on an inert-gas piping branch—part of the IG piping network, *"piping assemblies."*
6. Ventilation/Air Supply	Compressed Air System	Air Line Pipes	These are pressurized mechanical piping lines for compressed air distribution, treated under "piping" in scope definitions.
7.Mooring System	Winch Outer Drum (Units W4 & W7)	Safety pin securing plate	The plate is a mechanical component of the winch safety mechanism—categorized as deck machinery, *(mechanical assemblies)*.

System	Subsystem	Component	Classification as Mechanical or Piping Assembly
8.Steam Supply System	Deck Steam Lines for COTs and WBTs	Main & return steam supply pipes, including flanges, bolts, nuts	These are ASME-type pressure piping assemblies for steam distribution on deck, *squarely within piping-systems scope per classification-society rules.*
9.Steam Supply System	Deck Steam Lines for COTs and WBTs	Main & return steam pipes, flanges, bolts, nuts (Aft Piperack)	Identical function but a distinct installation location, part of the overall steam-piping network, *hence "piping assembly."*
10.Steam Supply System	Deck Steam Lines for COTs and WBTs	Main & return steam pipes, flanges, bolts, nuts (Aft Piperack)	Identical function but a distinct installation location, part of the overall steam-piping network, *hence "piping assembly."*

3.2.2 Risk Priority Number and Downtime Risk Number

The following describes the scoring system for Severity, Occurrence, and Detectability (S/O/D) is defined based on academic literature and standard FMECA protocols.

This scoring system is based on standard FMECA practices [104] as presented in the Tables 3.2, 3.3, 3.4. Moreover, numerous studies in the field of ship operations and other fields have implemented this very scoring system [96], [105].

Table 3.2: Severity Scoring Categories (1–5) for Ship General Equipment and Machinery Failure Modes
This table is based on the author's framework, with data conceptually adopted from [106], [107], and [104].

Score	Descriptor	Ship-Operation Definition
1	Very low or none	Negligible effect on the ship's integrity.
2	Low or minor	Minor performance degradation.
3	Moderate or significant	Moderate reduction in safe operating margin.

Score	Descriptor	Ship-Operation Definition
4	High	Loss of function requiring prompt repair.
5	Very high or catastrophic	Catastrophic failure with potential complete downtime of the ship or crew safety.

Table 3.3: Occurrence Scoring Categories (1–5) for Ship General Equipment and Machinery Failure Modes
This table is based on the author's framework, with data conceptually adopted from [106], [107], and [104].

Score	Frequency	Ship-Operation Definition
1	Rare ($\leq$1 per 10^4–10^6 operations)	Very unlikely (e.g., appears $<$ once per lifetime).
2	Infrequent (2–10 per 10^4–10^6 operations)	Occasional events (e.g., discovered ~monthly during surveys).
3	Moderate (11–25 per 10^4–10^6 operations)	Moderate frequency (e.g., seen in every dry-dock).
4	Frequent to high (26–50 per 10^4–10^6 operations)	Frequent occurrences (e.g., noticed in weekly inspections).
5	Very high ($>$ 50 per 10^4–10^6 operations)	Continuous issues (e.g., repeated failures in active degraded components).

Table 3.4: Detectability Scoring Categories (1–5) for Ship General Equipment and Machinery Failure Modes
This table is based on the author's framework, with data conceptually adopted from [106], [107], and [104].

Score	Descriptor	Ship-Operation Definition
1	Detectable during normal voyage inspections	Faults spotted by the bridge or deck crew during regular voyage rounds or class surveyor checks at sea.
2	Detectable during routine in-service maintenance	Faults found in day-to-day/weekly maintenance activities (engine-room rounds, lubrication checks, visual hull walk downs).
3	Detectable during scheduled maintenance	Faults uncovered during major planned overhauls or dry-dock inspections.

Score	Descriptor	Ship-Operation Definition
4	Detectable only when performance degrades noticeably	Faults only become apparent through abnormal readings or symptoms (vibration spikes, pressure drops, small leaks).
5	Undetectable until actual failure	Hidden defects that escape all inspections and manifest only at failure.

Figures A.1 and A.2, in Appendix A, present the complete dataset that draws directly on the detailed inspection reports. For each failure mode, the affected component is specified, the root cause is identified, and the effect on system performance is described. The S/O/D scores are assigned on a 1-5 scale using established FMECA criteria (see above Tables 3.2, 3.3, 3.4).

Starting with the first failure mode, mushroom-style ventilation wheels mounted in exposed areas, such as the monkey island, the steering wheel well, and the elevator shaft, have collected salt crystals and lost their grease. The harsh environment has steadily eroded the bearings and sliding surfaces, causing the wheels to stiffen or lock up completely. Routine inspections rely solely on visual cues instead of spinning each wheel, meaning the problem remains hidden until a handwheel is rotated and found nearly frozen. In an emergency, this delay could prevent the vents from opening quickly enough to dissipate accumulated gas or smoke, thereby posing a moderate risk to crew safety and possibly slowing the evacuation.

For the second identified failure mode, inspectors observed a 50 cm length of conduit on the port bridge-wing lighting circuit filled with thick, hardened rust. This had not been noticed during routine visits because inspections had focused on appearance rather than functionality, and the conduit was not included on the maintenance list. Corrosion progressively thins the metal and can penetrate the insulated power cable inside. If the insulation fails, the bridge lights could go out just when they are needed most, compromising safe navigation in fog or darkness.

For the third identified failure mode, the pipes and manifold valves on the ship's deck, for fuel oil, diesel oil, cylinder oil, and lubricating oil, the seawater generator, and the sludge system are heavily rusted. Years of salt spray and sunlight have stripped their original coating, and because recoating and the use of rust inhibitors were omitted, the steel has begun to thin. During routine visits to the deck, inspectors considered the condition merely cosmetic and deferred repairs, suggesting only that the lines be replaced in the future. If the rust continues to progress, stress concentrations could develop, causing leaks or even pipe rupture when the system is under pressure. A line failure here would spill oil, contaminate the sea, and create a major fire hazard, especially when high-flash-point fuels are present.

For the fourth identified failure mode, on the right winch, the rod stopper pin has worn into an oval shape after countless load-bearing insertions and removals. This wear-induced deformation prevents the pin from being securely seated, the stopper cannot lock the anchor chain as firmly as designed. Inspectors detected the issue during a routine deck check, noticing a loose pin that allows slight movement of the plug rod, leading to reduced overall anchoring reliability. If this loose pin is not repaired, the anchor might slip or let go altogether during use, putting the vessel at risk of drifting, colliding, or running aground in confined waters.

For the fifth identified failure mode, the control valve on the inert gas system's ballast tank control line to the No. 2 COT port has suffered severe corrosion and significant material loss due to continuous exposure to a harsh, moisture- and chemical-laden tank atmosphere. The protective coating had either degraded prematurely or had never been applied to the required standard, allowing rust to penetrate the valve body and its internals. During routine maintenance visits, visual inspections revealed corrosion and metal delamination around the valve cap and body joints. This corrosion compromises the valve sealing surfaces and actuator linkage, with the risk of sticking or failing to open or close on demand. Should the valve seize or leak, the crew could lose precise control of ballast operations, potentially leading to unsafe trim conditions or unintentional discharges, with serious safety and environmental consequences.

For the sixth failure mode, the vessel's compressed-air system air-line pipes, exposed to fluctuating humidity and salt-laden atmospheres,have developed surface rust and pitting over time. When temperatures fluctuate, moisture condenses on both the inner and outer surfaces of the air lines. If they are not regularly maintained, for example, through the application of fresh coatings or protective wraps, rust quickly gains a foothold and begins to attack the pipe walls. Over time, this corrosion can develop into hairline cracks or even perforate the metal, allowing compressed air to escape. Once the lines lose integrity, system pressure drops, and that reduces the performance of pneumatic tools, valve actuators, and other safety-critical controls that depend on a stable air supply.

For the seventh identified failure mode, the retaining plates on mooring winches W4 and W7, which secure the safety pin and keep the clutch locked in the disengaged position, have lost metal through a combination of corrosion and mechanical wear. The plates were left exposed to the salty sea air after servicing and before re-installation, which accelerated rust formation. With the metal now thinned, the plates no longer grip the pin firmly, so the drum clutch may creep back toward engagement when the winch is under load. Routine officer rounds missed the defect; it was detected only later during an external audit's visual inspection. If the clutch re-engages unexpectedly while a mooring line is under tension, the drum could lurch or a line could snap, putting deck personnel in danger.

Next, the eighth failure mode concerns to the deck steam supply pipes (main and return). During the last voyage, severe cold and heavy seas battered the deck's main and return steam lines, along with their flanges, bolts, and nuts. The harsh conditions delaminated sections of insulation and stripped away the protective coating, leaving bare metal exposed. Rust has already begun to form on these spots, and without their insulation, the steam pipes shed heat inefficiently while corroding more rapidly at the damaged areas.

The final two failure modes relate to the oil tanker's aft piperack deck. Extreme weather, freezing temperatures, combined with loose fittings stripped the protective coating from the main and return steam lines—flanges, bolts, and nuts. This coating failure allowed small steam leaks at the flanges and exposed bare metal to the atmosphere, leading to localized material wastage. A related problem emerged a few feet farther along the same deck: extensive corrosion. Water and salt infiltrated beneath the damaged coating, attacking the bare steel, leaving rust and pitted areas behind. This corrosion produced another small steam leak at a flange and has been quietly thinning the pipe wall ever since.

The FMECA process advances by prioritizing the failure modes identified based on the defined S/O/D scores (see tables 3.2, 3.3, 3.4. Each failure mode is assessed and prioritized based on three key factors: Severity, Occurrence, and Detectability.

The Risk Priority Number (RPN) is calculated. This number gives a clear way to compare the criticality of each failure mode in the system.

$$\text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection} \tag{3}$$

Table 3.5: Overview of RPN scores for the main failure modes in the scope of general machinery and equipment components.

#	**Failure Mode**	**Severity**	**Occurrence**	**Detectability**	**RPN**
1	corrosion	3	3	3	27
2	corrosion	3	3	2	18
3	corrosion	4	3	2	24
4	deformation	4	2	2	16
5	corrosion	4	3	2	24

#	Failure Mode	Severity	Occurrence	Detectability	RPN
6	corrosion	3	3	2	18
7	corrosion	4	3	3	36
8	corrosion	4	3	2	24
9	coating	4	4	2	32
10	corrosion	4	4	2	32

The RPN is determined by multiplying a risk's severity, occurrence, and detectability ratings. In the bottom line of this criticality analysis, *corrosion* is identified as the dominant failure mechanism across general equipment and machinery subsystems. In more detail, corrosion is the most frequently found failure mechanism, the most hazardous one, and the hardest-to-detect threat.

In Figure 3.2, a heatmap, risk matrix, is illustrated where only severity and occurrence scores are shown. This heatmap is not presented as an alternative to the full RPN calculation, but as a complementary risk matrix. It stands as a visualization that informs at a glance where hotspots are when severity and occurrence factors are combined. Additionally, it serves as a bridge to the next steps of this analysis. The vertical axis corresponds to occurrence ratings from 1 (rare) to 5 (very high), while the horizontal axis shows severity from 1(very low or none) to 5 (very high or catastrophic). Each cell is color-coded green (low criticality), through yellow, orange, to red. The failure mode tags are assigned to the SxO number that it belongs to. The color code makes the hot spots obvious, for instance, FM9 and FM10 (failure mode 9 & 10) show up the highest-risk square (S=4, O=4).

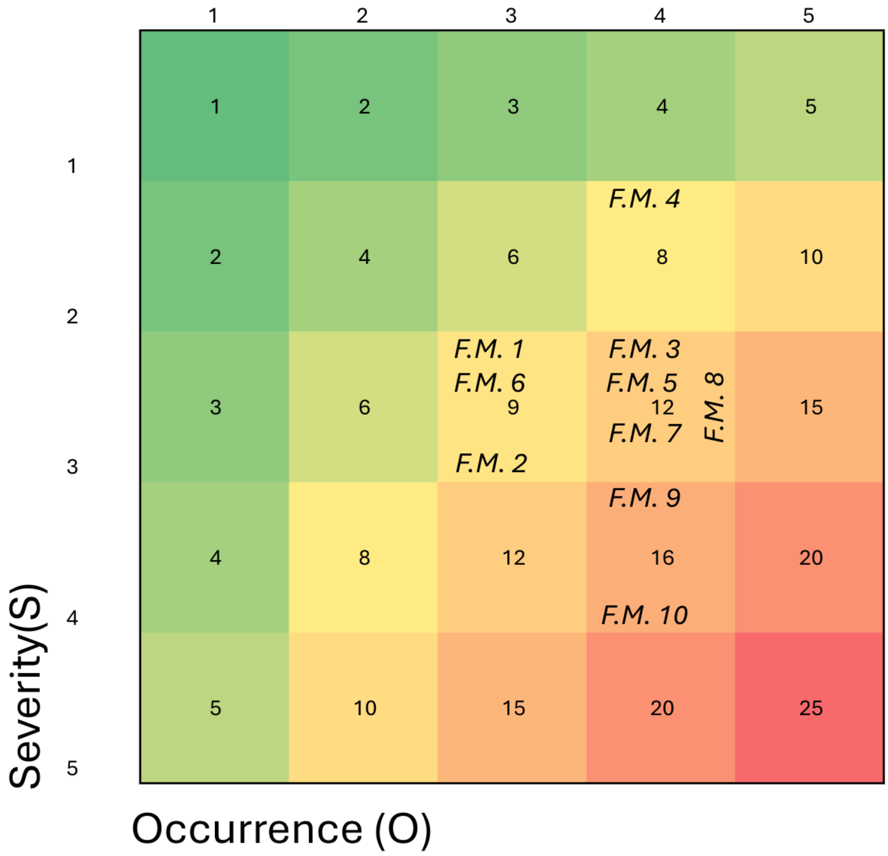

Figure 3.2: Heatmap of failure modes mapped by Occurrence (O) and Severity (S) scores, illustrating the relative risk levels and guiding prioritization.

Hinging upon the main ***RQ: How can a socio-technical modeling approach to maintenance and inspection activities help to identify opportunities for improvement and ultimately mitigate downtime in ship operations?***, the aspects of ship downtime and ship availability are points of critical significance within this study, thus they are considered within the analysis.

In the following, the critical subsystem among the general equipment and machinery is identified. System criticality is grounded not solely in RPN but also on the operational downtime caused by the corrosion incidents identified within the study's defined system boundaries. Thus, while RPN is used to prioritize the failure mechanisms, for the top-ranked failure mode, the subsystems are further analyzed using the DRN.

Daya and Lazakis (2022) provide the key maritime precedent for a two-stage FMECA approach [89]. By clustering the severity levels with downtime impact, the critical subsystem is identified. Since RPN analysis revealed corrosion as the dominant failure mode, only subsystems in which corrosion failure mechanisms occur are considered in this second stage of the analysis.

A system is considered critical if, at its most severe failure mode, its malfunction forces the vessel to complete or partial shutdown that exceeds a predefined downtime threshold [89], [108].

In Table 3.6, the defined 1-5 severity levels presented above in the Table 3.2 are clustered against empirically observed downtime intervals. Wahid et.al. (2018) explicitly connect the concept of severity to the likelihood and impact of downtime-causing factors in their paper[109]. While clustering severity against downtime is based on well-established FMECA and maritime-maintenance sources [89]–[92], [110].

Table 3.6: Severity levels clustered against downtime intervals. *This table is based on the author's framework, with data conceptually adopted from [89]–[92], [110].*

Severity	**Downtime Impact (hrs)**	**Descriptor**
1	0–2	Repair during scheduled maintenance—almost no downtime.
2	2–8	Minor in-service fixes.
3	8–24	Moderate loss interrupts non-critical operations.
4	24–48	Major loss, requires > 1day corrective maintenance.
5	≥ 48	Catastrophic loss, vessel offline > 2 days.

Table 3.6 presents the corresponding downtime category for each system, where the corrosion failure mechanism is identified. Each failure mode is assigned to an interval based on the corrective and preventive actions taken, which are derived from the inspection reports. For reasons of space constraints, this table does not display the corrective and preventive actions for each failure mode; however, they are determined in detail, above in Tables A.1, A.2.

Table 3.7: Corrosion failures with the corresponding component, severity score, and the associated downtime impacts based on the preventive and corrective actions.

#FM	**Component**	**Severity**	**Downtime (hrs)**
1	Mushroom-Type Ventilation Wheels	3	8–24
2	Conduit Pipe for External Light Cable (Port Bridge Wing)	3	8–24

#FM	Component	Severity	Downtime (hrs)
3	Pipework and manifold connection valves (poop deck – port & stbd sides)	4	24–48
5	IG to Ballast Tank Control Valve (No. 2 COT Port)	4	24–48
6	Air Line Pipes	3	8–24
7	Safety pin securing plate	4	24–48
8	Main and return steam supply pipes (including flanges, bolts, nuts)	4	24–48
10	Main and return steam pipes, flanges, bolts, nuts (Aft Piperack)	4	24–48

For the failure modes to be prioritized based on their impact on ship availability, the Downtime Risk Number (DRN) is introduced.

$$\text{DRN} = \text{Occurrence} \times \text{Midpoint of Downtime Band} \tag{4}$$

While this metric is similar to the Occurrence x Severity term in RPN, here severity is first clustered against the downtime intervals and then to the corresponding midpoint values. Thus, DRN combines the frequency that a failure mode occurs with the average repair downtime, giving a straightforward estimate of its overall impact on the vessel's availability.

Hammed et al. (2015), introduce the "downtime-weighted risk number", as the probability of the failure (analogous to occurrence score in the scope of this study) weighted by a repair-time interval, to rank maintenance priorities [91]. Furthermore, Khan & Haddara (2003) define a "Risk Index" as the product of failure rate and corrective action duration, utilizing interval estimates of repair time to optimize inspection priorities and scheduling [92].

The midpoint of each downtime band is calculated by averaging the lower and upper bounds. For instance, the 8-24 band has midpoint $\frac{8+24}{2} = 16\text{h}$, and the 24-48h band had midpoint $\frac{24+48}{2} = 36\text{h}$. To convert the severity-downtime clustering into a single point estimate, the writer follows Rausand and Haugen (2020), who recommend the utilization of the arithmetic mean of an interval when only range data are available [111], and Fauriat & Zio (2020), who explicitly employ mid-interval values in their paper [93].

In Table 3.8 below, the DRN for each instance of corrosion failure is computed utilizing its Occurrence score from the dataset and the appropriate midpoint value.

Finally, the failure mode with the highest DRN identifies the subsystem whose failure most severely compromises vessel availability, and is therefore selected as the critical system, further analyzed in Section 3.3.

Table 3.8: Overview of DRN scores for the main failure modes in the scope of general machinery and equipment components.

FM	**Occurrence**	**Downtime (hrs)**	**Midpoint (hrs)**	**DRN**
1	3	8–24	16	48
2	3	8–24	16	48
3	3	24–48	36	108
5	3	24–48	36	108
6	3	8–24	16	48
7	3	24–48	36	108
8	3	24–48	36	108
10	4	24–48	36	144

Given the primary objective of minimizing downtime within ship operations, the DRN is calculated to quantify the expected impact on the out-of-service time of each corrosion instance.

For this study, centered on the availability of ships, the *steam supply system* of the oil tanker (FM10), which has a DRN of 144, is determined as the most critical system for operational downtime.

An overview of the most critical system is given. The oil tanker steam supply system is a set of boilers, pipes, valves, controls, and accessories that, among other duties, facilitate the generation and distribution of steam for propulsion, cargo heating, tank washing, and fuel oil heating [112].

To give an overview of the system components, the network runs through the pump rooms, cargo tanks, and ducts with attendant valves, hatches, insulation, drains, and inspection ports, and must be routed safely for access and functionality. Oil-fired water-tube boilers are the primary steam generators in modern tankers. Steam from the boilers is directed through main steam stop valves into a primary header, and from there, there are branch lines with dedicated stop and control valves that route steam to propulsion auxiliaries, cargo-heating coils, tank washing manifolds, and fuel-oil heaters. Tie-in points and reduction stations assure the right pressure and flow rate for each service, and the cross-pipe allows pressure conversion when required [112].

Furthermore, critical steam services, such as cargo heating and fire suppression, are supported by dual boiler feeds and feed pumps, with fast-acting bypasses that can reroute steam if high-pressure lines fail. These setups are thoroughly tested before sea trials. In terms of safety, every steam branch is equipped with calibrated safety valves, alarm gauges, and interlocks connected to fire and inert gas systems, allowing automatic isolation and rerouting during emergencies. [112]–[114].

The control and valves are typically remotely operated from the machine room or boiler front, and are interconnected with other fire or explosion prevention devices to synchronize steam or inert gas flows. Insulation, drainage hatches, and inspection holes prevent moisture accumulation and facilitate safe drainage of condensates, and gastight or flameproof access ports require routine interior inspection [115].

Steam piping is typically integrated with the inert gas system and the conduit network to remove vapor from the cargo or duct after a fire or leak, or to maintain a safe state during cargo operations by discharge of oxygen with steam or inert gas [116].

Lastly, failure mechanisms in an oil tanker can create direct ship downtime through loss of critical services from cargo, heating, tank washing, etc., to full propulsion auxiliary shutdown [117]–[120].

3.3 FRAM: Socio-Technical Modeling of Operational Failures

The following subsection focuses on the Functional Resonance Analysis Method (FRAM). A total of three expert semi-structured interviews were conducted. Classical grounded theory [121] recommends carrying out interviews sequentially until theoretical saturation is achieved, when additional interviews do not yield new themes. However, more recent guidelines [122] stress the depth and relevance of the data, its information power, rather than the sheer size of the sample.

The analysis aims to identify performance variability within the inspection and maintenance operational process, leveraging the expertise of two expert structural analysts, plus a project manager/team leader specialized in hydroelasticity. Each interview generated dense, highly relevant insights. To guard against potential gaps, interview insights are triangulated with data extracted from the company's inspection reports and with academic literature [123].

Once the preliminary FRAM model is completed, member checks are conducted by presenting it to the same three participants for feedback. This step is widely seen as a way of enhancing the reliability of a study, and it also allows verifying that the interpretation reflects experts' opinion [124]. The experts are asked to criticize performance variability that is identified and the associations/chains between functions, in other words, the propagation of the variability throughout the process. Any suggested revisions are incorporated to keep the final model firmly anchored in the real-world operations.

3.3.1 Function Identification and Variability Mapping

The FRAM is a comparatively recent tool for obtaining system performance in risk assessments and accident investigations. Grounded in resilience engineering, it embraces the "Safety II" perspective, which examines how work unfolds during everyday operations, rather than the traditional "Safety I" that focuses on isolated failures (FMECA) [125], [126]. In this analysis, FMECA and FRAM are used in tandem to capture a holistic safety perspective. FMECA (see Section 3.2) takes the classic Safety I angle, systematically documenting structural failure modes. FRAM hinges upon Safety II thinking, maps core inspection and maintenance functions, and shows how their performance can vary. Together, the two methods lead not only to the pursuit of the highest priority structural failures but also to the revealing of how everyday shifts in inspection routines can propagate through the system.

The FRAM follows four principles [125]:

- The equivalence of success and failure: outcomes that turn out well and those that end badly arise from the same underlying sources. The very factors that make things work can easily make them fail.
- Approximate adjustments: the day-to-day performance of any socio-technical system, people acting alone or together, continuously adjusts itself to fit the situation at hand.
- Emergence: most of what is observed by people (and much of what is missed) should be viewed as emergent, rather than as simple, direct results of single causes.
- Functional resonance: links and dependencies between the system's functions must be described as they unfold in a given context, not as fixed cause-and-effect chains. FRAM captures these evolving interactions through the idea of functional resonance.

To capture both the internal and external factors of system performance, the writer adopts the Structured Socio-technical Approach, illustrated in Figure 3.3. Endogenous variables, such as organizational, human, and technological aspects, are taken from the corporate, supervisory, and technical levels of operation [127]. In contrast, exogenous variables include social, economic, and regulatory factors at the world, national, state, and municipal levels [127]. The interaction between these two sets of variables causes positive consequences, as well as significant adverse incidents.

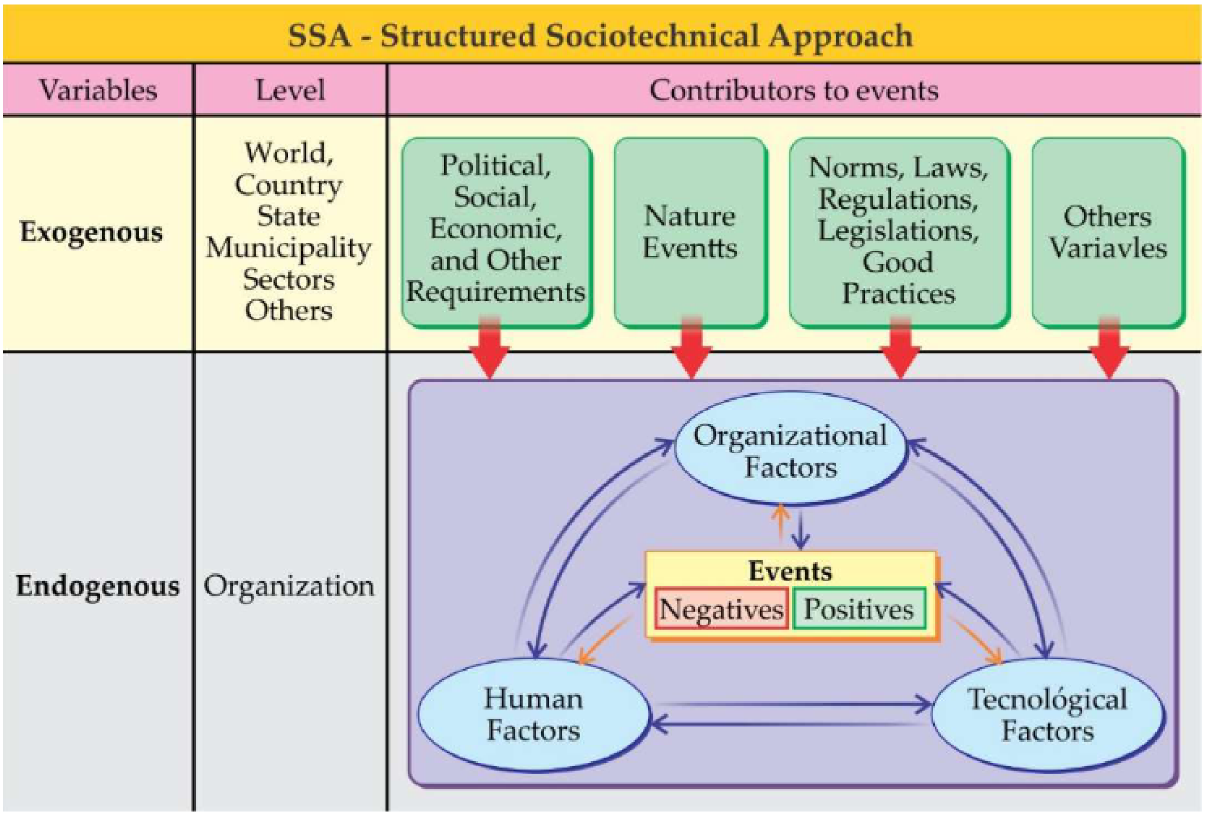

Figure 3.3: The structured socio-technical approach. Reprinted from [127]. Licensed under CC BY-NC 4.0.

Figure 3.5 illustrates the basic steps for FRAM.

- Step 0: Define the purpose of the FRAM. The goal of the analysis is nailed down [125]. For this project, the objective is defined in Section 3.
- Step 1: Every function, and that is every activity or set of activities needed for the system to achieve the intended outcome, is identified. Each function is described by six aspects, as illustrated below in Fig. 3.4 (see also Section 3). The focus is on how work is done, and not how the work is imagined, so the analyst can identify where variability might resonate throughout the system. Furthermore, interactions among the functions, couplings, are also mapped to note which are upstream (earlier) and which are downstream (later) in the flow of the operational process [125].
- Step 2: Identification of performance variability. Both potential variability and the actual or expected variability for the given scenario are characterized. In such a

way, the model shows what could vary within the operational process. Endogenous variability relates to the way that functions might be influenced by internal factors, while exogenous variability reflects outside disturbances [125].

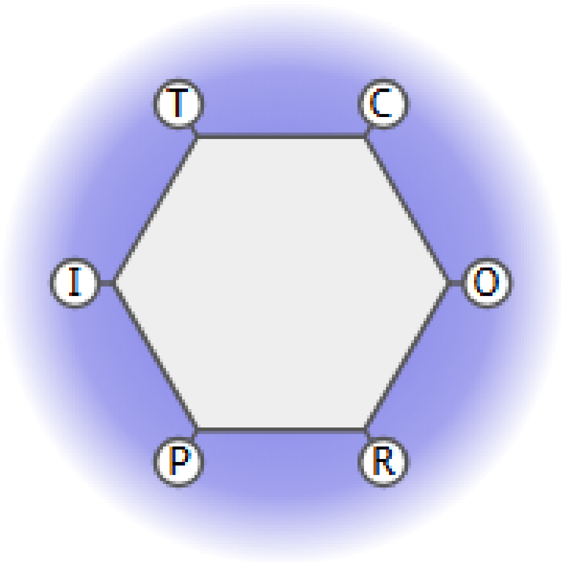

Figure 3.4: The six aspects of a function.
Data adopted from [125].

- Step 3: Aggregation of variability. The focus shifts from single functions towards the system as a whole. How variations in one function can resonate through the couplings, amplifying variability elsewhere, is identified. This phenomenon is called functional resonance and leads to the identification of unexpected, or out-of-scale, outcomes [125].

- Step 4: Consequences of the analysis. In this step, the performance variability is managed so that the desirable outcomes are reinforced or the identified black spots are mitigated. Traditional safety measures, such as eliminating hazards, installing barriers, or relying on defenses, have a place in FRAM. However, also monitoring key performance indicators to detect emerging variability early and reducing variability in the functions most likely to resonate with the process, can strengthen resilience and reduce the risk of surprise failures [125].

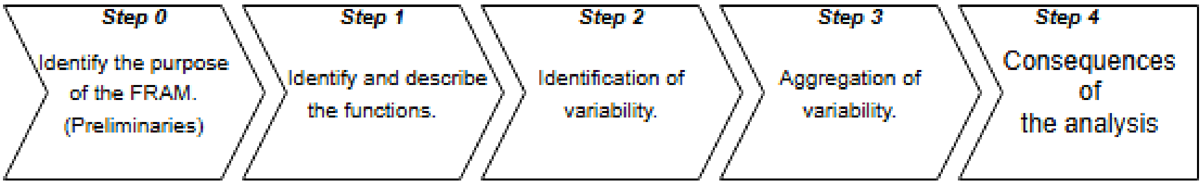

Figure 3.5: Main FRAM steps.
Data adopted from [125].

Hinging upon the results of Section 3.2, the top failure mode and the most critical system in general equipment and machinery components of oil tankers are identified. This is *Corrosion in the Steam Supply System*, in more detail, corrosion in deck steam lines, main and return steam pipes, flanges, bolts, and nuts. Although FM9 and FM10 share the same DRN, corrosion of the steam supply system is chosen. This choice is based on the fact that corrosion and coating go hand in hand [59], while at the same time corrosion is the underlying black spot which, if left unaddressed, perpetuates repeat coating failures and incurs greater downtime over time.

Following the FRAM basic procedure, initially, the essential steps for these operational activities are determined based on classification societies' reports. After examining the fundamental steps followed during the operational inspection and maintenance process for the top failure mode, a set of generalized functions for the FRAM model is defined. While allowing context-driven variation in task execution, abstracting the generalized functions of the operational inspection and maintenance process into a flexible framework helps support the determination of important aspects that can influence downtime, ultimately resulting in recommendations that can shape a more efficient inspection and maintenance process.

Table 3.9: Set of activities for inspection and maintenance of operational processes of the top failure mode.

Function	**Corrosion–Steam Supply System [65], [112], [128], [129]**
F1. Survey Planning and Scope	Establish a steam supply management plan

Function	**Corrosion–Steam Supply System [65], [112], [128], [129]**
F2. Preparation	Isolate and depressurize the steam lines, remove or strip away insulation and jacketing to expose the bare pipe surface, ensure steam traps and condensate drains are open, and the lines are dry, remove or strip away insulation and jacketing to expose the bare pipe surface
F3. Visual Inspection	Cable brush or low-pressure blasting off old rust and paint, grade coating breakdown
F4. Advanced Inspection and Measurement	Wall-thickness measurement, leak and joint integrity testing, non-destructive testing
F5. Maintenance Actions	Corrosion protection, maintenance, and replacement/repair (material selection and internal coatings, cathodic and anodic protection, chemical treatment of steam and condensate, steam trap and drainage management, visual and thickness inspections, non-destructive testing, thermo graphic surveys, local coating renewal or re-lining, component replacement, weld overlays and stopped welding, upgrades to steam-system design [130]–[132])
F6. Report Format, Evaluation, and Repair Criteria	Record-keeping and reporting

The inspection and maintenance process is described below in more detail.

The operational cycle for corrosion at the steam supply system begins with the Steam System Management Plan, with every pipe, valve, and fitting to be specified by material and minimum wall thickness. Then the steam lines are depressurized in safety, the insulation is removed, and the drains are opened so the metal is properly visible. Next is the hands-on inspection, wire-brushing or light blasting to reveal corrosion, careful visual scan for pitting or under-film rust, and ultrasonic measurement of wall-thickness in straight runs, bends, and welds. The crew tops this off with a steam-pressure joint-leak test and, where necessary, magnetic-particle or dye-penetrant inspection in the vicinity of high-stress points. The collection of the data follows the cleaning and painting of rusted areas, re-insulating the pipes to prevent water entry, and replacing any section with remaining wall-thickness below safe levels (or welding in a new spool in compliance with repair guidelines). Finally, every finding, measurement, and repair is reported in the plan, and the trends are reviewed regularly, so the wear can be detected before failure occurs, in order for the steam system to be maintained in a safe condition [65], [112], [128], [129].

3.4 Case Study Setup and Data Collection

The Table 3.10 below presents the performance variability that was identified in the exploratory interviews. Each performance variability is supported by direct quotes from the interviews. Furthermore, each performance variability code is triangulated with peer-reviewed literature or data from industry inspection reports. The merging of information from semi-structured interviews with findings collected from peer-reviewed literature embodies data source triangulation, a method that strengthens the rigor and credibility of the analysis [133].

Table 3.10: “Code book" of performance variability themes, each paired with sample interview quotes and Triangulation sources from the literature and inspection reports.

Variability Theme	**Interview Quotes**	**Triangulation**
Personnel competence	• Inconsistent inspection regimes due to shifts in personnel, leading to missed or delayed inspections. • Standardization of inspection routines: implement more robust, standardized training program to ensure new crew members follow consistent inspection protocols • Human error in maintenance execution means these components often go unprotected, accelerating failure. • Inspection is currently based on visual observation by personnel. Human inspectors rely on their experience to detect potential failures. • Assessing how many people are on board and whether the available personnel can effectively perform the task. • The high personnel rotation rate leads to inconsistent application of inspection procedures. • Execution varies based on leadership style, some teams maintain pristine condition while others neglect routine maintenance. • The training and experience of onboard personnel directly affect the inspection quality.	• Based on the industry inspection report: a junior team member lacked the deep familiarity and confidence needed to navigate a high-pressure inspection. Under stress and faced with ambiguous instructions, their underdeveloped competence led them to misinterpret the company’s procedure and make the wrong selection. • [134] • [135] • [136]

Variability Theme	Interview Quotes	Triangulation
Access to inspection areas	• Limited access to inspection areas. Some welds and tubes are non-detectable by visual inspections, which can lead to undetected degradation. • If inaccessible areas deteriorate, critical failures could occur without prior detection. • Routine inspections focus on zones prone to wear, but in reality, confined-space areas cannot be reached, leading to variability in inspection outcomes, as unseen failures may persist until they become critical. • Automated or tool-assisted inspection: lack of advanced tooling for visual inspection is a gap that could be addressed with sensor-based monitoring to inspect hard-to-reach areas. • For hard-to-reach areas, manual inspections are difficult.	• [137] • [138] • [139] • [140]

Variability Theme	Interview Quotes	Triangulation
Equipment availability	• The factors that influence repair quality: equipment available on board • Among the conditions or preparations that must be in place before an activity begins is available equipment. • The team relies on existing onboard equipment for inspections and repairs. • Some repairs require specialized tools, which may not always be available offshore. • Ship structure maintenance is different from equipment and machinery maintenance, and each may require different tools and specialized resources. • Lack of resources leads to repair delays.	• [141] • [142] • [143]

Variability Theme	Interview Quotes	Triangulation
Time window		
	• If a vessel has to enter the yard for unplanned repairs, it often results in rushed work and significantly higher costs. • Repairs are often delayed until the next harbor visit, meaning issues could escalate before intervention. • Shortened timelines force modifications in repair approaches, potentially affecting long-term reliability. • Ships often have limited maintenance windows, which may be insufficient for proper repairs.	• [144] • [145]

Below the Figure 3.6 depicts a hierarchical grouping of performance variability drivers identified in the FRAM analysis. The top level is the macro-group, and it represents the ‘Quality of inspection’. This captures the overall outcome affected by the identified variability scenarios, which, in turn, has multi-dimensional impacts such as economic, social, and environmental [146], [147]. Middle layer, the four core performance variability themes: ‘Personnel competence, Equipment availability, Time window, and Access to inspection areas’. Then the base level, which represents concrete sources of variation and shows how each theme may manifest in practice.

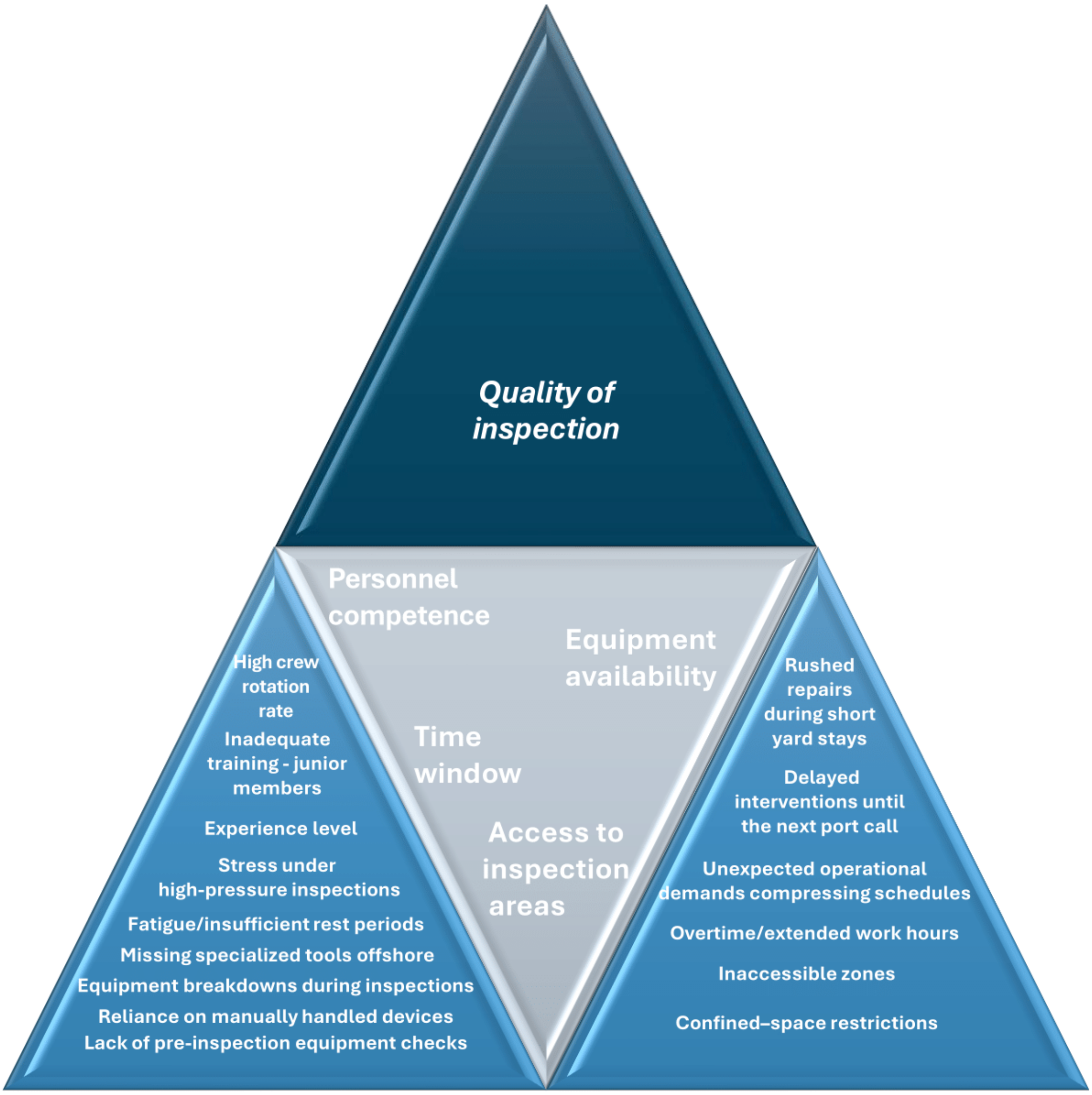

Figure 3.6: Hierarchical pyramid of performance variability scenarios

In the FRAM models: 3.7, 3.8, 3.9, 3.10, each function is coupled to other sets of activities via its outputs [125].

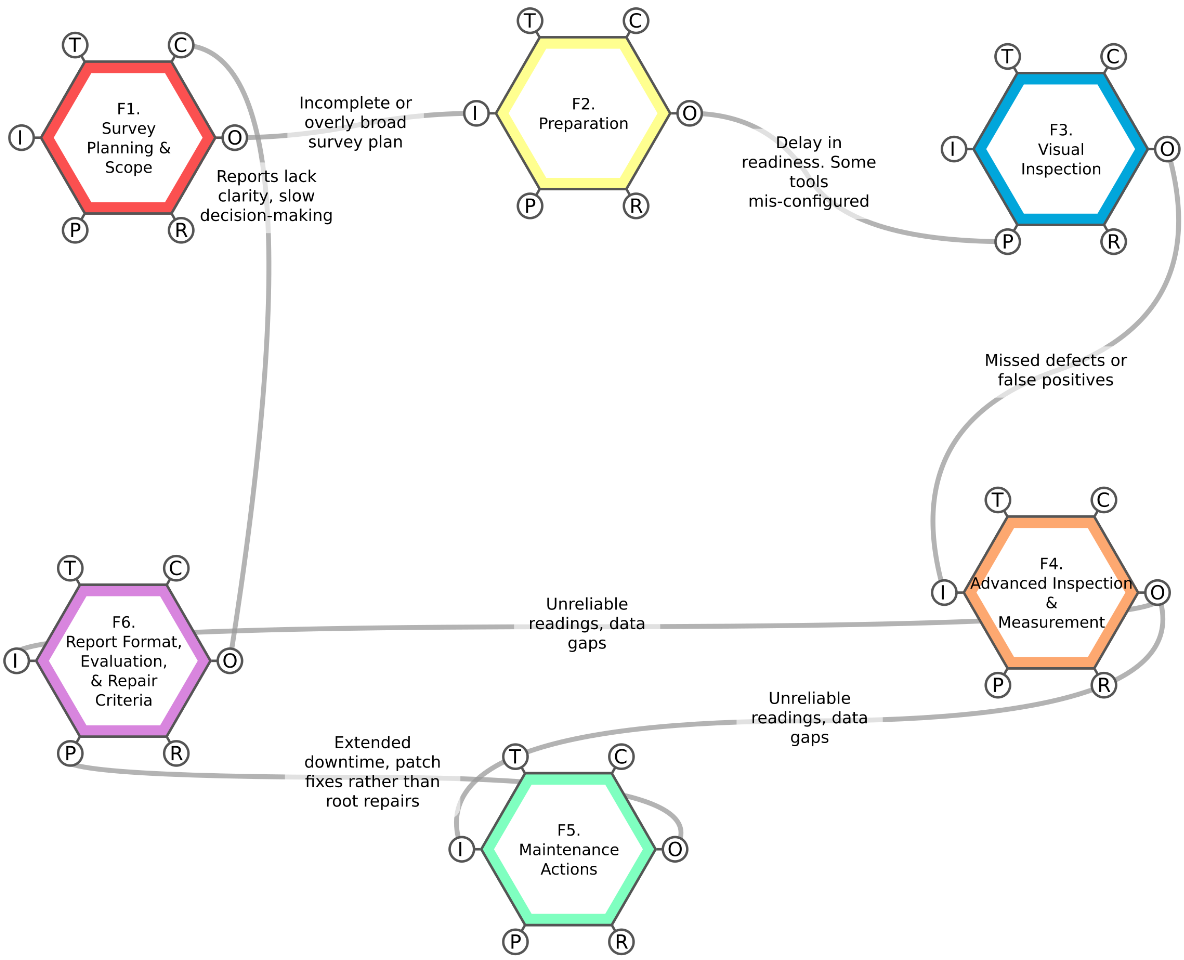

Figure 3.7: A representation of personnel performance variability

Figure 3.7 shows the variability in performance because of personnel competence. Each activity in the model contains both exogenous and endogenous variability, and this variability resonates throughout upstream and downstream connections, shaping the model. The crew represents the resource and control aspect of F1. Survey planning & scope. Crew's experience level, training, and focus vary (endogenous) among the different members of the team and are combined with exogenous pressures such as fluctuating shifts. This may lead to omitting key areas, inspecting with an insufficient technique, or misinterpreting the data. The subsequent preparation activity is misaligned: tools may arrive too late or be incorrectly configured. In turn, visual inspection is degraded, and this allows defects to slip through and distort the information passed to the advanced measurement stage. If a failure mode is identified inaccurately, the crew should conduct future unplanned repair activities, while the reports are unclear or delayed, weakening the feedback loop for future planning.

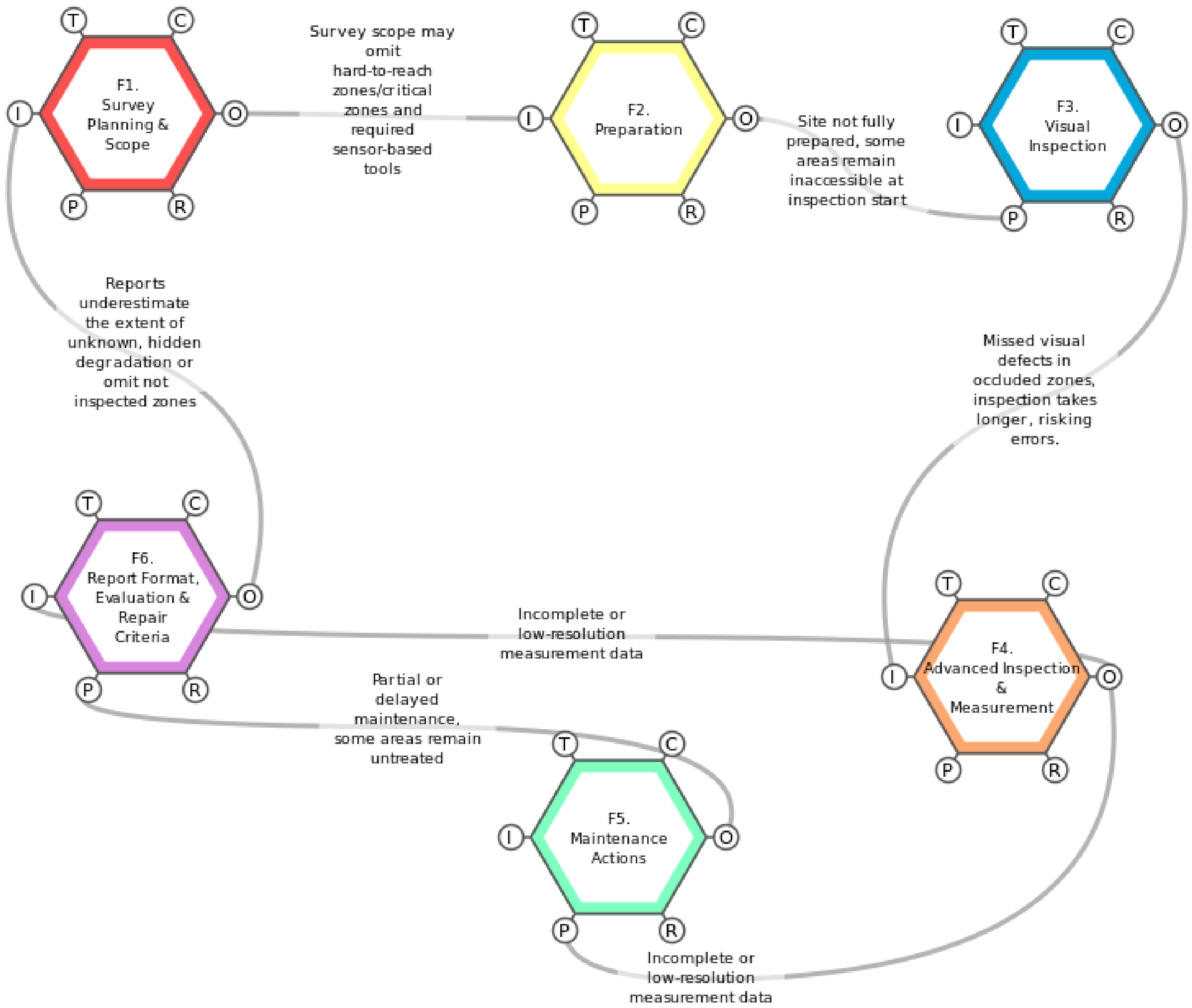

Figure 3.8: A representation of limited access areas' performance variability

FRAM model, Figure 3.8, illustrates the performance variability that arises from limited access to inspection areas. As an upstream constraint, confined spaces (endogenous variability) and physically unreachable areas, in tandem with the lack of specialized tools (exogenous variability), such as embedded sensors, prevent full coverage in F1. Survey Planning & Scope and F2. Preparation. Although inspection plans aim for the areas that are the most likely to wear, in practice, when confined-space procedures have to be followed, hidden damage may accumulate until it triggers sudden failure. Consequently, F3. Visual Inspection set of actions suffers from poor sampling, leading to a potentially hidden failure that remains unidentified. The undetected defects propagate to F4. Advanced Inspection & Maintenance, where the measurement data ends up being few or low resolution, and to F5. Maintenance Actions, with partial or delayed maintenance in these hard-to-inspect systems. Ultimately, F6. Report Format Evaluation & Repair Criteria actions result in incomplete damage patterns, which reduces the quality of the feedback loop for the next operational cycle.

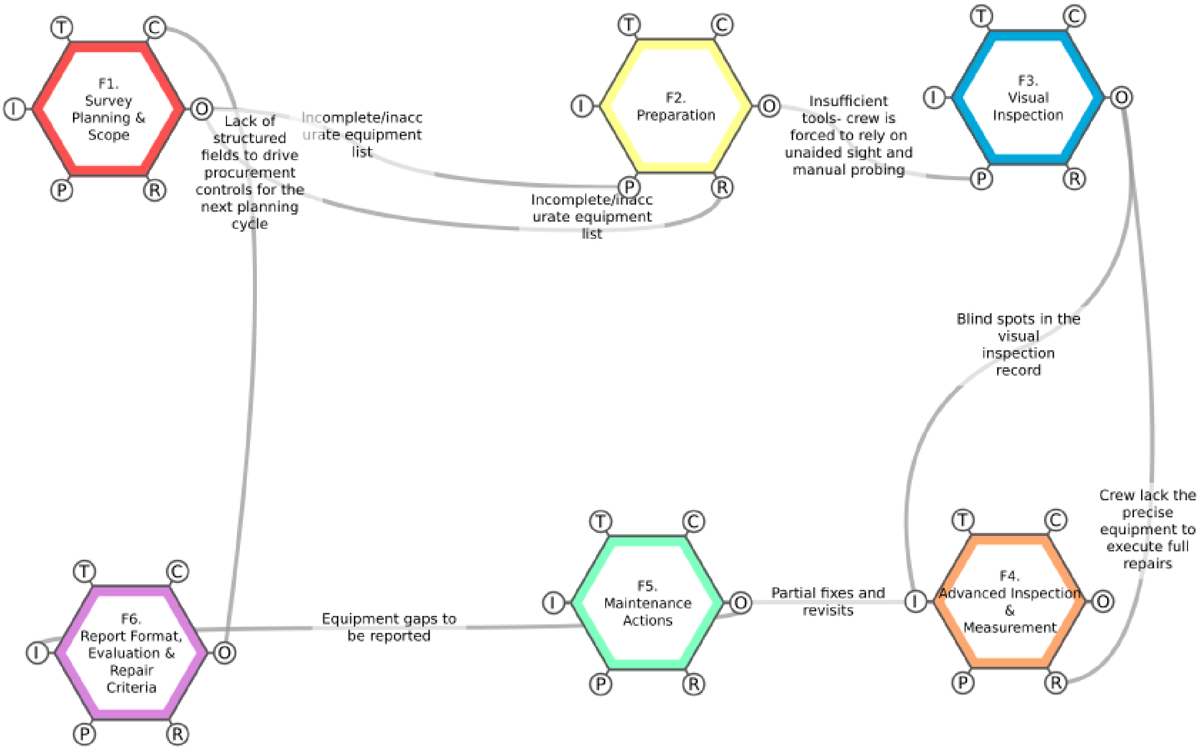

Figure 3.9: A representation of limited equipment availability performance variability

FRAM model, Figure 3.9, depicts how limited equipment availability propagates throughout the inspection and maintenance operational process. As an upstream resource, equipment, such as routine inspection gauges, specialized repair tools, endogenous variability that arises from stock levels or exogenously from supply chain delays, stands as of paramount importance for an efficient inspection and maintenance process. On-board resources may be adequate for standard checks, however, specialized equipment is not always available offshore, which determines whether F2. Preparation can be performed properly. When the inspection team lacks the essential tools, the surveys are completely paused or can be continued using less effective methods. The requirements for specialized tools for equipment and mechanical maintenance further amplify this limitation (F3. Visual inspection - downstream). Without resilient logistics and built-in redundancy, this performance variability spread to prolonged delays, data gaps, and delayed or incomplete repairs (F4 and F5). This may lead to an increased probability that the failure remains undetected or is resolved insufficiently.

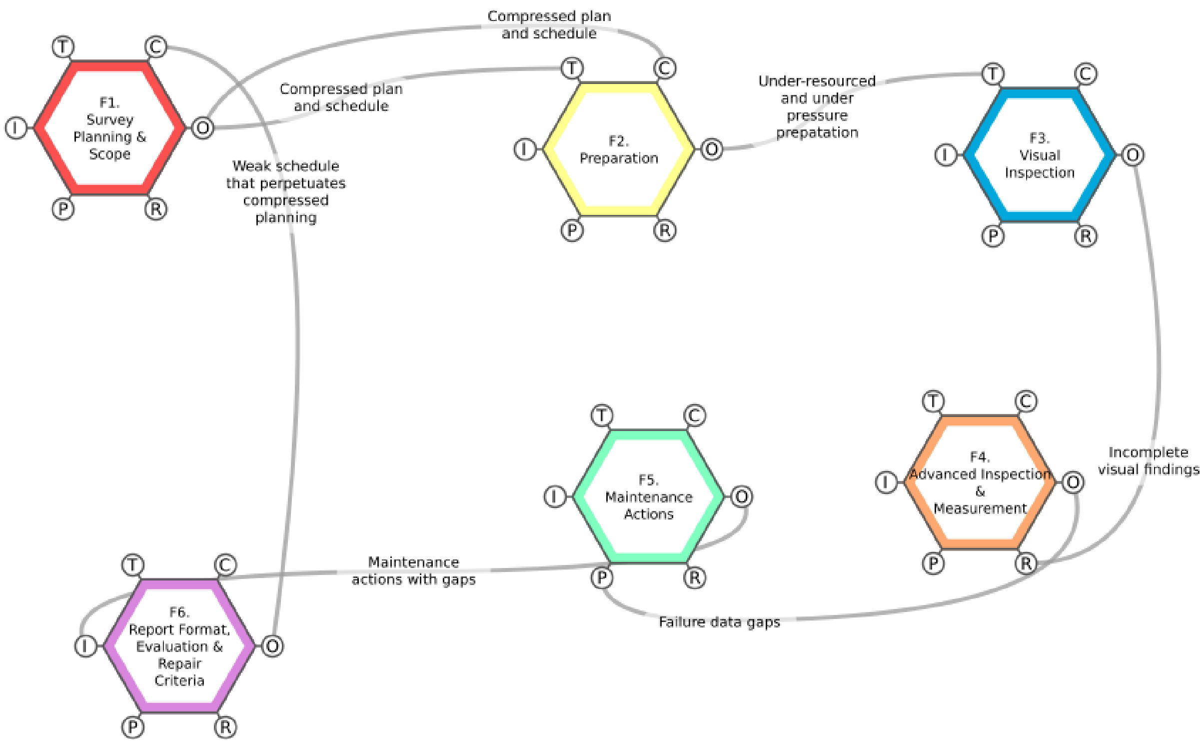

Figure 3.10: A representation of limited time window performance variability

FRAM model, Figure 3.10, presents the propagation of performance variability that a limited time window creates. Inspection and maintenance operational processes often face, as an upstream constraint, a narrow time window, either due to unplanned yard visits that force rushed work or due to insufficient time for full repairs during scheduled port stays. When schedules are compressed, exogenous pressure is imposed on the F1 and F2 sets of actions. The scope is limited and the planning hurried, while the preparation phase is compressed. Mobilization of the required equipment and ensuring access to the inspection zones is conducted within an exceptionally limited time frame. Therefore, this limited time window-driven endogenous urge accelerates during the F3 and F4 set of activities, skipping or rushing certain steps and leading to cursory checks and data gaps. Those data gaps resonate towards F5, so repair teams conduct faster repairs than thorough treatments, and towards F6, so reports are finalized in a way that details or follow-up actions may be passed over. This propagation of performance variability creates degradation in both immediate quality and long-term efficiency and reliability of the operational process, so failures escalate between inspection and maintenance operational cycles.

The FRAM models presented above are capable of revealing how the dynamics of the operational process can be impacted by small deviations within the everyday work-as-done.

This information is useful in developing instructions and guidelines to better manage the operational process, which ultimately aims to achieve a more efficient operational procedure.

4 Integration of FMECA and FRAM

In this section, a risk management strategy is developed, aiming to address the determined variability in the operational process and ultimately enhance ship availability. Additionally, FMECA and FRAM are integrated to verify if there is an actual reduction on the operational downtime.

4.1 Hierarchy of Controls

The Hierarchy of Controls (HoC) [148] relies on a structured framework that guides control strategies by their comparative effectiveness and can provide direction for adjusting an operational process, such as the inspection and maintenance process, to affect its safety and efficiency, and ultimately enhance ship availability.

The FRAM offers a deeper understanding of how performance variability scenarios propagate throughout the operational process. After identifying the resonant variability paths, remedial actions are assigned to the most effective HoC level.

By treating identified black spots as hazards that need to be controlled and following the five levels of the hierarchy of controls 4.1, the operational workflow becomes more effective, safer, and the ship downtime is mitigated. This method contributes to determining the types of control that are most effective in reducing risk. Figure 4.1 below illustrates the hierarchy of controls.

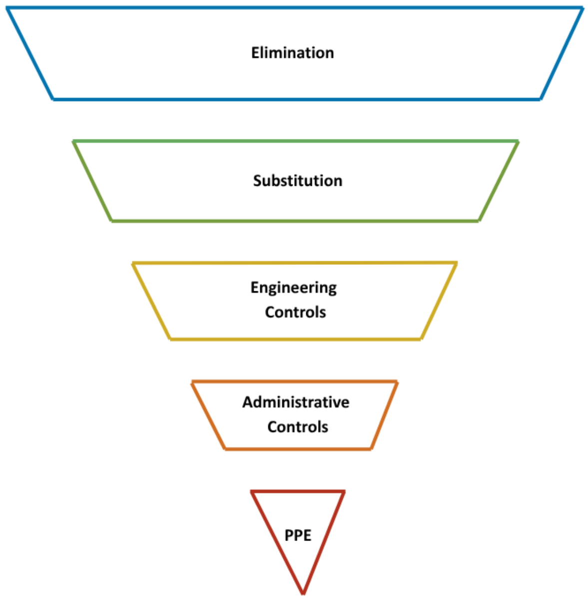

Figure 4.1: The Hierarchy of Controls (Data adopted from [148]), *where PPE stands for Personal Protective Equipment.*

In more detail, for each identified performance variability scenario, the analysis determines whether a risk can be eliminated or substituted; if none of these control levels is feasible, it assesses whether the risk can be addressed through engineering controls. If engineering controls are insufficient, it defines the administrative procedure or the PPE. In this way, each suggested control remedial measure is grounded in the socio-technical diagnosis and positioned at the appropriate HoC level.

Table 4.1 below clarifies the description for each control and the corresponding performance variability within the scope of this study. According to the Canadian Center for Occupational Health and Safety (CCOHS, 2023), in some cases, a single control method may not be sufficient to manage a black spot, so when elimination is not possible, it may be necessary to use a combination of different control measures [148].

Table 4.1: Hierarchy of Controls paired with corresponding performance variability themes.

Hierarchy of Controls	**Description [148]**	**Corresponding Performance Variability Theme**
Elimination	This is the strongest form of control. Elimination means getting rid of the hazardous element (black spot) altogether so it no longer exists in the work setting. Once the source of danger is gone, the risk disappears as well.	(None - read below)
Substitution	This involves swapping out a known hazard (black spot) for an alternative that carries a lower degree of danger. Before implementing the change, the risks tied to the proposed replacement must be rigorously evaluated to confirm that it is truly safer. This careful review helps ensure the new option genuinely reduces harm instead of merely exchanging one peril for another of equal or greater severity.	Equipment availability
Engineering Controls	These consist of physical or mechanical solutions that target a hazard (black spot) at its point of origin, isolating or removing it so that workers are never exposed to it.	Access to inspection areas, Equipment availability, Time window
Administrative Controls	These center on designing and refining work procedures so tasks are performed in a way that keeps exposure to hazards (black spot) as low as possible. Typical actions include writing or revising policies, upgrading employee training and education, and sharpening day-to-day work methods and protocols.	Equipment availability, Time window, Personnel competence
Personal Protective Equipment (PPE)	This encompasses any gear an employee puts on to guard against hazards (black spot) encountered in the workplace.	Equipment availability, Time window

The relationship of the HoC with this study, as well as an explanation for the linkage with each corresponding performance variability, is explained below.

Elimination, the strongest form of control, is not applicable in the scope of this research because the performance variability scenarios are intrinsic to the current system design and the existing operational procedure, so they cannot be eliminated. Hence, the risk has to be controlled through the use of lower-level controls.

Substitution control applies where the specialized equipment is not available, or is unreliable offshore. Substituting the handheld tools with a permanently installed sensor array, the reliance on variable equipment availability is reduced through regular inspection results without relying on operators' skills at the time of inspection or the availability of the tool. Permanently installed sensor arrays have been shown to greatly improve the detection of degradation through the provision of automated, continuous data, overcoming the limitations of manual and handheld inspections [149].

Engineering controls treat access limitations, equipment availability, and time constraints through the implementation of physical or technological measures. These may be robotic crawlers for confined spaces, embedded sensors in blind spots, and improved access to isolate variability at its source. The suggested placement of the robotic crawler and sensor array resonates with this principle through the automation of inspection processes in restricted and inaccessible areas, effectively isolating inspectors from exposure to dangers and hidden degradations to accelerate. The enhanced access also offers engineered physical access to difficult areas of inspection with the aim of improving safety and avoiding time delays. These controls reduce performance variability through the minimization of the use of manual access and inspection techniques, addressing the identified access limitations and the constraints in the time window. Furthermore, these engineering controls support an automated monitoring process and reduce the need for specialized tools, which may not be available offshore. Hinging upon the exploratory interviews' insights and the cross-member checking sessions, experts stressed that the industry is working towards greater automation to mitigate inefficiencies that cause variability in inspection and maintenance processes. This is in recognition of the fact that manual inspection procedures, particularly when carried out under adverse conditions such as on oil tankers, are subject to variability due to factors such as people, availability of machinery, and access restrictions. The use of automation technologies is seen as a solution option to mitigate variability, enhance data reliability, and overall operational safety and efficiency.

Administrative controls aim to mitigate variability in employee competency, equipment readiness, and scheduling through the application of standard training programs, handover policies, equipment inspections, and dynamic scheduling of inspections to minimize errors and deliver consistent inspection quality. These are consistent with safety theory, where these controls are defined as organizational and procedural measures to reduce, but not eliminate, risk exposure [148].

PPE is the least effective control; however, it is required to support risk mitigation and fill the gap that other controls cannot fully bridge, providing a higher-level risk elimination. Considering the performance variability that equipment availability causes, PPE such as chemical suits, hard hats, safety footwear, and protective clothing addresses performance variability indirectly. By increasing the safety of the team when tools are not available, the ability to inspect areas of the ship is better. Furthermore, when the time window is limited, the PPE, such as high-visibility garments, gloves, goggles, and face shields, enhances the crew's ability to perform the inspection and maintenance process quickly, while at the same time ensuring safety.

Collectively, the controls constitute a ranked, multi-level risk reduction strategy specifically designed to respond to the themes of performance variability noted by the analysis in this study.

4.2 As low as reasonably practicable concept

The "As Low As Reasonably Practicable" (ALARP) concept is a safety regulation and it advocates that risks must be minimized to the lowest point that is reasonably practicable, considering both the seriousness of potential harm and the cost or feasibility of safety measures [150]. The main features of this concept are risk reduction, reasonableness, decision-making, and legality & ethics. Risk reduction demands relevant decisions that balance the seriousness of potential harms with the available means of controlling the risk [150]. Yet, it is not pursuing a complete elimination of risks since, in most cases, it is not feasible or possible. Furthermore, reasonableness brings in a cost-benefit test [150]. Control measures should be adopted in case that they cut down the risk appreciably; however, not in case that the cost of taking them is out of proportion to the benefits in reducing the risk [150]. Additionally, decision-making requires decisions that are balanced when considering the level of harm with the availability of resources for managing risk, and it is used in regulatory frameworks to guide the decision-making process in cases of uncertainty and trade-offs [150]. Legal and ethical principle of ALARP is typically integrated into frameworks of regulation and are a requirement in a number of different pieces of law in various jurisdictions [150].

ALARP concept is consistent with the HoC approach, in which the higher-level controls, such as elimination or substitution, are pursued first, and lower-level controls are applied if the higher-level ones are not possible or cost-effective. Within the scope of this research, the ALARP utilization is essential because it provides rationality and balance to the prioritization and selection of the desired controls for minimizing the black spots identified in the inspection and maintenance operational process.

Initially, in the context of ALARP, a cost-benefit analysis is essential to provide direction to the decision-making process. However, considering that such a process is highly sensitive to the specific goals, operational, and financial conditions of each company or operator, the quantification of costs and benefits for the identified controls (Table 4.2 below is an overview) is not conducted within the scope of this study. This is suggested to be done internally at the organization in order to take into account the particular operating conditions, available technologies, as well as financial capabilities. This was also confirmed by industry partners during cross-member checking discussions.

Table 4.2: Overview of suggested controls for each performance variability scenario

Performance Variability	**Suggested Controls**
Equipment Availability	Substitution (Permanent sensor arrays), Engineering Controls (Embedded sensors, robotic crawlers), Administrative Controls (Standardized equipment inspection procedures, scheduling), PPE (Personal protective equipment to mitigate risk exposure when equipment is limited).
Access to Inspection Areas	Engineering Controls (Robotic crawlers, embedded sensors for inaccessible or restricted areas).
Time Window	Engineering Controls (Robotic crawlers, automated inspection systems), Administrative Controls (Dynamic scheduling, improved operational procedures), PPE (Facilitating quicker inspection performance safely).
Personnel Competence	Administrative Controls (Robust standardized training programs, improved handover procedures, consistent implementation of inspection protocols).

The Table below 4.3 is a decision-making framework suggested for use as a tool to guide the selection and prioritization of controls, following ALARP principles. Although it is generally driven by cost-benefit analysis and risk reduction, in this project, the decision-making framework is grounded in the literature [151].

Table 4.3: Control selection using ALARP

Control Type	Risk Reduction	Estimated Cost-Complexity	Feasibility	Prioritization Reason
Elimination	Very High	Very High (Not feasible)	Low	Not feasible. Intrinsic nature of variability scenarios to the current ship design and operational process.
Substitution	High	Medium-High	Medium	Effective. Requires evaluation and investment.
Engineering Controls	High	High	Medium	Strong mitigation. Costs justified.
Administrative	Medium	Low	High	Easily implemented. Supportive of the higher-level controls.
PPE	Low	Low	High	Last line of controls. Necessary residual protection.

Elimination and substitution are first in the HoC, as they have the highest potential to remove or minimize the performance variability at its source. Elimination (re-engineering of the vessel), as explained above, is not practicable in the case of current ships, and substitution, such as replacing some of the manual devices with more advanced technology, should be assessed cautiously to determine whether they mitigate the black spots at an acceptable cost. Replacement of a manual task with an inherently safer technology removes the variability path, thus resulting in high risk reduction [152]. The cost and integration effort are significant; however, they are less than full redesign, so feasibility is medium. Control measures such as sensor arrays require specialized crew training, so the complexity of implementation is medium-high.

Engineering controls such as the suggested sensor systems and robotic crawlers offer a combination of effectiveness and cost, since they hugely minimize the kind of risk involved by automating checks (high risk reduction) and eliminating exposure for people to danger zones. They are practicable, particularly with the advances in technology, though they are judged for cost-effectiveness (high cost and medium feasibility)[153].

Administrative controls, such as training and handovers, are given highest priority since they are low-cost, high-benefit controls that minimize the likelihood of human error [154]. The application of ALARP in this way ensures that they are applied effectively, reducing risk with minimal capital investment.

PPE is applied as a final line of defense in response to remaining risks when other controls have already been utilized [155], [156]. This is consistent with the concept that PPE is utilized only when other controls are not sufficient to remove or minimize the hazard.

Finally, the ultimate mitigation strategy can be determined based on strategic priorities, availability of resources, goals, and the organization's safety and quality policy.

FRAM does not exclusively address errors and their propagation throughout the whole system; instead, it attempts to describe how the functions of a system are tuned, or how the influence of a variability resonates, sometimes leading to positive results as well [125]. Taking into account the principle of the equivalence of success and failure (explained in Section 3.3), the variability of daily operations is the same both when things go well and when they lead to undesirable events [125], [126]. In particular, Hollnagel (2012) notes that "the variability of day-to-day performance is the reason why things usually go well, but at the same time it is also the reason why they sometimes go wrong."

Hinging upon FRAM principle, the suggested controls (see Subsections above 4.1, and 4.2) for eliminating or minimizing the identified performance variability scenarios (see Table 3.10), a modified FRAM model is developed and presented in this subsection.

This model serves as an asset for operators. Through capturing both the technical and human aspects and their interactions within the procedure, and by adopting the mitigating means to overcome the identified performance variability key factors that cause downtime or a less efficient operational process, an operator can expect a more efficient inspection and maintenance formula. In this new model, the original set of activities that shape the procedure of the inspection and maintenance is maintained; however, the mitigation means are taken into consideration. In such a way, the functional interactions are modified, and the updated FRAM visualization demonstrates how each performance variability scenario is either avoided or minimized, and a more efficient and reliable operational process is achieved.

Figure 4.2 below illustrates the enhanced operational process, in which every original function of the inspection and maintenance workflow has been complemented with the control measures. Technical measures, such as sensor arrays and crawlers, and administrative ones, such as standardized instruction protocol, dynamic scheduling, and handover documents, are integrated into the six aspects of the set of functions. A complete picture of how the six aspects of each aspect have been supplemented is provided in the Appendix B. In such a way, the previously found performance variability is either avoided or minimized. The new couplings explain how high-quality inputs are fed to each function and how the enforceable aspects regulate them. Finally, the feedback cycle from F6 to F1 aims to ensure that lessons learned are integrated into the next survey cycle straight away. In this way, the joint use of technical and human-based controls is outlined, ultimately identifying opportunities for improvement and reducing downtime or mitigating it in ship inspection and maintenance operations.

Similarly to the development of the initial FRAM models, experts' feedback gained through the semi-structured cross-member checking process is once again integrated into the suggested controls and the enhanced FRAM model.

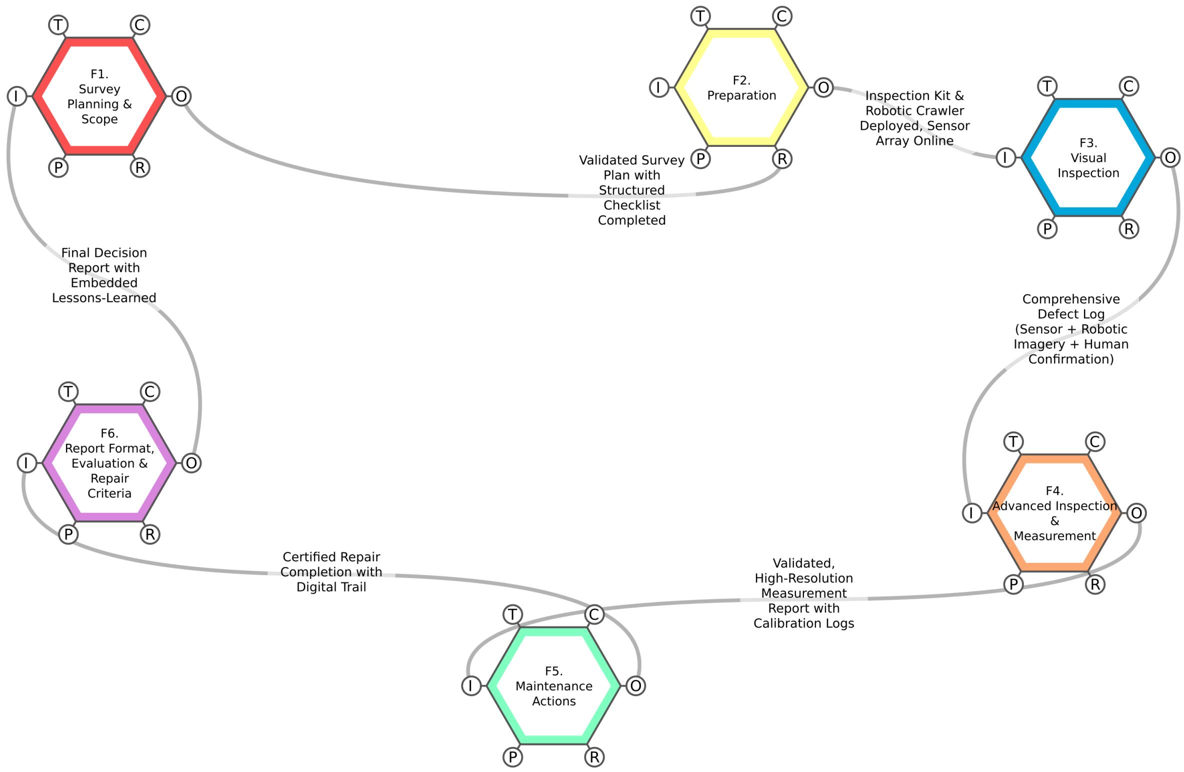

Figure 4.2: Modified FRAM model integrating suggested control measures.

Figure 4.2 illustrates how the black spots have been filled by adding the targeted control measures.

F1. Survey Planning & Scope in the enhanced model embeds a structured inspection checklist, 'trained planning personnel' as a resource, and 'digital handover protocol' as a control. In this way, the output is a completely 'validated survey plan' instead of a vague draft.

F2. Preparation incorporates a 'Verified sensor system status' as a precondition, requires 'Robotic crawler pre-deployment' as a resource, and is based on a 'Dynamic scheduling algorithm' as a control. This leads to a complete 'Inspection kit & robotic crawler deployment', sensor array online, instead of a misconfigured inspection kit.

F3. Visual inspection is assisted by mandating an 'Embedded sensor data feed' as a precondition, utilizing a 'Robotic crawler assist' as a resource, and establishing a 'Standardized visual inspection protocol as a control' aspect. In such a way, this set of activities provides a 'Comperhensive defect log', instead of an incomplete "spot-miss" log.

F4. Advanced inspection & measurement includes 'Real-time sensor threshold alerts' as a precondition aspect, a 'Robotic precision probe resource', and an 'Instrument calibration tracker' as a control. Consequently, it is ensured that the F4 set of activities produces a 'Validated high-resolution measurement report with calibration records', and not unreliable or partial measurements.

F5. Maintenance actions bring automation in spare parts inventory check as a precondition of this set of activities. A 'Specialized robotic welding arm' is used, as well as a 'Dynamic work permitting system'. In this way, a 'Certified repair completion with digital training' is conducted as a result of this set of activities, in place of ad hoc patchwork repairs.

F6. Evaluation & report format and repair criteria rely on the 'Integrated data dashboard' that is a precondition, an 'Automated digital report template' that is a resource, and has a 'continuous feedback loop' back to F1's control aspect. This makes the output of this set of activities a 'Final decision report' with embedded learned lessons, which enable improvement feedback input into the next operational cycle.

The enhanced FRAM model, with these aspects placed on the functions, illustrates how the performance variability scenarios that were identified make the operational process insufficient, and are overcome. New connections block the recognized black spots, making the inspection and maintenance process a seamless, trustworthy, and more efficient flow, mitigating downtime.

4.3 FMECA and FRAM Integration

Building on Patriarca et al. (2017), the DRN components: Occurrence and Midpoint of Downtime Band are embedded as attributes in each suggested control measure [157]. By doing so, the performance variability scenarios that are qualitatively modeled via FRAM are translated into a quantitative DRN_baseline (DRN_base) metric, enabling a direct comparison of control measures by their projected impact on ship availability.

In more detail, the predefined FMECA Occurrence scale as defined in Table 3.3) is applied to each control's anticipated effect on deviation frequency (Occurrence_baseline - Occ_base). Likewise, each control is assigned a Downtime_baseline (DT_base) equal to the mid-point of the predefined downtime bands. In such a way, direct comparability across all DRN calculations is preserved [157].

The DRN_baseline for each control measure is computed as:

$$DRN_{\text{base}} = Occ_{\text{base}} \times DT_{\text{base}} \quad (5)$$

This approach is consistent with the best practice in semi-quantitative risk analysis, thereby numeric Occurrence and downtime are multiplied to provide a single, comparable metric.

To translate each control measure into the two quantitative DRN_base components, the Occ_base and DT_base, HoC principles are applied together with established FMEA/FMECA practice [104], [148], [157].

Each successive HoC step leads to a gradual drop in occurrence score. These reductions are grounded in the HoC inherent effectiveness ordering.

- Elimination and substitution are the first two forms of control. They remove the hazard at source, explaining up to a two-level occurrence reduction.
- Engineering controls target the performance variability at its point of origin. Thereafter, they deliver a one-level drop in the occurrence scale.
- Administrative controls facilitate the design and refinement of work procedures to keep exposure to variability as low as possible. Therefore, these controls reduce the occurrence by up to one level, often conservatively rounded down by 0.5 - 1 level.
- PPE is the final, in the hierarchy, control, and does not contribute to reduction.

In FMEA/FMECA, each successive HoC step reduces the severity factor [99], [104]. Considering that the severity levels were initially clustered against the impact of downtime (Table 3.6), and the inherent effectiveness ordering of the HoC, bands are reduced as follows:

- Elimination and substitution controls contribute to a two-level downtime band drop.
- Engineering controls suggest that part of the process is automated or isolated; however, some setup and maintenance are still required. Thereafter, downtime is reduced by one band.
- Administrative controls introduce procedures, checklists, and training sessions that aim to standardize, but not completely automate, the process. They prevent variability, but still, the operational process is executed manually. A one-band downtime reduction may be achieved as well.
- Lastly, PPE control measures do not contribute to a reduction in the repair time.

Based on the modified FRAM model presented in Figure 4.2, the HoC principles discussed in Subsection 4.1, and the ALARP framework that is developed in Subsection 4.2 and guides the analysis of each control measure· the following analysis evaluates each control measure in terms of its expected impact on DRN_base:

1. Substitution controls:

   The installation of sensor arrays aims to address the variability that equipment availability introduces into the system. Looking at 'F3. Visual inspection', data feed is facilitated through an embedded sensor, while 'F4. Advanced inspection &measurement' includes real-time sensor threshold alerts.

2. Engineering controls:

   Robotic crawlers aim to address the variability that limited access to inspection areas introduces into the system. Robotic crawler deployment is a resource for 'F2. Preparation' and aims to provide a complete and not a misconfigured inspection kit, ultimately leading to a more efficient inspection process.

3. Administrative controls:

   Standardized equipment procedure scheduling, training programs, improved handover procedures, and consistent implementation of inspection protocols, address the variability introduced by personnel competence and equipment availability. They stand as of resource and control aspects of a different set of activities within the operational STS representation/

4. PPE measures:

   Address the time window variability through facilitation of quicker inspection performance safely, and stand as a resource for F3. Visual inspection and F4.Advanced inspection & measurement

DRN for FM.10. (Occurrence 4 $\times$ DT 36 h = 144) is recalculated (DRN_base) under each control category, and presented in Table 4.4, to quantify the expected downtime reduction.

Table 4.4: Overview of DRN_base scores for each suggested control measure

Control Type	**Occ$_0$ & Occ$_1$ (Δ)**	**DT$_0$ & DT$_1$ (Δ)**	**DT$_1$ midpoint**	**DRN_base**
Substitution	$4 \xrightarrow{-2} 2$	24–48 → 0–8 (−2)	4 h	8
Engineering	$4 \xrightarrow{-1} 3$	24–48 → 8–24 (−1)	16 h	48

Control Type	Occ_0 & Occ_1 (Δ)	DT_0 & DT_1 (Δ)	DT_1 mid-point	DRN_base
Administrative	$4 \xrightarrow{-1} 3$	$24–48 \to 8–24\ (-1)$	16 h	48
PPE	$4 \xrightarrow{0} 4$	$24–48 \to 24–48\ (0)$	36 h	144

In sum, substitution controls collapse the DRN from 144h to 8h, which is a 94,44% reduction. Engineering controls reduce the DRN to 48h, which is a 66,67% reduction. Administrative controls achieve the same DRN reduction. Lastly, PPE controls do not reveal a change on the DRN, it remains 144h.

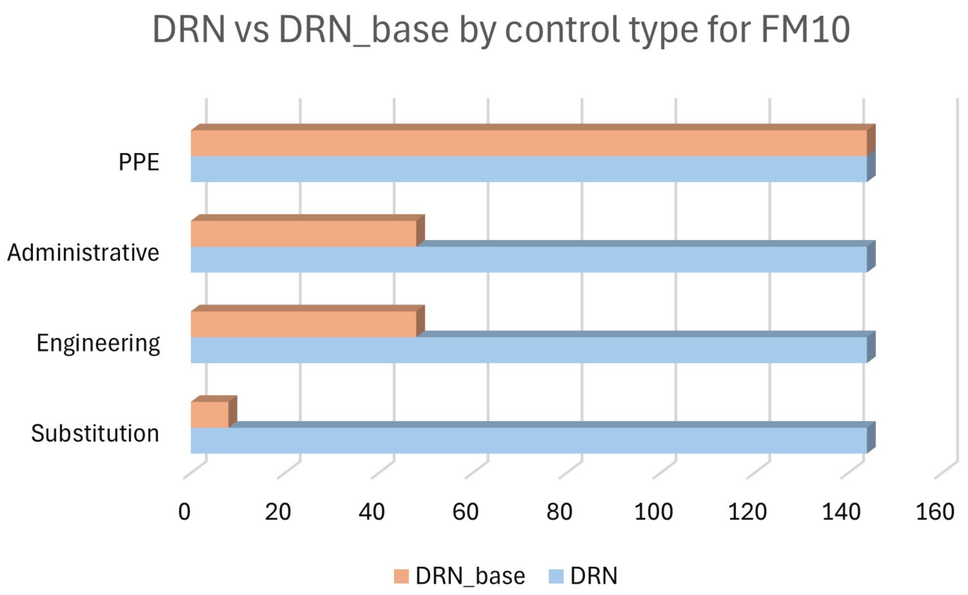

Figure 4.3: Overview of original DRN (144 h) and post-control DRN_base for FM10 across controls. Quantitative impact of each control type on ship availability.

4.4 Validation through Expert Feedback and Iterative Refinement

This subsection demonstrates how the study's findings are verified within a member-checking procedure with the industry experts. Aiming to enhance the credibility, validity, and practical relevance of the study, experts' feedback covers preliminary FRAM models, as well as the suggested risk management strategy.

The final version of the models and the risk management strategy presented in this study incorporates refinements based on the results of the member-checking sessions. The functions of the operational process, the identified performance variability scenarios and their propagation throughout the system were discussed. Moreover, the risk management strategy was examined as well.

Participants confirmed that all performance variability scenarios and the FRAM models are realistic and can be used in real-world situations. Before implementing full-scale changes in shipping operations, it is advisable to conduct virtual trials. An expert cites this approach as a methodology used within a European research project, in which virtual scenarios are used to assess the impact of different approaches aimed at more efficient CBM. Another instance is the Holiship program, a European R&D project, within the scope of which the researchers utilize virtual testing for maneuvering gear under computer-simulated ship-handling conditions [158].

Furthermore, interviewees approved the feasibility of the suggested mitigation controls. Considering the technical feasibility of robotic crawlers that are suggested for enhanced confined spaces access, and for more efficient time management, a paradigm of remotely-operated crawlers that have already been in service for tank cleaning and hull work was discussed [159], [160]. Remote inspection techniques are gradually being incorporated into classification rules and regulations [161], [162]. Additionally, the transition towards digitalization is noted; however, the readiness of the technology depends on the type of variability that it aims to address. For instance, acoustic emission measurements for corrosion or cracks in the hull structure are already quite developed. Lastly, automated and remote methodologies should be used in complement to the social aspect in operational processes, as already occurs in real-world examples. An expert provided a paradigm of a remote inspection system in which failures are detected automatically. However, when a predefined threshold is exceeded, human intervention is required, and a full-scale inspection is then carried out by the crew.

Additionally, within a member-check session, the introduction of Key Performance Indicators (KPIs) as an assessment means for the effectiveness of the proposed risk management strategy was discussed. Participants stressed that such indicators should be tailored to the specific organization's operational goals and financial resources. A single, one-size-fits-all bundle of KPIs risks falling short. Moreover, one of the experts pointed out that even the governments' framework of requirements and goals for their fleet is dynamic and constantly evolving.

Finally, the potential to treat the suggested risk management strategy as not only a one-off solution for a single vessel, but also for further development and adoption in sister ships that experience similar failures at different times or under different climatic conditions - to create a continuous learning loop for the entire fleet - was raised during a session. This is further discussed below in the Sections 6 and.

5 Results

In this section, the results from the conducted FMECA and the FRAM models developed to visualize the inspection and maintenance operational process from a socio-technical lens are recapitulated. The results stress the critical failure modes identified, the selection process of the top failure mode, and the outcome of the FRAM model about performance variability scenarios and system resonance.

5.1 FMECA Output: Critical Failures Identified

FMECA is carried out in two stages, with a focus on the general equipment and machinery components of oil tankers. The dataset consists of ten major incidents, with coating, corrosion, and deformation being the dominant failure mechanisms.

The first stage of the FMECA reveals the fundamental failure mode. Each failure incident is evaluated based on three parameters: Severity, Occurrence, and Detectability, with RPNs calculated as a product of these three parameters, to identify the top failure mechanism. Corrosion stands out as the hazardous failure mechanism in terms of frequency, severity, and detectability.

5.2 Selection of Top Failure Mode for Deep Dive

The second stage of the FMECA introduces the DRN as a product of the Occurrence and the Midpoint of the Downtime Band. This metric contributes to the classification of corrosion incidents based on their repercussion on the ship's availability.

The steam supply system is revealed as the most critical system, which contributes to the higher operational downtime.

5.3 FRAM Analysis of Inspection and Maintenance Process

The inspection and maintenance operational process is modeled using the FRAM. While taking as a starting point the determined critical system, the steam supply system, the functions are intentionally formulated in a generalized manner, to represent the core operational structure of inspection and maintenance activities among the different ship subsystems.

Five sets of activities shape the FRAM models:

- F1. Survey planning and scope
- F2. Preparation

- F3. Visual inspection
- F4. Advanced inspection and maintenance
- F5. Maintenance actions, and
- F6. Report format, evaluation

Additionally, four performance variability scenarios are identified based on insights gathered through semi-structured interviews with industry experts. These performance variability scenarios are rooted in personnel competence, limited access to inspection areas, limited equipment availability, and a limited time window.

The FRAM models reveal findings such as:

- Variability in training of the different teams that inspect and repair the vessel, in combination with exogenous pressures such as fluctuating shifts, leads to inconsistent inspection planning and misinterpretation of the data. This upstream variability degrades the visual inspection quality and affects the reporting activity. Ultimately, feedback mechanisms for the future operational cycles are weakened.
- Confined spaces in combination with a lack of embedded inspection gauges affect the operational quality. In such a way, critical areas may not be inspected, and defects in different subsystems remain hidden until they turn into failures. This variability reduces the comprehensiveness of maintenance and degrades the quality of inspection reporting.
- Endogenous variability factors, such as routine inspection gauges, and exogenous supply chain delays affect the availability of inspection and maintenance equipment. This may turn into delayed or even paused inspection activities that affect inspection data collection and detection of degradations and failures on the ship's systems.
- Limited time window, whether from unplanned yard visits or port tight schedules, leads to hurried inspection planning and execution activities. This rushed work leads to a more superficial and degraded inspection and maintenance quality. In turn, this has short-term and long-term impacts on the operational process and an elevated risk of missed or insufficiently addressed failures.

6 Discussion

6.1 Implications of FMECA Findings for Downtime Risk

In this research, the operational process of inspecting and maintaining ships is studied, implementing the socio-technical modeling approach. The human and technical elements of the operations are interconnected and constantly interact, affecting the quality of the operations.

SRQ1: What are the key socio-technical elements and their interrelations involved in inspection and maintenance processes? is answered through advancing the operational process by studying it as a socio-technical system. The categorization of the operational process as a complex socio-technical system relies on the theoretical and academic background of the socio-technical system that is adopted. In the scope of this study, the STS is embraced according to Carayon et al. (2015), a joint optimization of two interconnected subsystems, the technological and the social subsystem. Furthermore, emphasis is given on the relationships within the system and its adaptability [9], [19]. In such a way, the interactions between individuals, technology, and the context where these take place, their environment, show the interrelationship of these elements under the real-world variability. The classification of the ship inspection and maintenance operational process as a complex STS starts with the identification of the involved key actors and technical elements through a literature review and official report analysis.

Onboard crew, such as engineers and deck officers, who carry out daily visual checks and essential servicing, specialist inspectors who perform advanced tests, maintenance planners who allocate resources and take care of the scopes, and external stakeholders, whose risk tolerances and commercial pressures shape inspection intervals are the social elements of the system. Physical assets, such as the general equipment and machinery broken into subsystems and elements, inspection tools and equipment, information systems, and governance artefacts such as inspection checklists, classification society rules, and safety management procedures, are the technical elements of the system. The crew continuously interacts with the physical assets, inspectors operate the inspection equipment, data flows through the information systems, and governance procedures guide crew activities. The environmental context, such as sea state, temperature, and humidity, affects asset degradation and tool performance. The inspection and maintenance operational process is a tightly coupled socio-technical system.

Thereafter, the complementary utilization of the FMECA method and FRAM stands as a means in addressing the *SRQ2: How can the identified elements and their interrelations be modeled from the socio-technical perspective to support inspection and maintenance?*.

A two-stage FMECA leads to the identification of the fundamental failure mode and the most critical subsystem of oil tankers, according to the scope of the study.

FMECA is selected as a methodology through a review of the risk management methodologies in ship operations. Its suitability is justified by the capability that it gives to the researcher to break down the system under study into subsystems and components, allowing the prioritization of the failure mechanisms. The hierarchical decomposition of the system aligns with the complexity of the system under study and the STS approach, where the system is considered as a set of integrated parts [19].

In the first stage of FMECA, the common analysis steps are followed, studying incidents obtained by corporate inspection reports that refer to the general equipment and machinery systems of oil tankers. The corrosion failure mechanism is identified as the fundamental one. Subsequently, at the second stage of the FMECA, the availability factor of the ship is considered, and the Downtime Risk Number of corrosion incidents, identified in the first stage, is calculated to determine the critical subsystem.

This two-stage FMECA approach is adopted to support the decision-making process and to facilitate the development of an analysis that gradually leads to the answer to the main research question. In this way, this analysis methodically unfolds from what fails most critically to what is more hazardous, in terms of availability. The steam supply system is determined as the most critical one.

Hence, the FMECA reveals the steam supply system corrosion failure responsible for the highest amount of ship downtime during inspection and maintenance operations. As a result, maintenance planning should prioritize early corrosion detection techniques over less urgent tasks. In such a way, and by redirecting a percentage of annual maintenance effort towards improved corrosion surveillance and detection, the detection and repair time is reduced, and ultimately, the ship's availability is enhanced. Additionally, considering the DRN when scheduling the inspection and maintenance operations leads to a more effective operation process with reduced downtime events. At the same time, focusing on DRN within operations not only reduces downtime costs but also mitigates safety hazards.

6.2 Insights from FRAM on Socio-Technical Process Weaknesses

Several approaches integrate the socio-technical perspective into research. After reviewing them within high-quality academic and peer-reviewed literature, the FRAM is selected. This method allows the researcher to study the operational dynamics of the system and their impacts on its performance. Also, it gives the capability to study the inherent variability in the complex socio-technical system. Moreover, focusing on the Safety I and Safety II perspectives, the implementation of the FRAM in conjunction with the FMECA enables a holistic analysis of both the fixed causes of failure (Safety I) and the dynamic variation of operations in daily practice (Safety II) [126].

The **SRQ3:** *In what ways can a socio-technical analysis of inspection and maintenance practices reveal opportunities to improve system reliability and reduce downtime?* is answered through the systematic setting solidly in empirical data into the FRAM models. The fundamental issue that leads to performance variability scenarios within the operational performance is the daily inconsistency of work-as-done. The management and execution of the inspection and maintenance operational process vary from day to day [28]. In this study, the key identified performance variability scenarios that lead to this issue are: personnel competence, equipment availability, access to inspection areas, and the time window. These performance variability scenarios affect the different aspects of the set of activities that shape the whole operational process. Small deviations in time or quality deficiencies are coordinated through the couplings throughout the models and turn into significant variability in inspection and maintenance quality, ultimately leading to increased downtime within ship operations. The variability pathways and the critical resonance points turn into targeted, practical recommendations.

Adopting a risk management approach using FRAM methodology, which is based on variability analysis, the Safety II framework is strengthened by examining how deviations in human and machine interactions influence the system's performance outcomes [126]. The aspect of the human factor within the operational process is dependent on the human-machine interrelationships and the work-as-done. Thus, any operational modifications must guarantee that changes in the socio-technical system operational process do not negatively affect safety and effectiveness levels or obstruct the attainment of operational objectives, such as ensuring the continuous availability of the vessel.

This is pursued through a structured alignment of HoC with the four FRAM-derived performance variability scenarios, thereby translating socio-technical insights into stacked risk mitigation measures. To ensure that these pyramided control measures are not only technically sound but also financially and ethically defended, the ALARP principles are applied. ALARP principle follows the HoC, and ensures that any suggested measure provides a performance variability reduction that outweighs its associated cost and complexity.

The HoC and ALARP framework facilitates the translation of FMECA and FRAM into a coherent decision-making process. While FMECA results in failure prioritization, FRAM provides a deeper qualitative understanding of performance variability scenarios. HoC offers a comprehensive classification principle for each variability scenario, so it is translated into a control type. ALARP offers a more holistic view of the decision-making process and evaluates whether the selected controls are worth implementing. In addition, the HoC helps to identify the quantitative effect of the suggested control measures on ship availability, with the DRN base metric, and finally to close the methodological loop.

6.3 Comparison with Existing Literature

Budimir et al. (2025), [163] in their paper, investigate the ship availability through enhancing maintenance of the engine and ultimately mitigating ship downtime. This is a highly data-driven and component-centric study, focusing on failure statistics to time interventions and also rank budgets.

On the one hand, the Markov chain used by Budimir et al. (2025) reveals how much downtime a suggested preventive step can reduce. This study misses the quantitative amount of downtime that is expected by implementing the suggested measures, as well as proper economic data. On the other hand, the socio-technical approach adopted within the scope of this study and the revealed FRAM patterns may enhance Budimir et al.'s research by predicting the variability that leads the human element included in the process to miss interval windows or misuse gauges. Taking into account the human factor and how it affects the availability of the ship, perhaps the optimized preventive maintenance strategy would be more holistic. It would combine the quantitative strength it already possesses (large-n dataset, goodness-of-fit tests, explicit cost and benefit numbers) with qualitative insights that can explain why variability happens and how controls change crew routines. In such a way, it would be easier for line managers to engage their teams and gain their support.

Furthermore, Gosavi et al. (2025) enhance operational availability by optimizing in-port ship maintenance operations. Although ship downtime is viewed from a different perspective, the idle period a vessel spends waiting for a free dry dock could be addressed through the implemented methodology. The hybrid Agent-Based Modeling (ABM) and Discrete-Event Simulation (DES) framework could inform this study. In more detail, the ABM-DES optimizer could be repurposed to prioritize the high-DRN failure modes identified within the scope of this study. At the same time, their trade-off curves between idle-time cost and maintenance expenditure would provide the quantitative backbone that ALARP is currently missing. However, the socio-technical approach adopted within this study, as well as the relative methodologies, could enrich Gosavi et al.'s research. A FRAM model would assist in explaining the reason why dockside schedules sometimes slip even when optimal durations are selected. Also, the HoC, in tandem with the ALARP framework, could serve as a template to assess whether additional measures would deliver cost-effective benefits beyond pure scheduling optimization.

6.4 Recommendations for Industry Practice

For operators and organizations, this study offers a four-pillar framework to consider when aiming to improve ship availability.

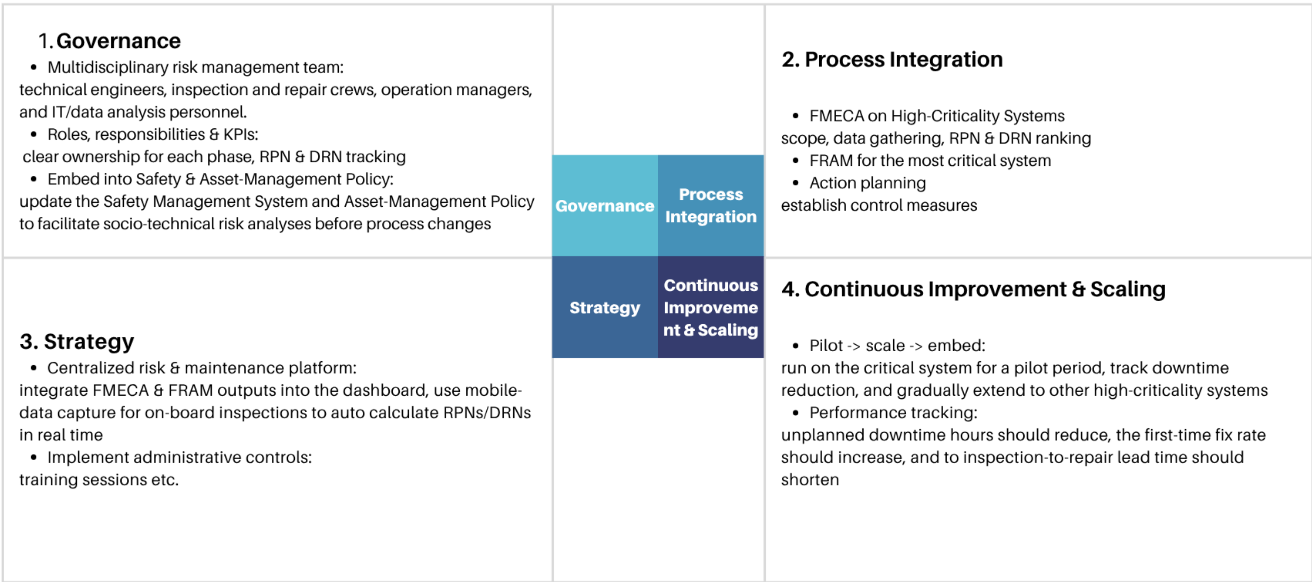

Figure 6.1: Four-pillar framework for operators

Figure 6.1 depicts a holistic framework that adopts a STS approach, therefore taking advantage of the insights such an approach and the human-machine interrelationships give to ship availability enhancement.

A FMECA that combines high-quality quantitative data, such as historical inspection logs, with robust qualitative insights from daily work-as-done FRAM models can effectively identify and prioritize fundamental failures, address critical systems, and capture performance variability that needs to be addressed, to ultimately enhance ship availability. The implementation of the HoC-ALARP framework starts with elimination and substitution ideas, and moves down the hierarchy only when higher levels of controls are impracticable or insufficient to address the performance variability scenario.

Furthermore, for the pilot phase, virtual testing of the control measures, preceding their immediate installation, may be more realistic. While in the scope of this study, a cost-benefit analysis is not conducted because of resource limitations, it is advised for an organization to conduct a cost-benefit analysis to tighten the decision-making process to the specific internal goals, operational, and financial conditions. After a first pilot test, a Monte Carlo simulation is advised to be conducted in order to translate FRAM variability ranges into probability distributions and re-run virtual tests to see the full downtime effect.

Lastly, it is suggested to involve experts from different disciplines, such as engineers, inspectors, maintenance planners, repair crews, project engineers, and personnel responsible for budget, investments, and alignment with the organization's goals. The inspection and maintenance operational process, the performance variability scenarios, and the dataset for analysis must combine both the technical perspective and the social and governance dimensions. Knowledge and experience of diverse disciplines should be leveraged. Additionally, each step of the structured methodological process should be communicated to and reviewed by all members of the interdisciplinary team, so that iterative improvements can be made toward a holistic socio-technical approach.

6.5 Methodological Limitations and Assumptions

For the research carried out in this thesis project, several assumptions are made, and multiple methodological limitations are encountered. To begin with, the assumptions:

1. The socio-technical lens of FRAM stands as an effective means to capture performance variability scenarios in the work-as-done in the oil tankers inspection and maintenance process, and therefore reveal black spots that cost the ship's availability.

2. The traditional bottom-up FMECA methodology, with a scoring system on a 1 to 5 Severity/Occurrence/Detectability scales, is sufficient to screen technical risks, such as the most critical system, and the fundamental failure mode, before conducting the FRAM.

3. The amount of inspection reports is representative of failure behavior on oil tankers in general.

4. The findings obtained on a single ship type, the oil tanker, can be conceptually transferred to other vessels of a similar type.

5. Three semi-structured expert interviews, combined with cross-member checking sessions, provide sufficient and valid domain knowledge.

6. DRN is calculated as a product of the occurrence and the midpoint of a broad repair-time band.

7. The HoC steps are assumed to reduce occurrence and downtime levels by fixed levels.

These assumptions contribute to the feasibility of this research; however, it is essential to establish clear boundaries beyond which the insights cannot be applied.

Apart from the assumptions, there are some limitations within the scope of this research.

1. This research focuses exclusively on a single vessel type, the oil tanker. When generalizing the framework to enhance ship availability for other ship types, such as LNG or passenger ships, operational behavior and material considerations may differ.

2. The focus is on the general equipment and machinery of oil tankers. Subsystems outside the defined scope are excluded; thus, critical cross-system interactions may be overlooked.

3. Potential sampling and reporting bias may occur within the research of this thesis project. The data set, drawn from inspection reports, is obtained from a single fleet operator, and parameters such as age, trade, and climate are not considered; therefore, rare failure incidents may be overlooked.

4. No sensitivity analysis is performed for the severity, incidence, and detectability scores. This may lead to subjectivity of risk scores.

5. Severity, occurrence, and detectability are ordinal scales rather than interval scales. Every level change is treated equally when multiplying to get the RPN. Moving from 1 to 2 counts the same as moving from 4 to 5. However, the second jump may reflect a bigger real-world increase in risk.

6. The RPN formula assigns identical importance to all three factors (severity, occurrence, detectability), but ship operators may tolerate low detectability better than high occurrence, or vice versa.

7. Failures with catastrophic severity but low detectability scores may end up with moderate RPNs and lead to under-prioritization of failures.

8. The suggested control measures have not been tested in terms of real-world feasibility or a quantitative cost-benefit analysis. This leads to questions regarding actual return on investment.

9. Several mitigation control measures are related to emerging technology artifacts.

10. The DRN calculation is simplistic. A mid-point of broad downtime bands is used, and a linear cost of time lost is assumed, so potential variance is neglected and reliability barriers are not analyzed.

11. The occurrence score is an ordinal scale of 1 to 5, with equal intervals between points. This fails to capture true failure probabilities and ends up with a score of 3 that could correspond to anything from a very low to a very high actual failure rate. Consequently, the precision of the DRN can be overestimated, and the impact of the suggested controls on ship availability could be either overestimated or underestimated.

12. Both the selection of downtime bands and the occurrence scoring hinge on one simple dataset. Consequently, the absence of broad validation results in DRN values that may not generalize beyond the studied vessel or fleet.

13. A proper cost-benefit analysis is left outside of the scope, so the ALARP decision-making framework is left to the operator based on internal goals, operational, and financial conditions.

14. The suggested controls are treated in isolation, even though in reality their effect may interact or scale non-linearly.

The limitations indicate where further research is needed before the results can be broadly used by fleet operators for asset management and regulatory decisions. This is further discussed in Subsection 7.3.

7 Conclusions and Future Work

7.1 Summary of Key Contributions

The research conducted for this thesis project contributes to the scientific community by developing an integrated FMECA and FRAM methodology that identifies opportunities to enhance inspection and maintenance activities and ultimately mitigate operational downtime. Furthermore, what is revealed from this methodological approach and how the STS insights can be translated into deployable, hierarchically ranked results to enhance ship availability is investigated. In such a way, maritime asset-management research is enriched with integrative, availability-focused, and operator-validated approaches.

In this study, a bottom-up engineering tool is used, the FMECA, with a top-down methodology, the FRAM. FMECA initially filters the failure incidents dataset, while FRAM uncovers performance variability caused by human-machine interactions, allowing the most critical subsystem and the fundamental failure mode to propagate through the day-to-day operational process. In such a way, the research gap between purely technical risk tools and socio-technical safety science in maritime operations is bridged, ultimately enhancing ship availability.

The research introduces the Downtime Risk Number measure.

$$\text{DRN} = \text{Occurrence} \times \text{Midpoint of Downtime Band} \tag{6}$$

Additionally, the classical FMECA scores are converted into a metric that directly represents ship downtime. In such a way, operators are capable of ranking failure modes by ship availability and business impact, and not solely by hazard severity.

Furthermore, the FRAM models illustrate how equipment availability, confined-space access, limited time window, and personnel competence propagate throughout the operational process and affect the ship downtime.

Moreover, this study reveals empirical evidence that corrosion in the steam supply system is a primary failure mechanism that affects ship availability. The analysis of 10 representative failure modes which gained from inspection reports, revealed corrosion as an emerging and frequent failure mechanism, and the steam-supply subsystem of an oil tanker as the most critical subsystem to ship downtime.

The HoC and ALARP framework stands out as an important methodological approach that offers mitigation control measures. Within the study, performance variability insights are translated into a set of controls accompanied by an ALARP framework to support the decision-making process, ultimately enhancing ship availability with balanced risk-reduction measures against complexity and cost.

The integration of the FMECA method and FRAM creates an innovative framework that delivers a clear, quantitative basis to compare and select improvement options that ultimately mitigate operational downtime.

Lastly, iterative interview sessions to gain feedback and validate the results, through member-checking with industry experts, add to the realism of the FRAM models and the feasibility of the proposed controls.

In the scope of this thesis project, the socio-technical analysis using the FMECA and FRAM approach is applied on a single vessel type and a specific fleet of oil tankers. Nevertheless, the method is inherently transferable to different vessel types and operational contexts. In order to obtain valid transferability, the same structured methodological process can be applied in different types of vessels, such as a container ship, considering the different operational contexts. Initially, the system-boundary definition and system decomposition hinge upon a template that can be adopted to every vessel-specific architecture, by substituting the relevant components of the selected subsystem and the corresponding failure mechanisms. Second, the FMECA scoring scales and downtime bands are grounded on literature; however, they can be re-weighted based on locally sourced inspection logs and expert judgments to reflect each context's risk profile. Third, the FRAM functions have been built for generic inspection and maintenance activities that are common to all vessels, while the six aspects of each function are more tailored to the specific context and input. Finally, the HoC-ALARP framework remains the same regardless of the vessel type or the operational context.

This research stands as an asset for the industry. However, some key aspects need to be considered, and it is advised to:

1. Begin with a pilot vessel and a single subsystem that has a high impact to keep the initial FRAM model manageable.

2. Ensure, in time, a high-quality dataset. In such a way, high-resolution results are also guaranteed.

3. Run virtual scenario to experiment with the FRAM pathways, and later on, the suggested control measures.

4. Combine controls that give immediate improvement, such as training sessions for the personnel, with longer-term investments such as the robotic crawlers, for the stakeholders to take the direct benefits while waiting for the longer-term advantages.

Below, Table 7.1 discusses some advantages and barriers that are related to the practical applicability of the methodology developed in this research.

Table 7.1: Overview of facilitating and constraint factors for the practical contribution of the methodology.

Facilitating Factors	**Constraint Factors**
DRN converts abstract failure scores into lost availability hours, so operators and managers can see an immediate economic impact and justify budgets	DRN still require high-quality historical downtime logs
Safety-I (FMECA) is combined with Safety-II (FRAM) in order to address both hardware weaknesses and everyday work-as-done variability that let a fundamental failure propagate	Building a FRAM model is labor-intensive: the organization may need multidisciplinary workshops, iterative modeling, and validation sessions

Facilitating Factors	Constraint Factors
Results in a pyramided package of suggested controls (HoC and ALARP framework). In such a way, the analysis is translated into concrete interventions	ALARP requires an internal cost-benefit analysis
The member-checking sessions validate the methodology and the results.	Same cross-member checking sessions cautioned that virtual trials are an important prerequisite, which at the same time adds lead-time before the tangible results
Engineering controls, such as the robotic crawlers and embedded sensors, can directly address performance variability, such as access to confined areas and the limited time window	Capital cost and technology readiness vary

7.2 Answers to Research Questions

The main research question: *How can a socio-technical modeling approach to maintenance and inspection activities help to identify opportunities for improvement and ultimately mitigate downtime in ship operations?* is addressed through three sub-questions analyzed in detail in Subsection 6.

(i) A bottom-up FMECA is conducted in two stages (RPN and DRN calculation). This analysis points out corrosion on the steam supply system as the dominant downtime driver.

(ii) Consequently, the top-down FRAM reveals the propagation of the four determined performance variability scenarios. Finally, the HoC-ALARP framework is established to identify control measures.

(iii) The integrated FMECA-FRAM structured framework embeds DRN components into the identified control measures. This gives the opportunity to quantitatively evaluate the control measures based on their impact on ship availability.

For SRQ1: *What are the key socio-technical elements and their interrelations involved in inspection and maintenance processes?* the social, technical elements and their interactions are mapped. The social subsystem comprises actors such as inspectors, engineers, classification society members, maintenance planners, docking coordinators, as well as roles and relationships, including the way inspectors hand off findings to planners, planners negotiate resources with operators, and operators coordinate with class surveyors. The technical subsystem comprises general equipment and machinery assemblies, inspection tools, digital checklists, classification rules, maintenance manuals, data management systems, and analysis software. External conditions such as the sea state, temperature, humidity, and operational constraints such as port time windows, yard availability shape the context of the inspection and maintenance process.

This first SRQ can be strengthened by conducting actual vessel visits. A chance to observe a real-world inspection and maintenance workflow and capture the informal coordination and communication patterns among the different teams and individuals, workarounds, will both validate and enrich the literature-derived data. Additionally, the investigation of the role of additional actors such as asset owners, insurance companies within the operational process will contribute to a more holistic socio-technical view.

For SRQ2: *How can the identified elements and their interrelations be modeled from the socio-technical perspective to support inspection and maintenance?* a two-stage FMECA is conducted and the FRAM is used for socio-technical modeling. Every step of this sequential workflow feeds into the next. The oil tanker is broken into subsystems, and by calculating RPNs, the dominant failure mode is identified. Then the DRNs are calculated, and the most critical system, considering downtime, is determined. The FRAM tool is used to model core inspection and maintenance activities and trace the way that performance variability scenarios propagate throughout the operational process.

This second SRQ can be improved through modeling the dynamic behavior of the two distinct perspectives of the socio-technical system, to test what-if scenarios, for instance, sudden equipment failure during port entry, and define the propagation of such a type of probability. Additionally, the data that feeds into the FRAM models can become more robust if collected through multiple vessel visits. By observing different operational processes, performance variability scenarios can be gathered, and their propagation throughout the whole process can be modeled more efficiently and realistically.

For SRQ3: *In what ways can a socio-technical analysis of inspection and maintenance practices reveal opportunities to improve system reliability and reduce downtime?* a risk management strategy is developed and the innovative FMECA-FRAM integration using the socio-technical system perspective. Potential interventions to address performance variability scenarios are mapped, while a quantitative effect on the ship downtime is calculated.

Detailed financial models for each control measure can reveal a more robust risk management strategy. Additionally, embedding a Monte Carlo simulation in the FRAM to quantify the variability propagation throughout the operational process can provide probabilistic estimates of how performance fluctuations cascade across the set of activities. In such a way, the most critical socio-technical interactions that affect downtime will be revealed, and the suggested control measures will be more precisely targeted.

However, it is noteworthy that each new application would need new scoring assignments, based on a high-quality dataset and a cost-benefit analysis that relies on accurate financial data to support decisions under the ALARP principle. The cost-benefit analysis has to be conducted internally at the organization and accordingly to the unique goals, operational, and financial situation. Additionally, it is advised to start implementing the determined control measures with virtual trials, rather than direct fleet deployment.

Hence, the main research question is fully answered for the specific dataset, but partially resolved for utilization in a broader population of vessels.

During the research, the alignment of the FMECA with FRAM needed multiple iterations. While experts' availability for exploratory interviews and cross-member checking sessions lengthened the time frame of the project. The dataset acquisition proved the most intractable part of the methodological process. Access to high-quality and detailed historical failure and downtime logs depends on the availability and cooperation of industry partners. Also, the interpretation of inspection reports into a proper dataset demands manual reviewing and cleaning up.

The study addresses the research gap of existing literature on risk identification in ship maintenance and inspection operations that focuses primarily on technical and engineering solutions. The integration of a two-stage FMECA with the FRAM is an innovative contribution to the literature that reveals a quantitative downtime reduction, which feeds back from a qualitative FRAM without losing traceability. In this way, a closed-loop framework is created that prioritizes failures and investigates the human-machine interactions that need to change. Furthermore, the analysis reveals four performance variability scenarios that occur in the inspection and maintenance operational process, yet are underrepresented in the existing frameworks. Lastly, the risk management strategy and the HoC-ALARP framework stand out as a transparent road map for operators.

7.3 Directions for Future Research

In this Subsection, directions for future research are discussed to enhance ship availability further and mitigate vessel downtime in ship operations.

1. The research conducted for this thesis study focuses explicitly on oil tankers. Fur-

ther investigation is suggested to adopt and validate the developed framework for different types of merchant vessels, such as LNG carriers and cargo ships. Operational urgency, maintenance challenges, and system behavior are diverse in different ship types.

2. The scope is limited to general equipment and machinery subsystems. Further investigation should consider different subsystems, such as structure-related failures, and more complex cross-subsystem interactions. In such a way, additional performance variability scenarios and other critical downtime factors may be revealed.

3. Enriching the dataset with findings from multiple operators and fleets would assist in lowering sampling and reporting bias. Considering factors such as ship age, trade routes, environmental conditions, and maintenance priorities would reveal a more valid result.

4. Sensitivity analysis on the Severity, Occurrence, and Detectability scores would further contribute to a more robust and objective FMECA output.

5. A more sophisticated model for Downtime Risk Number metric calculation, that would consider the non-linearity of the cost variance in repair time, and system-specific reliability data would reveal a more robust output.

6. The suggested control measures may be further tested in a real operational context in order to further validate and verify their feasibility, safety, and effectiveness.

7. An extended cost-benefit analysis that hinges upon high-resolution data would further support the decision-making framework. Quantified potential returns on mitigation control measures investments in alignment with the ALARP principle would provide a more rigorous contribution to the maritime community.

8. The current RPN and DRN metrics are calculated following traditional scoring techniques, which rely on deterministic ratings. These ratings stem from data that are inherently uncertain or incomplete. Further investigation of Dempster-Shafer Theory adoption in the scope of this research would assign belief degrees to RPN and DRN assessments. In this way, the uncertainty would be reduced, and prioritization of failure modes would become evidence-based. Moreover, the confidence in maintenance planning would be enhanced, and a more realistic socio-technical modeling of ship operations would be revealed.

9. The development of a lightweight digital twin prototype that aims to visualize FRAM key performance variability aspects in the context of the vessel's operational process would enable what-if scenario testing in order to bridge the gap between the theoretical results and suggestions and the practical application. In such a way,

a new dimension would be added to the decision-making framework regarding ship availability.

10. Develop a framework that advances the FRAM by adopting a Monte Carlo simulation to assign probability distributions to each function's aspects, thereby generating a distribution for overall system performance and computing function-level sensitivity indices.

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A Full FMECA Dataset

# Failure Mode	Date the inspection was completed	Vessel Type	Products being handled	Hull Type	System	Subsystem	Component	Failure Mode	Cause	Detection (How?)	Local Effect	Global Effect	Severity	Occurrence	Detectability	Corrective Action	Preventive Action	Human Factor
1.	27 Mar 2025	Oil Tanker	Crude Oil	Double hull	Ventilation, A/C & Heating Systems	Mechanical +G2:G8Vents (Monkey Island, Steering Gear, Elevator Space)	Mushroom-Type Ventilation Wheels	*Corrosion:* mechanical stiffness/blockage due to salt buildup and degraded grease	Environmental exposure (salt), inadequate inspection, reliance on assumptions	Identified during inspector's physical check, wheels very tight	Vent wheels hard to operate, potential obstruction or delay in gas ventilation	Potential safety risk if venting is delayed or inaccessible in emergency	3-Moderate (could impact safe ventilation or evacuation access)	3-Moderate (likely in exposed areas without active inspection)	3-Moderate (not visible unless manually tested)	Salt and grease buildup removed, and new grease applied	Additional training, procedure emphasis on verifying, not assuming	Safety officer skipped physical verification - over-reliance on routine schedule
2.	09 Nov 2024	Oil Tanker	Dirty petroleum prodcuts (high flash)	Double hull	Accommodation Electrical Systems	Bridge Wing Lighting	Conduit Pipe for External Light Cable (Port Bridge Wing)	Severe *corrosion* : hard rust scale on 50cm conduit	Inadequate inspection, cosmetic maintenance plan not followed in this area	Visual inspection during audit , not identified during crew inspection	Deteriorated conduit, risk of exposure or failure of electrical cable insulation	Reduced reliability of safety lighting, potential hazard in low-visibility navigation scenarios	3-Moderate localized failure with potential safety impact	3-Moderate identified as isolated, missed during routine rounds	2-High easily visible in safety rounds if properly conducted	Maintenance prioritized, briefing conducted, officer re-trained	Fleet-wide communication, inspection routines reinforced	Safety officer oversight, deviation from procedural expectations
3.	13 Oct 2024	Oil Tanker	Crude Oil	Double hull	Deck Piping Systems	Fuel Oil (FO), Diesel Oil (DO), Cylinder Oil (CYL), Lube Oil (LO), SWG and SLDG lines	Pipework and manifold connection valves (poop deck – port and stbd sides)	External *corrosion:* widespread rusting	Prolonged exposure to marine environment, aging coating, lack of protective maintenance	Visual inspection noted as cosmetic rust, recommendation for possible pipe replacement	Localized weakening of pipes and fittings increased leak or rupture risk	Potential leakage of fuel/lube oils, pollution risk, fire hazard	4 - High (depending on system contents: e.g. FO/DO leaks are critical)	3-Moderate (rust common in exposed deck piping)	2-High (visible during deck rounds)	To be de-rusted and replaced as required	Scheduled repainting, coating maintenance, increased inspection frequency	Degradation overlooked or deferred due to cosmetic classification
4.	13 Oct 2024	Oil Tanker	Crude Oil	Double hull	Anchoring System	Windlass Mechanism	Starboard Windlass Bar Stopper Pin	*Deformation:* worn hole on bar stopper, (wear-induced), unsafe securing of pin	Mechanical wear from repetitive use	Visual inspection during deck survey	Pin insecure, reduced anchoring safety	Risk of anchor loss or uncontrolled release	4	2	2	Rectify in engine workshop	Regular wear monitoring and replacement protocol	
5.	09 Feb 2025	Oil Tanker	Products/ Last cargo mogas 92 ron	Double hull	Inert Gas System	Ballast Tank Control	IG to Ballast Tank Control Valve (No.2 COT Port)	Heavy *corrosion* and material depletion	Prolonged exposure to harsh tank atmosphere, inadequate protective coating	Visual inspection during routine maintenance	Valve integrity compromised, potential malfunction	Loss of control over ballast operations, safety/environmental hazard	4	3	2	To be maintained or replaced	Scheduled coating checks and environmental protection measures	

Figure A.1: Detailed FMECA dataset (Part 1)

# Failure Mode	Date the inspection was completed	Vessel Type	Products being handled	Hull Type	System	Subsystem	Component	Failure Mode	Cause	Detection (How?)	Local Effect	Global Effect	Severity	Occurrence	Detectability	Corrective Action	Preventive Action	Human Factor
6.	09 Feb 2025	Oil Tanker	Products/ Last cargo mogas 92 ron	Double hull	Ventilation/Air Supply	Compressed Air System	Air Line Pipes	*Corrosion* /Rust formation on external surface	Condensation, salt atmosphere, lack of periodic maintenance	Visual inspection, noted during routine check	Material weakening, potential air leaks	Reduced system pressure or failure of pneumatic components	3	3	2	Maintain or renew affected parts	Improve coating maintenance and protective wrapping	
7.	4 Feb 2025	Oil Tanker	Dirty petroleum prodcuts (high flash)	Double hull	Mooring System	Winch Outer Drum (Units W4 and W7)	Safety pin securing plate	*Corrosion* leads to material wastage (unable to secure clutch in disengaged position)	Corrosion and mechanical wear, fabrication delay before reinstallation	Visual inspection, missed during officer's area inspection	Insecure clutch, risk of unintended drum engagement	Safety risk during mooring operation	4 - High (deck machinery failure under load = serious hazard)	3 - Moderate (degradation occurred unnoticed)	3 - Moderate (missed in crew inspection, caught in audit)	New plates fabricated and fitted after sailing	Inspection of all winch plates confirmed rest in good condition	
8.	4 Feb 2025	Oil Tanker	Dirty petroleum prodcuts (high flash)	Double hull	Steam Supply System	Deck Steam Lines for COTs and WBTs	Main and return steam supply pipes, including flanges, bolts, and nuts	Damaged insulation and coating breakdown leading to *corrosion*	Extreme cold weather and heavy sea conditions during last voyage, maintenance deferred	Visual inspection, rust and coating damage observed, insulation missing	Thermal inefficiency, potential pipe corrosion at exposed sections	Heat loss, risk of accelerated degradation of steam line integrity and safety hazard	4	3	2	Insulation and coating renewed, affected areas repaired	Not applicable. Extreme weather prevented earlier intervention	
9.	4 Feb 2025	Oil Tanker	Dirty petroleum prodcuts (high flash)	Double hull	Steam Supply System	Deck Steam Lines for COTs and WBTs	Main and return steam pipes, flanges, bolts, nuts (Aft Piperack)	*Coating* failure, minor leakage, material wastage	Severe weather conditions, deferred maintenance due to extreme cold, and loose fittings	Visual inspection. Rusted surfaces, insulation damage, visible leak at flange	Thermal inefficiency, steam escape, and localized material degradation	Progressive weakening of steam line integrity, potential operational risk	4	4	2	Insulation and coating repaired, bolts tightened, leaking flange section rectified	None recorded, maintenance delay due to harsh environmental conditions	
10.	4 Feb 2025	Oil Tanker	Dirty petroleum prodcuts (high flash)	Double hull	Steam Supply System	Deck Steam Lines for COTs and WBTs	Main and return steam pipes, flanges, bolts, nuts (Aft Piperack)	*corrosion* , minor leakage, material wastage	Severe weather conditions, deferred maintenance due to extreme cold, and loose fittings	Visual inspection. Rusted surfaces, insulation damage, visible leak at flange	Thermal inefficiency, steam escape, and localized material degradation	Progressive weakening of the steam line integrity, potential operational risk	4	4	2	Insulation and coating repaired, bolts tightened, leaking flange section rectified	None recorded, maintenance delay due to harsh environmental conditions	

Figure A.2: Detailed FMECA dataset (Part 2)

B Detailed FRAM function aspects

Table B.1: F1: Survey Planning & Scope detailed aspects overview

Function & Aspect	Description	Modified / Added (Control Measures)
F1: Survey Planning & Scope		
T (Time)	Scheduled survey window (often compressed).	— (unchanged)
I (Input)	Survey request from vessel operator (sometimes ambiguous).	— (unchanged)
O (Output)	Draft survey plan (sometimes incomplete or overly broad).	Validated Survey Plan with Structured Checklist Completed
(Precondition)	Available design drawings & past inspection records.	**Structured Inspection Checklist (Admin control):** The planner cannot output F1 if the checklist is not completed.
R (Resource)	Planning team and their expertise (varied competence).	**Trained Planning Personnel (Administrative control):** Only planners who have completed the standardized training module may execute F1.
C (Control)	Existing company guidelines for survey scope (inconsistent).	**Digital Handover Protocol (Administrative control):** F1's output is only "valid" when signed off by both the maintenance lead & the operations manager.

Table B.2: F2: Preparation detailed aspects overview

Function & Aspect	Description	Modified / Added (Control Measures)
F2: Preparation		

Function & Aspect	**Description**	**Modified / Added (Control Measures)**
T (Time)	Pre-survey preparation window (often short).	— (unchanged)
I (Input)	Draft survey plan (sometimes incomplete).	— (unchanged)
O (Output)	Ready inspection kit (sometimes misconfigured).	Inspection Kit & Robotic Crawler Deployed. Sensor Array Online
P (Precondition)	Accurate equipment list, docking schedule.	**Verified Sensor System Status (Engineering control):** All sensors must be active & calibrated before F2 can be completed.
R (Resource)	Tools and personnel (varied availability).	**Robotic Crawler Pre-Deployment (Engineering control):** Robot must be physically present, charged, and tested before F2 can output "ready."
C (Control)	Local supervisor's approval (sometimes rushed).	**Dynamic Scheduling Algorithm (Admin control):** Real-time reallocation of personnel & equipment; F2 cannot finalize if scheduling conflicts remain.

Table B.3: F3: Visual Inspection detailed aspects overview

Function & Aspect	**Description**	**Modified / Added (Control Measures)**
F3: Visual Inspection		
T (Time)	On-site inspection window (sometimes constrained).	— (unchanged)

Function & Aspect	Description	Modified / Added (Control Measures)
I (Input)	Ready inspection kit (often incomplete).	**Embedded Sensor Data Feed (Engineering control):** F3 cannot start unless sensors report no active alerts in that compartment.
O (Output)	Preliminary defect log (missed occluded zones).	**Comprehensive Defect Log (Sensor Alerts + Robotic Imagery & Human Confirmation)**
P (Precondition)	Adequate lighting & physical access (often limited).	— (original conditions still apply, but see R & C below)
R (Resource)	Human inspectors and handheld tools (varied competence).	**Robotic Crawler Assist (Engineering control):** Robot's camera and NDT probes feed into F3, eliminating many hidden-spot failures.
C (Control)	Supervisor "spot-check" (infrequent).	**Standardized Visual Inspection Protocol (Administrative control):** Tablet-based digital checklist; the inspector must complete each step before proceeding.

Table B.4: Function F4: Advanced Inspection & Measurement detailed aspects overview

Function & Aspect	Description	Modified / Added (Control Measures)
F4: Advanced Inspection & Measurement		
T (Time)	Specialized measurement window (often delayed).	— (unchanged)

Function & Aspect	Description	Modified / Added (Control Measures)
I (Input)	Preliminary defect list from F3 (often incomplete/low-resolution).	**Real-Time Sensor Threshold Alerts (Engineering control):** Sensor array flags priority areas so F4 focuses on actual hotspots.
O (Output)	Detailed thickness readings / NDT results (sometimes unreliable).	**Validated, High-Resolution Measurement Report with Timestamped Calibration Logs.**
P (Precondition)	Access to test points, calibrated instruments.	**Instrument Calibration Tracker (Administrative control):** Digital ledger ensures that probes/gauges are certified within the required interval before F4 begins.
R (Resource)	NDT technician, ultrasonic gauge, thickness probes.	**Robotic Precision Probe (Engineering control):** The robot holds the probe at a fixed angle for repeatable measurements, eliminating fatigue-induced errors.
C (Control)	Calibration certificate (occasionally expired).	— (moved into P as calibration tracker; original control "certificate" now enforced via digital check)

Table B.5: F5: Maintenance Actions detailed aspects overview

Function & Aspect	Description	Modified / Added (Control Measures)
F5: Maintenance Actions		

Function & Aspect	Description	Modified / Added (Control Measures)
T (Time)	On-board repair window (often very short).	— (unchanged)
I (Input)	Detailed inspection report from F4 (sometimes late/incomplete).	— (unchanged)
O (Output)	Completed repairs or temporary patches (sometimes patchfixes).	**Certified Repair Completion with Digital Trail:** Spares used, welding logs, and PTW records automatically logged.
P (Precondition)	Availability of spares, welder/technician, dry-dock slot.	**Automated Spare Parts Inventory Check (Administrative/Engineering control):** System confirms spares on board or issues real-time order fill & pre-deployment.
R (Resource)	Maintenance crew, tools, consumables (varied availability).	**Specialized Robotic Welding Arm (Engineering control):** Robot performs confined-space welds, ensuring uniform quality irrespective of human skill.
C (Control)	Work permit (often delayed).	**Dynamic Work Permitting System (Administrative control):** Auto-approves low-risk tasks when safety prerequisites are met, eliminating permit-hold delays.

Table B.6: F6: Report Format, Evaluation & Repair Criteria detailed aspects overview

Function & Aspect	Description	Modified / Added (Control Measures)
F6: Report Format, Evaluation & Repair Criteria		
T (Time)	Post-repair evaluation window (often compressed).	— (unchanged)
I (Input)	Completed maintenance action + initial measurements (sometimes delayed).	— (unchanged)
O (Output)	Final "Go/No-Go" decision or next inspection interval (often delayed).	**Final Decision Report with Embedded Lessons-Learned for Next Survey Cycle**
P (Precondition)	Compiled data from F3, F4, F5 (often patchy).	**Integrated Data Dashboard (Engineering/Admin control):** Consolidates time-stamped sensor logs, robotic imagery, and maintenance logs. No missing data.
R (Resource)	Data analyst or Quality Assurance officer.	**Digital Report Template with Automated Checks (Admin control):** Flags anomalies and prevents "OK to sail" until secondary reviews are triggered.
C (Control)	Company guidelines for pass/fail criteria (sometimes outdated).	**Continuous Feedback Loop to F1 (Administrative control):** Immediate push of lessons learned from F6 back to F1's Structured Checklist, ensuring continuous improvement.

C Interview Protocol and Questions

This appendix presents the structure as well as the conditions under which the exploratory interviews and the validation sessions through expert feedback are conducted in the scope of this thesis study.

Interviews intention is the collection of insights and domain knowledge for the oil tanker inspection and maintenance operational process. Information about failure modes, human-machine interactions, and performance variability is aimed to be gathered through the exploratory interviews. Furthermore, validation sessions through expert feedback are also conducted to present the scope, applied methodology, FMECA results, FRAM models, and the suggested control measures.

In the exploratory discussions, three experts are interviewed, while in the feedback sessions, the same three experts plus two members participate.

The semi-structured format gives flexibility to both the researcher and the participants, while at the same time reassures that important topics are covered. Exploratory interviews are guided by the set of predefined questions presented below. Validation sessions include a detailed presentation and follow-up questions, discussion, and feedback on the relevance, applicability, practicability, and completeness of the findings.

Some of the interviews are conducted in person and others via video call, and each of them lasted approximately 60 minutes. However, none of the sessions were audio-recorded due to the organization's confidentiality policy. For this reason, transcripts are not included in this appendix.

Noteworthy, before each session, each of the participants is informed about the research purpose and the aim of the information that is provided.

- Overview of Activities

    1. Does the process diagram in Figure C.1 correspond to the correct phases/stages of a generalized operational process?
    2. What are the main activities involved in the daily work of the inspection and repair personnel?
    3. How does the inspection and maintenance team prioritize tasks during routine operations, when dealing with the failure modes such as corrosion, coating, deformation, and fatigue-induced cracks?
    4. What signals or events indicate the start of a specific activity, and who is responsible for initiating it? (What triggers the decision to start the inspection?)

5. How do environmental or workplace conditions affect the ability of the inspection and maintenance team to carry out operations?

- Failure Mode Effect and Criticality Analysis
  1. What are the most common failure modes encountered in inspection and maintenance operations, and how do these failure modes affect ship operations?
  2. How does the inspection and maintenance team assess the most critical failures, considering their impact on safety, downtime, and operational efficiency?
  3. In your experience, what are the primary causes of these failures (e.g., technical defects, environmental conditions, or human error)?
  4. What strategies or interventions have been effective in preventing or mitigating the impact of these failures?
  5. Can you share an example of a failure incident, including what caused it, how it was resolved, and what changes were implemented to prevent recurrence?
- Performance Variability
  1. What adjustments do inspection and maintenance personnel make to perform tasks when conditions are not ideal?
  2. Can you describe situations where unexpected issues arise (e.g., interruptions or missing resources) and how the inspection and repair team responds to them?
  3. Can you describe situations where unexpected issues arise and how the inspection and repair team responds to them?
  4. Are specific inspection and maintenance activities prone to frequent changes or variability in execution?
  5. How does time pressure influence the work processes of inspection and maintenance personnel?
- Aspects
  1. What information, materials, or signals are required for inspection and repair personnel to start their tasks?
  2. What happens if these inputs are delayed or unavailable?
  3. What are the expected results of the inspection and maintenance team's work tasks?
  4. What challenges does the team face in achieving these outcomes, and how are they overcome?

5. What conditions or preparations must be in place before an activity begins?
6. What does the inspection and maintenance team do if these preconditions are not met?
7. What tools, equipment, or resources does the inspection and maintenance team rely on to perform their tasks?
8. How does the inspection and maintenance team handle situations where these resources are insufficient or unavailable?
9. What guidelines, protocols, or procedures guide the inspection and maintenance team's work?
10. How often does the inspection and maintenance team deviate from these protocols and why?
11. How do deadlines or time constraints affect the inspection and maintenance team's ability to perform tasks effectively?
12. How does the inspection and maintenance team communicate and collaborate with other team members or departments during their tasks?
13. What role does coordination play in ensuring the successful completion of activities?
14. Can you share an example of a task in which collaboration significantly impacted the outcome?

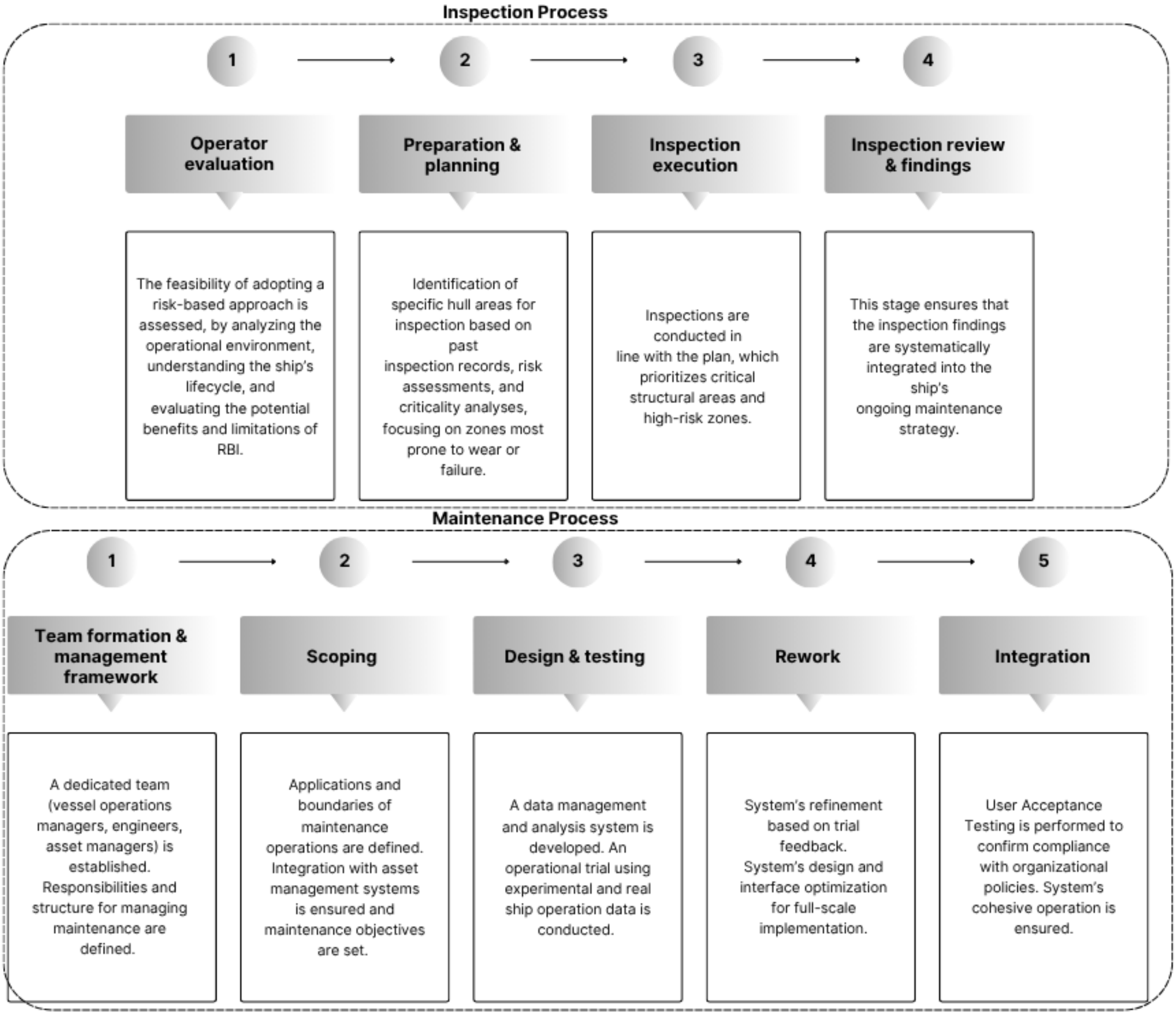

Figure C.1: Inspection and maintenance operational process