Incorporating Socio-Technical Perspective on Ammonia-Powered Ship Safety Risk Management

With a focus on the Engine Room

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by

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Preface

As the world aims to reduce global emissions, maritime transportation, one of the largest contributors to the carbon footprint, is transitioning to alternative fuels. Among these, anhydrous ammonia (NH3) has emerged as a notable option. However, its toxic nature presents significant safety challenges in implementation. This master thesis explores risk management strategies to enhance the safety of the ammonia-powered ship engine rooms by adopting a socio-technical perspective. This report is submitted as part of the graduation requirements for the Master Programme in Management of Technology at the Faculty of Technology, Policy and Management, Delft University of Technology.

The report is organized into several chapters, each focusing on a distinct aspect of the research, combining both qualitative (socio-technical system perspective) and quantitative (quantitative risk assessment) studies. The final chapter presents an integrated approach, evaluating the combined methodologies. Readers interested in the development and results of the socio-technical system within the ship engine room are directed to Chapter 4. Those seeking an understanding of the quantitative risk assessment (QRA) methodology for ammonia-powered ship engine rooms should refer to Chapter 5. Chapter 6 details the risk management strategies, including modifications, risk evaluations, and assessments.

I would like to express my gratitude to Prof. Dr. Ir. Pieter van Gelder, chair of the thesis committee, for his guidance and support throughout this process. Special thanks to Dr. Ming Yang and Rustam Abubakirov for their trust and for providing the opportunity to undertake this thesis project. Your invaluable supervision and discussions have been instrumental since the project's inception. I am also deeply grateful to Dr. Arie Adriaensen for his expertise and guidance in the FRAM model, which provided critical insights throughout the project. Additionally, I would like to thank our industrial partner, Anthony Veder, especially Machiel Mastenbroek, Karin Kuipers, and Stefan van der Harst, for their trust, collaboration, and invaluable guidance. Your professional qualities are ones I aspire to in my future career.

Lastly, I extend my heartfelt thanks to everyone who supported me during my master's studies at TU Delft. To my parents and family, thank you for your prayers, support, and for giving me the opportunity to study abroad. To my friends and the members of the Perhimpunan Pelajar Indonesia di Delft (PPI Delft), thank you for brightening these two years in the Netherlands. And to "you know who you are," your support through the ups and downs of this process has meant everything to me. I wish you all the best in your future endeavors.

I hope this thesis inspires future research and development in the implementation of ammonia as a maritime fuel. May its findings contribute to the collective pursuit of sustainable shipping in the future.

"With thanks to my parents who allowed me to dream …"

—Randy Pausch (The Last Lecture)

Devano Yehezkiel Adipradhana
Delft, August 2024

Summary

This research integrates a socio-technical perspective into the safety risk management of ammonia-powered ships, with a particular focus on the engine room. The objective is to develop strategies that enhance crew safety by examining the complex interactions between humans, organizations, and machines within this high-risk environment.

The international shipping industry, responsible for a significant portion of global greenhouse gas emissions, faces an urgent need to adopt more environmentally friendly technologies. Anhydrous ammonia (NH3) has emerged as a promising alternative fuel due to its carbon-free nature and higher volumetric energy density compared to other fuels. However, ammonia's toxicity presents substantial challenges, especially in enclosed spaces like the engine room, where crew members are at increased risk of exposure.

Current research predominantly addresses the engineering aspects of ship design to minimize ammonia leakage risk but lacks a focus on safety risk management through a human-centered approach that enhances crew safety. This research addresses this gap by adopting a socio-technical system (STS) approach, emphasizing the intricate dynamics and implications of human interaction with new technology. The study demonstrates that incorporating a socio-technical perspective through the Functional Resonance Analysis Method (FRAM) provides a comprehensive understanding of human-machine interactions, enabling the development of human-oriented modifications.

Employing a multidisciplinary approach, this research combines qualitative and quantitative methods. FRAM is used for qualitative analysis, offering detailed insights into interactions and performance variability within the socio-technical system. This research developed the complex STS relationships through Work-as-Done FRAM, identifying actor roles, time spent, location, and procedures related to engine room activities. Complementing this, Fault Tree Analysis (FTA) and Quantitative Risk Assessment (QRA) provide a deeper understanding of risk factors and their implications.

The findings indicate that adopting a socio-technical approach to safety risk management can significantly enhance the safety of ammonia-powered ships. This research has developed modification frameworks that integrate human-machine interaction activities derived from FRAM with necessary system modifications. The study identifies on-board maintenance activities as having the highest probability of crew presence in the engine room (P_{ER}). By modifying the engine room layout and work procedures with the on-board maintenance as considerations, the Individual Risk Per Annum (IRPA) can be substantially reduced from the current value of $1.33E-05$ to $2.00E-06$. Normatively, these modifications result in an IRPA level that is lower than that of the currently operating LNG (CH4) powered ship engine room, which has an IRPA value of $3.16E-06$. Thus, these modifications meet the risk acceptance criteria as outlined by the IGF Code guidelines.

The research provides several recommendations for stakeholders within the maritime industry. These include modifications to engine room layout and task locations to minimize human exposure to ammonia leaks, advancements in on-board maintenance procedures specifically for ammonia, enhancement of gas sensor response times, and digitization of the engine room logbook. These strategies aim to ensure safe operations and support the adoption of ammonia as a sustainable maritime fuel.

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Nomenclature

Abbreviations

Abbreviation	Definition
AEGL	Acute Exposure Guideline Levels
ALARP	As Low As Reasonably Practicable
CDM	Critical Decision Method
CE	Chief Engineers
CFD	Computational Fluid Dynamics
CH4	Methane
DF	Dual Fuel
ECR	Engine Control Room
EPA	Environmental Protection Agency
EoW	Engineer on Watch
ER	Engine Room
ESD	Emergency Shut Down
ETA	Event Tree Analysis
FMEA	Failure Mode and Effect Analysis
FPR	Fuel Preparation Room
FRAM	Functional Resonance Analysis Method
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
GVU	Gas Valve Unit
HA	Hazardous Atmosphere
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HFO	Heavy Fuel Oil
IACS	International Association of Classification Societies
IGF Code	International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IMO	International Maritime Organization
IRPA	Individual Risk per Annum
ISO	International Organization for Standardization
LCP	Local Control Panel
LFL	Lower Flammability Limit
LNG	Liquefied Natural Gas
LOC	Loss of Containment
LPG	Liquefied Petroleum Gas
LSIR	Location Specific Individual Risk
MGO	Marine Gasoline Oil
NH3	Ammonia
OSHA	Occupational Safety and Health Administration
QRA	Quantitative Risk Assessment
SCRA	Slip Collision Risk Analysis
SNA	Social Network Analysis
STAMP	System-Theoretic Accident Model and Processes
STS	Socio-Technical System

Abbreviation	Definition
UMS	Unmanned Machinery Spaces
WAD	Work-as-Done
WAI	Work-as-Imagined

Symbols

Symbol	Definition	Unit
C	Concentration of the substance	[kg/m^3]
d	Leak hole diameter	[mm]
F_{DW}	Double-walled pipe factor	[-]
$IRPA$	Individual Risk per Annum	[-]
L	Engine line pipe length	[m]
$LSIR_{ER}$	Location specific individual risk (engine room)	[-]
N	Number of components	[-]
P_{ER}	Probability to be present inside the engine room	[-]
P_{exp}	Probability of exposure	[-]
P_{fat}	Probability of fatality	[-]
P_{gd}	Probability of gas detector failure	[-]
P_{leak}	Annual release frequency	[/year]
P_{sc}	Probability of scenario	[-]
P_g	Pressure of fuel system	[barg]
Pr	Probit functions	[-]
Q_g	Vapor source term	[kg/s]
t	Duration time of leakage	[s]
t_{exp}	Exposure time	[s]
t_{iso}	Isolation time	[s]
V	Volume of confined space (engine room)	[m^3]
v	Ventilation rate	[m^3/s]
ρ_g	Density	[kg/m^3]
λ_{LOC}	Frequency Loss of Containment	[-]

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Introduction

1.1. Background

The international shipping industry currently provides logistics services for 80% of global goods by volume, yet it contributes to 2.8% of global greenhouse gas (GHG) emissions (UNCTAD, 2023). Despite efforts to lower emissions per ton-mile, the vast fleet of the three main vessel types—container ships, tankers, and bulk cargo ships—remains responsible for a significant portion of total carbon dioxide emissions, with values exceeding 600 tonnes of CO2 emitted annually. With shipping demands increasing rapidly and outpacing improvements in fuel efficiency, the shift to more environmentally friendly technologies and operations has become an urgent priority to meet the goals of the Paris Agreement, established at COP21 in 2015 (UNCTAD, 2023). The International Maritime Organization (IMO) has proposed revised goals for GHG reduction, aiming to reduce CO2 emissions by at least 40% by 2023 compared to 2008 levels, suggesting a transition towards zero-carbon fuels (Internaional Maritime Organization, 2022; European Maritime Safety Agency, 2022).

Anhydrous ammonia (NH3), a carbon-free molecule, emerges as a promising alternative fuel for achieving zero-carbon maritime goals due to its potential for rapid market entry (European Maritime Safety Agency, 2022; Balci et al., 2024). Ammonia can be produced from fully renewable and carbon-free resources, aligning with the IMO's zero-carbon targets and termed as green ammonia (Balci et al., 2024). According to a study by Lloyd's List and Lloyd's Register (LR), ammonia is expected to be among the top three zero-carbon fuels in the maritime industry by 2050 (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). Additionally, ammonia is considered a viable option because ships will predominantly operate in remote areas, which reduces the risk of ammonia leakage and contamination in residential areas. Consequently, there is increasing research interest in developing ammonia-powered ships that are expected to enter service in the coming years.

Despite its advantages, such as higher volumetric energy density compared to hydrogen and methanol, suitability for combustion engines and fuel cells, and the absence of carbon dioxide emissions, ammonia's toxicity presents significant barriers to its implementation (Balci et al., 2024; Magpie, 2023). Ammonia leaks, even at a concentration of 0.27%, can result in fatalities within 10 minutes of total exposure (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). Although several shipping companies have experience designing vessels for transporting ammonia as cargo, no ships have yet entered service using ammonia as fuel due to the different risk levels compared to its use as cargo (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). Furthermore, despite the ships' operation in remote areas, the crew onboard remains exposed to the risk of ammonia leakage. Enclosed spaces, such as the engine room, present a higher risk of fatality due to ammonia exposure (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023).

Several research studies have been conducted to understand the potential risks associated with using ammonia as fuel for ships and its impact on ship design, safety, and operations. A collaboration between Lloyd's Register Maritime Decarbonisation Hub (MDH) and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) focused on ship design recommendations for risk reduction using quantitative risk assessment (QRA) and considering human factors (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). Research has also improved understanding of safety zones, hazard identification, and ammonia bunkering safety guidelines for ammonia-powered ships (Duong et al., 2023). Studies examining the relationship between ship design, operations, human performance, and safety indicate that ship design can enhance safety by minimizing human errors (Endrina et al., 2019). Key human factors impacting ship safety include competency, processes and procedures, occupational safety, and process safety (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023).

1.2. Research Problem

Concerns about the safety of ammonia-powered ships have driven several research studies focusing primarily on quantitative risk assessment (QRA) methods. Engineering solutions have been developed to mitigate the risk of using ammonia as fuel to acceptable levels. However, most of these solutions concentrate on the mechanical components of ship systems and engineered solutions to minimize potential leakage. There is a notable lack of studies addressing safety risk management aimed at enhancing the safety of onboard crew members, particularly in critical enclosed spaces such as the engine room.

Given the complexity of ship systems and the presence of humans onboard with specific roles and responsibilities in operations and safety, understanding the intricate dynamics and implications of these systems is crucial. Limited research has focused on human interaction with new technology, especially concerning its potential future risks. Despite the similarities in tasks performed when operating ammonia-powered engines compared to LNG-powered engines, the onboard crew faces a higher probability of fatal risk due to ammonia toxicity. The time spent inside the engine room is critical to ensuring crew safety (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). It is highly recommended to adopt a human-centered approach in designing systems and specifications within critical spaces like the engine room (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). Enabling the crew to monitor and perform tasks remotely, outside the engine room, has emerged as a potential solution. However, it remains unclear which specific tasks within the engine room most significantly impact crew safety (Trivyza et al., 2021). Research that develops engineering solutions considering safety risk management through human interaction with machines is limited, presenting an opportunity for a new perspective on managing the risks associated with ammonia as a ship fuel.

A multidisciplinary approach focusing on human and machine interactions to gain a more detailed understanding of the risks could enhance the safety and risk management of ammonia-powered ships. In the engine room, risks arise when individuals are present performing maintenance or operational tasks. Thus, it is essential to consider the human element within the system, which can be examined from a socio-technical system perspective. This perspective provides insights into "what actually happens," "when it takes place," "why it should be done," and "what the relationship between tasks is" inside the engine room. This approach in safety systems, known as resilience engineering, considers socio-technical systems to understand the impact of complexity on system behavior and performance (Patriarca, 2021). Additionally, enhancing socio-technical systems for risk assessment could improve the safety management of ammonia-powered ships, as safety is not solely a property of technical aspects but also an outcome of interactions within the systems (Yang et al., 2017). Understanding the complex interactions between humans, organizations, and technology could lead to more comprehensive hazard identification and a better understanding of the causes behind failures due to unsuitable processes. Consequently, this could facilitate the development of more suitable systems and risk management strategies to enhance the safety of ammonia-fueled ship crews.

1.3. Research Objective

The aim of this research is to develop safety risk management strategies that enhance crew safety on ammonia-powered ships by employing a socio-technical perspective for risk analysis. This approach, which examines the interactions between humans, organizations, and machines, offers novel insights into hazard identification and assessment. The research seeks to provide recommendations for ship manufacturers, operators, and regulators, with a particular focus on the engine room, where time spent inside has a significant impact on the Individual Risk per Annum (IRPA) for the engineering team (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). Recommendations will be used to assess safety levels through Quantitative Risk Assessment (QRA) and to evaluate results in relation to the Risk Acceptance Criteria (RAC).

1.4. Research Question

To achieve the research objective, author comes up with the main research question:

What strategies can be employed to enhance safety risk management in Ammonia Powered Ships engine room by incorporating socio-technical system perspective?

With the following sub-questions:

1. What socio-technical elements inside the Ammonia Powered Ship engine room that can be identified?
2. What is the relationship between the socio-technical elements performed the engine room?
3. How to enhance the safety of the ammonia powered ship engine room by understanding the relationship between elements of socio-technical systems?

1.5. Relevance to MOT Programme

The Management of Technology (MOT) aims to provide students with an understanding of technology as a corporate resource and to determine how industries can leverage technology to enhance existing processes. The program also addresses the challenges associated with technology implementation, including limitations such as safety concerns. Ammonia, as a maritime fuel, is considered a new innovation that faces challenges in its development and implementation phases, despite its promise to meet the increasing demand for shipping while reducing carbon emissions. However, the development and implementation of this technology are hindered by ammonia's toxic nature. Ensuring the safety of the onboard crew is a significant concern, and strategies must be developed that consider the feasibility, complexity, and practicality of solutions.

This research does not focus solely on the technical or mechanical aspects of ammonia-powered ships. Instead, it examines the socio-technical system of the ship's engine room and fuel preparation room, including human and organizational tasks, communication, and activities within the process. Enhancing onboard safety through a risk management strategy could support the implementation and development of this technology by emphasizing readiness to adopt it with respect to crew safety, considering corporate resources, organizational structures, and knowledge.

This research aligns with the MOT program's criteria, which explores how firms can use technology to design and develop products and services that improve outcomes. In this case, the focus is on enhancing employee safety, demonstrating the program's commitment to integrating technology management with practical safety considerations.

2

Theoretical Background

2.1. Ammonia Powered Ship System

The ammonia-powered ship shares similarities with that of the Liquified Natural Gas (LNG) powered ship that has been in operation. LNG fuel can be utilized in internal combustion engines, akin to diesel-fueled ships, often in a dual-fuel engine configuration. This setup enables the ship to utilize a mixed source of energy, transitioning the fuel from diesel to gas and vice versa.

The ammonia cargo tank that is independent and specified in the IGC Code can be used as the ammonia fuel tanks (ClassNK, 2022). As illustrated in Figure 2.1, the location of the fuel tank could be installed on the open deck with a dedicated fuel tank, which might be less complex, or below the deck by using the cargo tank as the fuel tank (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). The configuration of the ammonia fuel tank depends on each ship design and manufacturing company, with each design choice having its own advantages and disadvantages in terms of engineering and economic evaluation (Seo and Han, 2021).

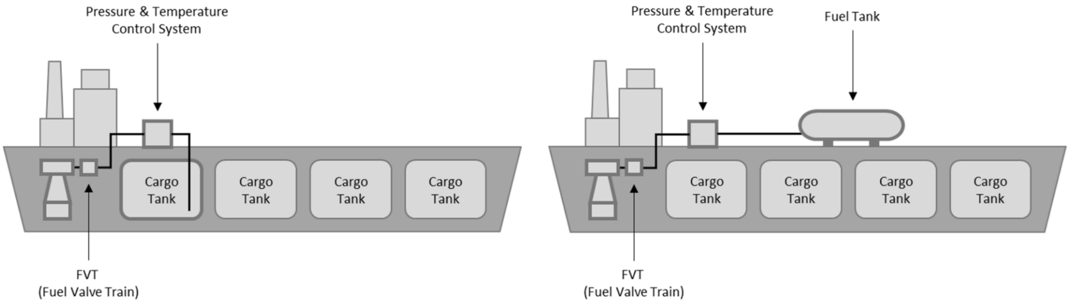


Figure 2.1: The two conifgurations of fuel tanks for ammonia-powered ship (Seo and Han, 2021)

As the research will focus on the engine room, the following literature review will explain the technical system and the tasks performed within this space. The ship's general arrangement design is divided into four parts, as shown in Figure 2.2, consisting of the after body, engine room, cargo hold, and fore body (Roh and Lee, 2017). The engine room is typically located under the deck, directly below the accommodation space of the vessel, as illustrated in Figure 2.3. This space is dedicated to mechanical components such as auxiliary engines, boilers, fuel oil tanks, and other engine-related equipment. These spaces can be accessed by the engineering crew to perform operational tasks and maintenance. However, there are no explicit norms or dominant design standards in the maritime organisation that govern the location of the accommodation deck. Especially considering the effect of utilising ammonia as a fuel and its relationship to the location selection of the accommodation deck, which falls outside the focus of this research. As a result, the relationship between the engine room and the accommodation deck will not be examined in this study.

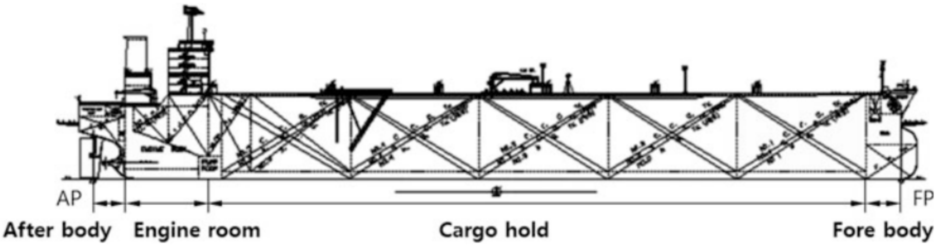
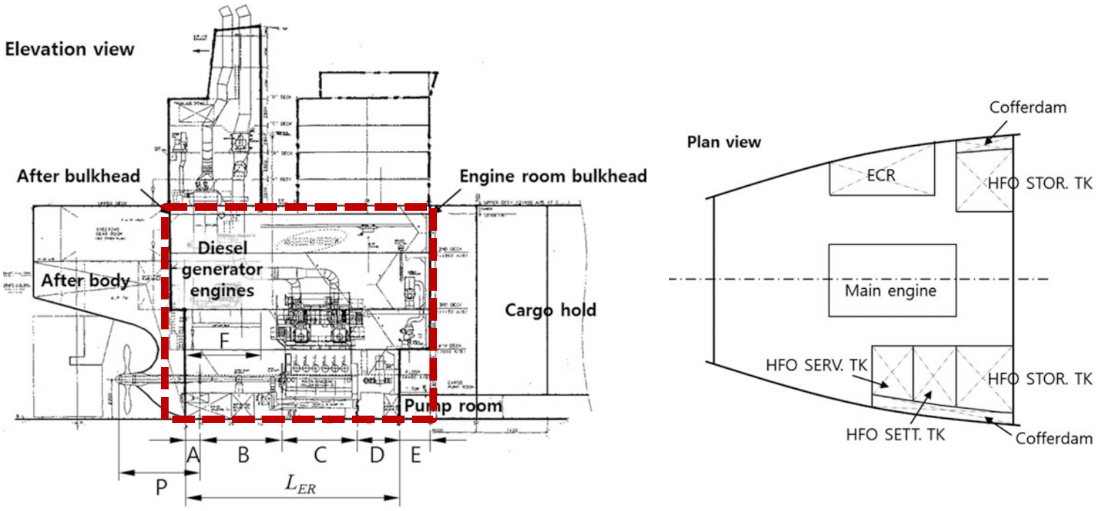


Figure 2.2: The four parts of the ships (Roh and Lee, 2017)

Several rooms exist within the general plan of the engine room, each serving operational, control, and maintenance purposes. The facility inside the engine rooms that described from the general arrangement plan for ships are (Roh and Lee, 2017):

1. **Engine Control Room (ECR)**: primarily functions to control the main engine, including tasks such as starting/stopping the main engine, controlling forward and backward motion, regulating speed, and managing states. This location is typically situated near the main engine for ease of monitoring and task execution.
2. **Pump Room**: located between the engine room and cargo tanks, primarily utilized for maintenance purposes.
3. **Emergency Exit Trunks**: the emergency access from the engine room to the upper deck to provide safety of the crew.
4. **Engine Room Workshop**: designated for storing machining tools and mechanical parts.
5. **Engine Room Store**: utilized for storing spare parts related to the engine.
6. **Purifier Room**: employed for purifying oil and lubricant oil for ship operations.



Side View

Top View

Figure 2.3: The general arrangement plan of the engine room from side view (red box) and top view (Roh and Lee, 2017)

The engine room should be ”gas safe,” indicating that all piping entering the engine room should be double-walled to ensure the safety of the engine room (Kokarakis, 2015). Gas valve units (GVU) serve as pressure control and safety systems ensuring the safe operation of the engine and might be located in the engine room, depending on the ship’s design (Bureau Veritas, 2019). Studies have shown that the large space of the engine room presents challenges for ammonia leakage detection (Lloyd’s Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). The detailed arrangement of the engine room and the other related system within an LNG-fuelled ship installation can be seen in Figure 2.4.

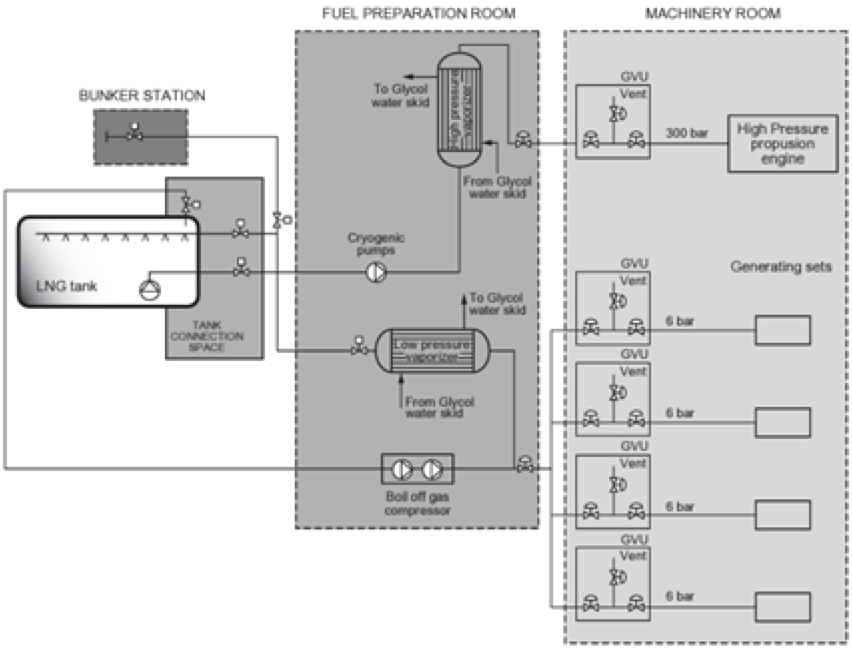


Figure 2.4: The detailed view of systems that related to the engine room system (Bureau Veritas, 2019)

The engine room is a closed area where the maintenance and inspection are performed by the crew members. The research conducted to ammonia-ship safety founds that time spent on the enclosed space such as engine room is critical to ensure the safety of the crew members (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). The further analysis to increase the safety level of the engine room will be conducted through out this research.

2.2. Risk of Ammonia as fuel

2.2.1. Flammability of Ammonia

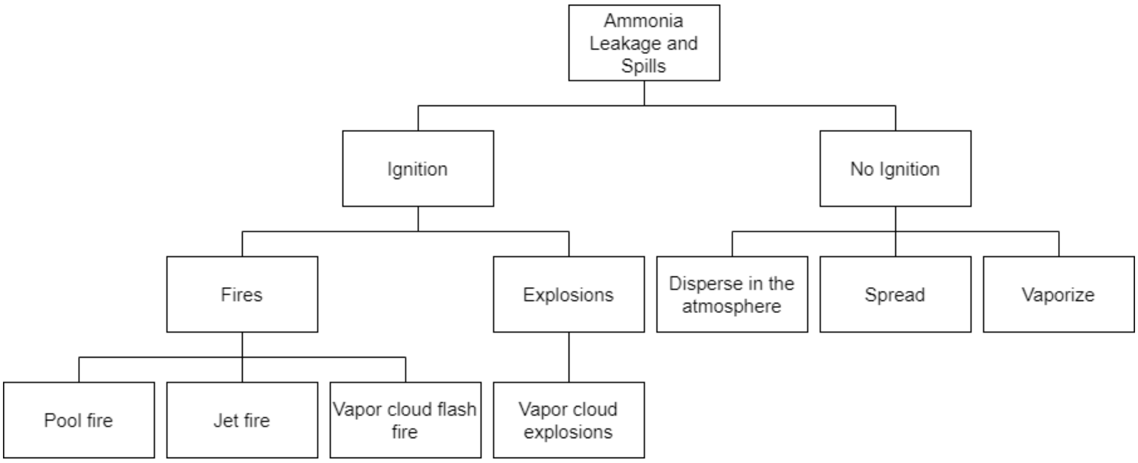


Figure 2.5: The main hazards of ammonia as fuel (Duong et al., 2023)

The leakage and spills of ammonia could lead to toxic effect on surroundings and even lead to an ignition of fires or even explosions (Duong et al., 2023). The main hazards of the ammonia leakage can be seen on Figure 2.5. When the leakage or spills take place, the ignition could start to four potential risk of vapor cloud flash fire, jet fire, pool fire and even vapor cloud explosion. The ignition temperature of ammonia is 651°C in atmospheric conditions, which is high compared to other LNG fuels. Additionally, compared to other LPG and LNG, ammonia has a low burning rate, and dispersion may take time, reducing the probability of ammonia fire risk (Pomonis et al., 2022). However, the leakage from a high pressure storage such as fuel tank Type C could lead to a faster diffusion of ammonia, exposed to a high level of danger for flammability, especially in semi-closed and closed spaces (Duong et al., 2023; ClassNK, 2022).

The findings shown that ammonia has a low risk probability compared to other LNG substance, despite having a potential to ignite the fire due to leakage. Therefore, flammability of the ammonia substance is not the top main risk that posed the hazard to the crew safety (Pomonis et al., 2022, Duong et al., 2023). The toxicity of the ammonia substance is the main focus of the fuel implementation safety on current researches, and will be discussed in the following chapter.

2.2.2. Toxicity of Ammonia on Human

The ammonia leakage also posses a great level of danger despite no ignition during the process. The leakage could lead to the potential of ammonia vaporization, spread and disperse in atmosphere. Considering it might produce a toxic clouds that rise into top of the atmosphere due to its lighter-than air properties, it posses toxic hazard for personnel and surroundings environment (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023).

The effect of ammonia on human based on the concentration level can be seen on Table 2.1. In general, the exposure to a high level concentration of ammonia could leads to burns on several body parts of human such as eyes, nose, throat and respiratory system. The exposure could also lead to a skin burns, blindness, lung damage and potential to death.

Table 2.1: The effect of ammonia on humans based on concentration level (ClassNK, 2022)

Ammonia concentration (ppm)	Effect on humans
5 - 10	Detectable by smell
50	Feeling of discomfort
100	Feeling of irritation
200 - 300	Irritation of eyes and throat
300 - 500	Bearable only for the short time (20 - 60 minutes)
2,500 - 5,000	Life threatening in short time (about 30 minutes)
5,000 - 10,000	Respiratory arrest (fatal in short time)

The limitations of ammonia exposure time are based on the Acute Exposure Guidelines (AEGL) developed by the Environmental Protection Agency (EPA) in the US, as shown in Table 2.2. The relationship between ammonia concentration and exposure times enables the identification of the risk level and its impact on the human body. These guidelines will serve as the basis for safety measures in this research to determine the maximum time when a certain level of ammonia leakage concentration occurs. The descriptions of each defined level are as follows:

1. **AEGL 1**: Discomfort. irritation or asymptomatic non-sensory effect
2. **AEGL 2**: Irreversible or serious long lasting health effect
3. **AEGL 3**: Life-threatening health effect or death

Table 2.2: The EPA Acute Exposure Guidelines Levels of Ammonia (EPA, 2023)

Levels	10 min	30 min	60 min	4 hrs	8 hrs
AEGL 1	30	30	30	30	30
AEGL 2	220	220	160	110	110
AEGL 3	2,700	1,600	1,100	550	390

The Figure 2.6 brings the perspective of ammonia concentration when the leakage occurs on the engine room with ventilation of 30 air changes per hour based on Computational Fluid Dynamics (CFD)

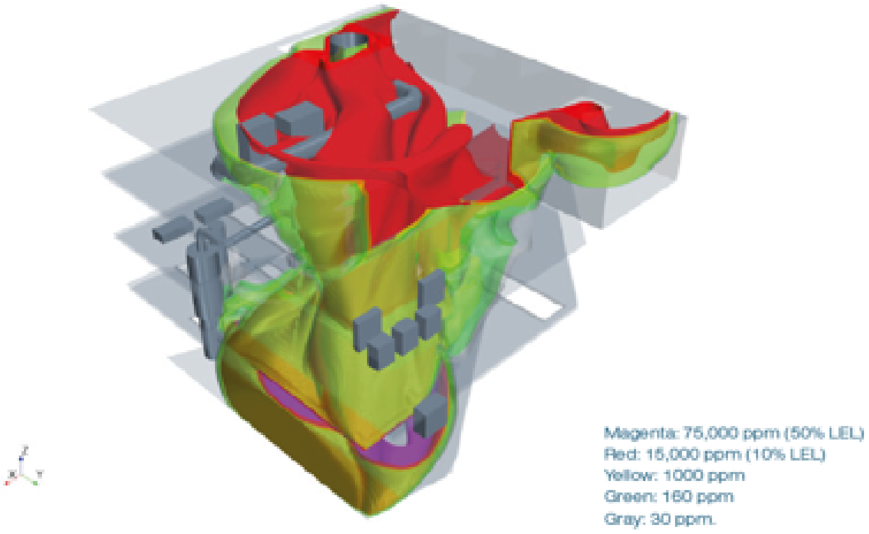


Figure 2.6: CFD simualtions of 0.23 kg/s leakage of ammonia on ventilated engine room (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023)

simulation (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). It is shown, despite the presence of ventilation, the highest concentration of ammonia could reach the value of 15,000 - 75,000 ppm which has a very high fatality on human body (ClassNK, 2022). Another research on ammonia leakage in the engine room has shown that a concentration of 5,000 ppm could be reached after 90 seconds in some parts of the engine room, indicating the need for quick gas detection and response under 10 minutes when leaks occurs (Pomonis et al., 2022; EPA, 2023).

The ammonia substance has a higher level of toxicity compared to other LNG fuels, indicating the need for robust safety management from handling outside the ships to its use as fuel in the combustion engine. The risk is amplified when ammonia exposure occurs in an enclosed space, with the engine room being one such critical enclosed space with a probability of gas leakage. A study conducted by Lloyd Register also showed that the presence of ventilation may reduce the risk levels of ammonia poisoning to a certain extent (Lloyd's Register and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). However, despite the engine room ventilation system, ammonia leakage could still reach life-threatening levels. Therefore, additional safety measures are required, and proper management of the engine room system is essential to maintain crew safety.

2.2.3. Ammonia Bunkering Accident

While the use of ammonia as maritime fuel may still be under development, its transportation as cargo has been practiced for several decades. This sub-chapter will analyze the statistics of accidents involving ships carrying ammonia as cargo. The review from this chapter will be utilized to understand the current risks and failures related to ammonia leaks, which will provide valuable "lessons learned" for improving ammonia engine room safety. The list of accidents on Table 2.3 is based on data collected by Jang et al., sourced from the IHS Seaweb database covering the period from 1978 to 2021 (Jang et al., 2023).

Table 2.3: The ship carrying ammonia accidents based on the list collected by Jang et al. (Jang et al., 2023)

Year	Ship type	Accident type	Severity	Fatalities	Cause of ammonia leakage
1978	LPG Tanker	Hull/Machinery Damage	Non-serious	0	Ammonia leak in the storm
1981	Crude Oil Tanker	Hull/Machinery Damage	Non-serious	0	Ammonia leak due to pipe damaged while discharging

Table 2.3: The ship carrying ammonia accidents based on the list collected by Jang et al. (Jang et al., 2023)

Year	Ship type	Accident type	Severity	Fatalities	Cause of ammonia leakage
1982	Fishing Vessel	Hull/Machinery Damage	Serious	14	Ammonia leak from one of the cargo near accommodation space
1982	LPG Factory Ship	Fire Explosion	Serious	0	Rupture of refrigerant pipe
1983	LPG Tanker	Hull/Machinery Damage	Serious	46	Explosion in engine room due to rupture of ammonia storage tank
1996	LPG Tanker	Hull/Machinery Damage	Serious	1	Miss-operation during tank cleaning preparation
1999	LPG Tanker	Hull/Machinery Damage	Non-serious	0	Ammonia leakage on the loading arm
2005	Container Ship	Hull/Machinery Damage	Non-serious	0	Ammonia leakage due to fully fish filled net with the pipeline while discharging at the port
2007	Fishing Vessel	Hull/Machinery Damage	Non-serious	6	Hose burst whilst discharging ammonia
2014	Chemical Tanker	Collisions	Serious	0	Ammonia exploded and caught fire whilst undergoing repairs by welders torch
2014	Fishing Vessel	Hull/Machinery Damage	Serious	38	Ammonia dripped from valves while loading, leads to failures of heating coils
2021	LPG Tanker	Fatality/Injury	Serious	4	Ammonia leakage with unknown causes

The data in Table 2.3 shows that out of the 12 recorded accidents related to ammonia leakage, 7 had serious severity, with the highest fatality reaching 46 persons due to an explosion of an LPG-fueled engine and a ruptured ammonia storage tank. Despite being carried only as cargo commodities, a robust procedure for handling ammonia is highly required to ensure the safety of the onboard crew. Using ammonia as fuel for the engine and operating it within a tightly closed space poses another level of risk for the crew. The high toxicity nature of ammonia hinders its implementation as a ship fuel up to this day (Jang et al., 2023).

2.3. Safety Risk Management in Maritime

2.3.1. System Safety and Risk Management Methods

System safety is the process of identifying, evaluating, and controlling hazards and risks within a system, which was first mentioned and developed in the aerospace sector (Bahr, 2014; Roland and Moriarty, 1990). System safety should consider both engineering and management aspects within the system to develop optimal design solutions, incorporating persons, management, and the environment, similar to the socio-technical perspective (Roland and Moriarty, 1990).

In this research, the scope of risk will focus only on safety risk. The general system safety process consists of (Bahr, 2014; Roland and Moriarty, 1990; Federal Aviation Administration, 2023):

1. **Objective Definition**: the objective of the system under review is need to be developed as the main goal of the risk management. In this research, the objective definition is the explained research objective on the first chapter of the report.
2. **System Description**: the descriptions of interactions and relations between people, procedure, technical equipment and environments. This steps give understanding regarding the system that would be analysed.

3. **Hazard Identification**: potential hazards might arise from internal and/or external sources within the system and the consequences of the hazard scenarios need to be addressed for the risk analysis step. Some tools that can be used for this steps are Hazard Identification (HAZID), Hazard and Operability Study (HAZOP), Failure Mode and Effect Analysis (FMEA) and 'What-if' method.
4. **Risk Analysis**: in this step, hazard is characterized based on their probability and level of severity. The methodology of this step could be qualitative, quantitative or both of them. Tools that usually used for the maritime sector are Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Ship Collision Risk Analysis (SCRA).
5. **Risk Assessment**: This step focusing on the review of the risk acceptability, by comparing with agreed criteria and reduction methods identification. One of the used tools in maritime industries is the Quantitative Risk Assessment (QRA) which provides the basis for design and operation of the systems through quantification.
6. **System Modification**: this step is an iteration process that necessary need to be done if the safety level of the existing system does not passed the risk acceptance criteria given. The modification of the system will effect the hazard identification, re-entering the iteration process until the modified system's risk level could be accepted.

The risk management enables the closed-loop system of the system safety process, indicating that engineering and management organizations periodically review the safety of the program to ensure control of the risk, as seen in Figure 2.7 (Bahr, 2014; Federal Aviation Administration, 2023).

In general, the content of the steps for each safety risk management case is similar. However, the flowchart of the system safety and risk management is depends on the case of the study. Therefore, there are no standardized flowchart to conduct the safety risk assessment and management. The risk management framework for this study will be discussed on the Chapter 3 of this report.

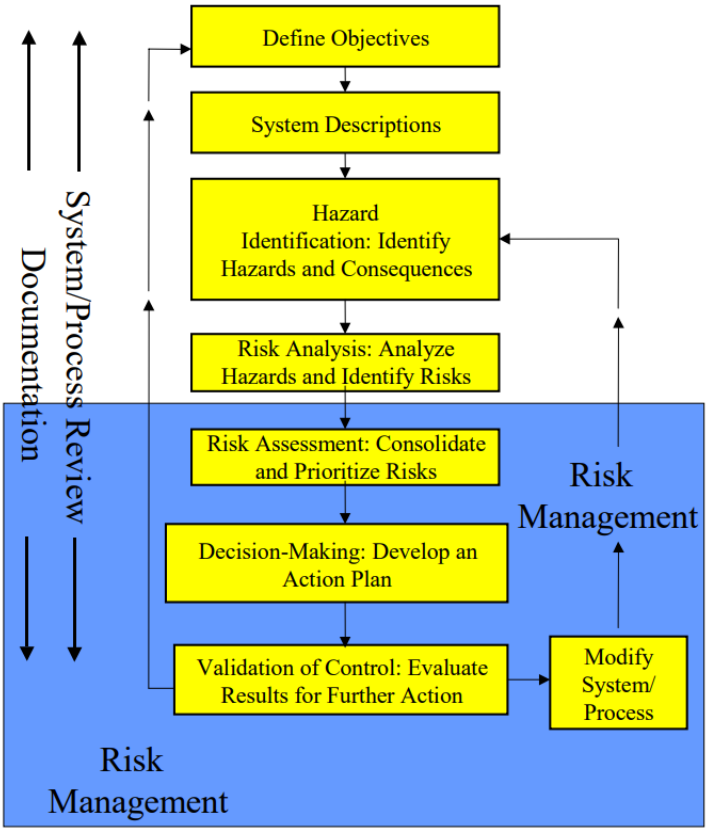


Figure 2.7: The system safety process (Federal Aviation Administration, 2023)

2.3.2. Existing Risk Management for Ammonia-powered ship

The risk management standarization for the ammonia-powered ship has been developed through out the year. The three important risk management documents provided are developed by International Standards (ISO 31000 and ISO 31010) and IMO Formal Safety Assessment (Jang et al., 2023).

The ISO 31000 states the basic principles and guidelines for the steps and content of the safety risk management, including risk identification, risk assessment, risk mitigation and risk monitoring & review. The risk assessment part are standardize on the ISO 31010, providing information to conduct the risk assessment technique so it could suits the specific needs by the organizations. The tools that could be used for ammonia-powered ship based on ISO 31010 are HAZID, HAZOP, FMECA, ETA an FTA. The FSA provided by IMO is evaluating and proposed the solution of the safety related to the ammonia powered ship design and operation. This includes the hazard identifications, determine potential risk related to hazard, evaluates the existing safety measures, providing solutions of safety measures to reduce risk and evaluate environmental impact. The IMO's FSA regulation are suitable for the stakeholders within maritime transportation, allow them to make decisions and implement safe operational procedure in practice (Jang et al., 2023).

Several international organizations and EU legislation have developed the safety measures and regulations to ensure the safety of ammonia as maritime fuel. Class NK, developed the safety guidelines of using ammonia as fuel based on two steps. First, the gap analysis between conventional fuel oil and liquefied gas. The second step is the safety requirements of ammonia ship should equivalent to the safety of methane fueled ship as stated in the International Maritime Organization (IMO) IGF Code in Part C-1 of the Guidelines for Ships using Alternative fuel and Chapter 16 IMO IGC Code in Part C-2 of the guidelines for Ships Using Alternative Fuels (ClassNK, 2022). Where the IMO IGF Code states the requirements for use of liquefied gas as a fuel such as methane and IMO IGC Code states the requirements for transport the ammonia as cargo.

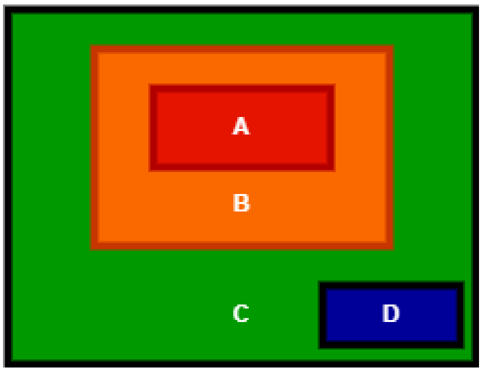


Figure 2.8: The area classification based on fuel presence (ClassNK, 2022)

The IGF Code provide the classification of area on ship as the safety measures for liquefied gas, shown in Figure 2.8. The detail classification of the area are:

1. **Area A** is the area of components such as fuel tanks and piping equipment, where the presence of fuel is always existent. As this area has a high probability of gas leakage, isolation from any external damage is required and crew are not allowed to enter the area. The special consideration of corrosiveness of ammonia is required in this area.
2. **Area B** is the area where the fuel is not normally presence but it only happens when leakage occurs. The example of this area is fuel preparation room (FPR), tank connection spaces, double-walled pipes and ducts. In this area, the probability of fuel leakage should be minimized through detection of leaks, immediate system to shut down the fuel flow and minimizing damage. Personnel are allowed to enter the space for operational needs only. The special consideration of flammability and toxicity of ammonia is required in this spaces.
3. **Area C** is the location where the fuel is not present where must be isolated from Area A with two boundaries and Area B with one boundary.

4. **Area D** is the part of Area C. The fuel should not be presence in C and this location should not be in direct contact with Area B. The example of this area is accommodation spaces.

Based on the safety classification provided by the Class NK, the engine room categorized as the ”Area B”, where the ammonia fuel is not supposed to be present but only occurs when a leakage takes place. As there will be piping and other components that supply the ammonia-fuel to the combustion engine, people that work inside the engine room are exposed to the possibility of the risk of ammonia. The risk of ammonia will be discussed in the following sub-chapter of this research.

Other organizations have also developed regulatory frameworks for ammonia bunkering in the maritime sector. The Korean Register provides regulations and requirements for the design, safety, ventilation, and operations of ammonia-powered ships. DNV GL also offers specific requirements for designing ammonia gas supply systems following the IGF code provided by the IMO. The International Association of Classification Societies (IACS) also provides information regarding preparation and maintenance procedures for ammonia-fueled ships. Generally, all of these organizations share a common recommendation for developing a safety zone designed to have limited access to personnel not involved in the bunkering process, aiming to improve safety (Duong et al., 2023).

However, there to only limited research known to the writer that evaluates and conducts the human-machine system inside the ship to determines which components or tasks that should be avoided next to the ammonia-fueled engine in order to improve safety. Therefore, this research will be focusing on the recommendation of system modification, including task and components location, if required to increase the safety levels.

2.4. Socio-Technical System (STS)

2.4.1. Definition of Socio-Technical System

The Socio-Technical System (STS) has emerged in usage and popularity in modern engineering and design, where the incorporation of humans, machines, environments, tasks, and organizational structures within systems has become the main focus. Many researchers have implemented the socio-technical perspective in their studies, resulting in a broader view of the systems, aiming for the goal of ’joint optimization of the social and technical systems’ (Carayon et al., 2015). In the basic theory of socio-technical systems, the system is categorized into technology/technical subsystems and social subsystems. The technology/technical subsystems consist of the physical system (machines, technology, and tools) and tasks. On the other hand, the social subsystems consist of individuals (people) and organizations (teams), along with the interactions and coordination between each other (Carayon et al., 2015). The figure of the basic elements inside socio-technical systems can be seen in Figure 2.9.

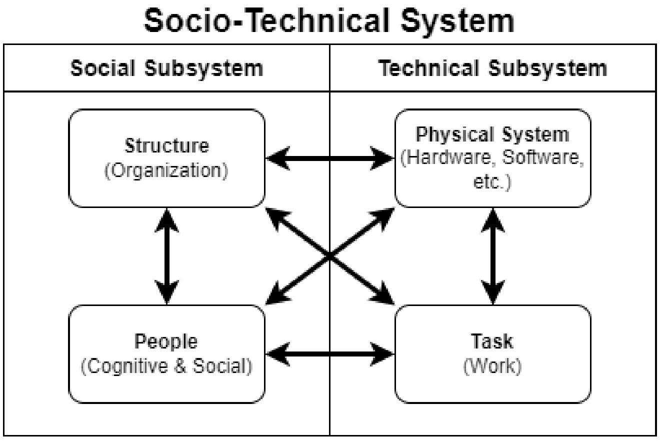


Figure 2.9: The Socio-Technical System (Carayon et al., 2015; Bostrom and Heinen, 1977)

Despite its ability to come up with solutions and designs that consider both human and machine aspects, writers have found that there is a lack of consensus regarding the usage and understanding of socio-technical systems in research. A previous study by Menting (2023) focusing on the risk management framework with a socio-technical perspective concludes several lacks of consensus in the socio-technical system literature. The findings of the lack of consensus are (Menting et al., 2023):

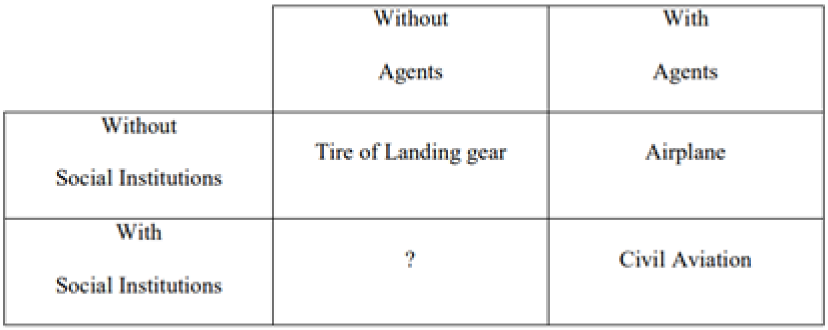
1. The usage of socio-technical systems has emerged in the past years. Originally scoped to focus on the workplace's social and technical factors impacting organizational performance, the concept has been used for broader applications beyond the workplace.
2. Despite several papers including the "socio-technical system" concept, it is often used without further elaboration and treated as a "buzzword."
3. There is a lack of definition of what is considered a socio-technical system in multiple research studies. This leads to a superficial understanding of the concepts and varying ideas on how to determine a socio-technical system.
4. There is an absence of specific and standardized methods for analyzing socio-technical systems in general. This leads to research that adapts or develops its own approach to analyzing socio-technical systems based on research objectives.

Based on the review of the challenges behind understanding the socio-technical system (Menting et al., 2023), the writers have identified limitations of the research due to the lack of common ground on what is considered as socio-technical systems. They find it quite challenging to determine whether a system can be considered as a socio-technical system or not due to the lack of consensus.

Therefore, the research will implement the socio-technical system based on current scientific definitions. Several definitions of socio-technical systems are analyzed, and the concepts that are suitable for this scope of research will be used as the base theory to determine the approach to analyze the subsystems and identify its elements.

The research conducted by Kroes et al. (2006) describes that the determination of the engineering system's boundary or socio-technical system is by including anything inside the system that is necessary to perform its intended function. This definition uses technical artifacts as the basis of the starting point. The Figure 2.10 below explains the definition from the point of view developed by Kroes et al., using the example of the civil aviation context. The definition is categorized as follows:

1. The engineering systems that can perform its function without agents and social institutions performing the sub-function (e.g., Tire of Landing Gear).
2. The engineering systems that can perform its function with agents performing the sub-function without social institutions performing the sub-function (e.g., Airplane).
3. The engineering systems which require both agents and social institutions to perform its function (e.g., Civil Aviation).



	Without Agents	With Agents
Without Social Institutions	Tire of Landing gear	Airplane
With Social Institutions	?	Civil Aviation

Figure 2.10: The Socio-Technical System Definition (Kroes et al., 2006)

However, in practice, engineers design artifacts without considering the presence of agents inside them. The problem does not arise as long as the user makes use of the artifact in the way intended by the engineers. If the user does not use the technical artifact properly, then the intimate relationship between functions and agents decreases.

The socio-technical analysis research conducted by Adriaensen et al. (2019) argues that a socio-technical system is a structure consisting of interrelated and interdependent social and technical elements, which directly or indirectly influence each other to maintain activity in order to achieve the main goal. The study focuses on the aircraft cockpit environment, which the research states is considered as a socio-technical system. A number of agents are involved in the work inside the system, each having their own goals and interacting to ensure the main goal, which is safe and efficient flight. It is shown that the propagation of task performance inside socio-technical systems from several agents affects the main goal of the whole complex system.

Based on the definition above, it is well-suited for analyzing the safety of the engine room inside an ammonia-powered ship. Using the concept introduced by Kroes et al. (2006) and Adriaensen et al. (2019), the ammonia-powered ship can be categorized as an engineering system that can perform its function with agents (crew on board) performing the sub-function without the addition of social institutions. The interaction of the ship organization onboard with the technical elements of the ships ensures the goal of the complex system, which is performing safe and efficient sailing operations. Without the presence of people onboard, the ship system cannot perform its main function and achieve its goals, and vice versa.

Lastly, as argued by Kroes et al. (2006), the incorporation of the presence of agents in engineering aspects might ensure that the design of the technical artifact could increase the relationship and understanding between functions and agents. As ammonia-powered ships bring risks to the agents (people) onboard, the design of the technical systems should also consider the relationship between humans and machines, ensuring the safety of the crew onboard. Since developing system safety by incorporating socio-technical systems is not considered a classical method to evaluate safety, the following sub-chapter will explain the incorporation of the concepts towards system safety.

2.4.2. Socio-Technical System in System Safety Management

The concept of socio-technical systems did not originate to support the analysis of system safety management. The incorporation of socio-technical perspectives has emerged alongside the increasing complexity of systems. In this sub-chapter, the writer will discuss the incorporation of socio-technical perspectives in system safety management and the reasons behind its development and implementation in modern system safety management.

The perception of system safety management has evolved over the years, transitioning from viewing ”technology as the source of the problem” to recognizing the ”interaction between social and technical subsystems as the source of the problem” (Dechy et al., 2011). Human-machine interaction in system safety management was introduced in the 1980s, following major accidents such as the Three Mile Island accident in 1979, which highlighted human error as a significant factor. Industrial operational procedures were subsequently enhanced, and knowledge improved through training to increase system safety. Later in the 1980s, the concept of the socio-technical system within system safety gained popularity, particularly after accidents like Bhopal (1984), Challenger (1986), and Chernobyl (1986), with the root cause identified as the interaction between social and technical subsystems (Dechy et al., 2011; Barbosa et al., 2023). This evolution has led to a new perspective on safety within systems, focusing on understanding the root causes of negative events.

Accidents or negative events often result from multiple factors and a nonlinear sequence of causes. Studies on air and maritime accidents have shown that organizational factors and human error are the main causes, followed by equipment/technical failures and other factors (Qureshi, 2007). Considering both social and technical subsystems leads to analyzing safety in complex systems. The complexity of these systems makes it challenging to implement traditional safety management methods that forecast risk assessment through a linear path from individual failure to top-event disaster. This linear perspective for forecasting the origin and propagation path of risks becomes extremely difficult, if not impossible, to implement in current complex systems (Patriarca, 2021).

In contrast to the traditional safety perspective, which follows a linear sequence, the consideration of emerging socio-technical system safety is strictly dependent on logic relations and involves identifying patterns that may result in non-linear and unpredictable outcomes (Patriarca, 2021). Implementing socio-technical systems allows people to understand the relationships between elements within the systems and develop proactive solutions to improve system safety (Barbosa et al., 2023).

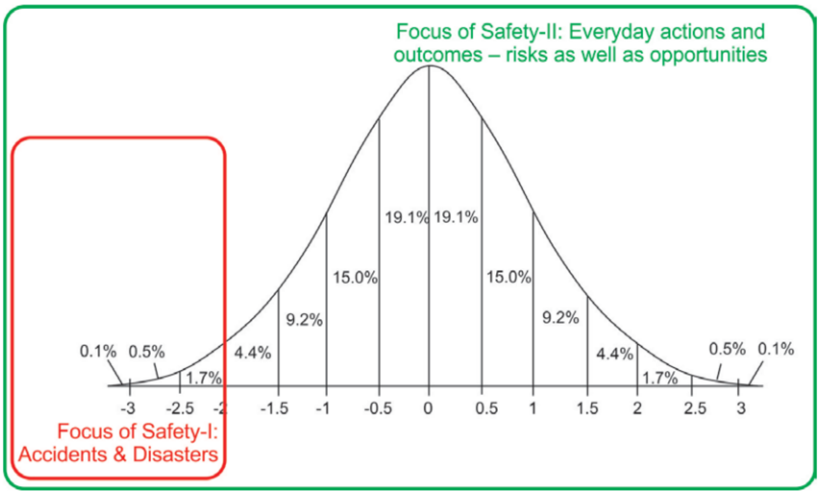


Figure 2.11: The focus of Safety-I and Safety-II (Hollnagel et al., 2015)

This concept of safety thinking leads to two perspectives of safety thinking, known as Safety-I and Safety-II, considered as the past and the future of safety management (Frédéric, 2015). Safety-I adopts the definition of safety developed by minimizing things that could possibly go wrong, shown by a more reactive principle responding to negative events. This understanding categorizes humans as liabilities for hazards and negative outcomes, where the risk assessment method shows that failures and malfunctions are the causes of failures (Hollnagel et al., 2015). The Safety-I requires understanding of the whole system and reasons behind the function or malfunctions, assuming the reasons of ”things go wrong” is different with ”thing go right”. This is difficult to implement in current technology and system where this get more complex to understand and control (Hollnagel et al., 2014).

On the other hand, the concept of Safety-II focuses on the many things that could possibly go right to increase the safety level, with a more proactive principle to continuously anticipate negative events. This concept sees humans as resources for system flexibility and resilience towards unwanted events. Safety-II shows that accidents take place due to variability in performance and its challenge to monitor and control this variability (Hollnagel et al., 2015). Thus, this way of thinking can provide designers and engineers with opportunities to enhance safety by also focusing on and learning from what goes right and controlling to keep it on the right track. The focus of Safety-I and Safety-II can be seen in Figure 2.11, developed by Hollnagel (2015).

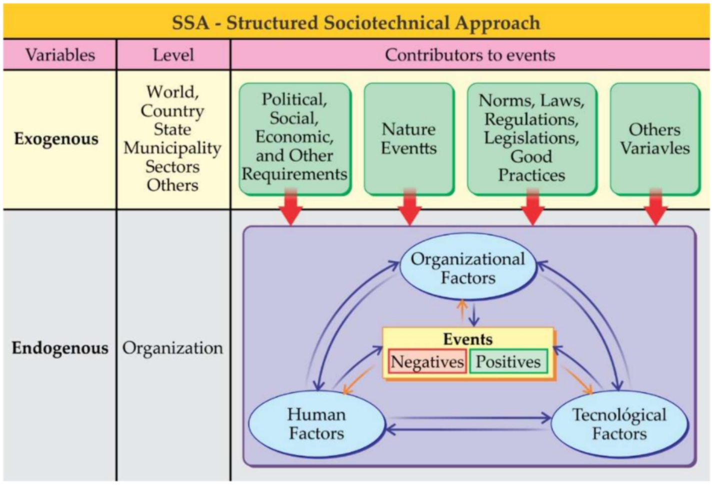


Figure 2.12: The structured socio-technical approach for system safety (Barbosa et al., 2023)

The socio-technical system perspective often adopts the Safety-II concept, where the variability of performance becomes the challenge to ensure the safety of the system. Based on its level of approach, the variables are defined as endogenous and exogenous, as shown in Figure 2.12 (Hollnagel et al., 2014; Barbosa et al., 2023). The endogenous level is defined as an organizational level and consists of organizational, technological, and human factors. The explanation of these factors and their variability are discussed below.

1. **Organizational factors:** Senior management levels that have actions of corporate procedures and operations, or could be groups of people where activities are organized. Factors such as effective communication, organizational culture, and knowledge form the base of this variable.
2. **Technological factors:** Infrastructure of the company such as machinery, equipment, and software. These factors can be more complicated due to the difficulties in explaining the technology functions and how they work. The variables may also vary due to the degradation of mechanical components over the life-cycle or operational use.
3. **Human factors:** Actions of supervisors, middle managers, and technicians who perform the works of the operations. Variability may occur due to physiological factors such as fatigue and work stress. Additionally, bias in assessment and decision-making also contributes to the variability of output.

On the other hand, the exogenous variables are often found at a wider scope level of approach such as the world, country, state, or municipality level. The exogenous variables are contributors from external to inside the organization such as political, social, economic, legal, and natural events. The interaction between endogenous and exogenous variables could lead to positive or negative outcomes, depending on each specific case (Barbosa et al., 2023).

In this scope of research thesis, writers will analyze the socio-technical aspect up to the organizational level, especially inside the ships during the operational phase. Therefore, exogenous contributors will be mostly neglected within this scope limit of research. The identification of elements inside the organizational level consisting of organization, human, and technology will be discussed in Chapter 3.

2.4.3. Socio-Technical System Methods for Safety Management

There are several methods to incorporate socio-technical perspective into system safety management, where System-Theoretic Accident Model and Processes (STAMP) and Functional Resonance Analysis Method (FRAM) are the most used and cited methods. Each methods has its main objective, scope and limitations which will be discussed in this sub-chapter.

1. System-Theoretic Accident Model and Processes (STAMP)

The STAMP methods is developed based on system theory, focusing on the level of controls in socio-technical structure of the systems (hierarchical). This method has paradigm of feedbacl control system. ‘Each level of the socio-technical system are controling their properties, where it stated that the level of safety are based on components failures, dysfunctional interactions among components or unmanaged environmental disturbances at lower level. This methods defines that accident occurs due to the inadequate control on each level of socio-technical structure of the condition of the designed system (Leveson, 2004; Adriaensen et al., 2019).

2. Functional Resonance Analysis Method (FRAM)

The FRAM is a concept for a systemic analysis of complex process inside socio-technical system that focusing on the resonance arising from performance variability on each elements. The FRAM follows the Safety-II thinking, which underlies the importance of understanding the everyday works succeed. The FRAM identifies on how a certain conditions or performance could lead to an accident, focusing on the work-as-done rather than work-as-imagined (Hollnagel and Goteman, 2004; Leveson, 2004; Hollnagel et al., 2014). There are four basic steps of FRAM development:

1. Modelling the system
2. Determine the variability of work-as-done
3. Aggregating the variability of performance
4. Managing the variability of performance

Based on the review of the methods, the FRAM has the advantages over the explainability and the sequence of the resnonance that leads to accident. On the other hand, the STAMP has lacked clarity in sequence for analysis. In this research, the clarity of the resonance sequence is essential since the existing procedure of LNG ship operations will be analysed, and prerequisite of each task is essential to ensure operational safety inside the ships.

2.4.4. Implementation of Socio-Technical System in Maritime Safety

In this sub-chapter, the research on the maritime sector, which implements the socio-technical system in system safety, will be analyzed. The incorporation between socio-technical system and safety management has been implemented in several research studies of transport systems, with some specifically focusing on maritime safety, as shown in Table 2.4.

Table 2.4: The examples of research that implements socio-technical perspective in maritime safety

Source	Topic
(Sultana and Haugen, 2023)	The research on extended FRAM to analyse the safety barriers and system risk evaluation within complex system, using case study of ship-to-ship (STS) transfer of LNG
(Salihoglu and Beşikçi, 2021)	Using FRAM as qualitative risk analysis tools to modelling the Prestige accident with the time sequence
(J.-H. Lee et al., 2019)	Developed the framework to consider informal and temporary human collaborations on maritime sector safety through FRAM
(De Vries and Bligård, 2019)	Developing safety assesment and design on the case of Vessel Traffic Services operatores and maritime pilots using FRAM
(Franca et al., 2020)	The using of FRAM to analyse the level of complexity and relevant human factor that critical for the safe operations of oil well drilling and construction
(J. Lee and Chung, 2018)	The identification of network to evaluate interactions bertween shipboard operations and crews, through human-system interaction (HIS) based on FRAM
(Smith et al., 2018)	The analysis of ship navigation of Exxon Valdez case using the FRAM which provides new perspective on the safety of complex operations
(De Vries, 2017)	Enhance the maritime safety navigation by analysing the work-as-done by VTS and maritime pilot through FRAM
(Tian et al., 2016)	The case study of ferry accident analysis using the FRAM variability to understand the effect of performance variability on complex interactions towards system safety
(Praetorius et al., 2015)	Modeling the highly complex VTS to analyse the resilience on everyday operations through FRAM

Based on the example of safety management through socio-technical safety in maritime safety over the past 10 years, the tool that is often used to analyze complex systems is FRAM. Based on the research, FRAM enables understanding of how the socio-technical system works, focusing on human tasks in collaboration with machines. This tool also enables the identification of risks arising from variability in human or machine performance, thereby improving the resilience of the system. This methodology is often used to predict broader causes of risk based on the Safety-II concept.

2.5. Key Findings, Research Gap and Limitations

2.5.1. Key Findings

Based on the first section of this chapter, it is evident that the technical components of the ship systems related to the engine room are complex. With several tasks encompassed within the engine room, including operational, maintenance, and inspection duties, human collaboration holds essential keys to performing effective and safe work inside the engine room.

The risk associated with ammonia lies in its toxicity, making it the top safety concern for this research. The enclosed space within the engine room exposes engineering crew to a high level of risk in the event of ammonia leakage. While necessary ventilation systems are already adopted and regulated, they are only acceptable up to a certain concentration level. The risk of poisoning only occurs when humans are present inside the engine room. However, the crew must perform tasks to ensure the operations of the ship systems. This dilemma and complex interaction between human-human and human-machine could be analyzed using the socio-technical perspective.

The Functional Resonance Analysis Method (FRAM) is considered one of the most effective tools for visualizing and analyzing functions within complex systems. As shown in Table 2.4, most recent safety analyses using the socio-technical perspective implement FRAM due to its advantages in analyzing unpredictable potential risks. FRAM complements the analysis of the root causes of risk through elements interactions and performance variability.

2.5.2. Research Gap

The current research on ammonia-powered ship risk management mainly focuses on technical or engineering solutions. There is limited to no research focusing on human-machine interactions to enhance onboard safety in ammonia ship operations. The incorporation of socio-technical systems through FRAM could provide a better understanding of unpredictable behaviors that could lead to failure, broaden hazard identification in risk assessments, and enable optimal risk management of the system. Therefore, this research aims to develop the safety risk management of ammonia-powered ships by incorporating the socio-technical perspective to gain a better understanding of potential hazards and risks associated with the new technology.

2.5.3. Research Limitations

This research has significant limitations, which the writer has studied and acknowledged:

1. This research will only analyse ammonia poisoning as the top event, disregarding the flammability risk of ammonia due to its low risk probability compared to its toxicity (Pomonis et al., 2022; Duong et al., 2023). The reasoning for using ammonia poisoning due to leakage will be explained in Chapter 5 of this research.
2. The research will assume that the ammonia and LNG fuel entering the engine combustion system via the engine line are gaseous. In some locations where ammonia is still a liquified gas, the ammonia leakage may still be liquid, and the vaporisation period of ammonia (NH3) from liquid to gas is delayed compared to methane (CH4) due to its higher boiling point (Pomonis et al., 2022). As a result, ammonia leakage will be investigated primarily in gaseous form, with any ammonia liquid spills being overlooked in the study, particularly in the quantitative approach.
3. The research will only focus on design and task modification recommendations within the engine room. Other specific locations that may be at risk of ammonia leakage, such as the fuel preparation room (FPR), are outside the scope of this report. The analysis for the location of the accommodation deck also will be out of the scope of this study.
4. The research will focus on using three identical four-stroke dual fuel (DF) engines for an LNG carrier ship with a small-scale cargo capacity (1,000 m^3 - 40,000 m^3). There is also an alternative layout that uses a single large two-stroke DF engine, which is outside the scope of this research.

3

Methodology

This chapter outlines the research design of the study, mapping the connections between the background, research questions, methods, and outcomes. The study procedure is illustrated in the research methods flowchart. Finally, the chapter will explain the strategy for incorporating FRAM as a qualitative tool and FTA as a quantitative tool.

3.1. Research Design

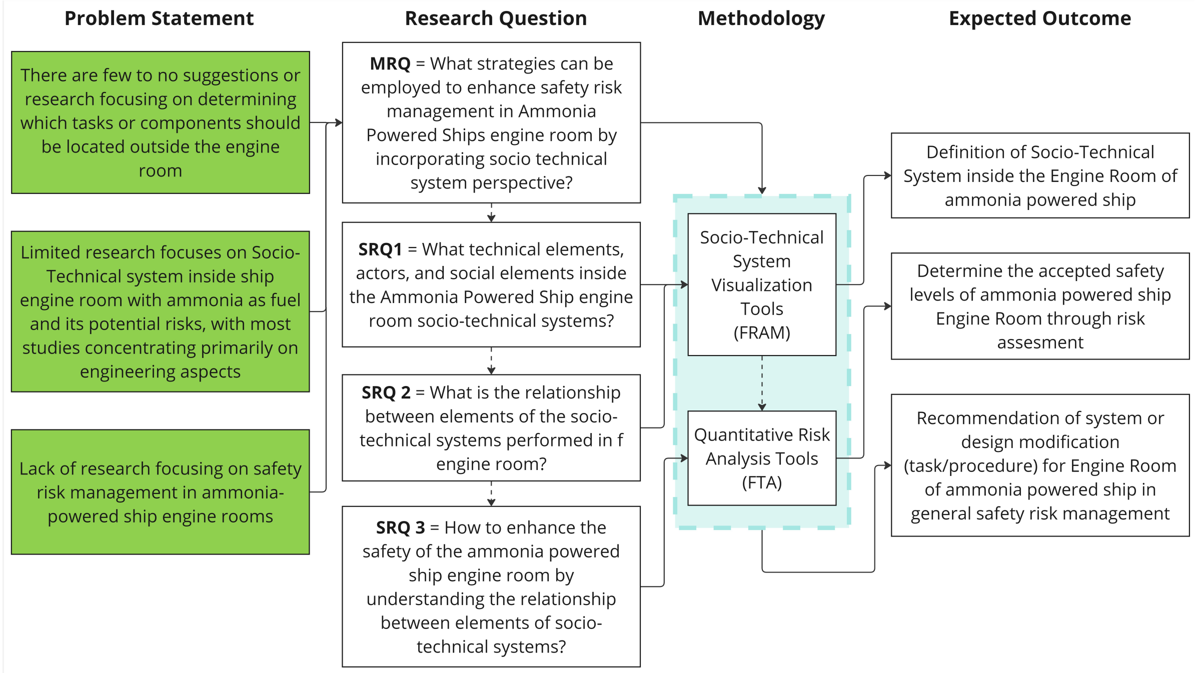


Figure 3.1: The visualization of Problem Statement, Research Question, Methodology and Expected Outcome

Figure 3.1 depicts the study design, linking the problem statement from Chapter 1 with the expected result, which is the answer to the research questions. The first sub-research question (SRQ1), second sub-research question (SRQ2), and third sub-research question (SRQ3) stem from the limited research on human interaction with new technologies for ammonia-powered ship applications. The sub-research questions and primary research question were answered using both qualitative methodology (through socio-technical systems) and quantitative methodology (through quantitative risk assessment).

In this research, the Functional Resonance Analysis Methods (FRAM), a socio-technical systems tool, will be employed as a qualitative method to find linkages between human, machine, and environmental elements. The data collection for the qualitative analysis will be covered in the following sub-chapter.

The data obtained from FRAM will be used to generate the Fault Tree Analysis (FTA) as part of the quantitative method. Using detailed tasks and operations from FRAM, the FTA could carry out a deeper analysis (Belmonte et al., 2011). The quantitative data collecting will also be described in the Chapter 5.

The combination of both methodologies intended to comprehend the socio-technical system (STS) within the ship engine room and how the system's safety could be improved by understanding the relationships between STS elements, with the safety level and modification quantified using the FTA. As a result, any system modification will be constrained and based on the safety-critical resonance between STS elements.

3.2. Research Methods

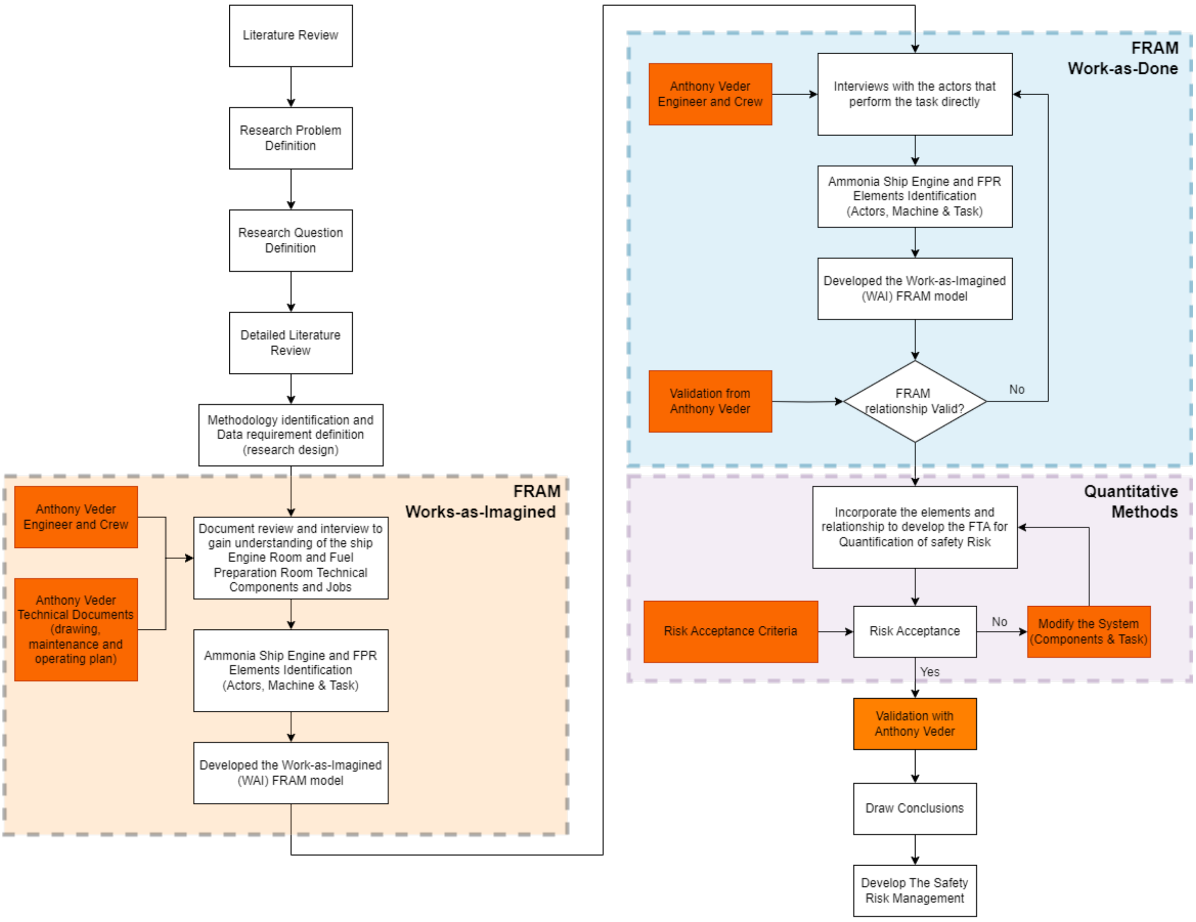


Figure 3.2: The research method of the study

Figure 3.2 depicts the research methodology that was established to fulfil the research objectives. The research began with an initial literature analysis to get a knowledge of technological advancements, opportunities, problems, and gaps. Later, the research problem was determined based on the findings through research gaps and previous study recommendations, which leads to the development of research questions.

The detailed literature was reviewed to identify the identification of detailed methodology and data required to carry out the designated technique. The methodology and tools used in the research are described in the following subsection.

3.2.1. Qualitative Methods: Functional Resonance Analysis Method (FRAM)

The FRAM acted as the first qualitative method used in this study. The qualitative research began with the Work-as-Imagined FRAM, which was developed after reviewing technical documentation and conducting exploratory discussions with company engineers and specialists. Later, aspects inside the STS are discovered and developed into a Work-as-Imagined FRAM. This model represents the ideal model for how the actual system should function based on its design and purpose.

To gain an understanding of how the ship engine room's tasks and systems work, the Work-as-Done (WAD) FRAM is built through interviews with personnel who do the actual work on the work site. The WAI FRAM, which serves as an ideal basis, is reviewed and altered based on real workplace practice, yielding a WAD FRAM as the model's final form. The complete method of FRAM development is described in the following Chapter 4.

3.2.2. Quantitative Methods: Quantitative Risk Assesment (QRA) and Fault Tree Analysis (FTA)

The FTA aimed to visualize the logical failure sequence leading to the top event. This sequence supports the quantitative risk assessment (QRA) by providing insights into the individual risk per annum (IRPA) associated with ship operations using ammonia as fuel. Chapter 5 will detail the definition of the risk acceptance criteria and outline the steps involved in developing the QRA.

3.3. Incorporating FRAM and QRA

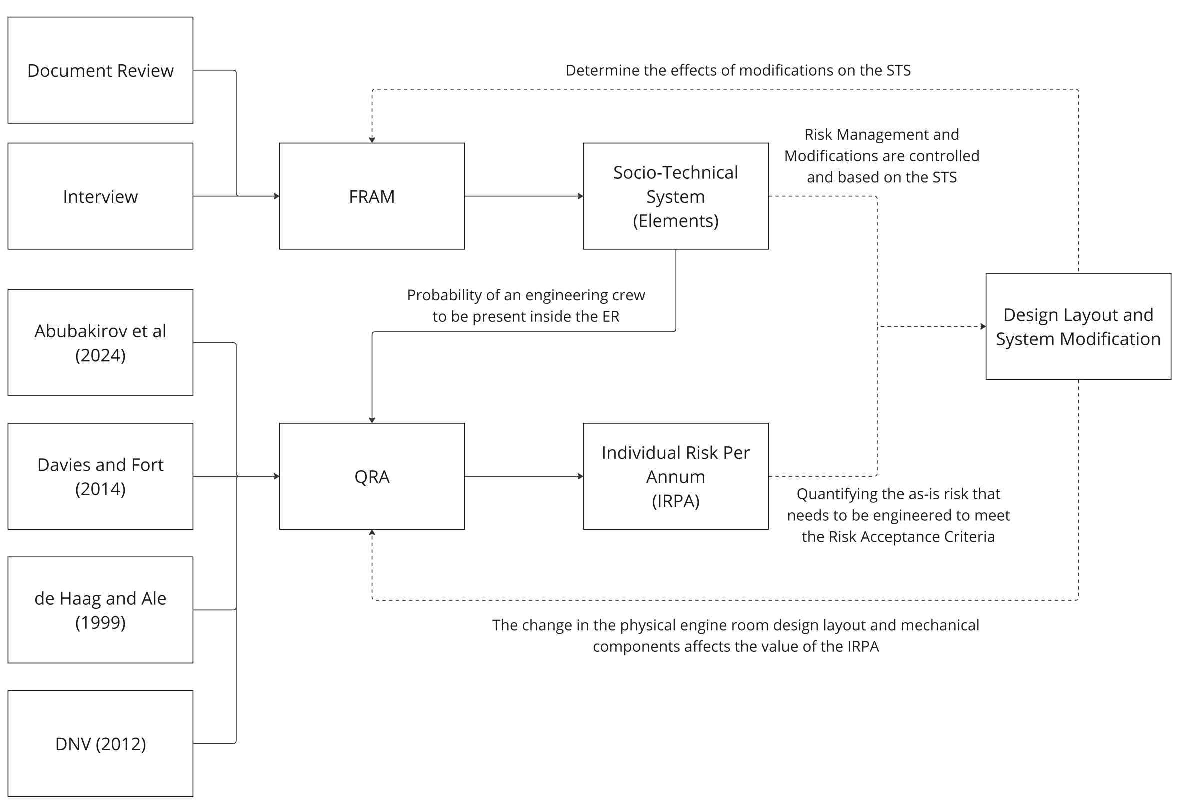


Figure 3.3: The Incorporation of FRAM and FTA

Figure 3.3 illustrates the detailed integration of FRAM and FTA. This figure demonstrates how the socio-technical system (STS) aspects derived from FRAM enhance the development of FTA, which is also informed by a review of relevant research material. The STS provides a framework that guides the design layout and system modifications. Conversely, these modifications may impact the STS reflected in the existing FRAM. The FTA yields a logical sequence of top event failures that supports the quantitative risk assessment (QRA) by evaluating the individual risk per annum (IRPA). The design layout and system modifications will be assessed to ensure they meet the risk acceptance criteria.

The details of FRAM and FTA development will be explained in Chapters 4 and 5, respectively. Risk management through system modification will be described in Chapter 6, along with its framework, consideration of modification, iteration, and the outcome of modification with regard to of safety and operability.

4

Functional Resonance Analysis Model (FRAM) of Engine Room Operations

This chapter discussed the steps involved in the development of FRAM, distinguishing between the two categories of FRAM: work-as-imagined (WAI) and work-as-done (WAD). The detailed strategy for FRAM development is outlined in Section 4.1, followed by discussions on data collection, data analysis, and results for both WAI and WAD FRAM.

4.1. Framework of FRAM Development

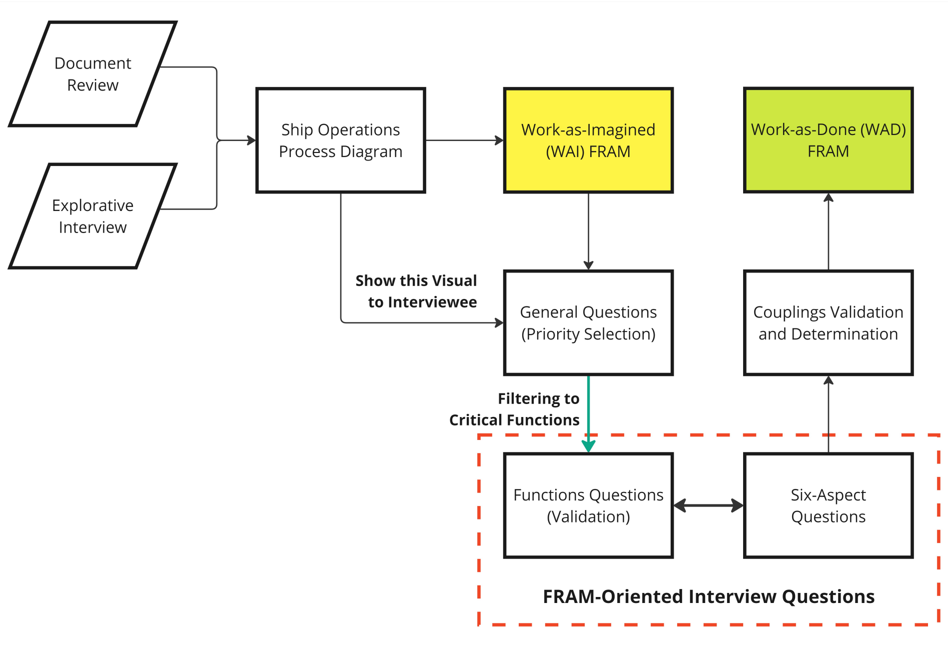


Figure 4.1: The framework of the research FRAM development

Figure 4.1 depicts the study FRAM development system, including data collecting for both Work-as-Imagined (WAI) and Work-as-done (WAD). The approach began with the creation of a ship operations process diagram through document analysis and exploratory interviews, which identified the tasks/functions within the ship operations from the departure-,sailing-, and docking-stages. The second aggregate level of the ship operations diagram evolved into a Work-as-Imagined (WAI) FRAM model, with specified actors for each process.

Following the development of the WAI FRAM model, an interview with an actual practitioner of the duty of onboard ship operations. The ship operations process diagram was provided to the interviewee that has experience as former practicioner for the basis of the discussions, and the following general questions contained in Table 4.2 will be discussed to validate the overall ship operations process. Based on the general questions, the critical-safety tasks will be selected and thereafter asked in FRAM-Oriented Interview Questions. The couplings between functions will be reviewed and validated before determining the final form of the Work-as-Done FRAM.

4.2. Work-as-Imagined (WAI)

The words of Work-as-Imagined (WAI) in FRAM indicate how the process should be executed based on the manuals, procedures and its designated design. The data gathering of this step derived from the document study and exploratory discussion with the company partner. The goal of this step is to produce and visualize the ideal socio-technical system based on its design, which is then validated and compared to the Work-as-Done model to identify deviations that may impair the system's process and safety. The FRAM scope is then set, focusing solely on ship activities such as engine operations, inspections/monitoring, on-board maintenance, and engine room-related emergency actions.

The next steps in WAI development use a bottom-up method, in which the writers first identify the engine room-related operations and tasks before incorporating them with the assigned actors.

4.2.1. WAI Data Collection

As stated in the previous section, data collection in this step is done through company partner documentation and exploratory discussions, performed prior to the WAD interviews.

The document review was conducted using the data provided by the company partner and focused on ship technical documents, engine manuals, and company safety rules and procedures (standing order). First, an investigation of the ship's general arrangement plan drawing and system is performed to better comprehend the ship engine's technical system. This stage enables writers in determining a list of actions and components that may be relevant to ship operations.

The exploratory discussion was conducted with professionals from the company partner who have backgrounds in chemical process engineering, maritime engineering, maintenance planning, safety, and ship sailing expertise. This step allows the writer to comprehend the experts' current progress, issues, and recommendations. This phase provides a better understanding of general ship operations and ship organization, which helps to clarify the societal part of the study.

The company also provided an additional data gathering opportunity through a ship visit to a ship undergoing dry dock maintenance in the Gibraltar shipyard. The ship that was visited was one of the first ships to use LNG as a fuel, and the corporate partner was able to build the ship and demonstrate its safety level so that it was accepted by the regulator. The visit allows the writers to grasp the company's prior plan to improve the safety of the new technology despite the lack of safety regulations at the time, which is nearly identical to the situation of the ammonia-powered ship. Furthermore, the exploratory interview with the ship's engineering crew allows for a better understanding of extra safety measures and ship operations, as well as the ship organization activity.

4.2.2. WAI Data Analysis

The data analysis technique for developing the FRAM is inspired by the research conducted by Adriaensen et al. (2019), which focuses on the FRAM application in the aircraft cockpit. According to the Abstraction Hierarchy theory, the identification of functions can be established through two layers of aggregate levels. The first layer consists of abstract functions focused on the broader ship operations stages, beginning with engine start-up, sailing, and engine shutdown. Figure 4.2 depicts the first-level aggregate of ship activities.

Appendix A provides a detailed second-level aggregate of the foreground first aggregate functions. The functions at the second-level aggregate represent general activities necessary to achieve the abstraction level and serve as the foundation for the FRAM functions. The six aspects of these functions are constructed based on document review and exploratory discussions with experts, as described in the preceding subsection. The identified functions are then grouped by location and integrated with the

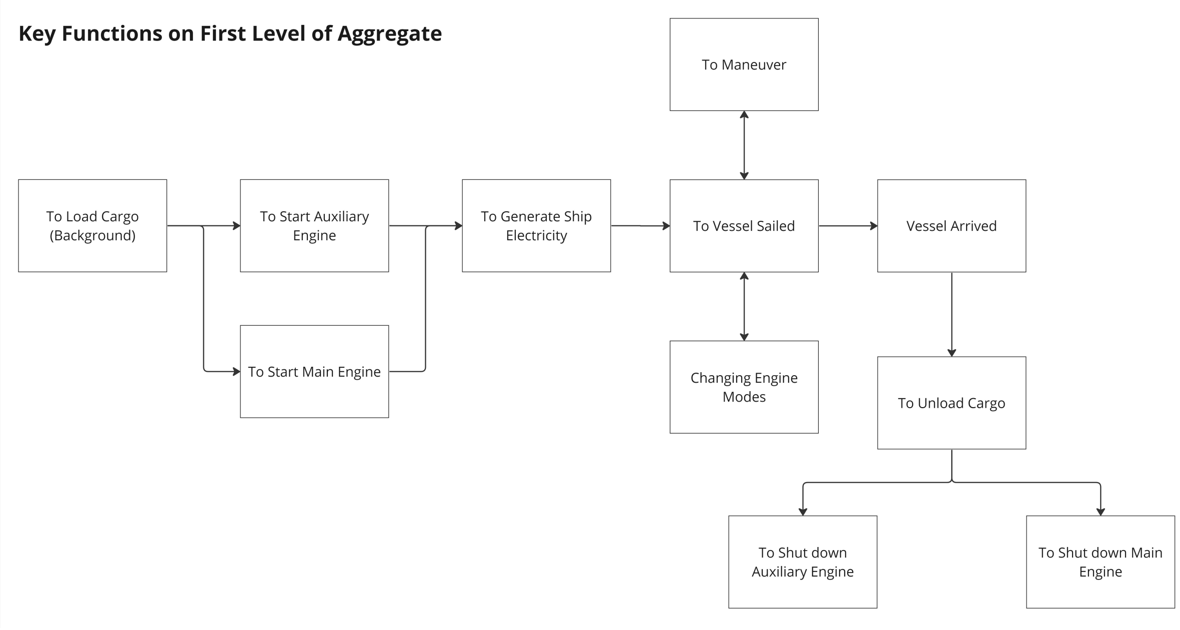


Figure 4.2: The First Level Aggregate of the General Gas Shipping Operations

actor who performs the task, in accordance with the ship's organizational chart.

4.2.3. WAI Result

Figure 4.3 organizes FRAM functions into eight color-coded groups corresponding to different system actors. These actors include human actors (such as the Chief Engineer, EoW in the engine room, EoW in the engine control room, and EoW at both the control room and engine room), organizations (e.g., company offices), mechanical ship artifacts (e.g., ship, engine system), and documentation as a control mechanism. The EoW, performed by a single individual per shift, is classified into three distinct actors in the FRAM due to variations in location and components of human-machine interaction. Hence, the colors display the actor roles, not the individual actors.

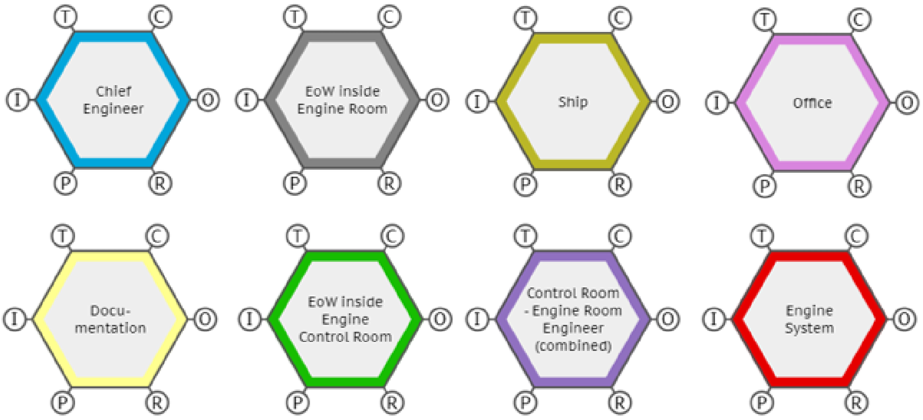


Figure 4.3: WAI FRAM Legend for the list of actor roles

Figure 4.2 presents the initial aggregate flowchart, which evolves into the second-level aggregate shown in Appendix A and the FRAM functions depicted in Figure 4.4. The WAI FRAM is grouped into six clusters visualized in columns, following the ship operation phases indicated in the first aggregate in 4.2. The first cluster includes document preparation activities by "documentation," "chief engineers," and "office" actors. "Documentation" produces outputs that serve as controls for engineering crews, such as work procedures, administration, and regulations. The ”office” is responsible for developing preventive maintenance schedules based on engine component lifecycles. Lastly, chief engineers act as decision-makers in the engine room, providing necessary permits and administration to be complied with by the Engineers on Watch (EoW).

The ”Start the Engine” phase involves actors working locally inside the engine room (e.g., EoW inside the engine room), remotely (e.g., EoW at the engine control room), and in combinations (e.g., EoW at control room & engine room) alongside engine systems. Both local and remote methods for starting the engine are available, offering redundancy in the ship’s systems. In this phase, any malfunctions identified must be reported to the chief engineers (CE) for decision-making.

The ”Monitoring/Inspection” phase involves actors from ”ship,” representing the ship’s mechanical artifacts. Monitoring and inspection activities align with ”ship” operations, particularly during mooring and maneuvering.

The ”Onboard Maintenance” phase includes functions performed solely by the ”EoW inside the engine room” as it is a local activity. The WAI FRAM indicates no relationships between maintenance functions and other functions; further interviews for the WAI FRAM will likely provide additional insights into the couplings between maintenance and other functions.

The ”Change the Engine Mode” phase involves interactions among the ”chief engineer,” ”EoW inside the engine room,” ”EoW in the control room & engine room,” and ”engine system.” This phase includes critical prerequisite steps controlled by the function ”Consult Document ’Engine Operations and Inspections Guidelines’,” ensuring compliance is crucial for the success and safety of the engine operation.

Lastly, the ”Shut Down the Engine” phase includes activities that can be performed both locally and remotely, similar to the ”Start the Engine” phase, to ensure system redundancy.

The WAI FRAM indicates the relationship between each function based on the FRAM six aspects. However, based on document study and exploratory interviews, the relationship of the ”Maintenance” category remains unidentified. This was created by the requirement to understand the real task performed throughout onboard operation, including maintenance.

Onboard maintenance is widely used among shipping operators since it is effective and efficient in terms of timing and ensures the ship’s life cycle. The engine manufacturer controls the scheduling and process of onboard maintenance, however the Chief Engineer adjusts the practical work based on the ship’s operational conditions. This missing link will be the key point mentioned during the FRAM interview while building the final FRAM model, which is Work-as-Done (WAD) FRAM.

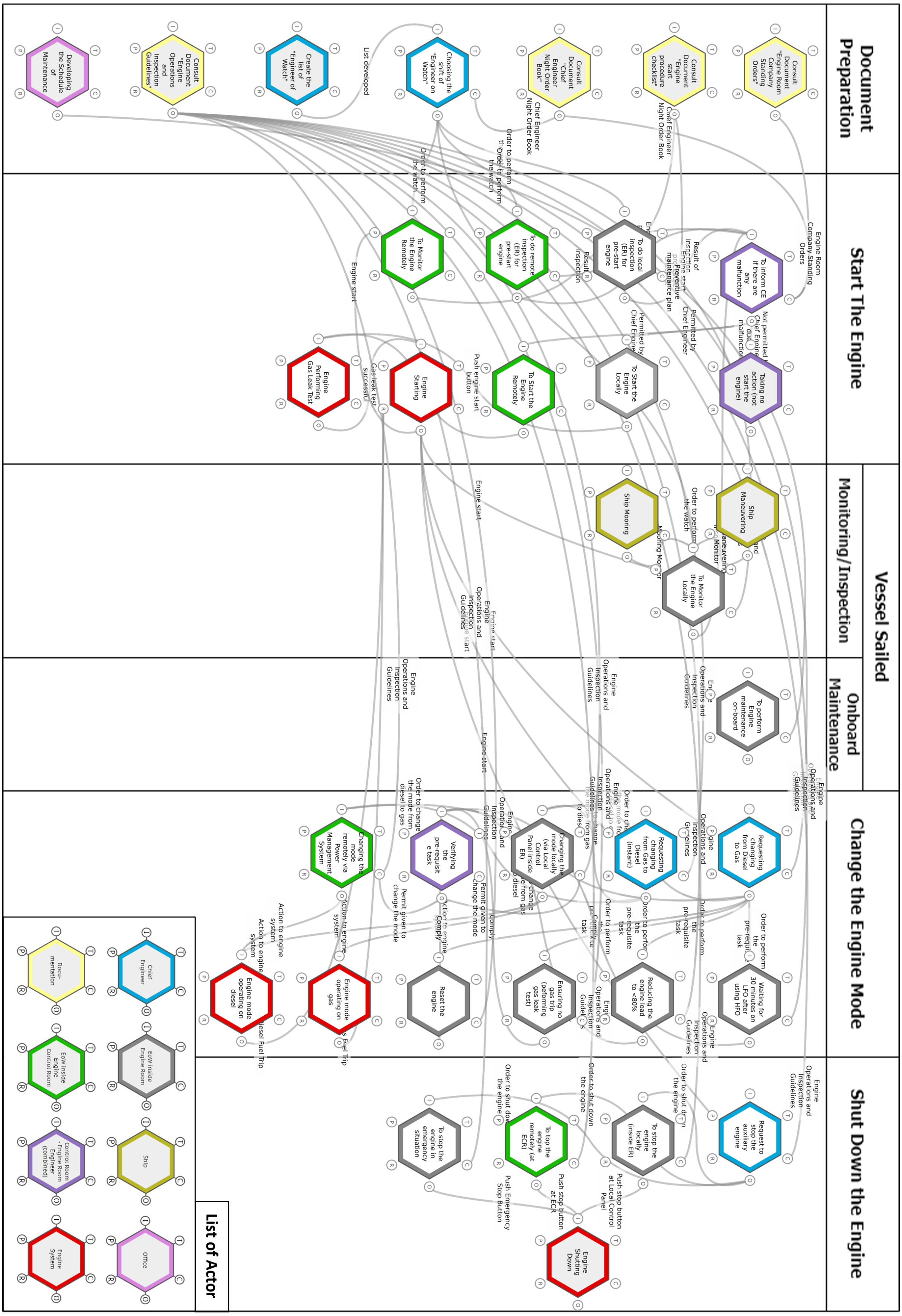


Figure 4.4: The Work-as-Imagined (WAI) FRAM

4.3. Work-as-Done (WAD)

The Work-as-Done (WAD) FRAM indicates how the process is actually carried out in the workplace context. The goal of this step is to develop the actual socio-technical system using FRAM based on the actual activity, rather than the ideal conditions mentioned in the documentation. The method of developing WAD FRAM is explained in the sections below.

4.3.1. WAD Data Collection

FRAM data gathering via interviews was based on the research saturation concept, rather than statistical hypothesis testing. In qualitative research, research saturation is regarded as the gold standard for defining sample size and when data collection or analysis should be discontinued. Data saturation occurs when no new information or themes emerge after collecting multiple samples (Saunders et al., 2017; Urquhart, 2013; Sparkes et al., 2012; Denny, 2009; Guest et al., 2006; Dey, 1999).

The purpose of FRAM is to better understand how complex human-machine interactions occur within the system. The interviews were centred on people who directly conduct responsibilities in the ship's onboard engineering department. This department is led by the Chief Engineer, and there are 2nd and 3rd engineers, each with their own set of tasks and responsibilities. Initially, interviews will be conducted with five people, and data collection will continue until saturation is attained, as defined by Saunders et al. (2018). At this point, data gathering through interviews will be discontinued without compromising research quality.

The interview questions were designed to gather information on work-as-done for the LNG-fueled Dual Fuel Engine operations inside the ship. The existing Dual Fuel Engine's activities was used to construct the Functional Resonance Analysis Model (FRAM) and establish links across functions. This analysis will primarily focus on the placement of functions, the time spent performing functions, and the resonance between functions.

The interview questions were inspired by Klein et al.'s Critical Decision Method (CDM), which was established in 1989 to analyse tasks with high-time pressure, high information content, and changing conditions (Klein et al., 1989). The CDM were modified to be used in this research, particularly for generating the work-as-done of the LNG Dual Fuel Engine Room inside the ship. Table 4.1 shows the altered CDM probe content that will be applied to FRAM-Oriented interview questions during the later discussion.

Table 4.1: List of Adapted CDM Questions Inspired by Klein et al. (2019)

Probe Type	Probe Content
Cues	What cues (trigger) are leading you to start activity ...?
Knowledge	What information did you use in performing task/making decisions in this process? And how is it obtained?
Goal	What is the goal of this function/task?
Options	What other options/alternatives were considered or available to you for this task/function?
Pressure	Are there any pressures that influence this activity? And how do they affect your task/function?
Time Pressure	How much time pressure was involved in this activity? And why does it give pressure on you?

The CDM probing questions were developed and deployed to correspond with conventional FRAM thinking questions. To ensure that interviewees understood the questions, the list of questions was updated to use more common English rather than FRAM's technical terminology. Furthermore, to help interviewees grasp the questions while remaining focused on the interview's goal, the interview procedure began with a graphic flow chart of the ship's operations. This step served as a screening process for the interview, followed by more comprehensive FRAM questions for safety-critical jobs. Table 4.2 provide a list of generic questions for the first phase of FRAM.

Table 4.2: List of General Questions

General Questions
Does this diagram give you a complete picture of your activities? What is missing?
How long do you spend the time of doing tasks inside the ER for a day?
Do you spend more time than that in case of problems? If yes, what is the reason?
What is the task or group of tasks which you spend the most time on in the ER during normal operating conditions?
What is the task or group of tasks which you spend the most time on in the ER during maintenance tasks?
Which typical activities that are hard to predict in terms of how long they will actually take (unpredictability of duration)?
Which task gives you the highest probability to create a leak?
How can you tell whether a leak has occurred?
Which of these responsibilities required you to remain in the ER even after the leak occurred? And what happens if you leave the ER?

After defining the important or safety-critical activities, the interview proceeded to ask specific tasks using the ”FRAM-Oriented interview Questions” based on the six aspects of FRAM’s duties. Table 4.3 contains a list of these questions.

Table 4.3: FRAM-Oriented interview Questions

FRAM six-aspects	Guided Question
Input	What triggers you to start the activity?
Output	What was the outcome of your activity? What additional tasks/activities may be affected by the prior task’s output quality?
Pre-conditions & Resource	What are resources (technical, physical, time, number of crew) needed to perform the task?
Control	Do you have any suggestions for improving the success and safety of your task? Is there anything that makes your task more difficult? Can the task be conducted locally or remotely?
Time	How does delay/early completion affect time after the preceding task? How often the frequencies of the task inside the ER in a day? How long you spent inside the ER to performing the task/function? What are the bottleneck tasks or situations causing the extended time spent in the ER? What are examples of activities with unpredictable durations? What is the bottleneck for ”typical activities that are hard to predict in terms of time spent” within the ER?

Table 4.3: FRAM-Oriented interview Questions

FRAM six-aspects	Guided Question
	Are there any ways to reduce time spent in the ER while accomplishing tasks? Will reducing task time influence task quality and crew safety?

The WAD FRAM interview strategy, shown in Figure 4.5, represents the optimum interview process. The initial interview procedure began with a broad question interview covering all areas of ship operations. This interview aimed to provide a basic picture of critical safety functions and validate the entire process, which would then serve as the basis for a more specialized interview employing FRAM-Oriented Interview questions. This technique was intended to assist in identifying the most crucial functions and directing the interview to focus solely on those tasks.

The subsequent step involved a comprehensive interview, which covered only 1-2 functions per session. This in-detailed interview addressed all six aspects of FRAM's functions, as outlined in Table 4.3. The findings were then evaluated by the research committee, and follow-up validation was performed with the initial interviewee.

However, the ideal approach that had been envisaged proved impractical for this project due to the interviewee's limited time and scheduling availability. Discussions with the research committee led to the conclusion that the recommended strategy could not be followed in the proposed order, but rather had to be adapted according to the interviewee's availability.

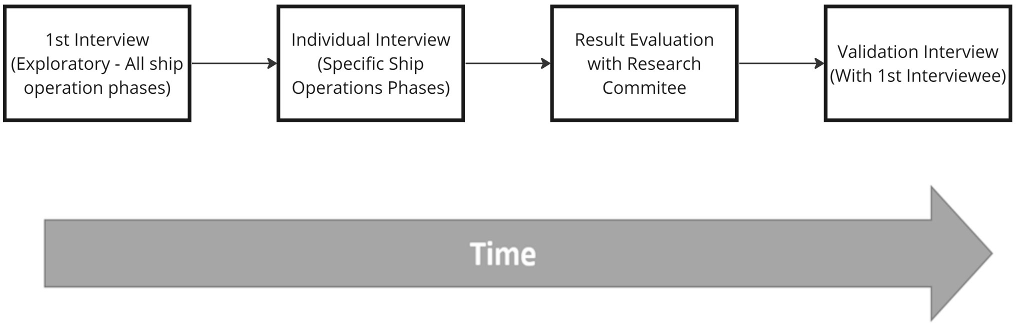


Figure 4.5: The Ideal Sequence of Interview Process

4.3.2. WAD Data Analysis

The data obtained from the Work-as-Done (WAD) data collection were used to validate the ship's operational processes and the information related to the six aspects of FRAM. The operational processes and sequences of the ship were revised based on findings from the interviews, which utilized prompts from Table 4.2. Additional functions and actors were incorporated based on the actual processes observed. Detailed analysis of critical safety activities conducted inside the engine room for FRAM functions followed the questions listed in Table 4.3. The data collection demonstrated a saturation of results and responses, indicating that interviewing five participants was sufficient for the research data collection. A summary of the interviews can be found in Appendix C.

4.3.3. WAD Result

The results from the Work-as-Done (WAD) FRAM reveal more complex interactions, actors, and functions compared to the Work-as-Imagined (WAI) FRAM, underscoring the differences between planned procedures and actual work practices. This complexity is highlighted in the validation and findings from the actual work procedures, as illustrated in Figure 4.6 and Figure 4.7. There are additional actors on the STS such as the ”Officer on Watch at the Bridge”, ”Scheduler” and ”Gas Detector (sensors)”, enrich the elements within the ship engine room.

One of the initial changes is the addition of the ”Gas Detection During Operations” box, which underscores the impact of gas sensors on the socio-technical system. According to the IGF Code, gas detection sensors are mandatory safety measures that must be present in the engine room, serving as one of the systems that trigger the emergency shutdown (ESD) of the engine (International Maritime Organization, 2016; International Maritime Organization, 2015). Consequently, the presence of gas detection sensors can influence local activities such as inspections and maintenance, which may not be conducted locally due to hazardous conditions in the engine room and the automatic shutdown of the engine.

Other significant changes are observed in the relationships of the ”On-board Maintenance” phase, which previously had no associations with other functions in the WAD FRAM. The detailed relationships between maintenance and other functions will be explored in the following chapter, providing a deeper understanding of the interconnected nature of shipboard operations.

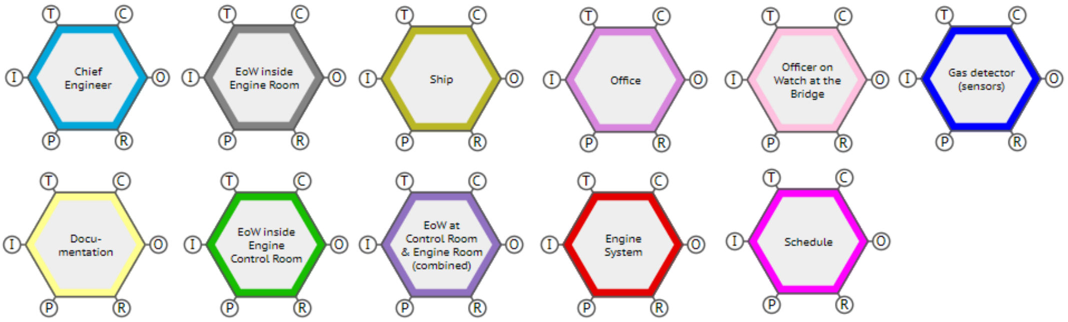


Figure 4.6: WAD FRAM Legend for the list of actor roles

4.3.4. WAD Result Analysis

This subsection will focus into the findings of the Work-as-Done (WAD) Functional Resonance Analysis Method (FRAM) and analyze these results to deepen our understanding of the Socio-Technical System (STS) within the engine room. The insights derived from the WAD FRAM are based on operational observations from LNG dual-fuel (DF) engine ships. These observations form the foundational baseline from which we will develop strategies aimed at enhancing the safety levels of ammonia (NH3) powered ships.

Redundancy of Local and Remote activity

Redundancy within ship systems is a common strategy to ensure the reliability and safety of the ship’s operations, where critical decision-making and high-level control activities often occur remotely (Bielecka and Muc, 2018). Figure 4.7 illustrates redundancies in activities such as ”Start the Engine,” which can be initiated locally, from the engine control room (ECR), or remotely from the bridge. The choice of location for these activities depends on directives from the master or chief engineer, and the availability of multiple locations enhances operational reliability. Typically, the decision to start the engine is made by the chief engineer based on the master’s orders, usually about one hour before departure. This redundancy is similarly applied to the engine shutdown procedures.

On the other hand, some activities combine both remote and local operations as complementary actions. In this setup, engineers do not restrict themselves to a single activity location but utilize both remote indicators from the ECR and local indicators on the engine. For instance, both pre-start and post-start engine inspections involve using remote indicators from the ECR alongside local indicators on the engine to verify consistency between the ECR monitor and the actual engine component indicators. Additionally, certain pre-start activities require calibrations and visual inspections of engine components locally, which are subsequently verified through the ECR monitor. This method of incorporating both local and remote checks increases redundancy, ensuring that the information displayed on ECR monitors aligns with the actual conditions on the engine components.

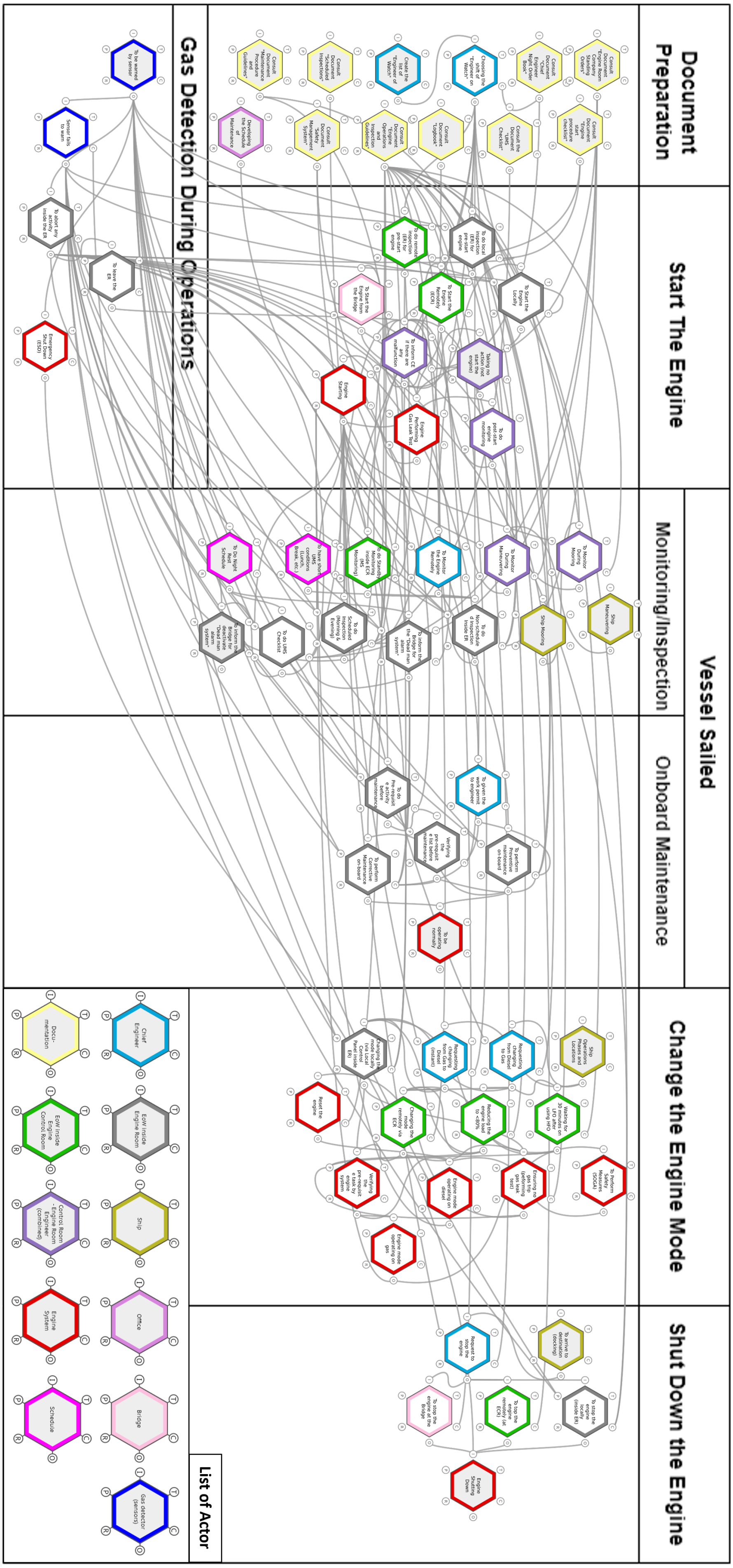


Figure 4.7: The Work-as-Done (WAD) FRAM

Monitoring and Inspections Work-as-Done Procedure

Monitoring and inspection activities on ships are categorized into three types: scheduled monitoring, unscheduled monitoring, and the unmanned machinery space (UMS) checklist. Both scheduled monitoring and the UMS checklist are standardized activities with predefined procedures and a focus list of components. Scheduled inspections occur in the morning (08:00 - 09:00) and evening (16:00 - 17:00), while the UMS checklist is completed before the engineering crew's nightly rest period (around 22:00 - 23:00).

Given that the engineering crew typically works daily shifts from 08:00 to 17:00, they often do not remain inside the engine room outside of scheduled monitoring times and the UMS checklist. This is due to the challenging conditions within the engine room, which include high temperatures, vibrations, and noise. According to interviews conducted for the Work-as-Done (WAD) study, the engineering crew usually monitors indicators remotely from the engine control room (ECR) while on standby. Unscheduled monitoring is triggered when anomalies are detected on the ECR monitor, requiring direct local investigation by the crew. Thus, outside of performing specific maintenance tasks, the engineering crew predominantly monitors engine conditions remotely and only conducts local checks when necessary.

Relationship Between Monitoring and Maintenance

Preventive maintenance is initiated according to a schedule developed by the company, based on the engine manufacturer's manual. This schedule details the maintenance intervals and specific components to be maintained. However, there is a possibility of component breakdowns occurring before the scheduled maintenance due to factors such as operational demands, environmental conditions, and installation quality.

The strong relationship between monitoring and maintenance is illustrated in Figure 4.7 and supported by findings from interviews. Monitoring activities, which may involve indicator checks or visual inspections, often trigger corrective maintenance. These monitoring activities are crucial in identifying component breakdowns, which must then be reported to the Chief Engineer (CE) before any further decision-making can occur. Additionally, findings during preventive maintenance can also initiate corrective maintenance. It is mandatory that any major failures or breakdowns of components be reported to the CE, and if the situation could potentially impact overall ship operations, the master must also be informed and involved in the decision-making process.

However, the relationship between visual monitoring and maintenance may not always be time-sensitive due to potential delays. Several sensors, indicators, and alarms serve as additional safety measures, providing notifications of any malfunctions or failures in the components. These systems act as redundancy measures to enhance the safety level and reliability of ship operations.

List of Critical Safety Functions: Activity Inside the Engine Room

The time spent inside the engine room by the engineering crew is associated with a high risk of exposure to ammonia leakage. Relocating tasks remotely could significantly reduce this risk level for the engineering crew (Trivyza et al., 2021). According to the FRAM six-aspects framework, Table 4.4 details the activities conducted locally within the engine room and provides information on the time spent and the frequency of these activities, which are crucial for quantitative analysis. The primary goal of this analysis is to reduce the duration that crew members spend near the engine, thereby decreasing their risk exposure. While some activity procedures and schedules are well-defined, others are unstructured and triggered by specific events.

Activities are categorized by frequency as ”once per voyage,” ”depends on ship route,” and ”daily.” The ”Start the Engine” and ”Shut Down” activities are typically scheduled only at the start of the voyage, although in practice, engine shutdown may occur as directed by the master based on operational conditions.

The ”change the engine mode” task varies depending on ship routes. Usually, ships use diesel marine gas-oil (MGO) fuel during departure, maneuvering in narrow areas, and arrival phases. Gas fuel is utilized during the ”sea passage” phase, where the ship operates on the open sea and requires less load due to reduced maneuvering needs.

”Daily” activities occur every day according to routine schedules, resulting in the highest annual time spent inside the engine room due to their frequency and duration. Scheduled monitoring typically occurs in the morning (08:00 - 09:00) and evening (16:00 - 17:00), while the Unmanned Machinery Spaces (UMS) checklist is completed before the crew's nightly rest period (22:00 - 23:00). Conversely, unscheduled monitoring is reactionary, prompted when engineering crew detect malfunctions from the ECR indicators, necessitating a direct check in the engine room.

According to the interviewed informants, the maintenance activities often become the bottleneck in engine room operations due to the extensive time devoted to these tasks. Maintenance can extend into the night if urgent, potentially impacting the ship's operational capabilities. The unpredictability of maintenance duration is influenced by factors such as component complexity, spare parts availability, and crew experience. To enhance safety, the current dual fuel (DF) LNG powered ships are equipped with prerequisite activities such as ensuring no system automation that could accidentally start the engine and purging gas residuals from pipes using nitrogen. Verification of these prerequisite activities is conducted to enhance safety and minimize human error, accompanied by a work permit for high-risk jobs like welding or working at heights.

Table 4.4 provides a baseline for estimating the probability of engineering crew presence in the engine room for the quantitative risk assessment (QRA), which will be further detailed in the subsequent chapter.

Table 4.4: List of activity inside the engine room with information of the time spent and frequency

No	Phase	Functions/Tasks	Location	Time-spent	Frequency	Uncertainty
1	Start the Engine	To do local inspection (ER) for pre-start engine	Engine and components	30 - 60 minutes	Once per ship voyage	Low (checklist available)
2		To start the engine locally	Local Control Panel (LCP)	Instant	Once per ship voyage	-
3		To do post-start engine monitoring	Engine components and ECR	10-30 minutes	Once per ship voyage	High (wait for RPM to be idle - engine dependent)
4	Vessel Sailed (Monitoring/Inspection)	To do Non-scheduled inspection inside ER	Engine and components	around 30 minutes	Daily	Medium (some unscheduled tasks are completed before leaving the Engine Room for short breaks, but others may be triggered by issues indicated in the Engine Control Room)
5		To do Scheduled Inspection (Morning & Evening)	Engine and components	1 hour each (2 times a day)	Daily	Low (scheduled with fixed checklist)
6		To do UMS Checklist	Engine and components	1 hour	Daily	Low (scheduled with fixed checklist and regulated)
7	Vessel Sailed (Onboard Maintenance)	To perform Preventive maintenance on-board	Engine and components	2-8 hours (component-based frequency is vary)	Daily	High (engine components and failure dependents)
8		To perform Corrective maintenance on-board	Engine and components	2-8 hours (frequency is very unpredictable)	Daily	High (engine components and failure dependents)
9		To do Pre-requisite activity before maintenance	Engine and components	around 1 hour	Daily	High (component dependent)
10		Verifying the pre-requisite list before maintenance	Engine and components	around 1 hour	Daily	High (component dependent)
11	Change the Engine Mode	Changing the mode locally (Via LCP)	Local Control Panel (LCP)	Gas to Diesel: instant	Depends on Ship Route	High (depends on the ship route and conditions)
12	Shut down the Engine	To stop the engine locally (inside ER)	Local Control Panel (LCP)	Instant	Once per ship voyage	Low (already have the checklist.)

Number of Couplings for Activities inside the Engine Room

Table 4.5: The Number of Couplings for Activity Inside the Engine Room

No	Phase	Functions/Tasks	Code	Total Couplings	Input Couplings	Output Couplings
1	Start the Engine	To do local inspection (ER) for pre-start engine	A1	6	1	1
2		To start the engine locally	A2	5	1	1
3		To do post-start engine monitoring	A3	2	1	1
4		To inform CE if there are any malfunction	A4	17	9	5
5	Vessel Sailed (Monitoring/Inspection)	To do Non-scheduled inspection inside ER	B1	11	4	1
6		To do Scheduled Inspection (Morning & Evening)	B2	11	2	2
7		To do UMS Checklist	B3	10	1	2
8	Vessel Sailed (Onboard Maintenance)	To perform Preventive maintenance on-board	C1	9	1	2
9		To perform Corrective maintenance on-board	C2	9	2	1
10		To do Pre-requisite activity before maintenance	C3	5	1	1
11		Verifying the pre-requisite list before maintenance	C4	5	1	1
12	Change the Engine Mode	Changing the mode locally (Via LCP)	D1	10	4	2
13	Shut down the Engine	To stop the engine locally (inside ER)	D2	6	1	1

The incorporation of the FRAM in STS research offers significant advantages, particularly its ability to map and identify relationships between functions through couplings. Table 4.5 summarizes the total couplings, input couplings, and output couplings for activities within the engine room, facilitating the analysis of potential resonance effects between functions. Functions with a high number of input couplings are likely to be significantly affected by the resonances of their input functions, while those with many output couplings can have a substantial impact on numerous other functions. These effects may manifest as delays or deviations from the expected timing or quality of the output, thereby resonating across other functions.

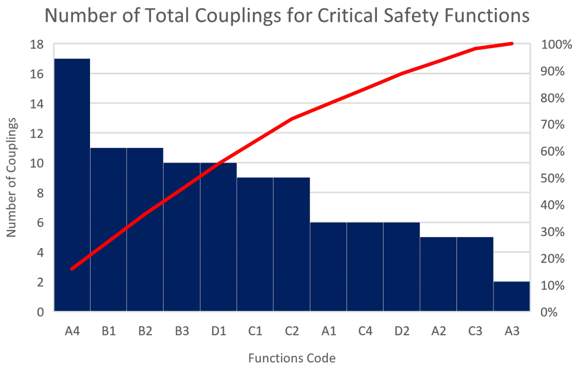


Figure 4.8: The Total Couplings of Activity Inside the Engine Room based on Work-as-Done (WAD) FRAM

According to Table 4.5 and Figure 4.8, the function ”to inform the Chief Engineer (CE) of any malfunctions” has the highest number of total couplings, totaling 17, helds 15% of the total couplings within the functions inside the ER. This is followed by ”to conduct non-scheduled inspections inside the ER” and ”to conduct scheduled inspections (morning & evening),” each with 11 couplings. This pattern reflects the hierarchical control within the ship’s engine room systems, where most activities involve monitoring and redundancy, with fewer directly related to control and decision-making (Bielecka and Muc, 2018). All malfunctions or deviations from normal operational procedures must be reported to the CE, who then decides the necessary actions. For instance, if a failure is detected during scheduled monitoring, the CE must be informed before corrective maintenance can commence. This process is crucial for determining the appropriate maintenance procedure, understanding the condition, and assessing the potential impact of maintenance actions on ship operations.

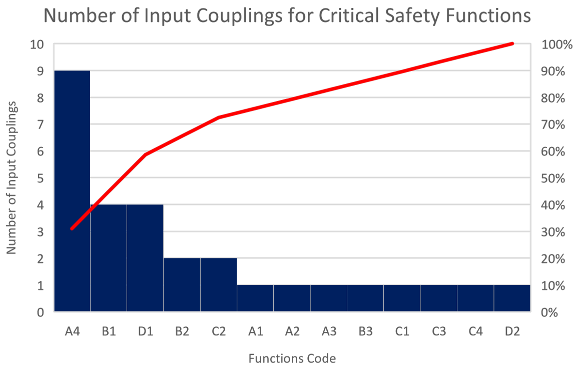


Figure 4.9: The Input Couplings of Activity Inside the Engine Room based on Work-as-Done (WAD) FRAM

The point is further supported by Figure 4.9, which shows that ”to inform CE of any malfunction” also possesses the highest number of input couplings with total of 30% of the total input couplings within the functions inside ER, receiving inputs from various tasks including unscheduled and scheduled maintenance, UMS Checklist, mooring monitoring, maneuvering monitoring, actions to take if leakage is detected, and engine pre-start procedures. This function becomes a procedural bottleneck, where decision-making is centralized in a single individual. In emergencies or complex situations, this can impact engine room safety due to the high concentration of responsibility for decision-making. Additionally, this function also exhibits the highest number of output couplings, indicating that the outcomes of these decisions influence multiple operations such as corrective maintenance and action permits.

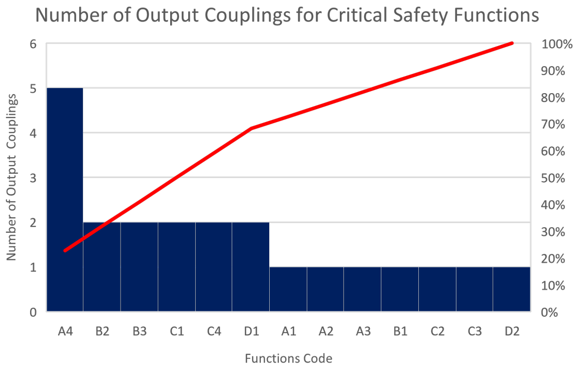


Figure 4.10: The Output Couplings of Activity Inside the Engine Room based on Work-as-Done (WAD) FRAM

Conversely, activities like monitoring/inspections, maintenance, and changing engine modes exhibit a high number of couplings due to the control and pre-requisite aspects of FRAM, which require adherence to documentation, permits, and pre-requisite activities beforehand. This structured approach ensures that all necessary controls are in place before activities proceed, enhancing the safety and efficiency of engine room operations.

5

Quantitative Risk Assessment (QRA) of Engine Room Operations

This chapter conducts Fault Tree Analysis (FTA) and Quantitative Risk Assessment (QRA) to quantify and analyze the safety level of engine room operations, which is a critical subsystem of the ship. The QRA uses the metric of individual risk per annum (IRPA) to assess risk and evaluate modifications to meet the defined Risk Acceptance Criteria in accordance with the IGF Code regulations. The FTA is employed to visualize the logical sequence of failure events for both LNG (methane) and ammonia-powered ship engine rooms.

5.1. Risk Acceptance Criteria

In this research, the authors utilize the risk acceptance criteria (RAC) outlined in the IGF Code. LNG-powered ships, such as those using methane (CH4), are widely operated and deemed ”safe” under established regulations, including the IGC Code and IGF Code. In contrast, NH3-powered ships, which represent new technology in the maritime sector, lack specific regulations defining the normative risk level.

To establish the RAC for NH3-powered ships, this research follows the IGF Code guidelines, which stipulate that new technologies should achieve the same level of safety as their preceding counterparts. Consequently, this study aims to evaluate the Individual Risk Per Annum (IRPA) for an NH3-powered engine room, ensuring that it aligns with the safety levels of current LNG-powered (CH4) ships as per IGF Code guidelines.

Although specific regulations defining required IRPA values for individual ship subsystems like the engine room are not available, the IGF Code provides safety criteria for the overall ship system. These criteria do not directly apply to this focused study. Therefore, the primary objective of the calculation phase can be summarized as follows:

$$IRPA_{\text{NH3}} = IRPA_{\text{LNG (CH4)}} \tag{5.1}$$

5.2. FTA of the Hazards Inside Engine Room

The FTA was developed through a comprehensive literature review on LNG-powered ships, the risks associated with ammonia-powered ships, maritime regulations, and insights from the FRAM model, which identified ”common cause” events. This study specifically explores the hazards in ship engine rooms, focusing on methane (CH4) and ammonia (NH3) as engine fuels, each reflecting distinct risk characteristics. The FTA serves as a qualitative tool to map out the logical sequence of failure events, aiding in understanding the unique risk profiles associated with CH4 and NH3 when used as engine fuels. This sequence forms the foundation for the IRPA calculations performed through QRA. The differing risk philosophies relating to failure events and their implications will be elaborated on in the following subchapter.

5.2.1. FTA of Methane (CH4) Dual-Fuel (DF) Engine Room

Methane (CH4), categorized as a flammable gas (FG), presents multiple event scenarios such as direct ignition, delayed ignition, and explosion (Abubakirov et al., 2024). The primary risks associated with methane-fueled ships are fire and explosion, which stem from gas leakage and subsequent ignition when concentrations reach the Lower Flammability Limit (LFL) of 50,000 ppm (Guan et al., 2016). Safety measures in the ship's engine room include gas detection systems, ventilation, and emergency shutdown (ESD) systems (International Maritime Organization, 2015; International Maritime Organization, 2016). The combination of gas leakage, potential failure of risk mitigation devices and ignition can lead to delayed ignition fires involving CH4 when LFL concentrations are reached. The FTA for methane-powered ships, based on research by Guan et al. (2016), has been adapted to meet the objectives of this study, as illustrated in Figure 5.1.

The FTA for CH4 as a marine fuel, shown in Figure 5.1, identifies three primary pathways leading to the top event failure of crew exposure to delayed ignition fires inside the engine room: the delayed ignition fire of the DF engine room, the presence of the engineering crew in the engine room due to operational tasks and the inability of the engineering crew to evacuate during the emergency situation.

The leftmost side of the FTA represents the scenario where the engineering crew is unable to evacuate during an emergency. This event is linked to specific safety procedures for emergency situations, crew response, knowledge, and the engine room layout. In this research, this event is considered an undeveloped basic event, indicating that the variables and probabilities associated with it are unknown and fall outside the scope of this study. Therefore, the QRA used for safety level evaluation will not consider this event.

However, it is important to note that for the top event of failure involving CH4, ignition and a high LFL concentration are required. This situation necessitates a certain duration to achieve such LFL conditions, providing the crew with sufficient time to react. The scenario may differ for NH3. Details regarding the outflow rate and the time required to reach the LFL limit for CH4 are provided in Appendix D.

The middle side of the fault tree indicates the presence of the crew inside the engine room due to tasks associated with operations, monitoring, and maintenance during the ship operation phase. These tasks include starting the engine, conducting monitoring and inspection activities, performing on-board maintenance, changing the engine mode, and stopping the engine locally. These tasks involving the engineering crew are identified through FRAM, as denoted in Figure 4.7 and detailed in Table 1. The probability of crew presence in the engine room during routine activities is quantified using the FRAM.

The right side of the FTA indicates the failure sequence leading to a ”delayed ignition fire” inside the engine room. This sequence combines ignition with the hazardous atmosphere created by gas leakage reaching the CH4 LFL threshold of 50,000 ppm. Although this study does not focus on the probabilities and causes of ignition—considering them undeveloped events—it analyzes the creation of a hazardous atmosphere with consideration for the presence of risk mitigation devices. In this analysis, only the existence of gas detectors is considered for the QRA.

According to the IGF code, the engine room should be equipped with gas detection sensors as a safety measure to initiate an ESD. This ESD is crucial for reducing the probability that gas leakage reaches the LFL concentration of CH4, thereby preventing a ”delayed ignition fire.” Nonetheless, there is a potential for failure in these risk mitigation devices, such as a gas detector failing to detect a gas leakage. Since CH4 has an LFL concentration level of 50,000 ppm, this allows sufficient time for gas sensors to detect leakage before reaching the LFL level. However, a source of fire ignition is required to create a delayed ignition fire once the gas leakage reaches the LFL level. This scenario results in two probabilities of fatality inside the engine room: when gas sensors successfully detect the leakage and when they fail.

The trigger for the gas leakage event is ”Loss of Containment (LOC)”, representing specific component failures. Derived from historical data in the oil and gas industry and considering LNG-powered marine applications, this data serves as generic safety design guidelines for gas-fueled ships (Davies and Fort, 2014). The focus is on pipe leakages with varying hole diameters, particularly in engine room components classified as Engine Line B. The LOC data, based on normal operations, startups, and shutdowns in the oil and gas production sector, indicate that the LOC value does not change with potential modifications to crew tasks, highlighting the need for further research into the impact of socio-technical system (STS) modifications within ammonia-fueled engine rooms on LOC values.

5.2.2. FTA of Ammonia (NH3) Dual-Fuel (DF) Engine Room

As discussed in Chapter 2, Ammonia (NH3) is recognized as both a toxic and flammable gas. In confined spaces, exposure to ammonia leakage can lead to fatal consequences due to poisoning before concentrations reach ignitable levels (Pomonis et al., 2022; Abubakirov et al., 2024). Therefore, this research focuses solely on the event of ammonia poisoning as its primary concern.

The ammonia leakage constitutes a catastrophic event, as ignition is not necessary to achieve the defined top-level event. Additionally, ammonia has a lower threshold concentration for fatality (AEGL-3) at 2,700 ppm, compared to methane's 50,000 ppm (EPA, 2023; Abubakirov et al., 2024). This underscores the potential for reaching fatal concentration levels even if the gas detector system detects the leakage and initiates ESD.

The FTA of ammonia (NH3) as a marine fuel, presented in Figure 5.2, identifies three primary pathways leading to the fatal exposure of engineering crew members to ammonia gas leakage inside the engine room: the development of a hazardous atmosphere due to NH3 leakage, the presence of the crew within the engine room due to operating tasks and inability to evacuate during emergency situations.

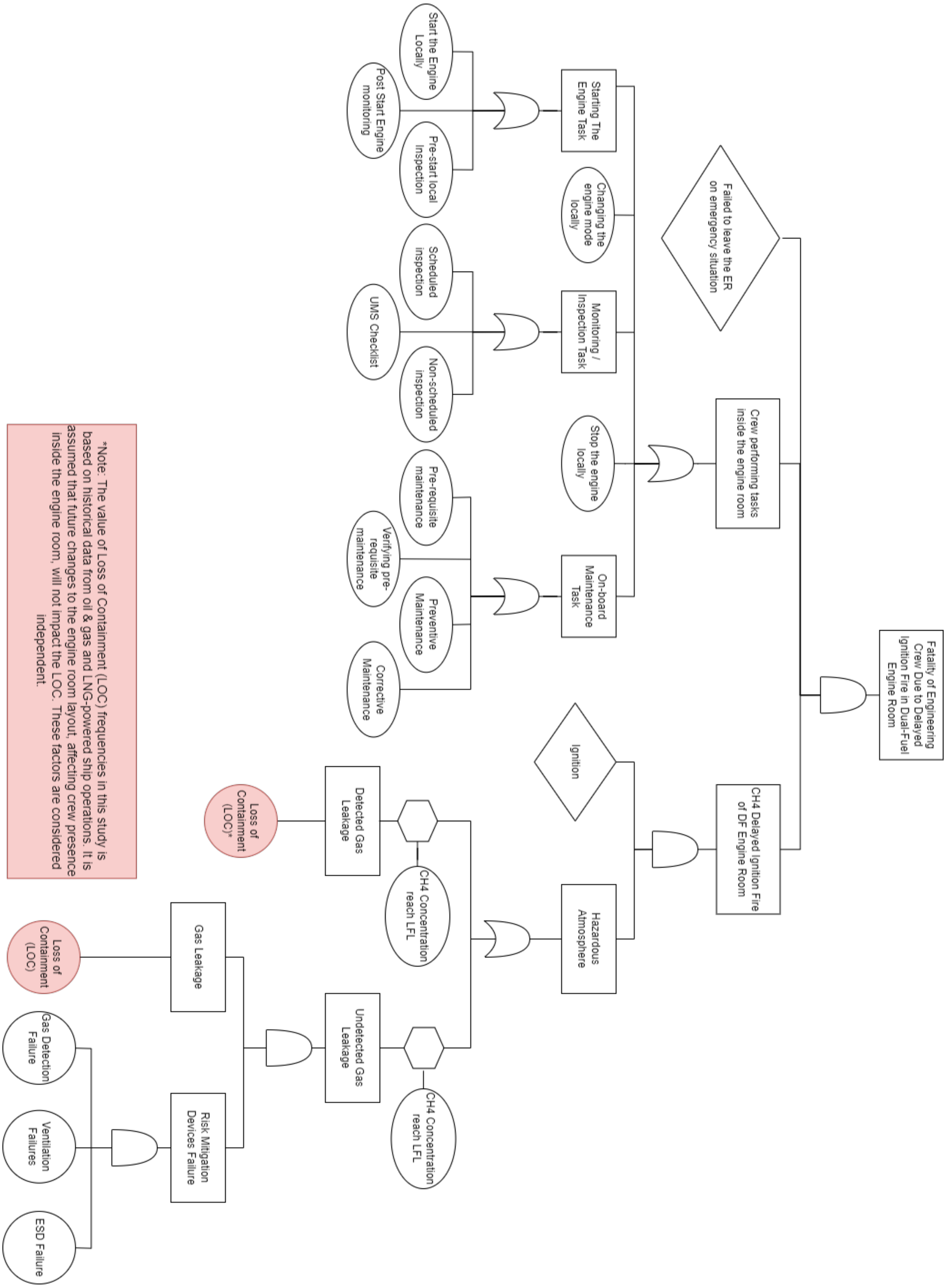
The leftmost event in the FTA is analogous to the CH4 FTA, representing the failure to evacuate the engine room during an emergency. Similar to the CH4 FTA, this event is considered an undeveloped basic event in this research. The probability and variables associated with this event remain unknown and require further development.

Furthermore, for NH3, the top event failure only necessitates leakage, without requiring ignition. Additionally, AEGL-3 for NH3 is significantly lower than that for CH4, which increases the likelihood that the crew may be unable to evacuate the engine room in a timely manner during an emergency. As with the CH4 scenario, this event will not be included in the safety level evaluation using QRA.

The pathway on the middle side of the fault tree reflects similar logic to that for CH4, attributing the presence of the crew inside the engine room to operations, monitoring, and maintenance tasks during the ship's operational phase. These tasks include starting the engine, conducting monitoring and inspection activities, performing on-board maintenance, changing the engine mode, and stopping the engine locally. The tasks involving the engineering crew are identified through the FRAM, as denoted in Figure 4.7, with detailed activities listed in Table 1. In addition to the crew's operational responsibilities, their inability to evacuate the engine room during emergencies significantly increases the risk of fatal exposure.

The third pathway, illustrated on the right side of the fault tree, focuses on the formation of a hazardous atmosphere due to ammonia leakage. This condition is achieved when NH3 concentration inside the engine room reaches the AEGL-3 threshold level of 2700 ppm. The gas leakage scenarios are categorized based on the gas detector's performance: successful detection leading to ESD and failure to detect resulting in no ESD. The distinction in the probability of gas leakage depends on whether the gas sensor successfully detects the leakage. However, calculations using Equation (5.2) show that the LSIR caused by "undetected gas leakage" is minimal, suggesting that the probability of fatality occurs before the gas sensor can detect the leakage, thus undermining the "undetected gas leakage" scenario.

The trigger for the gas leakage event is identified as LOC, which represents specific component failures. In this study, the LOC values are based on those observed in LNG (CH4) ships, details of which will be further explained in the sub-chapter on QRA limitations. The LOC data, derived from normal operations, start-ups, and shutdowns in the Oil and Gas Production (OGP) sector, demonstrate that the LOC value remains unchanged regardless of potential modifications to crew tasks. To achieve an accepted safety level on ammonia-powered ships, modifications such as maximizing remote operations and minimizing the probability of crew presence inside the engine room are necessary. However, changes in work procedures and locations may introduce new, undefined hazards not considered in the empirical LOC data, underscoring the need for future studies to assess the risks associated with these modifications.



*Note: The value of Loss of Containment (LOC) frequencies in this study is based on historical data from oil & gas and LNG-powered ship operations. It is assumed that future changes to the engine room layout, affecting crew presence inside the engine room, will not impact the LOC. These factors are considered independent.

Figure 5.1: The Fault Tree Analysis of Methane (CH4) powered DF Engine Room for Delayed Fire Risk Top Event

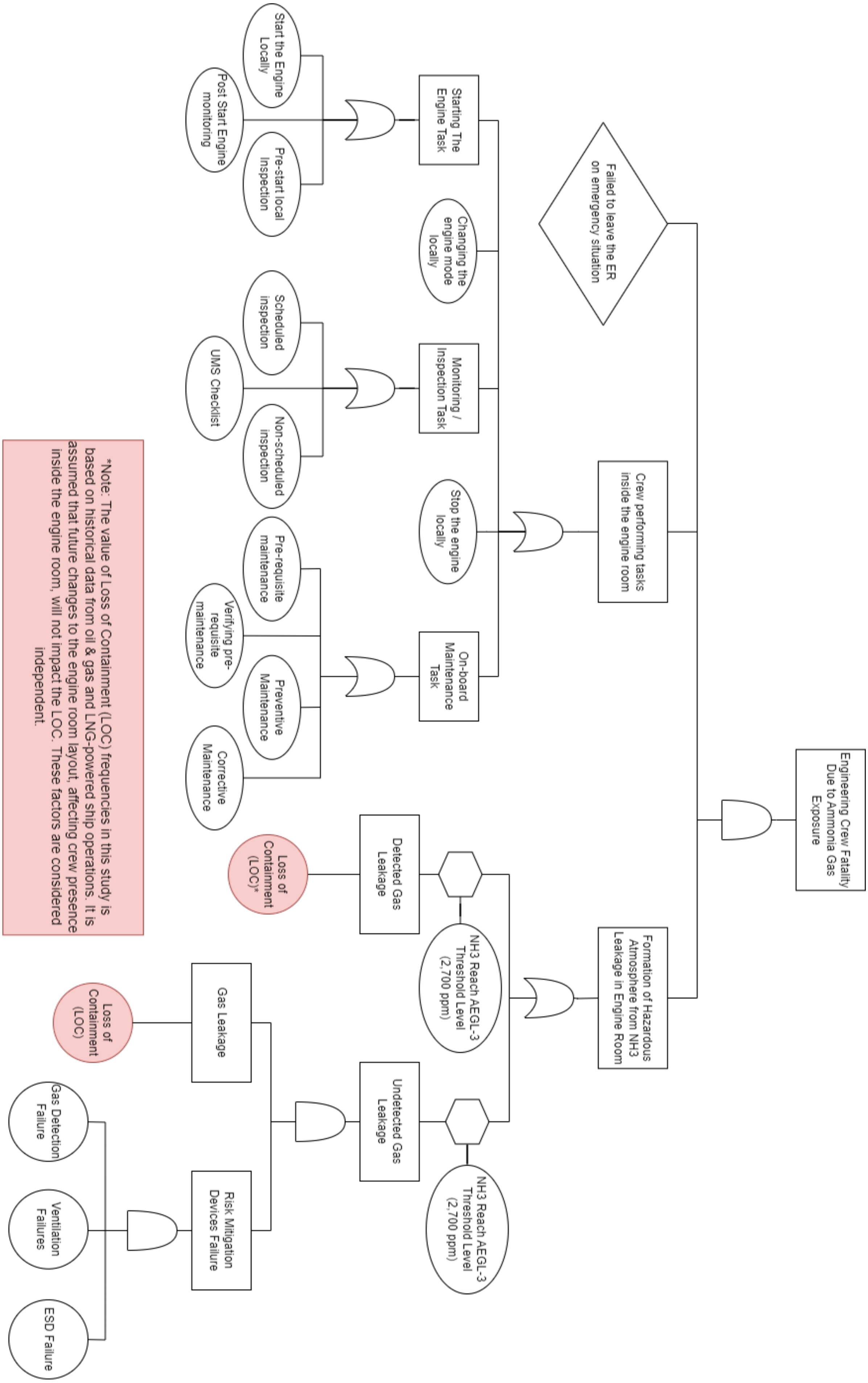


Figure 5.2: The Fault Tree Analysis of Ammonia (NH3) powered DF Engine Room for ammonia gas poisoning due to leakage Top Event

5.2.3. Factors Influencing Concentration Levels in the Engine Room

The occurrence of the top event in both methane (CH4) and ammonia (NH3) scenarios hinges on the failure of events while meeting specified conditions, as defined by the inhibit gate of the FTA. In this study, the critical condition for both gases relates to the concentration level inside the engine room. Once failure events lead to reaching a certain concentration level inside the engine room, a catastrophic event ensues. The concentration levels inside the engine room for both CH4 and NH3 are determined by various factors illustrated in Figure 5.3 (Abubakirov et al., 2024).

These factors will subsequently be incorporated into the QRA process to determine the probability of fatality (P_{fat}) and calculate the IRPA for the engineering crew.

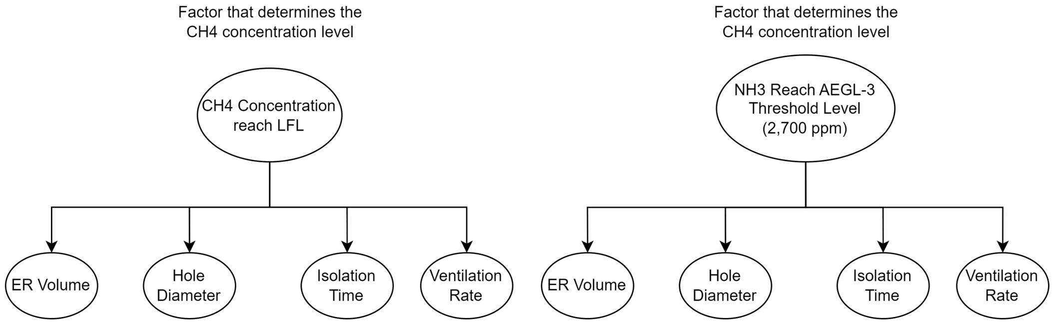


Figure 5.3: The factors that influenced the concentration level of gas-fuel inside the Engine Room (Abubakirov et al., 2024)

5.3. Quantitative Risk Analysis for Engine Room

The FTA developed in this study visualizes the logical sequence leading to the top event failure, which will be quantified through QRA in this chapter. QRA employs the IRPA metric to evaluate the risk of fatality exposure faced by the engineering crew on an annual basis, based on ship operations. IRPA is a metric commonly used in maritime regulatory codes such as the IGF Code and IGC Code, to determine the requisite safety levels for ships.

The QRA for determining the IRPA level is based on a comprehensive literature review of studies examining the risks associated with ammonia-powered ships, components of LNG ships, QRA methodologies used in the chemical industry, and component failure frequencies in the Oil & Gas industry (Abubakirov et al., 2024; Davies and Fort, 2014; de Haag and Ale, 1999; DNV, 2012).

The IRPA formula, influenced by the ”Purple Book” by de Haag and Ale (1999) and adapted by Abubakirov et al. (2024), quantifies risk in terms of the time spent by personnel in specific locations and the LSIR. This formula is illustrated as follows (Abubakirov et al., 2024; de Haag and Ale, 1999):

$$IRPA = P_{ER} \cdot LSIR_{\text{ER}} = P_{ER} \cdot \sum_{j} (P_{fat} \cdot P_{exp} \cdot P_{sc} \cdot \lambda_{\text{LOC},j}) \tag{5.2}$$

Where:

1. P_{ER} is the probability of a crew to be present inside the engine room of the ship in a fraction of year. This variable can be obtained through the actual time spent inside the engine room daily.
2. $LSIR_{ER}$ is the location specific individual risk inside the engine room. This variable is indicates the ”hazardous environment” on the FTA, which can be expressed into probability and frequency calculation.
3. P_{fat} is the probability of fatality due to exposure to unprotected person or crew inside the ER of accident scenario j.
4. P_{exp} is the probability of exposure to an unprotected person or crew present inside the engine room in case of accident scenario j. The probability of exposure on the small room is assumed to uniform at any given point at the engine room, where P_{exp} = 1 (Abubakirov et al., 2024).

5. P_{sc} is the probability of hazardous scenario j due to the loss of containment (LOC) event expressed by λ_{LOC}.
6. λ_{LOC} is the frequency of loss of containment (LOC) per ship year based on the empirical data of the reference used on this research (Davies and Fort, 2014).

The following subsection will determine the value of the variables in equation (5.2), which include P_{fat}, P_{exp}, P_{sc}, and λ_{LOC}. The calculations will be based on both reference and empirical data. The difference between $LSIR_{\text{LNG (CH4)}}$ and $LSIR_{\text{NH3}}$ will result in a difference between $P_{ER_{LNG(CH4)}}$ and $P_{ER_{NH3}}$, indicating the need for modifications (reduction) in time spent within the engine room for ammonia-powered ships. Therefore, the $P_{ER_{NH3}}$, or the probability of being within the engine room, will be the output of this calculation and used as the objective in system modification.

5.3.1. Frequency LOC (λ_{LOC})

The frequency of LOC represents the frequency of a particular component failure based on empirical data from oil and gas producers (OGP). Although there is no empirical data on LNG ship failure, the frequency acquired from the OGP can serve as guides for defining the safety design of gas-powered ships (Davies and Fort, 2014).

The LNG ship's engine room components include Engine Line B (S-9), Engine gas valve unit (S-10), and Boiler gas valve unit (S-11) (Davies and Fort, 2014). However, in this study, the writer assumed that the components applied in the LNG-powered ship and the ammonia-powered ship were identical. As a result, the components employed in the calculation are simplified to only Engine Line B, and there is no difference between the IRPA of LNG and ammonia because they cancel out in the calculations. This assumption results in research limitations, as ammonia gas has a lower energy density than methane (LNG), requiring a larger diameter pipe for ammonia gas trips. The specification of the Engine Line B that will be use for this calculation can be seen on Table 5.1.

Table 5.1: Specifications of Engine Line B

Attribute	Value
Length	15 m
Diameter	50 mm
Type	Double-walled

The Engine Line B is a 15-meter double-walled pipe with a diameter of 50 mm that transports gas from Engine Line A to the engine gas valve unit and boiler gas valve unit (Davies and Fort, 2014). As an outcome, one engine will have only one Engine Line B among the components that will be calculated.

The empirical data for pipe leak frequency is based on Davies and Fort's (2014) research. Table 5.2 shows the three categories of leak hole diameters based on Engine Line B specifications.

Table 5.2: The 50 mm (2") Diameter Double-walled Pipe Leak Frequency per year

Leak Hole Diameter	Frequency (per year)	Factors of Double-walled Pipe
1-3 mm	5.50 E-5	100
3-10 mm	1.80 E-5	75
10 – 50 mm	7.00 E-6	10

From Table 5.2, we can calculate the λ_{LOC} using the equation below (Davies and Fort, 2014):

$$\lambda_{\text{LOC}} = N \cdot P_{\text{leak}} \cdot \frac{L}{F_{\text{DW}}} \tag{5.3}$$

Where N represents the number of components; for example, if there are three engines in the engine room, the value of N will be three. In Table 5.2, P_{leak} represents the annual release frequency, L is the engine line pipe length, and F_{DW} is the double-walled pipe factor. The value of λ_{LOC} will be constant for both the LNG (CH4) and ammonia (NH3) engine rooms.

5.3.2. Probability of Scenario (P_{sc})

The probability of the scenario is obtained using the event-tree diagram of the hazard of utilising ammonia (NH3) and methane (CH4) as fuel (de Haag and Ale, 1999). In this research, CH4 is considered as a flammable material and becomes the top event of the major danger when used as a fuel as stated on the Figure 5.1, altering the value of P_{fat} later on. Therefore, the writer considers the delayed ignition hazard scenario with the value P_{scCH4} of 0.3 based on the references.

Despite the risk of fire explosion, poisoning with NH3 is regarded the most dangerous hazard scenario (Pomonis et al., 2022). The similar researches shows that the person inside the space with ammonia leakage has a high risk of death before the NH3 reaches the ignition temperature, shown on the result of Figure 5.2 (Abubakirov et al., 2024; Pomonis et al., 2022). In this research, the P_{scNH3} value is 1 for the hazardous hazard scenario based on the references.

5.3.3. Probability of Fatality (P_{fat})

The probability of a fatality can be determined by calculating the accumulated concentration of the chemical inside the engine room where the leak occurs. According to Table 2.2 of AEGL levels in Chapter 2, the concentration required for ammonia to reach a quick fatality level (within 10 minutes) is 2,700 ppm (EPA, 2023; Abubakirov et al., 2024). Methane (CH4) has a lower flammability limit (LFL) of 50,000 ppm, which is the minimum concentration required for ignition (Abubakirov et al., 2024). As a result, the concentration of ammonia required for death is approximately 20 times lower than that of CH4. The more detailed of CH4 and NH3 properties shown on Table 5.3.

Table 5.3: The properties of the fuel

Fuel	Threshold Concentration	Gas Density (ρ_g)
Methane (CH4)	50,000 ppm (LFL)	6.544 kg/m^3
Ammonia (NH3)	2,700 ppm (AEGL-3)	6.953 kg/m^3

Based on the research by Abubakirov et al. (2024), the first-order differential equation to determine the accumulation of the concentration on confined spaces (engine room) when the leakage occurs can be expressed as:

$$V\frac{dC}{dt} = Q_g - v \cdot C \tag{5.4}$$

Where V is the volume size of the confined space, C is the concentration level of the substance, t as the time of leakage, Q_g as vapor source term, and v as the ventilation rate that active every time given in calculation.

The gas detector sensor inside the engine room is mandatory as a protection against fire and poisoning for CH4 and NH3 respectively (International Maritime Organization, 2015; International Maritime Organization, 2016). The gas detector sensor is used as one of the many factors that trigger the emergency shutdown (ESD) of the engine systems as isolation measures to prevent the concentration level of the gas from reaching its threshold. In this research, both the success and failure of gas detection will be considered to determine the average value of P_{fat}.

The value of Q_g is a time-dependent calculation, where the initial vapor source term (Q_{gi}) starts at t=0. If the gas detector functions successfully, isolation will occur at an assumed time (t_{iso}) equal to 60 seconds, expressed as:

$$Q_{g,succ} = \begin{cases} Q_{g_i}, & \text{for } t \in (0, t_{\text{iso}}] \\ 0, & \text{for } t \in (t_{\text{iso}}, t_{\text{exp}}] \end{cases} \tag{5.5}$$

$$Q_{gi} = 1.4 \cdot 10^{-4} d^2 \sqrt{\rho_g P_g} \tag{5.6}$$

If the gas detector sensor fail to functioning, then there will be no isolation and the leakage will keep continue until the end of the time window of the exposure time (t_{exp}) with the same rate on Q_{gi} (DNV, 2012).

$$Q_{g,fail} = Q_{gi} = 1.4 \cdot 10^{-4} d^2 \sqrt{\rho_g P_g} \tag{5.7}$$

The d represents the diameter of the leak hole, which will be distributed uniformly for each discrete group based on Table 5.2 row. The ρ_g shows the gas density of fuel as indicated in Table 5.3, and P_g is the fuel pressure depending on the engine. The solution for the concentration over time ($C(t)$) can be solved using the equation of (Abubakirov et al., 2024):

$$C(t)_{succ} = \left(C(t_0) + \int_{t_0}^{t_{\text{exp}}} \frac{Q_{g,succ}}{V} e^{\frac{v\theta}{V}} \, d\theta \right) e^{-\frac{vt}{V}} \tag{5.8}$$

$$C(t)_{fail} = \left(C(t_0) + \int_{t_0}^{t_{\text{exp}}} \frac{Q_{g,fail}}{V} e^{\frac{v\theta}{V}} \, d\theta \right) e^{-\frac{vt}{V}} \tag{5.9}$$

The accumulation of concentration determined by Equation 5.4 used to determine the P_{fat} for both NH3 and CH4. Since the both probability of fatality (P_{fat}) for both success of gas detection and failure of gas detection is considered, the average probability of fatality (P_{fat}) can be written as:

$$P_{\text{fat}_i} = P_{\text{fat } i,\text{fail}} \cdot P_{\text{gd}} + P_{\text{fat } i,\text{succ}} \cdot (1 - P_{\text{gd}}) \tag{5.10}$$

where the $P_{\text{fat } i,\text{ gd fail}}$ and $P_{\text{fat } i,\text{ gd succ}}$ denote the probability of fatality in the event of gas detector failure and successful gas detection, respectively. The P_{gd} represents the probability of gas detector failure.

For the calculation of P_{fatCH4}, authors assumed to use a binary and discrete calculation expressed by:

$$P_{\text{fat CH4, succ}} = \begin{cases} 1 & \text{if } C_{succ} > 50,000 \text{ ppm}, \\ 0 & \text{otherwise.} \end{cases} \tag{5.11}$$

$$P_{\text{fat CH4, fail}} = \begin{cases} 1 & \text{if } C_{fail} > 50,000 \text{ ppm}, \\ 0 & \text{otherwise.} \end{cases} \tag{5.12}$$

On the other hand, the calculation of P_{fatNH3} is using the probit functions of toxic exposure based on the ”Purple Book” (de Haag and Ale, 1999):

$$Pr_{succ} = a + b \cdot \ln \left(\int_{t_0}^{t_{\text{exp}}} {C_{succ}}^n \, dt \right) \tag{5.13}$$

$$Pr_{fail} = a + b \cdot \ln \left(\int_{t_0}^{t_{\text{exp}}} {C_{fail}}^n \, dt \right) \tag{5.14}$$

The relations of probit functions (Pr) and probability of fatality (P_{fatNH3}) of the toxic exposure written as (de Haag and Ale, 1999):

$$P_{\text{fat NH}_3,succ} = 0.5 \cdot \left[1 + \text{erf} \left(\frac{Pr_{succ} - 5}{\sqrt{2}} \right) \right] \tag{5.15}$$

$$P_{\text{fat NH}_3,fail} = 0.5 \cdot \left[1 + \text{erf} \left(\frac{Pr_{fail} - 5}{\sqrt{2}} \right) \right] \tag{5.16}$$

5.3.4. Probability of a Engineering Crew Being Present Inside the Engine Room During the Operational Phase (P_{ER})

The variable representing the probability of an engineering crew being present inside the engine room (P_{ER}) is defined as the fraction of time spent inside the engine room due to activities outlined in the FRAM model, relative to the total 24 hours in a day, calculated on an annual basis. P_{ER} is only considered during the operational phase of the ship; thus, activities during dry-docking and docking are excluded from this research.

As indicated in Table 4.4, the frequencies of activities are categorized into ”daily activities” and ”once per voyage activities.” To calculate the number of annual voyages and operational days, the operational profile from a sample ship of Anthony Veder is used. The ship selected for this study is an LPG carrier with short-distance travel. This vessel not only carries LPG cargo but is also suitable for transporting liquefied ammonia and utilizes a Dual Fuel (DF) LNG-fueled engine, aligning well with the QRA methodology. Details of the ship’s 2021 operational profile are provided in Table 5.4.

Table 5.4: The Operational Profile of Sample Vessel (LPG Carrier Ship - Anthony Veder)

Annual Operational Profile (2021)	LPG Carrier Ship - Anthony Veder
Operational Day	260 days
Number of Voyage	80
Distance	36969 km
Route Type	Short Trip

Combining the findings from the Table 4.4 and Table 5.4, the value of the P_{ER} can be determined trough:

$$P_{\text{ER}} = \frac{\text{Avg.Time Spent (hrs)}}{24\,\text{hrs/day}} \cdot \frac{\text{Frequency}}{365\,\text{days/year}} \tag{5.17}$$

Table 4.4 presents the calculated values of P_{ER} for all activities inside the engine room as well as for daily frequency activities only. The results show that omitting the ”once per voyage” activities from P_{ER} calculations results in a difference of 0.01, indicating a minimal impact compared to daily activities. Consequently, the forthcoming system modifications and recommendations in this research will primarily focus on daily activities, which have the most significant influence on P_{ER}. The fraction of the P_{ER} on annual basis can be seen on Figure 5.4. However, this research assumes that the risk value associated with each activity is uniform, based on the LOC frequency, which is used as a general term for the failure frequency of engine components. In practice, each activity carries a different level of risk, which represents a limitation of this QRA study.

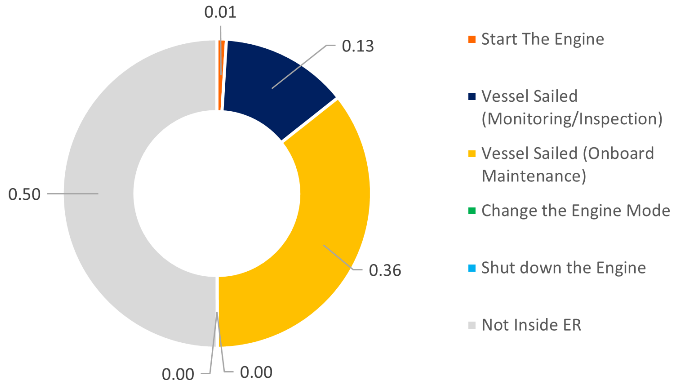


Figure 5.4: The Fraction of the Probability of the engineering crew to be inside the Engine Room annually

Table 5.5: The Probability of an engineering crew to be present inside the engine room annually

No	Phase	Functions/Tasks	Location	Avg. Time Spent (hours/day)	Frequency	Annual Frequency	P_{ER} (annual)
1	Start the Engine	To do local inspection (ER) for pre-start engine	Engine and components	0.750	Once per ship voyage	80	0.007
2		To start the engine locally	Local Control Panel (LCP)	0.000	Once per ship voyage	80	0.000
3		To do post-start engine monitoring	Engine components and ECR	0.333	Once per ship voyage	80	0.003
4	Vessel Sailed (Monitoring/ Inspection)	To do Non-scheduled inspection inside ER	Engine and components	0.500	Daily (Operational Day)	260	0.015
5		To do Scheduled Inspection (Morning & Evening)	Engine and components	3.000	Daily (Operational Day)	260	0.089
6		To do UMS Checklist	Engine and components	1.000	Daily (Operational Day)	260	0.030
7	Vessel Sailed (Onboard Maintenance)	To perform Preventive maintenance on-board	Engine and components	5.000	Daily (Operational Day)	260	0.148
8		To perform Corrective maintenance on-board	Engine and components	5.000	Daily (Operational Day)	260	0.148
9		To do Pre-requisite activity before maintenance	Engine and components	1.000	Daily (Operational Day)	260	0.030
10		Verifying the pre-requisite list before maintenance	Engine and components	1.000	Daily (Operational Day)	260	0.030
11	Change the Engine Mode	Changing the mode locally (Via LCP)	Local Control Panel (LCP)	0.333	Depends on Ship Route	-	-
12	Shut down the Engine	To stop the engine locally (inside ER)	Local Control Panel (LCP)	0.000	Once per ship voyage	80	0.000
Probability of an engineering crew to be present inside the ER							**0.500**
Probability of an engineering crew to be present inside the ER (only daily task)							**0.490**

5.4. Limitations and Assumptions

The quantitative method used in this study is dependent on various assumptions, which leads to limitations in the methodologies, as acknowledged by the author. The following are the limits and assumptions of quantitative approaches, ranked from most critical to least critical in terms of impact:

1. The ”complete mixing assumption” was assumed by the authors, which means that there is no vertical concentration gradient the gas due to density differences. It is critical to remember that the density of CH4 is lighter than air, causing the gas to flow to the top/roof of enclosed areas. This migration of the CH4 gas may result in a larger concentration of CH4 at the top of the engine room than at other locations within the engine room (Pettit and Linn, 1987).
2. It is assumed that the components system and pipe specifications (dimensions) between LNG (CH4) and NH3 were equal, which may not be the case in reality. For example, because NH3 has a lower energy density than CH4, bigger pipe diameters might be necessary for NH3-powered ship engine fuel supply. This variation has an impact on the quantitative calculation’s frequency loss of containment (λ_{LOC}).
3. The quantitative computation is simplified by focusing solely on Engine Line B, which affects the frequency Loss of Containment (λ_{LOC}). However, this simplification of the number of components has no significant impact on the computation because point number three specifies that we assume identical components for both the CH4 and NH3 engines. As a result, the frequency of LOC might be calculated using the IRPA formula stated in equation (5.1).
4. The purpose of these calculations is to determine the time reduction required for NH3 operations compared to LNG/CH4 operations to meet the risk acceptance criteria, specifically by using the probability of the crew being present inside the engine room (P_{ER}). Therefore, the engine room volume value used is an approximation to analyze the impact of modifying the engine room layout on the Local Safety Incident Rate (LSIR) and P_{ER}, ensuring that the defined risk acceptance criteria are achieved.
5. The research assumes that all activities indicated in the FRAM model carry the same level of risk, based on the LOC probability calculations. However, in practice, the risk of NH3 leakage varies with each activity, depending on the specific tasks and their complexities.

5.5. Time Reduction Requirements on As-is Condition (Scenario 1)

The initial calculation utilizes an engine room configuration identical in volume and component layout to both the CH4 and NH3 engine rooms, designated as scenario 1. This setup assumes that three engines are located within a single large engine room, encompassing all necessary components for operation, as depicted in Figure 5.5. As a preliminary estimate, the volume of the engine room is based on a reference ship operated by Anthony Veder that employs a dual-fuel engine. Table 5.6 provides detailed specifications for the engine room layout.

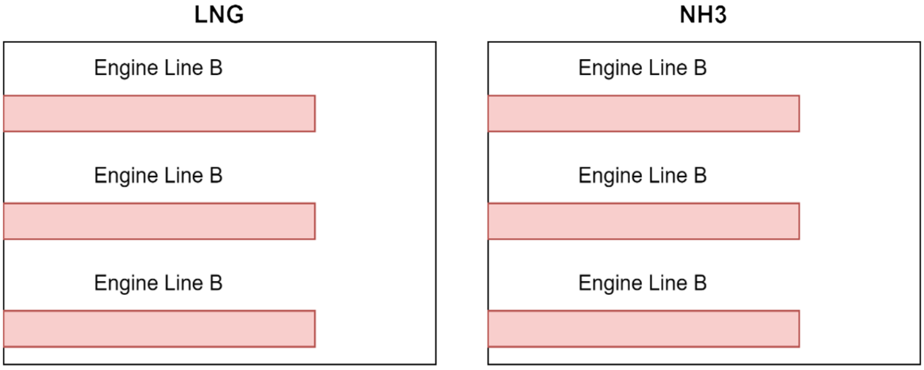


Figure 5.5: The first design layout scenario for the Engine Room

The IRPA calculations for comparing CH4 and NH3 in Scenario 1 are presented in Table 5.7. With the same engine room layout and similar activities, resulting in an equivalent P_{ER}, the IRPA value for NH3

Table 5.6: Specifications Design Layout Scenario 1

Specification	**Value**
Volume (V)	19 m x 14 m x 4 m
Ventilation Rate (v)	30 air-changes / hours
Number of Engine (N)	3 (in single space)
Fuel Pressure (P_g)	10 bar gauge

Table 5.7: Comparison of IRPA between LNG (CH4) and NH3 for Scenario 1

LNG (CH4) Fuel Ship						**NH3 Fuel Ship**					
d	λ_{LOC}	P_{sc}	P_{ex}	P_{fat}	LSIR	d	λ_{LOC}	P_{sc}	P_{ex}	P_{fat}	LSIR
1 mm	8.3E-06	0.3	1	0	0	1 mm	8.3E-06	1	1	0	0
2 mm	8.3E-06	0.3	1	0	0	2 mm	8.3E-06	1	1	0	0
3 mm	8.3E-06	0.3	1	0	0	3 mm	8.3E-06	1	1	0	0
5 mm	3.6E-06	0.3	1	0	0	5 mm	3.6E-06	1	1	0	0
8 mm	3.6E-06	0.3	1	0	0	8 mm	3.6E-06	1	1	2.00E-03	7.20E-09
10 mm	3.6E-06	0.3	1	0	0	10 mm	3.6E-06	1	1	7.00E-03	2.52E-08
23 mm	1.1E-05	0.3	1	0.01	3.15E-08	23 mm	1.1E-05	1	1	5.60E-01	5.88E-06
37 mm	1.1E-05	0.3	1	1	3.15E-06	37 mm	1.1E-05	1	1	9.79E-01	1.03E-05
50 mm	1.1E-05	0.3	1	1	3.15E-06	50 mm	1.1E-05	1	1	9.90E-01	1.04E-05
Total LSIR (annual)					6.33E-06	Total LSIR (annual)					2.66E-05
P_{ER} (annual)					0.500	P_{ER} (annual)					0.500
IRPA CH4					**3.16E-06**	**IRPA NH3**					**1.33E-05**

is approximately an order of magnitude higher than that for CH4. This outcome is anticipated, as with the identical engine layout and work procedures, the use of NH3 inherently carries a higher risk level, necessitating modifications.

To quantify the impact of modifications on safety levels, the value of P_{ER} will be the variable affected by these changes. Following the "Risk Acceptance Criteria" stated in Equation (5.1), the required value of time reduction can be expressed as follows:

$$P_{\text{ER, NH}_3 Target} = \frac{LSIR_{\text{ER, CH}_4}}{LSIR_{\text{ER, NH}_3}} \cdot P_{\text{ER, CH}_4} \tag{5.18}$$

Table 5.7 depicts the outcome of scenario 1 based on the LSIR calculation in equation (5.1), followed by the ratio in equation (5.18). It has been established that, for the same volume and architecture, the reduction in times within the NH3 engine room compared to CH4 is roughly equivalent to 4.2. The lower ammonia concentration threshold (AEGL-3) increases the likelihood of death (P_{fat}). This increased degree of likelihood results in a lower probability inside the NH3 engine room, necessitating a revision of the engine configuration and work to achieve the goal outlined in subsection 5.3.1.

Moving the crew's components and work outside the adjacent engine spaces could save time, but would necessitate the development of an extra isolation wall and separate gas-safe spaces. The modifying work procedures could also minimise the time required to complete the assignment, as explained in Chapter 6.

6

Risk Management Strategy

This chapter develops the risk management strategy through system modifications and evaluates the proposed changes in detail. The analysis begins with the adoption of frameworks based on the Hierarchy of Controls to prioritize the types of modifications. Subsequently, the modification strategy frameworks are developed by incorporating human-machine interactions derived from the socio-technical system (STS). Detailed recommendations for modifications are provided, and an evaluation of the resulting IRPA levels is conducted.

6.1. Hierarchy of Controls

The Hierarchy of Controls act as the guidelines to have a modification towards the system design, based on the modification impact towards the workplace safety, illustrated on Figure 6.1 (Occupational Safety and Health Administration (OSHA), 2023; Canadian Centre for Occupational Health and Safety (CCOHS), 2023).

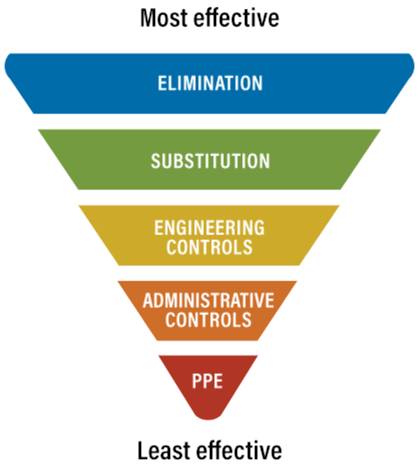


Figure 6.1: The Hierarchy of Control (Canadian Centre for Occupational Health and Safety (CCOHS), 2023)

Table 6.1 explains the definition of the hierarchy of controls and how it relates to research. The control hierarchy establishes rules and prioritises system modifications based on their impact and potential trade-offs. The control method's structure is based on rules issued by the United States Department of Labor's Occupational Safety and Health Administration (OSHA). Each alteration will be directed by the format provided by OSHA, as explained in the following chapters.

Table 6.1: The Hierarchy Control and Relation to the Research (Occupational Safety and Health Administration (OSHA), 2023; Canadian Centre for Occupational Health and Safety (CCOHS), 2023)

Hierarchy of Controls	Definition	Relation to Research
Elimination	This strategy is the most effective since it removes hazards from the workplace and ensures that they do not exist anymore.	The top level hazard for an ammonia-powered ship is ammonia poisoning, and elimination of toxic nature of ammonia as fuel is impossible or requires extensive research in the future.
Substitution	To minimise the hazard, replace any aspect (material or procedure) with a safer alternative. The substitution may result in a new hazard, and it is important to guarantee that the new hazard risk is lower than the previous one.	Substituting another fuel for ammonia could be one of the example of the substitution of the hazard. However, this substitution eliminates the objectives of this research and not applicable in this research scope.
Engineering Controls	This strategy reduces exposure by keeping the hazard from coming into touch with workers. This strategy is very reliable for controlling exposure as long as the controls are properly developed, used, and maintained.	This technique is the best fit for this study. It includes the process control through task relocation and enclosure & isolation through engine room layout. This control can provide a physical barrier to protect workers from the toxicity of ammonia.
Administrative Controls	This strategy alters the way work is done or provides workers with additional knowledge by giving applicable procedures, warnings, and trainings.	This strategy can be used as a second barrier to improve safety, but it may be ineffective due to the lack of a physical barrier to control the safety work being done. This study will seek to minimise the use of this step.
Personal Protective Equipment (PPE)	PPE should only be used as the primary method of exposure control in situations where elimination, substitution, engineering, or administrative controls are not practical.	Despite the applicability of this strategy for improving worker safety, it will not be analyzed or included in the research modifications, as the focus will be on higher-level control methods that have a greater significance for safety.

6.2. Consideration/Conditions for Design Modifications

This study develops engine room layout design scenarios and components systems relocation based on ship safety and operability considerations. Each design has advantages and disadvantages based on its safety and operability, which will be described in the subsequent sub-section. Each engine room layout has a distinct value for the variable in the formula, which results in a varied ratio of time reductions necessary. The consideration and conditions for the system modification of this research are:

1. Ability to perform maintenance onboard
2. Ability to maintain the control and operate the ship during engine ”failure” condition that related to the component inside the engine room
3. Should be practically operable in terms of design and safety procedure
4. Focusing on the engine room design layout, task (components) relocation and reduction of time spent on engine chamber

6.3. System Modification and Recommendation Framework

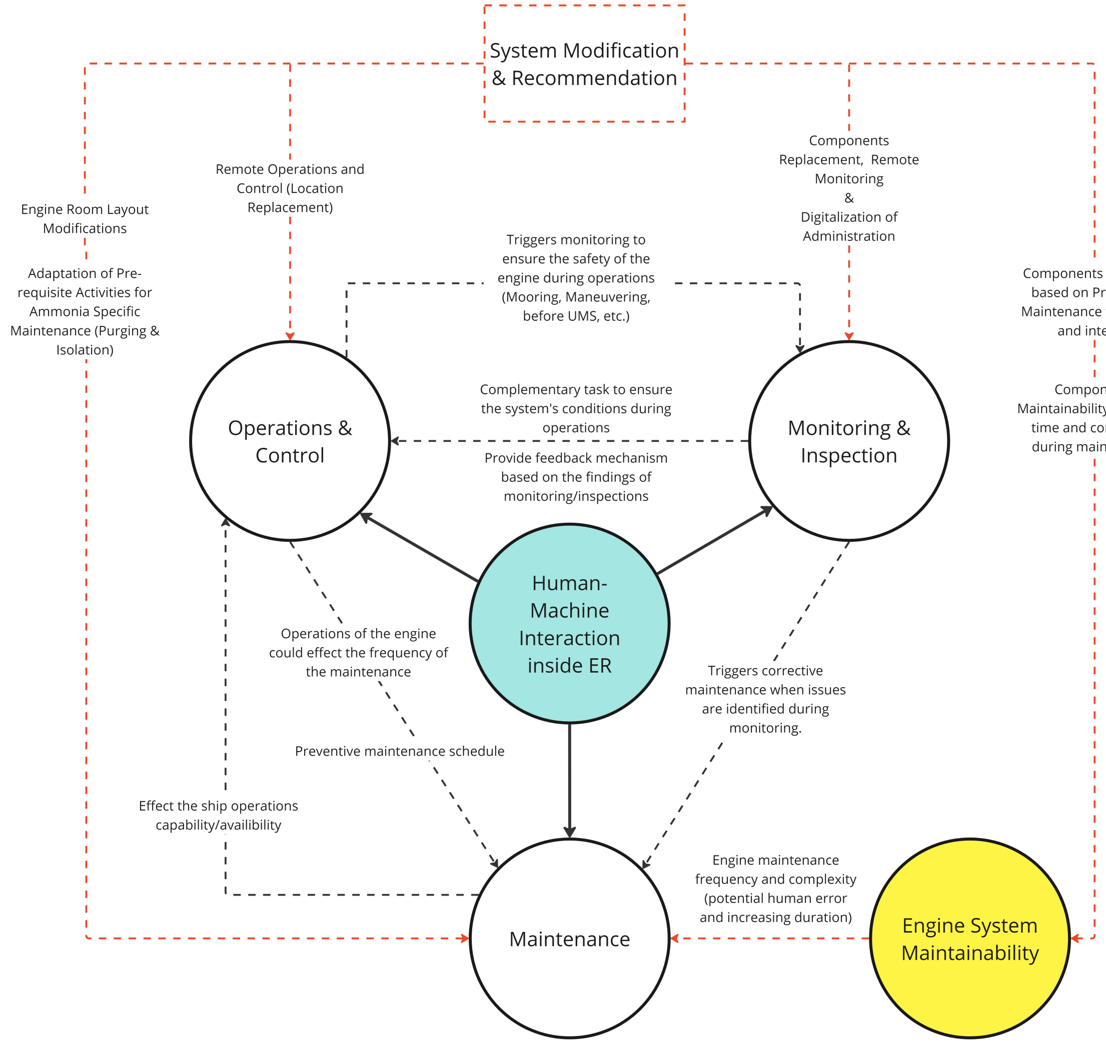


Figure 6.2: The Research System Modification and Recommendation Framework

6.3.1. Relationships Among Human-Machine Interaction Categories

Figure 6.2 summarizes the human-machine interaction within the Engine Room, categorizing activities into three main areas: operations & control, monitoring & inspection, and maintenance. Each category is interconnected with the others, as indicated by dotted lines in the flowchart, illustrating the dynamic interactions among these activities. The categorization of human-machine interactions is based on the findings from the Work-as-Done (WAD) Functional Resonance Analysis Method (FRAM) throughout the ship's operational phases. The details of the human-machine interaction activities derived from the WAD FRAM functions will be discussed in the following paragraphs.

The operations & control category encompasses activities such as starting the engine, shutting down the engine, changing engine modes, and other related control tasks. This category directly influences the monitoring & inspection activities, which are critical for ensuring the safety and operational conditions of the engines. For instance, an order to start the engine triggers pre-start engine inspections and post-start engine monitoring to verify operational integrity.

Conversely, monitoring & inspection activities serve complementary roles, maintaining system conditions during operations and providing a feedback mechanism based on observations. For example, if an Engineer on Watch (EoW) identifies malfunctions or failures during pre-start inspections, they must inform the Chief Engineer (CE), potentially resulting in a no-start decision that delays the ship's operational processes.

As discussed in Chapter 4's analysis, monitoring & inspection activities are closely linked to maintenance. Discoveries made during these activities can initiate corrective maintenance of the ship's engine. Additionally, there is the possibility of component breakdowns occurring before the scheduled preventive maintenance, highlighting the role of monitoring & inspection as a redundancy measure to detect potential component failures or malfunctions.

Engine operations also influence maintenance practices. Each engine comes with a manual that prescribes optimal operating procedures to maximize safety, condition, and life-cycle. However, actual operations may deviate from the manual due to operational constraints and environmental conditions, leading to variations in maintenance frequency and intervals. Maintenance activities, in turn, can impact the ship's operational capabilities and availability. For example, maintenance that requires shutting down one of the main engines can limit power supply, impede the ship's maneuverability under certain conditions, and affect overall ship operations and route selection. The duration of maintenance downtime is critical for maintaining the ship's operability and reliability.

Furthermore, the maintainability of the engine system influences maintenance activities. The complexity of engine components can increase the likelihood of human error and extend downtime. Non-standardized components may also prolong maintenance durations due to spare parts shortages, leading to extended downtimes and a higher risk of ammonia exposure. This interconnections underscores the critical nature of maintaining a balanced approach to engine room operations, inspections, and maintenance, ensuring safety and efficiency aboard the ship.

6.3.2. System Modifications and Recommendations for Each Category

By examining the relationships among the three main activities of human-machine interactions within the engine room, system modifications and recommendations are proposed, as illustrated by the red dotted lines in Figure 6.2. These modifications aim to enhance the safety of the ammonia-powered ship engine room.

For operations & control activities, it is recommended to enhance remote operations and control by adjusting component locations and controls. For instance, the start, shutdown, and engine mode change buttons could be activated through the Local Control Panel (LCP), which is part of redundancy measures (Bielecka and Muc, 2018). Originally located beside the main engine, relocating the LCP outside the engine chamber could reduce the risk of ammonia exposure and increase the reliability of LCP usage during gas leak situations.

In terms of monitoring & inspections, recommendations include component replacement, remote monitoring, and digitalization of administrative tasks (e.g., logbooks) to minimize the need for engineering crew to be present inside the engine room. This would allow for remote indicator checks and visual inspections, thereby reducing the risk of ammonia poisoning. However, some activities will still require in-person checks of engine components, currently documented using paper-based logbooks. Digitalizing these logs could decrease the time spent on administrative tasks and focus more on essential in-person checks, ultimately reducing overall time spent near engine components.

For maintenance activities, recommendations include changing the engine room layout and adapting pre-requisite activities specific to ammonia maintenance. The duration of maintenance varies based on component complexity, and reducing the time spent on maintenance is unlikely. Additionally, any reduction could potentially impact the quality of the maintenance performed. Altering the layout could decrease the likelihood of crew exposure to ammonia, a topic that will be elaborated in subsequent sub-sections. Adapting pre-requisite activities serves as a recommendation for engine manufacturers and regulators to maintain safety levels for onboard ammonia engine maintenance, addressing both regulatory and operational knowledge gaps. A more detailed analysis and rationale for these recommendations will be discussed in the next sub-section.

Lastly, as maintenance activities are influenced by engine system, recommendations are made for enhancing component reliability and maintainability. Improving component reliability could decrease the frequency and extend the interval between maintenance sessions, thus reducing the annual maintenance frequency of engine components. These recommendations depend on complex external factors, including operational behavior, component installations, and work environment, which may also impact the life-cycle of engine components. Enhancing component maintainability aims to reduce the time and complexity of maintenance tasks, lowering the potential for human error due to complex installations. Standardization of engine components is also advocated to prevent spare parts shortages and ensure modularity.

The detailed system modifications for the framework on Figure 6.2 will be provided in the following sub-section, where the impact of these modifications and further discussions will be explored.

6.4. System Modification for Scenario 2

Table 6.2 details the modifications for Scenario 2, as derived from the framework depicted in Figure 6.2. The control methods for these modifications are categorized under Engineering Control and Administrative Control, according to the Hierarchy of Controls theory. The recommendations prioritize engineering controls to enhance the effectiveness of safety management, while administrative controls are designed to support tasks that engineering methods cannot fully address.

The system modifications and recommendations focus on altering the engine room layout from the single-space configuration in Scenario 1, relocating components and tasks previously situated near the main engine to separate spaces. This change aims to reduce the time engineering crew spend in proximity to the main engine, which, according to the IRPA equation (5.2), should decrease the level of IRPA. The introduction of a partition separating the engine from other parts of the engine room ensures that tasks originally performed adjacent to the engine can now be conducted in safer areas where leakage is less likely to affect the crew.

Given that the changes to the engine room layout and the relocation of tasks and components are interdependent, the Quantitative Risk Assessment (QRA) considers these adjustments as a comprehensive package within Scenario 2. Consequently, the impact of each individual modification cannot be analyzed in isolation; instead, the effects are evaluated based on the overall modifications implemented in this scenario.

Figure 6.3 illustrates the impact of modifications E3, E4, and E6 on the socio-technical systems. These modifications facilitate the relocation of tasks and components, allowing the Engineer on Watch (EoW) to monitor operations remotely. In the event of malfunctions, initial inspections and actions can be performed remotely as a first line of defense. If these remote measures are insufficient, non-scheduled in-person inspections serve as a secondary barrier.

These changes enable the EoW to assess the conditions within the engine room via indicators and visual checks through cameras, thus mitigating the need for direct entry into the engine room without prior knowledge of its conditions. Moreover, with local controls and indicators now positioned outside the engine chamber—rather than adjacent to the engine—engineers can verify the redundancy of the indicators without exposure to potential ammonia gas leaks from the engine components. Therefore, the remote activity serves as the support mechanism and not as the substitute of local inspection.

The Figure 6.4 and Figure Figure 6.5 displays the effects of modifications E3, E4, and E6 on scheduled monitoring and the Unmanned Machinery Spaces (UMS) checklist. These modifications predominantly alter the location of task execution, shifting from purely local activities to hybrid activities denoted by the change of the functions color. This adjustment arises because certain tasks on the UMS checklist can be conducted remotely, while others still necessitate in-person inspections of the engines.

The implementation of hybrid activities for scheduled monitoring and the UMS checklist effectively reduces the time engineering crews spend inside the engine chamber, directly beside the engines. This reduction in presence lowers the P_{ER} and consequently the Individual Risk per Annum (IRPA), as outlined in equation (5.2). The detailed impact of the modification towards the task in terms of P_{ER} will be discussed in the next sub-section.

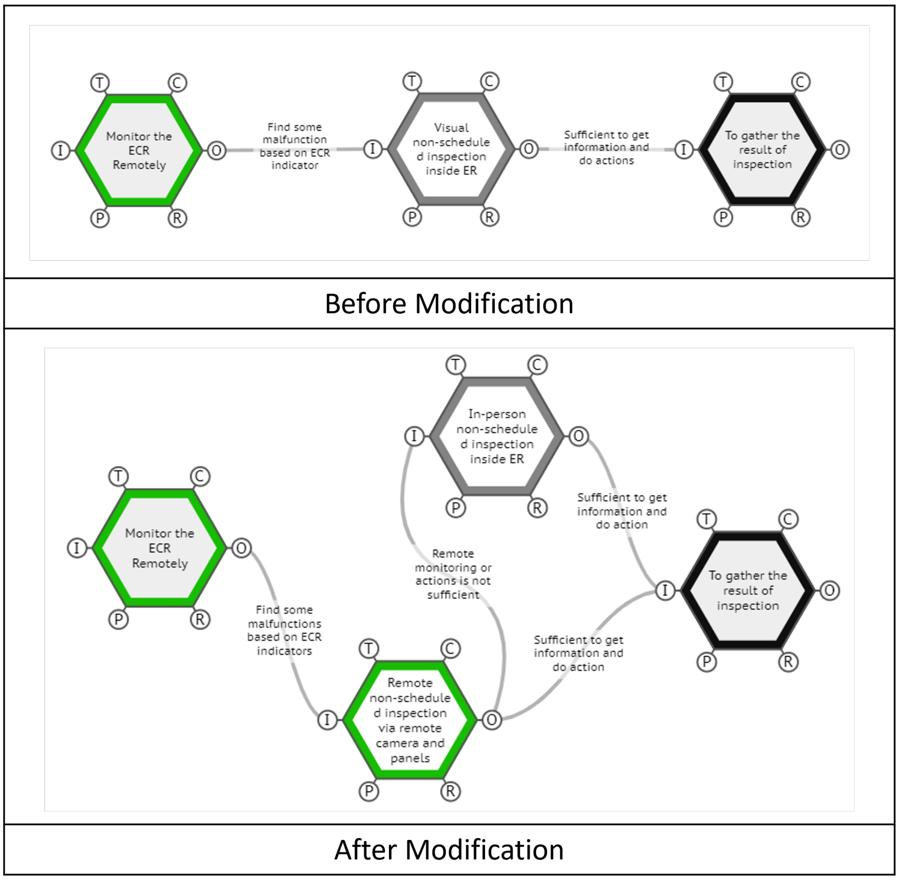
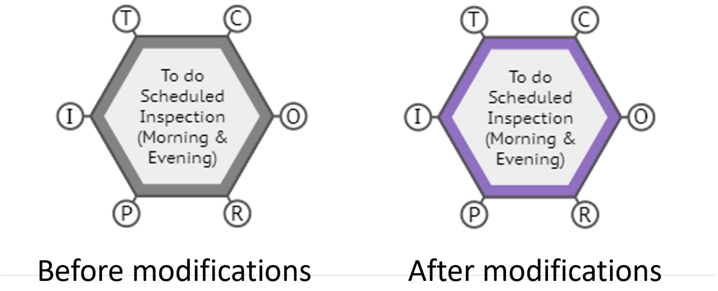
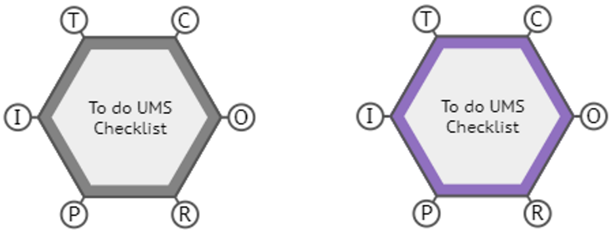


Figure 6.3: Change in the Socio-Technical System Scenario 2 through FRAM: Simplified Non-Scheduled Monitoring Activity



Before modifications After modifications

Figure 6.4: Change in the Socio-Technical System Scenario 2 through FRAM: Simplified Scheduled Monitoring Activity



Before modifications After modifications

Figure 6.5: Change in the Socio-Technical System Scenario 2 through FRAM: Simplified UMS Activity

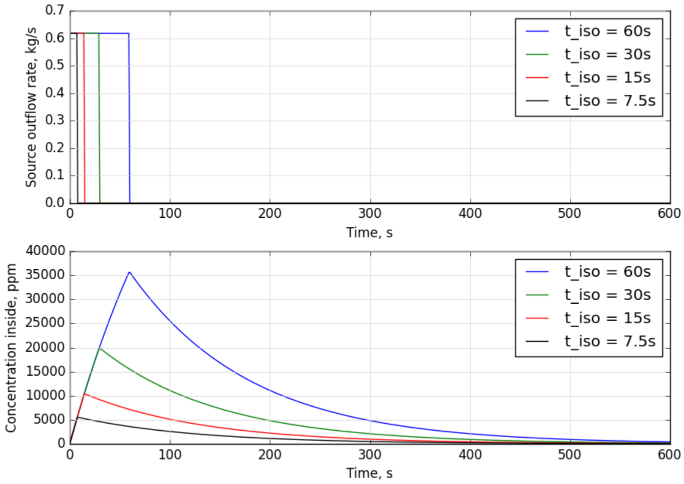


Figure 6.6: The graph of the leak outflow rate (top) and concentration level (bottom) between the t_0 and t_{exp} with variation of t_{iso} at hole diameter of 23 mm

The code E5 in Table 6.2 reflects the impact of gas sensor response time on the safety level in the engine room of ammonia-powered ships. Figure 6.6 illustrates the gas leakage outflow rate and concentration levels at varying response times (e.g., 60s, 30s, 15s, and 7.5s). The peaks on the graph indicate the response time at which isolation occurs (t_{iso}), demonstrating that reducing t_{iso} can significantly minimize peak concentration levels.

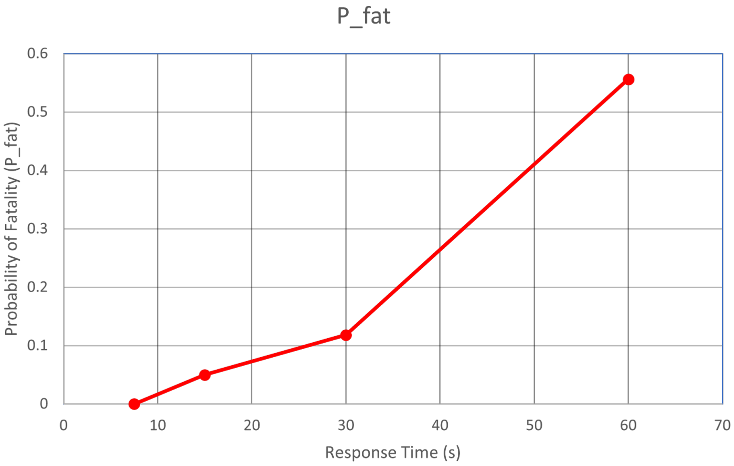


Figure 6.7: The graph of the probability of fatality (p_{fat}) with the variation of the gas sensor response time at hole diameter of 23 mm

Figure 6.7 shows the effect of response time (t_{iso}) on reducing the probability of fatality (P_{fat}) for engineering crew in the engine room. The results suggest that decreasing the response time variable (t_{iso}) can reduce P_{fat} more effectively compared to increasing the ventilation rate. However, the average response time for currently available gas sensors in the market is about 60 seconds. Therefore, future technology developments and research are required to reduce the response time of ammonia gas sensors to enhance safety in NH3 powered ship engine rooms.

The subsequent IRPA calculations will consider only the relocation of activities/components and modifications to the engine room design layout (e.g., E2, E3, E4, E6, A1, and A2). Modifications E1, E5, and E7 will not be included in the IRPA calculation but will serve as qualitative modification recommendations and suggestions for future work.

Table 6.2: The Details of the Modification for Scenario 2

Code	Control Method	Modification/ Recommendations	Reasons	Impact on Current Hazard	Potential New Hazard
E1	Engineering Control	Reduce Component Complexity and Introduce Standardization in Engine Components	Complexity in engine components often leads to bottlenecks in maintenance and increases the potential for human error, which may necessitate additional corrective maintenance.	Minimize the Mean Time to Repair (MTTR) by simplifying component design, reducing human error, and addressing limitations in spare-parts availability.	-
E2		Create a Separate Engine Chamber Within the Engine Room (Scenario 2)	Isolating the engine from other workspaces within the engine room allows tasks traditionally performed adjacent to the engine to be relocated outside the chamber, enhancing crew safety.	Enable tasks to be relocated outside, and other activities such as machining (workshop), controlling, and monitoring through remote systems to be conducted, thereby reducing time spent beside the engine.	Smaller engine chamber volume may lead to quicker accumulation of harmful concentrations during a leakage, potentially complicating work procedures as engineers need to frequently enter and exit the chamber.
E3		Move Local Control Panels (LCP) and Indicators Outside the Engine Chamber	Most inspections, both scheduled and unscheduled, aim to check engine indicators locally for redundancy.	Conduct local indicator inspections for scheduled monitoring and redundancy outside the engine chamber, reducing time spent beside engines.	Could reduce redundancy by eliminating traditional visual and in-person inspections and heavily relying on remote monitoring, potentially changing work behaviors.
E4		Implement Visual Remote Monitoring as a Support Method for Inspection (Not a Substitute)	Remote inspection could decrease the time required for inspection and serve as a support tool during emergencies to assess conditions inside the engine room.	Minimize time spent beside the engine during scheduled/unscheduled monitoring and provide a mechanism to assess emergency or uncertain situations.	Partial visual remote monitoring is limited by resolution and viewing angles, which may result in the loss of detail during visual inspections. This could also alter work behavior, leading to excessive dependence by the Engineer on Watch (EoW) on remote visual monitoring.
E5		Reduce Gas Detector Response Time to Activate Emergency Shutdown (ESD)	Decreasing the response time of gas detectors can be more effective than increasing ventilation in reducing the probability of fatality.	Quicken ESD activation to prevent ammonia from reaching hazardous concentration thresholds, reducing fatality risk.	Highly sensitive ESD may cause abrupt power loss, affecting ship control during critical operations such as mooring or maneuvering.
E6		Place Input Valves (Except for Ammonia Pipelines) Outside the Engine Chamber	Monitoring and inspection tasks often involve checking and controlling input valves.	Conduct analog/manual engine control and monitoring outside the engine chamber, reducing time spent beside the engine.	May alter work behaviors and affected the human-machine interactions.
E7		Add Sensors to Engine Components	Enhance predictive maintenance and enable more effective remote monitoring.	Reduce the frequency of corrective maintenance and ensure timely availability of spare parts.	Adding more sensors could enhance the predictive maintenance capabilities of the engine system. However, this would also increase the complexity of the engine components, potentially complicating the outcomes of Modification E1.
A1	Administrative Control	Implement a Digital Logbook	Reduce the time spent on local visual monitoring and manual paperwork.	Minimize paperwork within the engine room, thereby reducing time spent near engine components.	Dependencies on digital logbook could reduced attention to component details due to focus on digital entries.
A2		Advance Maintenance Prerequisite Procedures	While current maintenance pre-requisite activities are sufficient for LNG DF engines, they may not adequately address the specific risks associated with ammonia DF engines.	Enhance maintenance safety by minimizing potential risks of residual ammonia in the engine and pipeline components, supporting the effectiveness of having separate chambers for each engine.	-

6.4.1. Engine Room Layout Modification

The second engine room design layout scenario is nearly identical to the initial that introduced in Chapter 5, except that the authors contrasted the single LNG (CH4) engine room to an NH3 engine room that has been isolated and provides a ”outside space” to relocate potential components away from the engine. Figure 6.8 illustrates the second scenario. The ratio of engine spaces to ’outside space’ is established using the example of an Anthony Veder fleet that ran with two engine types: gas and diesel engines. The gas engine has a designated gas space engine chamber, which serves as a guideline for determining the ratio of engine space to ”outside space”. Table 6.3 contains a detailed specification for the second situation.

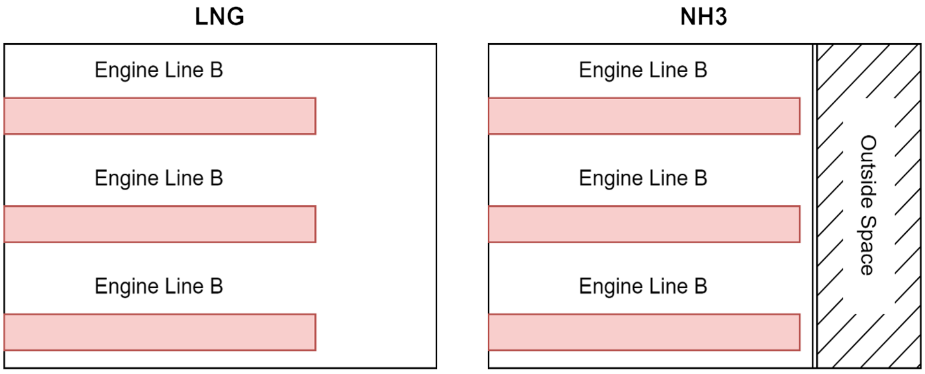


Figure 6.8: The second design layout scenario for the Engine Room

Table 6.3: Specifications Design Layout Scenario 2

Specification	Value
Volume Engine Chamber (V)	12 m x 14 m x 4 m
Ventilation Rate (v)	30 air-changes / hours
Number of Engine (N)	3 (in single space)
Fuel Pressure (P_g)	10 bar gauge

Table 6.4 presents a comparison of the LSIR results for the CH4 and NH3 engine rooms in Scenario 2. The introduction of a wall separator in the engine room leads to a reduced volume, which increases the P_{fat} because it accelerates the time needed to reach the AEGL-3 concentration level. Based on the LSIR result and considering the equation (5.18), the time reduction needed for the second scenario involving an NH3 engine room is 4.8 times that of the CH4 engine room located in a single area. This suggests that relocating components and crew tasks to ”outside spaces” could further reduce the time spent in the engine chamber. The outcomes of these system modifications will be explored in detail in the subsequent sub-section.

6.4.2. Modification Result on the P_{ER}

Based on the information provided in Table 6.2, the time reduction can be quantified through an analysis of the work document procedure. As stated in Chapter 5, the focus of the modification is on daily operational frequency, which has the most significant impact on the value of P_{ER}.

The method for estimating time reduction is based on the company’s activity procedures or checklists. The proportion of activities affected by the modifications relative to total activities serves as the baseline for calculating time reductions. The documents utilized for this approximation include the ship’s Unmanned Machinery Space (UMS) checklist, which comprises 50 activities. Of these, 33 activities are likely to be influenced by the proposed modifications detailed in Table 6.2. Furthermore, interview findings suggest that the activities in the UMS checklist and scheduled monitoring are almost identical, leading to a similar estimated time reduction for scheduled monitoring.

Table 6.4: Comparison of LSIR between LNG (CH4) and NH3 for Scenario 2

LNG (CH4) Fuel Ship						NH3 Fuel Ship					
d	λ_{LOC}	P_{sc}	P_{ex}	P_{fat}	LSIR	d	λ_{LOC}	P_{sc}	P_{ex}	P_{fat}	LSIR
1 mm	8.3E-06	0.3	1	0	0	1 mm	8.3E-06	1	1	0	0
2 mm	8.3E-06	0.3	1	0	0	2 mm	8.3E-06	1	1	0	0
3 mm	8.3E-06	0.3	1	0	0	3 mm	8.3E-06	1	1	0	0
5 mm	3.6E-06	0.3	1	0	0	5 mm	3.6E-06	1	1	6.00E-04	2.16E-09
8 mm	3.6E-06	0.3	1	0	0	8 mm	3.6E-06	1	1	7.00E-03	2.52E-08
10 mm	3.6E-06	0.3	1	0	0	10 mm	3.6E-06	1	1	2.00E-02	7.20E-08
23 mm	1.1E-05	0.3	1	0.01	3.15E-08	23 mm	1.1E-05	1	1	8.56E-01	8.99E-06
37 mm	1.1E-05	0.3	1	1	3.15E-06	37 mm	1.1E-05	1	1	9.98E-01	1.05E-05
50 mm	1.1E-05	0.3	1	1	3.15E-06	50 mm	1.1E-05	1	1	1.00E+00	1.05E-05
Total LSIR (annual)					6.33E-06	Total LSIR (annual)					3.01E-05

Conversely, unscheduled monitoring typically lacks a specific procedure and is triggered by anomalies detected in the Engine Control Room (ECR) indicators. In this research, a reduction factor of 0.5 is assigned based on the engineering crew's ability to remotely read indicators and conduct initial visual inspections via camera. However, due to limitations in resolution and viewing angles, there remains a high probability that in-person visual inspections will continue, as cameras only serve as supportive tools and are not substitutes for direct observation.

Regarding maintenance activities, the time reduction is set at 0. This decision reflects the reality that maintenance duration is difficult to reduce due to the unpredictable nature of the tasks, which depend on component conditions and human factors such as the engineering crew's experience and knowledge. Even when one engine is shut down for maintenance, the crew may still be exposed to operational risks from other running engines, maintaining similar P_{ER} conditions as in Scenario 1.

Table 6.4 indicates that a time reduction factor of 4.8 is required, a target not met according to the results shown in Table 6.2. Although the modifications impact monitoring activities, maintenance tasks continue to represent the most substantial portion of P_{ER}, acting as a bottleneck within the engine room. The subsequent sub-section will discuss the implications of these findings on the IRPA values for Scenario 2 modifications.

Table 6.5: The Result of Scenario 2 Modification towards P_{ER}

Functions/Tasks	Avg Time Spent (hrs/day)	Frequency	Frequency (/year)	P_{ER}old	Time Reduction (Fraction)	P_{ER}new
To do local inspection (ER) for pre-start engine	0.750	Once per ship voyage	80	0.007	-	0.007
To start the engine locally	0.000	Once per ship voyage	80	0.000	-	0.000
To do post-start engine monitoring	0.333	Once per ship voyage	80	0.003	-	0.003
To do Non-scheduled inspection inside ER	0.500	Daily (Operational Day)	260	0.015	0.5	0.007
To do Scheduled Inspection (Morning & Evening)	3.000	Daily (Operational Day)	260	0.089	0.660	0.030
To do UMS Checklist	1.000	Daily (Operational Day)	260	0.030	0.660	0.010
To perform Preventive maintenance on-board	5.000	Daily (Operational Day)	260	0.148	0	0.148

Continued on next page

Table 6.5 – continued from previous page

Functions/Tasks	Avg Time Spent (hrs/day)	Frequency	Frequency (/year)	P_{ER}old	Time Reduction (Fraction)	P_{ER}new
To perform Corrective maintenance on-board	5.000	Daily (Operational Day)	260	0.148	0	0.148
To do Pre-requisite activity before maintenance	1.000	Daily (Operational Day)	260	0.030	0	0.030
Verifying the pre-requisite list before maintenance	1.000	Daily (Operational Day)	260	0.030	0	0.030
Changing the mode locally (Via LCP)	0.333	Depends on Ship Route	-	0.000	-	-
To stop the engine locally (inside ER)	0.000	Once per ship voyage	80	0.000	-	0.000
New Total Probability of an engineering crew to be present inside the ER						**0.414**

End of Table

6.4.3. Modification Result on IRPA

The result of combining FRAM with the socio-technical system (STS) tools to determine the value of the variable P_{ER}, alongside the value of LISR, is provided using the QRA formula in Equation (5.2), as detailed in Table 6.6. The result shows that despite system modifications, the IRPA level for NH3 in Scenario 2 remains higher compared to that of CH4. This difference, approximately one order of magnitude, is driven by the higher LSIR associated with NH3 and the limited time reduction achieved through system modifications. In Scenario 2, the time reduction is only applicable to monitoring and inspection activities, whereas the bottleneck remains within the maintenance tasks. The inability to significantly reduce maintenance-related risks through P_{ER} leads to only a minor decrease in the overall IRPA.

Table 6.6: Comparison of IRPA between LNG (CH4) and NH3 for Scenario 2 After Modification

LNG (CH4) Fuel Ship						**NH3 Fuel Ship**					
d	λ_{LOC}	P_{sc}	P_{ex}	P_{fat}	LSIR	d	λ_{LOC}	P_{sc}	P_{ex}	P_{fat}	LSIR
1 mm	8.3E-06	0.3	1	0	0	1 mm	8.3E-06	1	1	0	0
2 mm	8.3E-06	0.3	1	0	0	2 mm	8.3E-06	1	1	0	0
3 mm	8.3E-06	0.3	1	0	0	3 mm	8.3E-06	1	1	0	0
5 mm	3.6E-06	0.3	1	0	0	5 mm	3.6E-06	1	1	6.00E-04	2.16E-09
8 mm	3.6E-06	0.3	1	0	0	8 mm	3.6E-06	1	1	7.00E-03	2.52E-08
10 mm	3.6E-06	0.3	1	0	0	10 mm	3.6E-06	1	1	2.00E-02	7.20E-08
23 mm	1.1E-05	0.3	1	0.01	3.15E-08	23 mm	1.1E-05	1	1	8.56E-01	8.99E-06
37 mm	1.1E-05	0.3	1	1	3.15E-06	37 mm	1.1E-05	1	1	9.98E-01	1.05E-05
50 mm	1.1E-05	0.3	1	1	3.15E-06	50 mm	1.1E-05	1	1	1.00E+00	1.05E-05
Total LSIR (annual)					6.33E-06	Total LSIR (annual)					3.01E-05
P_ER (annual)					0.500	P_ER (After modification)					0.414
IRPA CH4					**3.16E-06**	**IRPA NH3 (After modification)**					**1.24E-05**

As part of an iterative process to meet the Risk Acceptance Criteria, the forthcoming Scenario 3 will explore changes in design layout aimed at reducing risks associated with on-board maintenance and enhancing the reliability of engine operation. This scenario will also consider the safety of the engineering crew, especially in situations where one or more engines fail.

6.5. System Modification for Scenario 3

The third scenario considers the ship's engine room's ability to be maintained and operated. The first and second scenarios place all three engines in a single engine chamber. The first and second scenario layout limits the crew's ability to operate when:

1. **Onboard Maintenance:** On-board maintenance occurs frequently in the marine industry, with repairs taking place during sailings to ensure the effectiveness and efficiency of ship operations. However, if one of the three engines requires maintenance, the crew will be exposed to the risk of ammonia poisoning as the remaining engine keeps running.
2. **Engine/Components Failure:** The ammonia leak may be caused by one or more engine failures or a loss of containment (LOC). In a single large space, it might hinder the crew's ability to do local tasks (for example, inspection and monitoring), affecting the engine room's capacity to function correctly.

The details of the modifications for Scenario 3 are outlined in Table 6.7. The impacts of modifications E2, E4, and E6, as outlined in Table 6.7, are similar to the results observed in Scenario 2, depicted in Figure 6.3, Figure 6.4, and Figure 6.5 for non-scheduled inspections, scheduled inspections, and UMS checklists, respectively. The impact of the gas detectors also similar that has been described in Scenario 2, however it will be not the part of the QRA on this chapter.

The primary distinction from Scenario 2 lies in the second modification, ”Create Separate Engine Chambers for Each Engine.” This modification specifically addresses concerns related to onboard maintenance safety and the capability to operate the engine in the event of one or more engine failures, while ensuring the safety of the engineering crew. According to the system modification framework depicted in Figure 6.2, modifications to the engine room layout and the enhancement of maintenance pre-requisites specifically tailored for ammonia are necessary. The specifics of the engine layout modifications will be discussed in the subsequent section.

Table 6.7: The Details of the Modification for Scenario 3

Code	Control Method	Modification/ Recommendations	Reasons	Impact on Current Hazard	Potential New Hazard
E1	Engineering Control	Reduce Component Complexity and Introduce Standardization in Engine Components	Complexity in engine components often leads to bottlenecks in maintenance and increases the potential for human error, which may necessitate additional corrective maintenance.	Minimize the Mean Time to Repair (MTTR) by simplifying component design, reducing human error, and addressing limitations in spare-parts availability.	-
E2		Create Separate Engine Chambers for Each Engine (Scenario 3)	Isolating engines under maintenance or those experiencing failure from operational engines ensures operational reliability.	Allow engines to operate normally without frequency limitations on monitoring and inspection, and conduct maintenance with minimal risk even while other engines are running.	Smaller chamber volumes could lead to rapid concentration increases during leakage and increased complexity in local monitoring and inspection due to spatial separation.
E3		Move Local Control Panels (LCP) and Indicators Outside the Engine Chamber	Most inspections, both scheduled and unscheduled, aim to check engine indicators locally for redundancy.	Conduct local indicator inspections for scheduled monitoring and redundancy outside the engine chamber, reducing time spent beside engines.	Could reduce redundancy by eliminating traditional visual and in-person inspections and heavily relying on remote monitoring, potentially changing work behaviors.
E4		Implement Visual Remote Monitoring as a Support Method for Inspection (Not a Substitute)	Remote inspection could decrease the time required for inspection and serve as a support tool during emergencies to assess conditions inside the engine room.	Minimize time spent beside the engine during scheduled/unscheduled monitoring and provide a mechanism to assess emergency or uncertain situations.	Partial visual remote monitoring is limited by resolution and viewing angles, which may result in the loss of detail during visual inspections. This could also alter work behavior, leading to excessive dependence by the Engineer on Watch (EoW) on remote visual monitoring.
E5		Reduce Gas Detector Response Time to Activate Emergency Shutdown (ESD)	Decreasing the response time of gas detectors can be more effective than increasing ventilation in reducing the probability of fatality.	Quicken ESD activation to prevent ammonia from reaching hazardous concentration thresholds, reducing fatality risk.	Highly sensitive ESD may cause abrupt power loss, affecting ship control during critical operations such as mooring or maneuvering.
E6		Place Input Valves (Except for Ammonia Pipelines) Outside the Engine Chamber	Monitoring and inspection tasks often involve checking and controlling input valves.	Conduct analog/manual engine control and monitoring outside the engine chamber, reducing time spent beside the engine.	May alter work behaviors and affected the human-machine interactions.
E7		Add Sensors to Engine Components	Enhance predictive maintenance and enable more effective remote monitoring.	Reduce the frequency of corrective maintenance and ensure timely availability of spare parts.	Adding more sensors could enhance the predictive maintenance capabilities of the engine system. However, this would also increase the complexity of the engine components, potentially complicating the outcomes of Modification E1.
A1	Administrative Control	Implement a Digital Logbook	Reduce the time spent on local visual monitoring and manual paperwork.	Minimize paperwork within the engine room, thereby reducing time spent near engine components.	Dependencies on digital logbook could reduced attention to component details due to focus on digital entries.
A2		Advance Maintenance Prerequisite Procedures	While current maintenance pre-requisite activities are sufficient for LNG DF engines, they may not adequately address the specific risks associated with ammonia DF engines.	Enhance maintenance safety by minimizing potential risks of residual ammonia in the engine and pipeline components, supporting the effectiveness of having separate chambers for each engine.	-

6.5.1. Engine Room Layout Modification

The third alternative, shown in Figure 6.9, separates the engine chamber into three dedicated spaces for each engine, allowing the crew to do onboard maintenance while the other engines are running. It also allows the crew to continue operating and monitoring the engine locally in the event that the other engine fails. This scenario could improve the ship's safety while retaining its operational capability. Table 6.8 provides detailed engine chamber specifications.

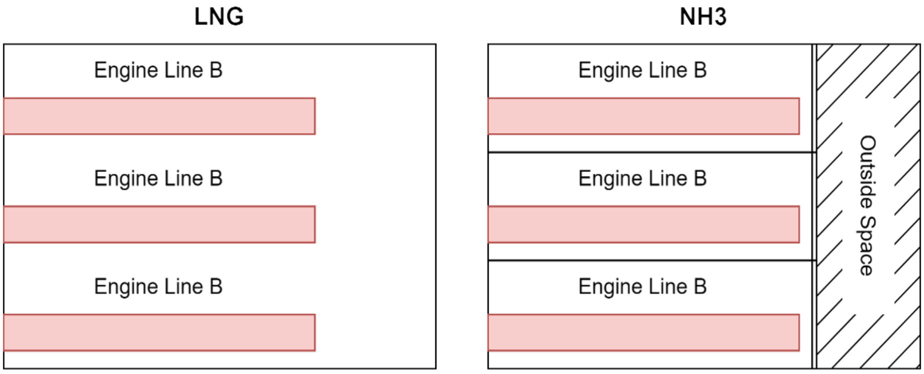


Figure 6.9: The third design layout scenario for the Engine Room

Table 6.8: Specifications Design Layout Scenario 3

Specification	**Value**
Volume Each Engine Chamber (V)	12 m x 4 m x 4 m
Ventilation Rate (v)	30 air-changes / hours
Number of Engine (N)	1 (in each chamber)
Fuel Pressure (P_g)	10 bar gauge

The computation of the Location-Specific Individual Risk (LSIR) for NH3 considers only one engine chamber. To calculate the Individual Risk Per Annum (IRPA) for operating three separate engine chambers, multiply the $LSIR_{ER_{NH3}}$ by three, corresponding to the number of engine chambers. Table 6.9 displays the LSIR results after changing the engine room layout, indicating that the modifications result in a higher LSIR compared to Scenarios 1 and 2. Despite the reduction in the number of engines per chamber to one, which decreases the likelihood of Loss of Containment ($\lambda_{\text{LOC NH3}}$), the significant reduction in chamber volume to one-third of that in Scenario 2 markedly affects the time dynamics. The smaller chamber volume causes NH3 concentrations to reach critical levels more quickly. Consequently, based on the results in Table 6.9 and Equation (5.8), the necessary time reduction for this scenario should not be less than a factor of 5.5 compared to the P_{ER} in CH4-fueled engines.

6.5.2. Modification Result on the P_{ER}

Table 6.10 presents the results of the system modifications on P_{ER}. The time reduction for monitoring and inspection in Scenario 3 is similar to that in Scenario 2. The notable difference lies in the maintenance activities, where the time reduction value is effectively a fraction of 1. This outcome is possible because, during the maintenance of one engine, the engineering crew is not exposed to the other two operating engines due to the separation walls in the engine room. Consequently, the time spent inside the maintenance chamber is not considered as time spent near operating engines, effectively eliminating the P_{ER}.

However, achieving these ideal conditions is contingent upon the availability of safety pre-requisite maintenance procedures specifically designed for ammonia-fueled engines, as provided by regulators and engine manufacturers. Current LNG dual-fuel (DF) engines employ pre-requisite activities to ensure ”gas-free” conditions before maintenance, which can be seen on the simplified FRAM of the main-

Table 6.9: Comparison of LSIR between LNG (CH4) and NH3 for Scenario 3

LNG (CH4) Fuel Ship						**NH3 Fuel Ship**					
d	λ_{LOC}	P_{sc}	P_{ex}	P_{fat}	LSIR	d	λ_{LOC}	P_{sc}	P_{ex}	P_{fat}	LSIR
1 mm	8.3E-06	0.3	1	0	0	1 mm	8.3E-06	1	1	0	0
2 mm	8.3E-06	0.3	1	0	0	2 mm	8.3E-06	1	1	0	0
3 mm	8.3E-06	0.3	1	0	0	3 mm	8.3E-06	1	1	1.00E-03	2.75E-09
5 mm	3.6E-06	0.3	1	0	0	5 mm	3.6E-06	1	1	1.30E-02	1.56E-08
8 mm	3.6E-06	0.3	1	0	0	8 mm	3.6E-06	1	1	2.62E-01	3.14E-07
10 mm	3.6E-06	0.3	1	0	0	10 mm	3.6E-06	1	1	5.96E-01	7.15E-07
23 mm	1.1E-05	0.3	1	0.01	3.15E-08	23 mm	1.1E-05	1	1	1.00E+00	3.50E-06
37 mm	1.1E-05	0.3	1	1	3.15E-06	37 mm	1.1E-05	1	1	1.00E+00	3.50E-06
50 mm	1.1E-05	0.3	1	1	3.15E-06	50 mm	1.1E-05	1	1	1.00E+00	3.50E-06
Total LSIR (annual)					6.33E-06	Total LSIR (annual)					1.15E-05
						Total LSIR on three Engine Chamber					3.46E-05

tenance process on Figure 6.10. This typically involves purging with nitrogen and air, followed by gas detection procedures to manage potential gas slip in components such as pipes and crankcases. The ”Lock out, Tag out, and Test out” procedures are also implemented in current maintenance practices to enhance safety.

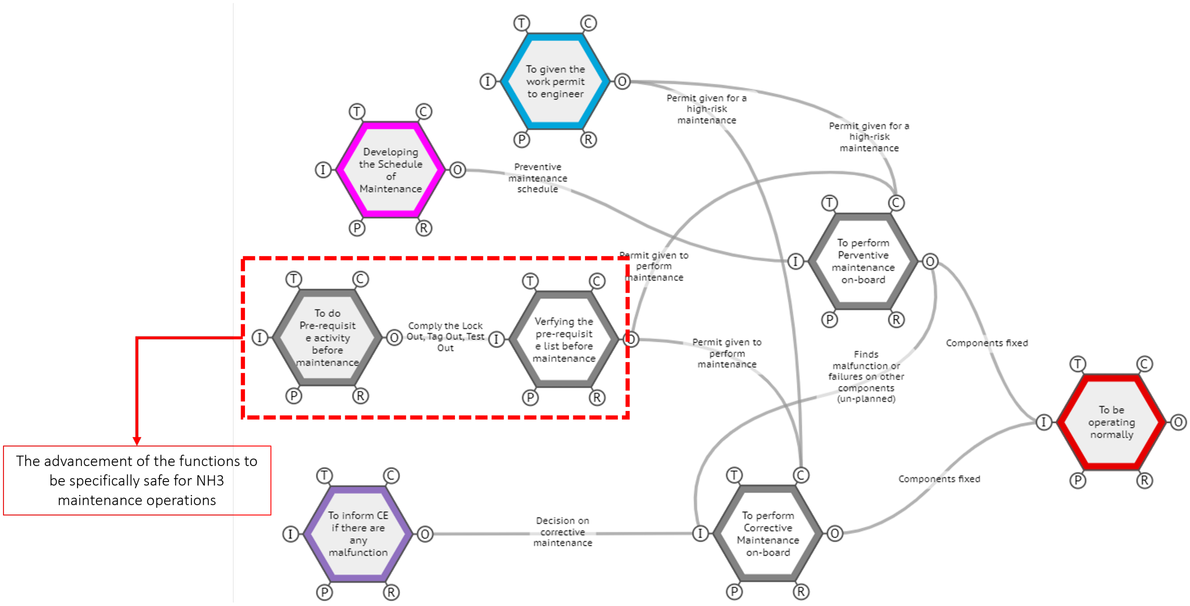


Figure 6.10: The Simplified FRAM of the maintenance process

As discussed in Chapter 5 and illustrated in Figures 5.1 and 5.2, CH4 and NH3 exhibit different risk characteristics and different threshold concentration levels that trigger top event failures. The procedures that are deemed safe for LNG DF engines, which allow for a delay in fire ignition, are not directly applicable to NH3 DF engines. For CH4, a minor gas slip may not lead to an immediate failure due to the lower concentration and the need for an ignition source. In contrast, a similar amount of NH3 could be sufficient to cause fatality among the engineering crew due to its toxic properties.

The additional use of personal protective equipment (PPE) for ammonia DF engine room maintenance could be an effective component of safety risk management. However, the limited time and challenging conditions due to high temperatures must be considered. The heat inside the engine room, compounded by the additional heat from Level A or B PPE required for ammonia resistance, could limit the working time of the Engineer on Watch (EoW) for safety reasons, necessitating a higher number of EoWs onboard to perform tasks.

Nonetheless, PPE could serve as a preliminary safety measure during the preparation stage of maintenance. Once safety procedures are verified, the EoW could transition to using less complex PPE, such as Level C or D, depending on the risk level of the maintenance task. This approach balances safety with operational efficiency, addressing both the physiological limits of the crew and the requirements of the task environment.

The inability to ensure safety in the prerequisite activities, as shown in Figure 6.10, may lead to the propagation of poor output quality in terms of safety to other functions, including preventive and corrective maintenance.

Table 6.10 demonstrates that by engineering the P_{ER} associated with maintenance activities, the total P_{ER} can be significantly reduced. The addition of a wall barrier between the engine and the prerequisite maintenance activities, tailored specifically for ammonia, could greatly enhance the safety level of engine room operations. The impact of these modifications on the final IRPA for Scenario 3 will be discussed in the following section.

Table 6.10: The Result of Scenario 3 Modification towards P_{ER}

Functions/Tasks	**Avg Time Spent (hrs/day)**	**Frequency**	**Frequency (/year)**	P_{ER}**old**	**Time Reduction**	P_{ER}**new**
To do local inspection (ER) for pre-start engine	0.750	Once per ship voyage	80	0.007	-	0.007
To start the engine locally	0.000	Once per ship voyage	80	0.000	-	0.000
To do post-start engine monitoring	0.333	Once per ship voyage	80	0.003	-	0.003
To do Non-scheduled inspection inside ER	0.500	Daily (Operational Day)	260	0.015	0.5	0.007
To do Scheduled Inspection (Morning & Evening)	3.000	Daily (Operational Day)	260	0.089	0.660	0.030
To do UMS Checklist	1.000	Daily (Operational Day)	260	0.030	0.660	0.010
To perform Preventive maintenance on-board	5.000	Daily (Operational Day)	260	0.148	1*	0
To perform Corrective maintenance on-board	5.000	Daily (Operational Day)	260	0.148	1*	0
To do Pre-requisite activity before maintenance	1.000	Daily (Operational Day)	260	0.030	1*	0
Verifying the pre-requisite list before maintenance	1.000	Daily (Operational Day)	260	0.030	1*	0
Changing the mode locally (Via LCP)	0.333	Depends on Ship Route	-	0.000	-	-
To stop the engine locally (inside ER)	0.000	Once per ship voyage	80	0.000	-	0.000
New Total Probability of an engineering crew to be present inside the ER						**0.058**

*Achieved under the assumption that there are safety pre-requisite maintenance procedures specified for ammonia-fueled engines.

6.5.3. Modification Result on IRPA

Table 6.11 presents the impact of system modifications on the Individual Risk Per Annum (IRPA) for ammonia (NH3) in Scenario 3 and for methane (CH4). According to the system modifications detailed in Table 6.7 and the associated time reductions outlined in Table 6.10, the IRPA for NH3 in Scenario 3 is 2.00E-6, which is lower than the IRPA for CH4 at 3.16E-6. Therefore, the modifications in Scenario 3 successfully meet the Risk Acceptance Criteria as defined in Equation (5.1).

Table 6.11: Comparison of IRPA between LNG (CH4) and NH3 for Scenario 3 After Modification

LNG (CH4) Fuel Ship						**NH3 Fuel Ship**					
d	λ_{LOC}	P_{sc}	P_{ex}	P_{fat}	LSIR	d	λ_{LOC}	P_{sc}	P_{ex}	P_{fat}	LSIR
1 mm	8.3E-06	0.3	1	0	0	1 mm	8.3E-06	1	1	0	0
2 mm	8.3E-06	0.3	1	0	0	2 mm	8.3E-06	1	1	0	0
3 mm	8.3E-06	0.3	1	0	0	3 mm	8.3E-06	1	1	1.00E-03	2.75E-09
5 mm	3.6E-06	0.3	1	0	0	5 mm	3.6E-06	1	1	1.30E-02	1.56E-08
8 mm	3.6E-06	0.3	1	0	0	8 mm	3.6E-06	1	1	2.62E-01	3.14E-07
10 mm	3.6E-06	0.3	1	0	0	10 mm	3.6E-06	1	1	5.96E-01	7.15E-07
23 mm	1.1E-05	0.3	1	0.01	3.15E-08	23 mm	1.1E-05	1	1	1.00E+00	3.50E-06
37 mm	1.1E-05	0.3	1	1	3.15E-06	37 mm	1.1E-05	1	1	1.00E+00	3.50E-06
50 mm	1.1E-05	0.3	1	1	3.15E-06	50 mm	1.1E-05	1	1	1.00E+00	3.50E-06
Total LSIR (annual)					6.33E-06	Total LSIR (annual)					1.15E-05
						Total LSIR on three Engine Chamber					3.46E-05
P_ER (annual)					0.500	P_ER (after modification)					0.058
IRPA CH4					**3.16E-06**	**IRPA NH3 (after modification)**					**2.00E-6**

These results demonstrate that strategic changes to maintenance activities, specifically through modifications in engine room layout and procedural adjustments, can effectively enhance the safety levels in ammonia-fueled ship engine rooms. This finding underscores the importance of targeted interventions in system design and operational procedures to mitigate risks associated with hazardous fuel types. Consequently, the maintenance work procedure emerges as a key recommendation for regulators and engine manufacturers to focus on in order to enhance safety levels in engine rooms.

6.6. Discussion on Modification Result

This section will discuss the result of the modifications iterations process to increase the safety level of the ammonia fueled ship engine room. The result will be analysed based on the impact of the modifications towards LSIR, P_{ER} and the IRPA of the engine room.

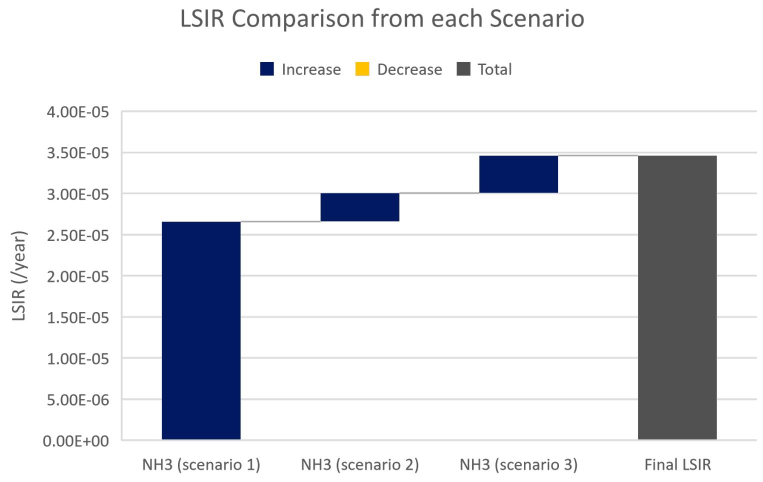


Figure 6.11: The LSIR Comparison for all of the System Scenario

Figure 6.11 illustrates that the modifications in Scenario 2, which involve creating a barrier separating the engine spaces from other areas within the engine room, result in a higher LSIR compared to Scenario 1 due to the reduced space. Conversely, Scenario 3 displays the highest LSIR value, attributable to the creation of enclosed spaces for each engine, leading to smaller volumes despite housing only one engine each. Although the engine room volume calculations are approximations and highly dependent on the actual size of the space, it is evident that creating separations between engine spaces and other engine room areas results in smaller engine spaces and consequently, a more hazardous environment. Therefore, substantial time reductions in P_{ER} are necessary to compensate for these risks in the human-machine interaction modifications.

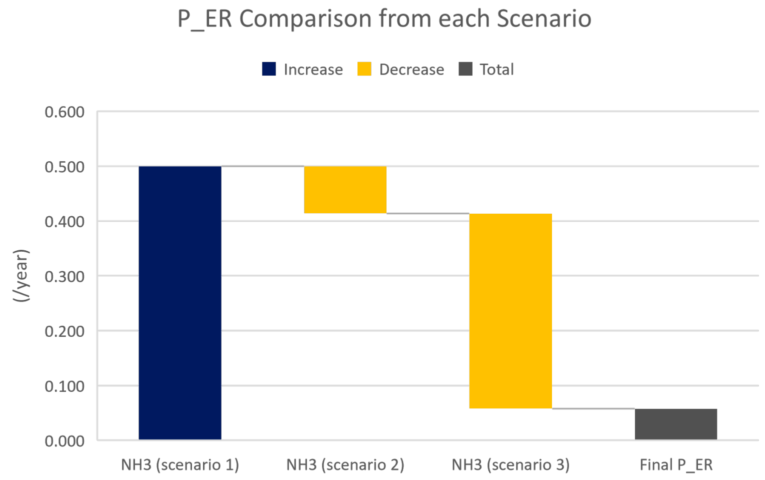


Figure 6.12: The P_{ER} Comparison for all of the System Scenario

Figure 6.12 presents results that are inversely related to the LSIR. While the system modifications in both Scenario 2 and Scenario 3 increase the LSIR, they reduce the P_{ER}. This reduction is facilitated by the construction of separation walls, which allow engineering crews to operate remotely by relocating certain components and indicators outside the engine spaces. In Scenario 2, a modest reduction in P_{ER} is achieved by moving monitoring and inspection activities to remote locations. However, these activities account for a relatively small proportion of the annual time spent inside the engine room compared to maintenance activities.

Scenario 3, which focuses on on-board maintenance activities, achieves a significant reduction in P_{ER}. This indicates that modifications to engine room layout and maintenance procedures have the most substantial impact. The pronounced effect is due to the frequent occurrence of maintenance activities, which are daily events lasting between 2 to 8 hours. These activities engage the engineering crew during work hours beyond the scheduled and unscheduled monitoring and UMS checklist periods, underscoring the critical role of maintenance in shaping engine room safety dynamics.

Figure 6.13 presents the final results of the modifications on the IRPA. The risk analysis in the IRPA discussions is categorized into two distinct types: descriptive risk and normative risk. Descriptive risk is used to analyze the impact of modifications on the IRPA metrics. If the modifications result in a decreased IRPA, this indicates that the modifications have positively impacted safety levels, specifying which activities contribute the most to this improvement.

Conversely, normative risk is employed to evaluate the descriptive risk results in relation to the RAC. If the resulting IRPA exceeds the RAC, additional modifications and evaluations are required to achieve compliance with the desired RAC.

6.6.1. NH3 Scenario 2 Risk Analysis

In Scenario 2 for NH3, the initial modification step resulted in a minor decrease in the IRPA value from 1.33×10^{-5} to 1.24×10^{-5}. This reduction is attributed to modifications focused solely on operational and monitoring activities within the engine room, which affect the P_{ER} value by only 13% on an annual

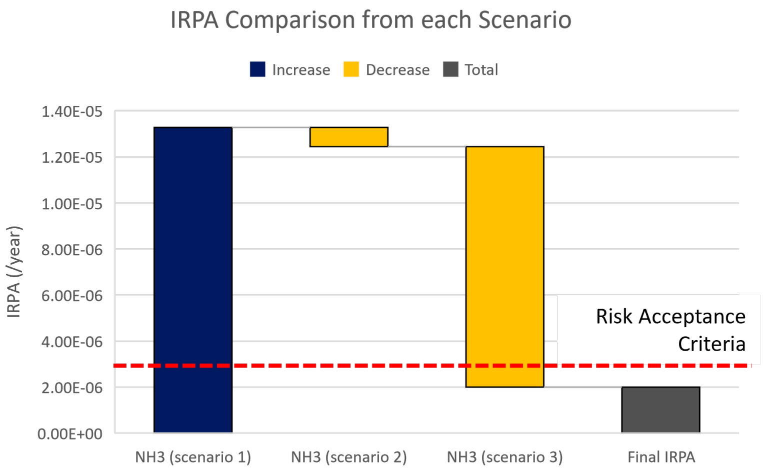


Figure 6.13: The IRPA Comparison for all of the System Scenario

basis. As shown in Figure 5.4, these operational and monitoring activities do not account for the highest P_{ER} values.

Despite the reduction in the IRPA value in NH3 Scenario 2 compared to NH3 Scenario 1, the risk level remains higher than the RAC value of 3.16×10^{-6}. The modifications, which focused solely on operational and monitoring activities, resulted in only a minor reduction in risk level. Therefore, to achieve the RAC level, a more substantial reduction in IRPA is necessary. This can be accomplished by further decreasing the P_{ER} value in subsequent iterations. As outlined in Equation (5.2), reducing the time represented by P_{ER} is critical for achieving this goal. Therefore, this scenario unable to meet the RAC and proven to not ”safe” enough following the objective given in the IGF Code. Further modifications on reducing the P_{ER} is required.

6.6.2. NH3 Scenario 3 Risk Analysis

The NH3 Scenario 3 shown a most significant decrease of IRPA level to value equal to $2.00E - 06$. The major reduction is caused by implementing the modifications of the on-board maintenance work through second iteration of engine room layout and the adjustment of the maintenance preparation, resulted to a significant reduction of P_{ER} as stated on Figure 6.12. As the change value of P_{ER} is linear with the IRPA, then the significant reduction of P_{ER} will significantly reduce the IRPA.

NH3 Scenario 3, which significantly reduces P_{ER} through modifications to maintenance procedures and engine room layout, successfully lowers the IRPA to below the RAC level. By targeting on-board maintenance—activities with the highest P_{ER} value—these modifications achieve a substantial reduction in IRPA, bringing it below that of the current operating CH4 ship engine room. As a result, these modifications meet the defined RAC and are considered safe for operation based on the descriptive risk results. Therefore, improvements in on-board maintenance are identified as the most effective means for reducing IRPA levels.

These modifications demonstrate that through QRA, changes in engine layout and human-machine interactions can enhance the safety level of engine room. However, the values used in the QRA are approximations and still relying on historical data from the oil and gas industry along with LNG DF engine components. The limited knowledge about the use of ammonia as a maritime fuel impacts the accuracy of QRA methods. Nevertheless, these findings highlight the influence of modifications on human-machine interactions, enabling to identify focal areas for technological development and regulatory measures to effectively improve the safety of ship engine rooms using socio-technical approaches.

6.7. Validation of The Modifications and Safety Result

Validation by both operators and ship design experts is essential to ensure that the modifications to the engine room system are practically feasible for implementation on ammonia-powered ships. This step is necessary to prevent solutions that are theoretically sound but limited in their industrial applicability. Additionally, the impact of these modifications on risk and work behavior must be validated by experts to confirm that they lead to a reasonable reduction in time and risk levels. The assumptions used in the analysis, which simplify quantification and evaluation while maintaining alignment with actual industry processes, also require validation.

The feasibility of the modifications and their impact on risk reduction, specifically in terms of Individual Risk per Annum (IRPA), have been validated by our industry partner, Anthony Veder, who is both a ship designer and operator. This validation occurred during an internal company meeting, where the results were presented, and the feasibility and rationale of the modifications were evaluated. The impact of the modifications on the results has also been validated, with detailed notes and observations included in this report.

7

Discussions

7.1. Developing the Socio-Technical System Approach for Engine Room Case

The development of the socio-technical systems (STS) approach for ammonia-powered ship engine rooms aims to address the research sub-questions SRQ1 (“What socio-technical elements inside the Ammonia Powered Ship engine room can be identified?”) and SRQ2 (“What is the relationship between the socio-technical elements within the engine room?”). This development begins by determining whether the ammonia-powered ship engine room can be considered an STS by analyzing theoretical understandings of STS through a literature review.

According to Menting (2023), various perspectives and interpretations of STS exist. The classification of an engine room as an STS depends on the theoretical view of STS adopted and the scope of the STS level. This study follows the understanding of STS as defined by Kroes et al. (2006), where the scope is limited to the endogenous level, capturing the relationships between humans, machines, and organizations.

The identification of STS elements begins with identifying actors potentially involved in engine room activities based on document reviews. Subsequently, the development of engine room operational procedures is conducted at two levels of aggregation based on detail. These steps are inspired by the FRAM development in the aviation sector by Adriaensen et al. (2019). Mapping the activity processes helps understand the functions and relationships of activities within the engine room, where further detail can be added during the WAD FRAM interviews with actual practitioners. Thus, the WAD serves as a starting point from the ideal conditions provided in documents and operational handbooks, while the WAI works to validate and adjust these to reflect actual practices in the engine room.

Activities are categorized into phases, as stated in Appendix A, with the WAD FRAM model depicting activities across various ship phases. Despite the high complexity of couplings, the relationships between actors and their functions can be visualized. However, identifying and determining safety-critical job relationships is challenging during WAD FRAM interviews due to knowledge gaps between operators and the engineers who designed the engine systems. Jobs are typically conducted based on procedures, with safety reasoning mostly acquired through training and work experience. The underlying rationale for each procedure is determined by the engineers of the manufacturer, highlighting a gap that requires further interviews and data collection with these engineers to detail the relationships between activities.

The analysis in Chapter 4 allows for the quantification of couplings, though this does not always determine safety-critical tasks. A job with many couplings does not necessarily represent high risk or workload. Further improvements through Social Network Analysis (SNA) could achieve a more comprehensive analysis. Additional analysis on the relationships between functions within the STS can be enhanced using SNA techniques.

This approach underscores the importance of integrating theoretical perspectives with practical insights to develop a comprehensive understanding of socio-technical elements and their interactions within ammonia-powered ship engine rooms.

7.2. Incorporation of Socio-Technical Perspective on the Risk Management of Ammonia Powered Ship Engine Room

The incorporation of socio-technical systems (STS) in this research aims to deepen our understanding of the complex interactions between humans and machines within the engine room, fostering a human-centered approach to system design that emphasizes safety. As stated in Chapter 3, the usage of Functional Resonance Analysis Method (FRAM) to identify the socio-technical interactions, combined with Quantitative Risk Assessment (QRA) as the evaluation tool for modifications, is employed to achieve this aim.

The FRAM model is instrumental in identifying the behaviors of workers, whether they are engaged remotely or on-site, showcasing their interactions with technology and the necessity for redundancy in operational locations. This model facilitates an understanding of how individual activities impact one another, a critical insight for enhancing operational safety and efficiency. By utilizing the Work-as-Done (WAD) Functional Resonance Analysis Method (FRAM), depicted in Figure 4.7, the research visualizes actual work procedures and their interrelations across various phases of ship operation. This visualization not only clarifies actual engine room practices but also aids in crafting design solutions that consider human interactions, workflows, and behaviors comprehensively.

One significant contribution of FRAM is its ability to outline critical safety tasks performed locally, which are pivotal in ensuring crew safety. These tasks, detailed in both Figure 4.7 and Table 4.4, include comprehensive analyses of procedures, time commitments, frequency, triggers, and outcomes. The synthesis of these elements through STS not only supports the development of Fault Tree Analysis (FTA) that integrates human activities and technical factors but also aids in the logical modeling of event sequences that could lead to failures.

The relationships between each activity depicted in the FRAM are identified in Figure 6.2, providing a general overview of the strategy recommendations based on activity categories. Subsequently, these modifications are quantitatively evaluated through Risk Assessment (QRA), with Individual Risk per Annum (IRPA) calculations considering human activity within the engine room. The results allow us to determine which groups of activities most impact safety, with maintenance activities requiring the highest portion of time spent annually and the inability to be conducted remotely. This leads to identifying future work needed to develop safety procedures for on-board maintenance to significantly enhance the ship's safety. Therefore, the incorporation of STS enables us to identify which activities can be moved remotely, the most impactful groups of activities on safety levels, their impact on current systems, their impact on safety levels, and the gaps that need to be filled to make these changes feasible.

Despite the benefits, integrating socio-technical systems (STS) complicates safety research, particularly in scenarios where human decisions and interactions play a significant role. This complexity is evident in the correlations observed between the time engineering crews spend performing tasks within the engine room and overall safety outcomes. Understanding these interactions is crucial for pinpointing effective system modifications. However, the applicability of STS depends on the research objectives and system characteristics, specifically whether human-machine interactions significantly contribute to risk evaluation. In this study, human-machine interactions that lead to the duration of presence inside the engine room substantially impact safety levels, highlighting the need and significance of incorporating STS in safety research.

The suggested modifications, while potentially increasing operational safety, also highlight the need for future risk assessments to evaluate the impact of these changes on emerging hazards. Current recommendations do not consider the possibility of new risks arising from systemic changes, such as the shift from local to remote operations potentially affecting LOC values and, by extension, risk assessments. This gap underscores the limitations of applying FTA in conjunction with FRAM, as FTA's discrete approach may not adequately capture the dynamic interdependencies within human-technical systems.

7.3. The Evaluation of Incorporation FRAM and FTA (QRA)

The Functional Resonance Analysis Method (FRAM) offers numerous benefits that were not fully utilized in this research due to time constraints and data availability. This method, known for its ability to capture the inherent variability in socio-technical systems, was not explored to its fullest potential, primarily because many relationships identified within the FRAM were excluded from analysis due to the study's scope limitations. This limitation underscores the model's high complexity and the challenges of maximizing its utilization within a constrained research setting.

Incorporating a risk management perspective through FRAM variability could significantly enhance the safety-II perspective by analyzing potential human errors or variability in the performance outputs of human and mechanical artifacts towards safety. The variability within FRAM can be categorized into endogenous and exogenous factors, as outlined by Hollnagel (2018).

Endogenous variability encompasses the internal fluctuations within the system that affect technological, human, and organizational functions. Technological variability might arise from the inherent complexities of mechanical artifacts, such as the degradation of engine components or issues with remote control software systems. Human variability is influenced by physiological factors like fatigue and stress, or psychological factors including cognitive styles and decision-making biases. Organizational variability stems from aspects like communication effectiveness, organizational culture, and the hierarchical control within the ship's organizational structure, shaping how operations are conducted and managed.

Exogenous variability refers to external factors that influence the system's behavior. This includes technological functions variability due to improper maintenance performance and operational deviations from the manufacturer's manual. Human functions variability can also be influenced by external social factors such as peer pressure and organizational expectations, which can affect individual performance and decision-making. Organizational variability might also be influenced by external regulatory standards, the availability of engine components' spare parts, and operational conditions affected by environmental factors such as weather and routing.

By incorporating the performance variability of FRAM functions, it is possible to uncover additional risk identifications and enhance safety measures for ammonia-powered ship engine room operations. This approach facilitates the identification of critical safety relationships between functions, revealing how the performance output of one function may affect others. However, employing this methodology requires extensive work and data collection. Generalizing activities also poses a challenge due to variations in work procedures across different vessels and operators, necessitating a comprehensive approach to data gathering and analysis to ensure the robustness and applicability of FRAM in enhancing maritime safety. This necessitates a methodical approach to data collection and analysis to ensure the robustness and applicability of FRAM in enhancing maritime safety.

FRAM and Fault Tree Analysis (FTA) are distinct methodologies that often present challenges when attempts are made to integrate them. FRAM focuses on analyzing Safety-II, which emphasizes the myriad ways in which daily activities can go right, thereby enhancing safety through performance variability. Conversely, FTA adopts a Safety-I perspective, aimed at minimizing failures by identifying and understanding the root causes of system malfunctions. This differing perspective situates FRAM in analyzing work-as-done procedures, whereas FTA elucidates the logical sequence of failure events.

The integration of these two methodologies poses significant challenges in finding a conceptual 'bridge' to connect them effectively. However, literature reviews and prior research suggest that reducing time spent in the engine room (ER) enhances safety, indicating a linkage between human and mechanical aspects of system operation. This connection is supported by the calculations of Individual Risk per Annum (IRPA), as outlined in equation (5.2), which incorporates human presence within the engine room alongside technical aspects such as component failures and the creation of hazardous atmospheres.

The presence of humans in the engine room is contingent upon the activities conducted within the human-machine system, depicted in the work-as-done FRAM model as safety-II perspective. System modifications, therefore, must ensure that changes in the socio-technical systems do not adversely affect the existing safety levels or hinder the process of achieving operational goals, such as maintaining ship safety. In this context, the Quantitative Risk Analysis (QRA) aspect of this research serves to bridge socio-technical systems (STS) and technical considerations, employing methodologies from both FRAM and FTA. This integration illustrates how human and technical factors interact and collectively influence safety outcomes.

The incorporation of FRAM and FTA also useful on the system modification recommendation frameworks, given in Figure 6.2. In this research recommendations, FRAM mainly used as a map delineating the boundaries and elements within the ER. On the other hand, while FTA acts as a compass guiding risk reduction efforts. The FTA able to determine the logical sequence and causes of the error, provide the direction of the modifications. Modifications suggested by FTA analyses should take into account existing STS conditions, assessing how changes affect current functions and their interrelationships.

Nonetheless, it is crucial to acknowledge that the integration of FRAM and FTA may not provide a universal solution. The appropriateness of combining these methodologies depends on the specific case and the research objectives, along with the proportion of risk to which humans are exposed and their role in creating or mitigating such risks. Future research should continue to explore the dynamics between human activities and technical failures within complex systems to better understand and enhance safety through tailored interventions. This investigation will provide a deeper understanding of the intricate balance required to manage safety effectively in environments where human and technical systems intersect.

In the conceptual framework of this study, FRAM serves as a map delineating the boundaries and elements within the ER, while FTA acts as a compass guiding risk reduction efforts. Modifications suggested by FTA analyses should take into account existing STS conditions, assessing how changes affect current functions and their interrelationships.

The research highlights significant limitations in the use of Fault Tree Analysis (FTA) within Quantitative Risk Assessment (QRA). The QRA formula, derived through extensive literature review, leverages FTA primarily for its ability to visualize logical sequences of events. This use reflects FTA's inherent constraints, as its discrete methodological approach often fails to fully capture the complex interdependencies that exist between human interactions and technical processes. Such interactions are frequently depicted in FTA diagrams, with human factors typically represented on the left side and technical processes on the right. This separation within the FTA framework can oversimplify the nuanced relationships between these two domains, leading to a potential underestimation of their combined impact on system safety.

FTA's limitations become particularly apparent when analyzing modifications in human tasks and their consequent effects on technical safety outcomes. The method's structure, while effective for identifying direct causal chains, struggles to accommodate the dynamic interactions characteristic of socio-technical systems where human and technical elements are deeply intertwined. This challenge points to the necessity for a more integrated approach that can more accurately reflect the reciprocal influences between human behaviors and technical operations. By expanding the analytical framework beyond the conventional boundaries of FTA, researchers can develop more robust models that accommodate the complexity of modern socio-technical environments, thereby enhancing predictive accuracy and improving safety outcomes in complex operational settings.

7.4. Excluding the "Failure to Evacuate the Engine Room During an Emergency" Event in the QRA

The FTA in this research presents several limitations, one of which is the exclusion of the ”Failure to Evacuate the Engine Room During an Emergency” event. This omission represents a significant consideration that could impact the safety results. The primary reason for excluding this event is the lack of detailed information on its probability, which can vary depending on factors such as engine room escape routes, layout, and ship operator safety management systems. Further analysis is needed to understand the factors influencing this event and to measure the impact of its absence on the QRAin terms of IRPA. Despite its significance, this event should be included in future studies to ensure that safety results accurately reflect real-world conditions.

The absence of this event may also affect the relevance of the recommendations. While some recommendations may reduce the value of P_{ER}, they could inadvertently increase the probability of failure to evacuate the engine room during an emergency. For example, the addition of an engine chamber in NH3 Scenario 3 reduces P_{ER} during maintenance but also complicates the engine room layout and escape routes, potentially hindering emergency evacuation. Further risk identification and assessment are necessary to balance the impact of modifications on P_{ER} with the crew's ability to evacuate the engine room in a timely manner during emergencies.

The probability of successfully evacuating the engine room during an emergency is closely tied to the maximum time available for evacuation. This evacuation time is influenced by the concentration level of ammonia gas leakage. The cumulative ammonia concentration in the engine room is determined by the release rate, which in turn is affected by the diameter of the leak hole, as outlined in Equation (5.6).

Double-walled pipes are effective in mitigating risk for small leak hole diameters (1-3 mm), significantly reducing the λ_{LOC} by a factor of 100, as shown in Table 5.2. However, for larger leak hole sizes (10-50 mm), the effectiveness of double-walled pipes diminishes, only reducing the λ_{LOC} by a factor of 10. Although the likelihood of large leak hole fractures is lower, the high release rate combined with the reduced efficacy of double-walled pipes can markedly decrease the probability of evacuating the engine room in time during an emergency.

It is important to note that other factors might affect the time required to safely evacuate the engine room under specific conditions, which is out of this thesis research scope. Future research should focus on analyzing the ability and time required for effective evacuation during emergency situations.

7.5. Limitations

The research presented in this thesis has several limitations and assumptions that could influence the generalizability of its findings. These limitations span both the technical aspects of the ship under study and the methodologies employed throughout the research. This sub-section aims to analyze these limitations and their potential impact on the generalization of the results.

1. The data collection for this research was conducted using a small-size LNG carrier, which may differ significantly in various aspects such as regulations, engine room size, fuel supply system, and engine configuration from other types of vessels like dry containers, yachts, or barges/feeders. These differences could potentially influence the generalizability of the findings across different ship types. For instance, safety measures and operational procedures that are effective for small LNG carriers might not be directly applicable to larger or differently configured ships.
2. The vessel focused on in this study is equipped with a dual-fuel engine, capable of operating on both diesel and gas fuels. This specific engine configuration impacts the operational dynamics and safety measures compared to single-fuel engines. Dual-fuel engines offer flexibility and efficiency but also introduce additional complexity in terms of fuel management and safety protocols, which could affect the outcomes of the risk assessments and safety evaluations conducted in this research.
3. At the time of data collection and analysis, there were no ammonia-powered ships in operation. Consequently, the Work-as-Done (WAD) aspect of the FRAM methodology could not be fully realized. Instead, the study extrapolated WAD data from LNG-powered ships to hypothesize operations on ammonia-powered vessels, essentially blending Work-as-Imagined (WAI) concepts with WAD realities. This approach introduces a level of uncertainty, as the actual operational dynamics and safety concerns of ammonia-powered ships might differ from those of LNG-powered ships. The absence of empirical WAD data for ammonia-powered ships limits the accuracy and applicability of the findings.
4. The complexity of systems within the engine room, the duration spent performing tasks, and the procedural specifics are likely to vary considerably depending on the ship's age, manufacturer, and operator. These variables introduce additional layers of complexity in standardizing safety assessments and interventions. Older ships may have different maintenance needs and safety challenges compared to newer vessels. Similarly, variations in manufacturer specifications and operator practices can lead to significant differences in how safety measures are implemented and how effective they are in mitigating risks.
5. It is assumed that any ammonia leakage occurs solely in gaseous form. This assumption is based on sources indicating that ammonia in marine engine systems is typically handled in its

gaseous state. However, if ammonia were to be present in liquid form, the risk dynamics and safety measures would likely differ. The assumption of gaseous ammonia leakage simplifies the risk assessment but might not capture all possible scenarios, potentially overlooking critical safety concerns.

6. The Quantitative Risk Assessment (QRA) implemented in this study faces limitations, including the adaptability of historical risk data primarily derived from oil and gas and LNG operations, which may not accurately reflect the risks associated with ammonia as a marine fuel. The reliance on historical data from different fuel types introduces potential inaccuracies in the risk models, as ammonia's chemical properties and behavior differ from those of LNG. This limitation underscores the need for updated risk models that more accurately represent the operational and safety dynamics of ammonia-powered vessels. Developing such models would require empirical data from actual ammonia-powered ship operations, which are currently unavailable.

In summary, the limitations of this study highlight the challenges in generalizing findings across different ship types and configurations. The reliance on LNG-powered ship data, assumptions about ammonia leakage, and the variability in ship systems and procedures all contribute to the complexity of accurately assessing safety risks for ammonia-powered ships. Future research should focus on obtaining empirical data from ammonia-powered vessels and developing risk models that reflect their unique operational characteristics to improve the accuracy and applicability of safety assessments.

7.6. Future Works

To improve the safety level of ammonia-powered ship engine rooms, further research and development areas have been identified from this study. This sub-section discusses these future directions in detail.

1. The Functional Resonance Analysis Method (FRAM) could be further utilized by employing dynamic propagation quantification for risk management. This approach, while promising, requires extensive data collection and significant effort. Dynamic propagation quantification would allow for more accurate risk assessments by capturing the variability and interdependencies within the socio-technical system. However, implementing this methodology necessitates a substantial commitment of resources and may involve the development of new tools and techniques to handle the complexity and volume of data required.
2. The current study has determined the number of couplings within the FRAM, a comprehensive assessment using Social Network Analysis (SNA) is recommended (Falegnami et al., 2019). SNA would provide a deeper understanding of critical safety functions and their relationships, extending beyond the immediate activities within the engine room. At present, the research assumes uniform risk across various functions, which may not accurately reflect the actual risk landscape. By employing SNA, it would be possible to identify which functions and relationships are most critical to safety and how interventions can be more effectively targeted.
3. The study on other types of vessels beyond LNG and LPG cargo vessels to analyze the relevance of the safety recommendations across different vessel types is essential. This would involve examining the engine room work procedures of various ship operators and engine manufacturers. By observing a broader range of vessels and operators, the generalization of the socio-technical systems perspective could be improved, and the relevancy of the system recommendations could be validated. This broader study would help in understanding whether the findings from this research are applicable to a wider array of maritime contexts or if they need to be tailored to specific vessel types.
4. Onboard maintenance, which involves the highest uncertainty and frequency, represents the bottleneck in terms of time spent inside the engine room. The modifications to maintenance activities, as proposed in Scenario 3, have been shown to effectively reduce the Individual Risk per Annum (IRPA) value. To further enhance safety, it is essential to develop research on safe maintenance procedures specifically designed for ammonia-powered ships. These safe maintenance procedures should address the unique hazards associated with ammonia, ensuring comprehensive safety measures are in place.
5. Future research is needed to determine the probability of evacuating the engine room ”on time” during an emergency. The maximum time available for safe evacuation depends on various fac-

tors, including the cumulative concentration of ammonia and the engine room layout. Therefore, future studies must identify and analyze these variables to ensure that the QRA results reflect real-world conditions accurately. Additionally, future research should evaluate how modification strategies impact the ability to escape during emergencies. This analysis will help balance recommendations by considering both the reduction in the probability of exposure P_{ER} and the probability of timely evacuation. Such an approach will provide more comprehensive and practical recommendations for enhancing safety in ammonia-powered ships.

In conclusion, while this study has provided valuable insights into improving the safety of ammonia-powered ship engine rooms, it has also identified several areas that require further research and development. By addressing these areas, future studies can build on the findings of this research to develop more effective and comprehensive safety strategies for ammonia-powered maritime operations.

8

Conclusions

The primary objective of this research is to develop safety risk management strategies aimed at enhancing the safety of crew members on ammonia-powered ships, leveraging a socio-technical perspective for comprehensive risk analysis. This objective is addressed through the main research question (MRQ) and the sub-research questions (SRQs), the conclusions of which will be presented in this chapter.

Additionally, this research aims to produce a set of safety risk management recommendations for ship operators, manufacturers, and regulators, as outlined in Chapter 1. This chapter will also discuss recommendations for future actions and research for these stakeholders, building upon the findings detailed in Chapter 6.

8.1. General Conclusions

SRQ1: What socio-technical elements inside the ammonia-powered ship engine room can be identified?

The identification of socio-technical elements within the ammonia-powered ship engine room began with a detailed analysis of the human, technical, and organizational components. Human elements include the engineering crew, who are critical to the operations and safety of the engine room. Engineering crew members, such as the Engineer on Watch (EoW) and the Chief Engineer, are responsible for monitoring the engine's performance, controlling engine systems, conducting routine maintenance, and responding to emergencies. The roles of the EoW are controlled and follow procedural documents as a control mechanism, pivotal in ensuring the smooth operation of the engine room and mitigating risks associated with ammonia leakage. The Chief Engineer acts as the decision-maker for the engine room, sometimes in collaboration with the ship's master if ship-level safety is involved. Another human actor outside the engineering crew is the Officer on Watch, located on the vessel's bridge. Although this actor might not be directly involved in engine room activities or directly exposed to ammonia risk, they collaborate with the engineering crew to monitor crew safety through the "Dead Man Alarm" procedure.

Technical components are another essential element, encompassing the whole ship systems, engine systems, and safety equipment like gas detectors. These components are interconnected, and their proper functioning is crucial for maintaining engine room safety. Some monitoring and control activities are determined by the vessel's conditions and operations. For instance, during vessel mooring, monitoring is required to ensure the fast response of the engineering crew if there is a malfunction in the engine system, as engine power output is essential for ship control. The technical system also provides additional automated safety barriers, enhancing the safety of the engineering crew and the entire onboard crew. For example, gas detectors are designed to quickly identify ammonia leaks, allowing the crew to initiate emergency protocols and perform the emergency shutdown (ESD) to minimize the risk of gas leakage. Additional safety barriers on the engine systems during engine system changes ensure that prerequisite activities before changing from diesel to gas are conducted to ensure engine component and crew safety. The integration of these technical components ensures a comprehensive safety net that can address various potential hazards.

Organizational elements include the developers of procedural documents (maintenance procedures, safety protocols, and regulatory guidelines), developers of the maintenance schedule, and the office department of the ship operator. These elements are established based on international maritime safety standards and are designed to provide a framework within which the crew operates. Organizational elements predominantly influence the control mechanisms of the EoW's work inside the engine room, providing documents and guidelines to ensure EoW safety and control the output performance of the work. Therefore, they do not directly involve the decision-making of the onboard crew, supporting the theoretical views of STS as stated by Kroes et al. (2006).

Critically, the interplay between these human, technical, and organizational elements forms a complex socio-technical system. Understanding this interplay is vital for identifying potential points of failure and developing strategies to mitigate risks. The Functional Resonance Analysis Method (FRAM) was instrumental in mapping these elements and their interactions, providing a holistic view of the engine room's operations. However, the STS elements developed in this research are based on a case study of a single ship operator, which might differ from other ship operators depending on their operational procedures, guidelines, and vessel organizational structure.

SRQ2: What is the relationship between the socio-technical elements within the engine room?

The relationships among the socio-technical elements in the engine room are characterized by complex inter-dependencies that significantly impact overall safety. Through the development of Work-as-Imagined (WAI) and Work-as-Done (WAD) models, these inter-dependencies were systematically analyzed. The WAI model represents the idealized version of how tasks should be performed, based on technical manuals and safety protocols. In contrast, the WAD model reflects the actual practices observed in the engine room, which can deviate from the ideal due to various factors such as time constraints, equipment malfunctions, and human error.

The complex relationships identified through the FRAM model were not fully utilized in the Quantitative Risk Assessment (QRA), where the primary focus was on the duration of tasks and analyzing the impact of modifications on the STS relationships. While the relationships between FRAM functions can be identified, determining the critical safety level of these relationships proved challenging in this study.

A more comprehensive assessment of the findings presented in Table 4.5 and Figures 4.8 to 4.10 could be achieved by incorporating additional measures from the Social Network Analysis (SNA) method, as demonstrated by Falegnami et al. (2019). However, integrating SNA measures with the WAD FRAM relationships was beyond the scope of this research. Therefore, the full potential of using FRAM for safety assessment purposes remains under-explored and presents a promising avenue for future research on engine room safety.

This study highlighted the importance of understanding the complex interplay of socio-technical elements within the engine room. By refining the approach to analyzing these relationships and incorporating advanced methodologies like SNA, future research can further enhance the safety and efficiency of maritime operations.

SRQ3: How to enhance the safety of the ammonia powered ship engine room by understanding the relationship between elements of socio-technical systems?

The socio-technical perspective provides a holistic approach to risk management by considering the interactions between human, technical, and organizational elements. Unlike traditional methods that often focus solely on technical components or human factors in isolation, this approach integrates multiple dimensions to identify critical functions and their inter-dependencies. This comprehensive view leads to more effective risk mitigation strategies.

In this research, activities within the engine room are categorized into three main groups: operational and control, monitoring and inspection, and on-board maintenance. The relationships among these categories are illustrated in Figure 6.2. Operational activities trigger monitoring activities, which serve as a feedback mechanism to ensure the quality of operational tasks. Monitoring activities facilitate the identification of component failures or malfunctions, enabling timely corrective maintenance. The performance of operational activities, combined with the manual, influences the life cycle of components, affecting maintenance frequency. Conversely, downtime during maintenance impacts the overall operational capability of the ship.

The integration of the STS perspective through FRAM enables the identification of key activities that could be modified to significantly enhance safety. Modifications aimed at reducing P_{ER} were found to be the most significant in lowering the overall risk level. In this research, on-board maintenance, which has the highest value of P_{ER}, was identified as a critical area for risk reduction, followed by monitoring and inspection activities. These findings address the research gap by identifying which components or activities need modification in terms of duration and location. This prioritization ensures the effectiveness of modifications by targeting the most influential activities.

The incorporation of FRAM into the QRA also facilitates the identification of potential changes to the STS within the engine room due to modifications. For example, changing work procedures to remote operations can reduce the P_{ER} variable in the QRA, enabling a more accurate evaluation of risk levels through IRPA. Additionally, FRAM maps the relationships between functions within the engine room STS, helping to identify changes in work processes and human-machine interactions, as well as ensuring the feasibility of modifications and potential new hazards.

Main RQ: What strategies can be employed to enhance safety risk management in Ammonia Powered Ships engine room by incorporating socio-technical system perspective?

To enhance safety risk management in ammonia-powered ship engine rooms by incorporating a socio-technical systems (STS) perspective, the research followed a multi-step approach:

The first step involved a detailed identification of socio-technical elements, including human actors like the engineering crew, technical components such as ammonia engine systems and gas detectors, and organizational elements like developers of safety protocols and the office of the ship operator. This comprehensive identification process ensures that all potential sources of risk and their interactions are considered.

The second step entailed developing WAI FRAM and WAD FRAM models to map out the interactions and dependencies between these elements. These models highlighted how deviations in one area could propagate risks across the system. By mapping these elements using the FRAM, the study provided a holistic view of the engine room's operations, emphasizing critical areas where interactions between elements could lead to safety risks.

In the third step, the integration of FRAM with FTA provided a quantitative basis for assessing risks and identifying critical areas for improvement. This combination allowed for a detailed understanding of how changes in the engine room's layout and maintenance procedures could reduce risks and their impact on the future socio-technical system through WAD FRAM.

The primary variable used from the STS perspective was the duration of activities and the relationships between them. The duration of activities is directly related to the safety level of the engineering crew, as stated in equation (5.2). Modifying the locations and procedures of activities could reduce exposure time in the same space as engine components, thus reducing the risk of ammonia poisoning. The variable of time spent on a single activity enabled the quantitative evaluation of safety levels using STS, expressed in IRPA metrics.

System modifications followed the developed framework in Figure 6.2, enabling the identification of which functions within human-machine interactions should be modified and understanding the impact of these modifications. This approach allowed for determining which activities should be developed in terms of procedure, location, and duration, helping prioritize future developments based on their impact on safety levels.

This research reveals that implementing the modifications in NH3 Scenario 3—focusing on reducing P_{ER} through engine room design layout changes and revised work procedures that consider the on-board maintenance—can decrease the IRPA from 1.33×10^{-5} to 2.00×10^{-6}. In terms of normative risk analysis, these modifications successfully achieve the risk acceptance criteria set by IGF Code guidelines, which are at 3.16×10^{-6}. This outcome is attained by addressing the "bottleneck" activities within the engine room in terms of P_{ER}. On-board maintenance, with a P_{ER} value of 0.36, represents the activity with the highest annual duration inside the engine room, followed by "monitoring and inspection" at 0.13 and "starting the engine" at 0.01. Identifying these P_{ER} values facilitates the determination of the most effective modifications to improve the IRPA level, as indicated in Equation (5.2). Although this result is an approximation of QRA with certain assumptions to simplify the risk evaluation, it provides a clear strategy for prioritizing activities and enhancing the safety of ammonia-powered ship engine rooms.

Evaluating this strategy, which integrates both STS and QRA through FRAM and FTA, presents challenges. This difficulty arises from the differing safety perspectives inherent in these methodologies—FTA focuses on Safety-I, while FRAM addresses Safety-II. The QRA, utilizing the IRPA metrics as described in Equation (5.2), bridges STS and QRA by combining human-machine interactions with the logical sequence of engine component failures. However, this approach may be particularly suited to specific contexts, such as engine room safety. In this research, the time spent in the engine room has a significant impact on safety levels, and there is limited understanding of which activities should be modified to enhance safety. Other scenarios may present different needs and relationships for applying STS in safety, necessitating an initial assessment of the interactions between human-machine elements and their impact on safety.

8.2. Recommendations

The recommendations for this study, based on the analysis in Chapter 6 and illustrated in Figure 6.2 and Table 6.7, are categorized according to the roles of different actors:

8.2.1. Ship Designers, Operators, and Manufacturers

The recommendations aimed for this actor are:

1. **Develop an engine room layout with a separate room for each engine**

   This spatial distinction minimizes the probability of ammonia leakage exposure during maintenance, ensuring the safety of the onboard engineering crew. However, further analysis on the engine room components and piping complexity and feasibility is required. The risk assessment and work procedure re-evaluation also required on this modifications, since having three distinct space for each engine might affect the work behaviour of the engineering crew.

2. **Relocating Components Outside the Engine Room and Partitioning with a Wall**

   These components include the Local Control Panel (LCP) and other engine local indicators used for redundancy in monitoring and inspection. Relocating input valves will also reduce the time spent in the same space as the engine, as monitoring and inspection often involve calibrations and controls. However, future risk identification and assessment, particularly in response to changes in work behavior, need to be conducted.

3. **Implement remote cameras for monitoring and inspection**

   The remote monitoring through cameras should complement, not replace, in-person inspections. Detailed views of components will still require engineers to enter the engine space, but overall, this measure will minimize the presence of engineering crew in the engine space. The implementation of remote cameras with adequate and standardized resolution is essential to ensure the accuracy and effectiveness of remote monitoring. Additionally, proper training and established work procedures for ship operators are crucial to prevent over-reliance on remote monitoring, which could introduce new hazards.

8.2.2. Research Institutions, Engine Manufacturers and Regulators

The recommendations aimed for this actor are:

1. **Enhancement of Safety Maintenance Procedures for Ammonia-Fueled Engine**

   Developing safety work procedures and guidelines specifically for ammonia-fueled engines is crucial to ensure safe maintenance practices. These procedures must address the unique characteristics of ammonia as a fuel, incorporating prerequisite maintenance protocols to guarantee safety. A thorough understanding of ammonia engine characteristics and potential failure modes is essential for creating these procedures, which will serve as comprehensive guidelines for ship operators. Therefore, sufficient experience in operating ammonia-powered ships is required to develop a deep understanding of these specific engine characteristics, as no ammonia-powered ships are currently in operation.

2. **Reducing Engine Complexity through Modular and Standardized Components**

   Create modular and standardized engine components to reduce maintenance complexity, time spent on maintenance, and the potential for human error. Standardizing component sizes will also support compatibility, decrease maintenance downtime, and reduce the necessity for crew presence in the engine room during maintenance. However, this required a collaborative approach from the engine components manufacturers to ensure the compatibility and standardization of the components.

3. **Enhancing Predictive Maintenance through Engine Sensor Implementation**

   Enhance engine sensors to improve predictive maintenance of engine systems, reducing the need for corrective maintenance and ensuring spare parts are available before downtime. However, this recommendation might conflict with the goal of reducing engine complexity through modular components. Further studies are required to balance these trade-offs.

8.2.3. Gas Detector Producers and Research Institutions

These actors are recommended to further **develop ammonia gas detectors to reduce their response time**. As indicated in Chapter 6, quicker response times can significantly decrease the likelihood of ammonia reaching AEGL-3 concentration levels, thereby reducing the fatality risk for the engineering crew.

8.2.4. Ship Operators

The ship operator is recommended to **develop a digital logbook to minimize the paperwork required during monitoring and inspection**, thereby reducing the time spent on these tasks. Crew training is essential to ensure the proper use of the digital logbook and to mitigate any new hazards resulting from changes in work behavior.

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A

Diagram of Process of Ship Operations

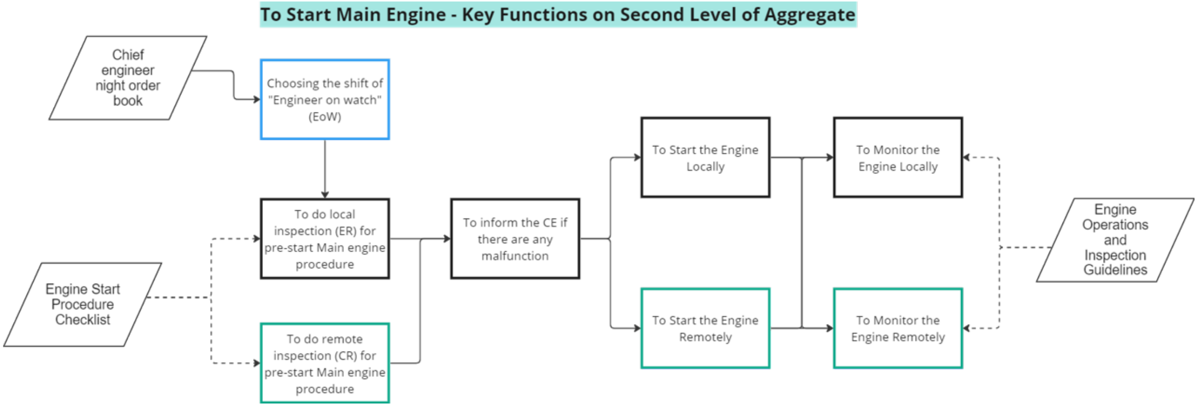

Figure A.1: The Second Level Aggregate of the Start The Engine Phase

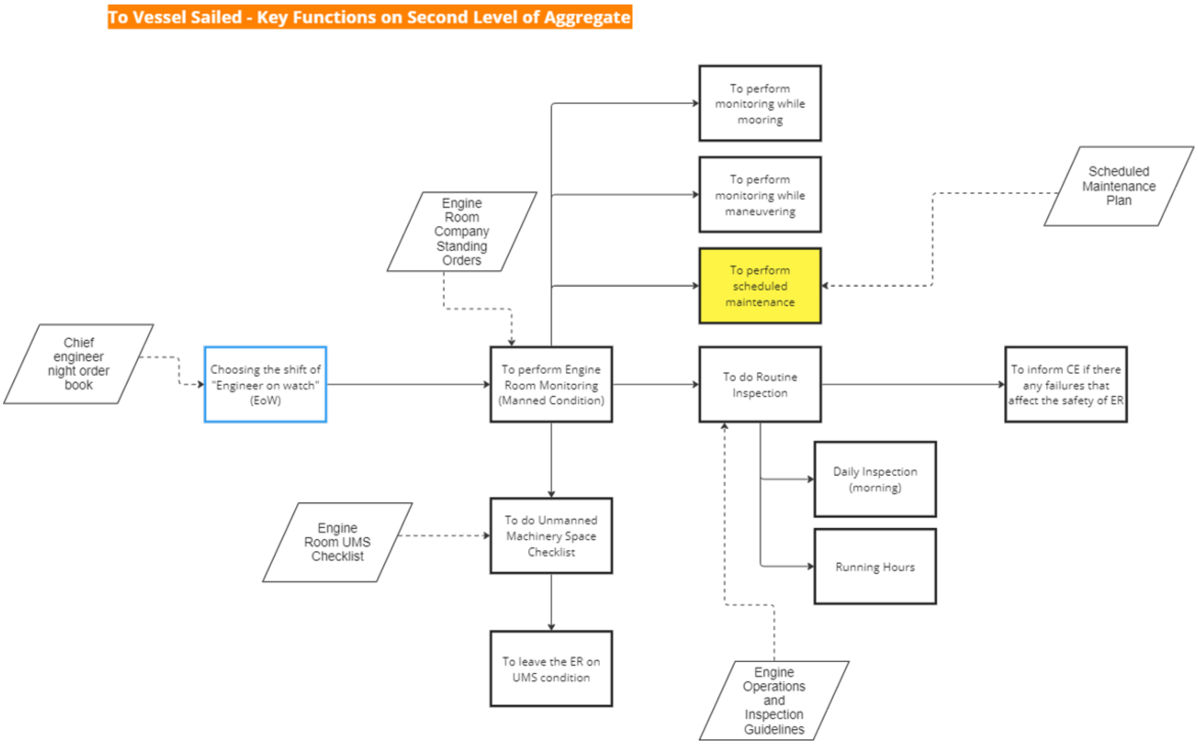

Figure A.2: The Second Level Aggregate of the Vessel Sailed Phase

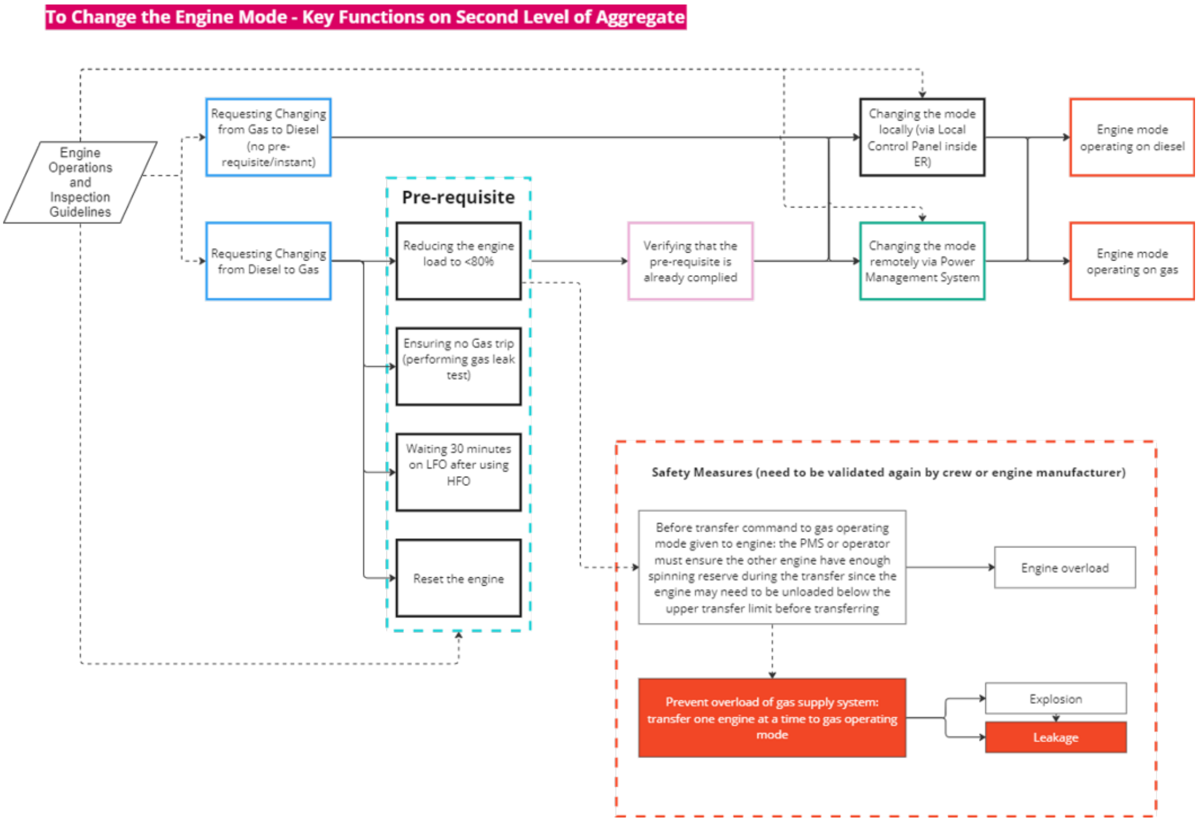

Figure A.3: The Second Level Aggregate of the Change the Engine Mode Phase

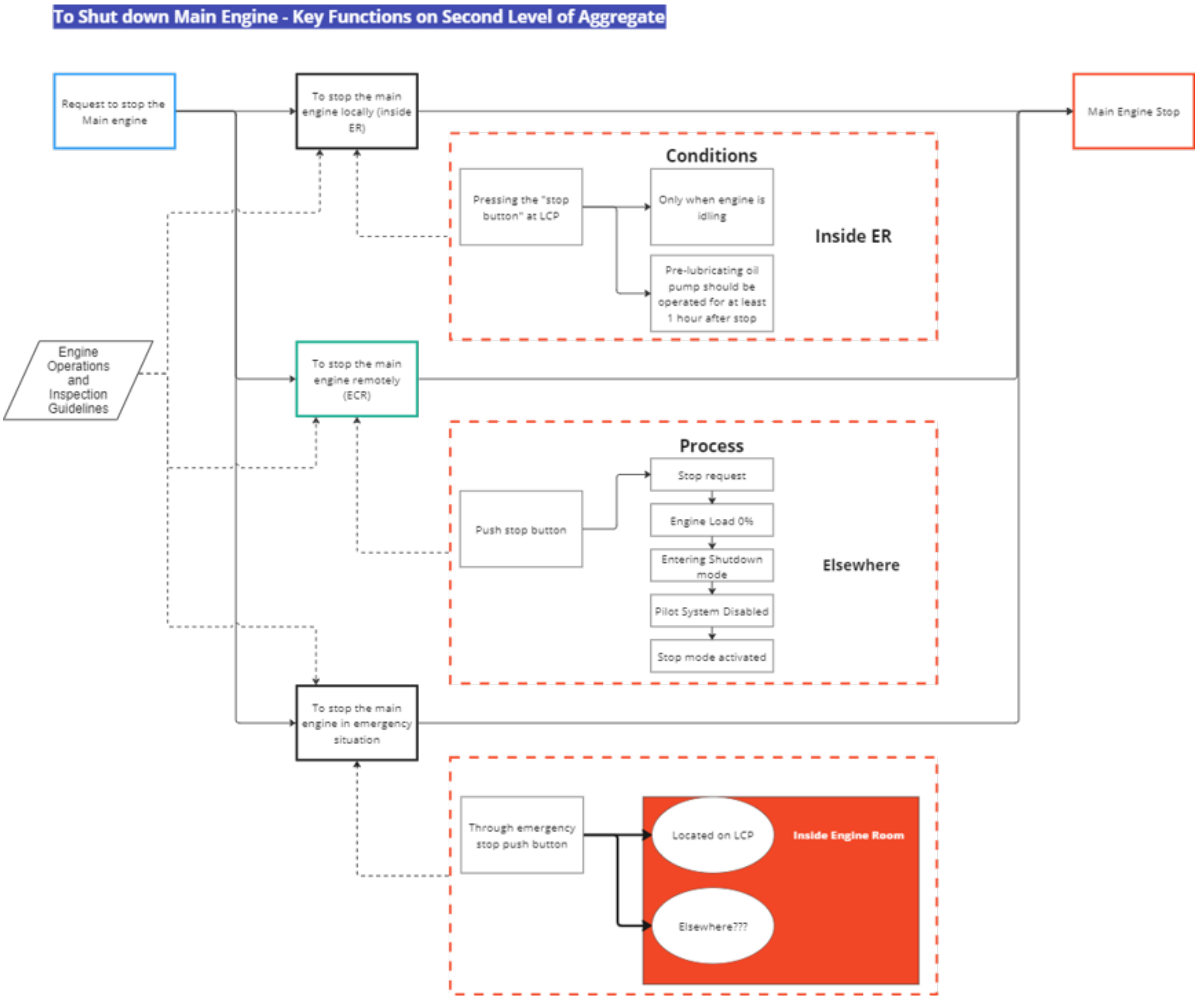

Figure A.4: The Second Level Aggregate of the Shut Down The Engine Phase

B

Interview Summary

B.1. Interview 1

Position: Chief Engineer
Experience: Engineer in DF Engine Ship and Diesel Engine Ship
Date of Interview: 28 May 2024
Location: Online

B.1.1. Scope of Interview

1. Start the Engine Phase
2. Shut down the Engine Phase

B.1.2. Start the Engine

Findings – General Questions:

1. **Does this diagram give you a complete picture of your activities? What is missing?**
    - The flowchart already shows the correct sequence and list of activities during the starting phase.
    - Important Note: Reducing the time inside the engine room cannot be done due to the schedule for monitoring and inspection. However, moving tasks outside to reduce time spent in the same chamber as the engine is acceptable.
    - The Chief Engineer prefers to:
        - Main engine: Always start remotely.
        - Auxiliary engine: Someone needs to stand by in the engine room during starting and checks, even if controlled from the Engine Control Room (ECR).
2. **How long do you spend doing tasks inside the engine room in a day?**
    - Normal Starting Total Time: Approximately 1 to 1.5 hours
        - 1 round of inspection and preparation (30 minutes – depending on crew experience and engine type): Inspection before starting the engine.
        - Push Start the Engine.
        - Wait for the engine to warm up (unpredictable but usually takes 10 minutes): Check temperature and pressure.
        - One more round of inspection and preparation (around 30 minutes).
        - Inform the Chief Engineer to take control of the engine.
    - Emergency Starting Total Time: 30 minutes
        - Details: …
3. **Do you spend more time in case of problems? (If yes, what is the reason?)**
4. **What is the task or group of tasks which you spend the most time on in the engine room during normal operating conditions?**
    - Preparation and inspection (30 minutes) – has a checklist procedure (controlled by documents).
5. **What is the task or group of tasks which you spend the most time on in the engine room during maintenance tasks?**
6. **Which typical activities are hard to predict in terms of how long they will actually take (unpredictability of duration)?**
    - After starting the engine procedure: Warming up the engine (usually 10 minutes but could take more).
7. **Which task gives you the highest probability of creating a leak?**
    - Starting the engine and then monitoring to check that everything is fine.

8. **How can you tell whether a leak has occurred?**
    - During the visual check after starting the engine.
9. **Under what conditions is your presence inside the engine room still required even when a leak happens? What is the effect on ship safety?**

B.2. Interview 2

Position: Marine Assurance Officer
Experience: 3rd Engineer in DF Engine Ship and Diesel Engine Ship
Date of Interview: 28 May 2024
Location: AV Office Rotterdam

B.2.1. Scope of Interview

1. Vessel Sailed
2. Change Engine Mode

B.2.2. Vessel Sailed

Findings – General Questions:

1. **Does this diagram give you a complete picture of your activities? What is missing?**
    - The process is already correct.
    - The schedules for daily visual inspection are grouped into:
        - Morning Round (08:00 – 09:00) – 1 hour.
        - Evening Round (16:00 – 17:00) – 1 hour (before end of EoW shift).
    - Followed by the daily schedule for Unmanned Machinery Space (UMS) checklist:
        - Total time around 1 hour.
        - Required before the crew leaves the ER to rest.
    - Another daily visual check before leaving the ER for breaks:
        - 09:30 – 10:00 (30 minutes).
        - 11:30 – 12:00 (30 minutes).
        - 14:30 – 15:00 (30 minutes).
    - The check objectives for UMS and daily inspection are the same:
        - Machinery Space.
        - Steering Gear Room.
    - General:
        - Monitoring and inspection goals are to ensure everything is okay and increase confidence in safety.
        - Sometimes the trigger is before leaving the ER for breaks to ensure everything is okay (confidence).
        - Monitor, inspection, and UMS checklist generally check the same things:
            - Whole Machinery Space.
            - Steering Gear.
2. **How long do you spend doing tasks inside the ER for a day?**
    - Based on the EoW schedule given by CE: 08:00 – 17:00 every day (work time).
    - Detailed in question 1:
        - Daily Inspection:
            - Morning round (08:00 – 09:00) – 1 hour.
            - Evening Round (16:00 – 17:00) – 1 hour (before end of EoW shift).
        - Mid-day Daily Visual Check:
            - 09:30 – 10:00 (30 minutes).

        - 11:30 – 12:00 (30 minutes).
        - 14:30 – 15:00 (30 minutes).
    - UMS Check:
        - 1 hour (conducted before the crew sleeps and needs to be informed to the bridge).
- Range: 2-6 hours.
- Range if there is any maintenance: up to 10 hours.
- Continuous stay: 1.5 – 2 hours.
- During inspection, you never stay in one place; you always move. Except during maintenance where you always need to stay in one place.

3. **Do you spend more time in case of problems? (If yes, what is the reason?)**
4. **What is the task or group of tasks which you spend the most time on in the engine room during normal operating conditions?**
    - Machinery Space Monitoring:
        - 08:00 – 17:00 – scheduled but only enter ER roughly 3.5 hours:
            - Morning inspection (1 hour).
            - Mid-day (3 x 0.5 hours = 1.5 hours).
            - Evening inspection (1 hour).
        - Despite the age of the vessels:
            - New vessels: Bottleneck is only monitoring.
            - Old vessels (>10 years): Bottlenecks are monitoring and maintenance.
5. **What is the task or group of tasks which you spend the most time on in the engine room during maintenance tasks?**
    - It is hard to answer but recommended to see the planned maintenance schedule list.
6. **Which typical activities are hard to predict in terms of how long they will actually take (unpredictability of duration)?**
    - Maintenance (details in the maintenance section).
7. **Which task gives you the highest probability of creating a leak?**
    - It is hard to answer; it is quite unexpected and doesn't have designated functions that cause it. It is complex and mainly started due to human factors (Safety-II?).
    - It could break when operating normally due to vibration and other factors. Not related to the routine activity itself (Material related).
    - It is hard to predict the task that leads to leakage.
8. **How can you tell whether a leak has occurred?**
    - Through visual inspection in the morning and evening.
    - Through parameter check during monitoring and go inside ER if there is anything strange from the ECR indicator.
9. **Under what conditions is your presence inside the engine room still required even when a leak happens? What is the effect on ship safety?**
    - Everything can be controlled remotely (ECR and Bridge) – control is doubled within ECR and Bridge:
        - Start the engine.
        - Stop the engine in an emergency situation.
        - And most of the systems.

- The ECR main engine control panel is doubled to the bridge.
- ER is mostly used for inspection and maintenance; control is mainly in ECR, doubled with the bridge.
- There are no reasons to stay inside the ER during leakage, except if there is anyone left inside the ER:
    - But this is complex and meeting with the crew is needed before saving the person stuck inside the ER.
- The things that are lost or cannot be done is a visual check – maybe remote monitoring through camera can support this to know the condition of ER through visuals.

FRAM Questions

1. **Monitoring (Manned Space)**
    - Mostly EoW and CE control everything in ECR because they have good information and view from the ECR monitor and panel:
        - They can see the parameters already in ECR.
        - Triggered to go inside ER if there is any malfunction on ECR and check it directly (visual on local panel) to ensure it is correct (redundancy):
            - Local indicator: duplex filters for backup measurements.
            - Know where to check and what to check.
        - Monitoring the parameters is key.
    - Trigger:
        - Find something in ECR monitor, then send EoW to check it directly (visual on local panel) to ensure it is correct (redundancy).
        - Before EoW leaves ER.
    - They are not standing by all day inside the ER machinery space.
    - Procedure on the effect of the result of this activity on other activities:
        - Inform CE about this.
        - Determine the risk with the CE.
        - Inform the Captain regarding the findings and risk.
        - Determine action.
    - Resources needed:
        - Only EoW.
        - In LNG, no need for gas detection devices (because it is not toxic) – could be required for ammonia due to mixing of substances (location of gas detectors also plays a role here).
        - In EnergICE, the Gas Leak Test is performed in GVU, which has its special isolated room.
        - The EnergICE gas engine room has different pressure to limit the number of gases leaving the ER.
        - The door is supported with an Air Lock system – takes some time to enter because of the more complex system.
    - Conduct the task remotely – remote visual check:
        - Visual remote check is not solving the problem.
        - It might help to see a big major accident event without needing a person to get inside:
            - Fire.

        - Smoke.
        - Etc.
    - But why it cannot replace the in-person visual check:
        - The inspection of very small details is hard to detect using a camera (due to image resolution).
        - Using a camera has a limited point of view compared to in-person inspection, which allows the crew to have various points of view to inspect.
        - The camera can be used for assisting the monitoring but cannot replace in-person inspection.
        - LEAD TO QUESTIONS: WHAT DO YOU DO DURING VISUAL CHECK?
    - Where is the perfect location to put the camera:
        - Diesel Engine: Fuel pipe – can detect leakage.
        - Gas Engine: Quite hard because gas leakage is hard to detect through remote visualization.
    - Conclusions:
        - Remote visualization is only used for monitoring the bigger picture and as a support system.
        - Much better to have camera remote inspection than only visual inspection.
- The effect of delays/early completion of the task on the next activity:
    - Delay or early completion has no risk.
    - The absence of the task (inspection and monitoring) is the risk.
- Does moving the work remotely affect safety and operations negatively?
    - In several cases, no.
    - It indeed increases safety.
- Control: Customized Checklist – Generally checking the same things for monitoring, inspection, and UMS checklist procedure.
- Time: Done between morning inspection (08:00-09:00) and evening inspection (16:00-17:00).
- Scheduled maintenance is conducted within this time window.
- Malfunction procedure:
    - Inform everything to CE.
    - CE and engineer need to decide the risk of this malfunction.
    - If the risk is high, we need to inform the captain to stop the procedure and perform maintenance.
    - Risk level:
        - Low: We can start the engine on load (idle?) and perform maintenance later during anchorage or the port stage (can be done by the crew itself).
        - High: Office involvement is required.

2. **UMS Checklist**
    - Total time around 1 hour (done at 22:00).
    - Required before the crew leaves the ER to rest.
    - Only one person will be inside the ER, so it is dangerous to be inside alone and need to inform the Bridge officer during the UMS Checklist to help monitor the crew who conducts the UMS checklist. Why?

    - If there is anything happen to the crew, nobody can help him directly. Therefore, the bridge needs to be informed.
  - Trigger: Schedule after workday before rest (sleep) time (at 22:00).
  - Goals: Ensure everything is right before putting into UMS before sleep.
  - Control: UMS Checklist Procedure – obligated by IMO, inform the Bridge during the round of UMS.

3. **Monitoring During Mooring**
   - Trigger: Ship's departure and arrival.
   - CE and EoW need to be inside ECR to control engine power output:
     - Just in case the captain wants to use a lot of mooring features – the ship needs a lot more power – the engineer might start another engine or control the engine fuel supply and power.
     - If something happens, engineers should be the first to do something inside ER.
   - This is critical for the ship's safety.
   - Goals: Inside ECR to control the engine power output, go inside ER to check if needed (redundancy).
   - Critical for having local control and monitoring.
   - Delay/Early effect.
   - Frequency:
     - Depends on the route.
   - Time spent inside ER for completion:
     - Around 1 hour during mooring.
   - Location: Stay in ECR.
   - Go inside the ER when something is wrong.
   - Restricted from doing anything except staying in the control room.
   - Activity outline:
     - Power control through ECR.
     - Engine monitoring through ECR.
     - Go inside ER if required.
4. **Monitoring During Maneuver**
   - Trigger: Ship's routes (usually when needing to maneuver a lot, such as in a canal).
   - Goals: Inside ECR to control the engine power output, go inside ER to check if needed (redundancy).
   - Delay/Early effect.
   - Frequency:
     - Depends on the route.
   - Time spent inside ER for completion:
     - Might be around 1 hour, but depends on the ship's route.
5. **Maintenance**
   - Could take 10 hours, but unpredictable (many uncertainties).
   - The frequency and time spent depend on the age of the vessels, type of engine, and manufacturer of the engine:
     - Age of Vessel: Newer vessels require less maintenance.

  - Type of engine: Diesel engines require frequent maintenance for cleaning compared to gas engines.
    - Change filters etc. (every 2 months).
  - Manufacturer of the engine: Some engine manufacturers have more complex engines, leading to longer maintenance times (and increasing the probability of human error).
- Cannot be done during maneuvering and mooring:
  - Due to the need for all engines to be available and operational.
  - For power control.
- Trigger:
  - Maintenance Plan – Maintenance Schedule and Manufacturer Manual.
  - Corrective Maintenance – if there are breakdowns, failures, or things not working as expected.
- Detail of activity (Maintenance on 1 engine):
  - 2 engines running, 1 engine shut down.
  - Make sure that (Only then you are allowed to start the maintenance – DF engines):
    - Electrical shut down.
    - Shut down any automation-related systems – to prevent accidental engine startup.
    - Close all fuel and gas supply.
    - Inform the bridge that one engine is under maintenance.
  - The procedures are controlled by:
    - Manufacturer Manual.
    - Maintenance Department Manual.
- Effect of this activity:
  - Engine performance.
- Resources:
  - Spare parts:
    - But the engine only undergoes maintenance if the spare parts are available (in the case of planned maintenance).
  - Engineering crew.
  - Timing (not during mooring and maneuver).
- Time Spent:
  - Small maintenance: 1-2 hours.
  - Major maintenance: >8 hours.
  - Factors:
    - Complexity of design leads to longer maintenance times.
- Causes of unpredictable duration/frequency:
  - Human factor:
    - Causes of breaking the component.
    - Knowledge.
  - Component modularity (manufacturer side) – affects the availability of spare parts.
  - Spare parts availability – waiting for delivery – until then, maintenance is always postponed.

- Frequency on DF engine:
  - Maintenance is performed on the diesel side of the engine:
    - Fuel injectors and filters (every two months).
    - Air filters on turbocharger (every month).
  - The gas side requires less frequent maintenance.
  - DF engines require less maintenance compared to diesel engines.
- Why can't maintenance be performed on time?
  - A lot of schedules, in LNG ships you cannot stop the engine for maintenance even during cargo loading at dock because the engine is needed for that phase.
  - It might lead to engineers forgetting to perform maintenance – QUESTIONS: WHAT IS THE GENERAL EFFECT OF FORGETTING THE MAINTENANCE AND HOW CRITICAL IS IT?
- Time related:
  - Don't rush – it can cause problems in the future.
    - Leads to 1-2 hours even for the smallest maintenance.
  - Find a good opportunity to do the maintenance (when it is allowed and feasible):
    - Not during mooring and maneuvering.

6. **Inspection**
   - Daily Inspection Schedule:
     - Morning round (08:00 – 09:00) – 1 hour.
     - Evening Round (16:00 – 17:00) – 1 hour.
   - Trigger: Schedule.
   - Goals: Ensure everything is all right (increase confidence in safety):
     - Enough to see if there are any leaks or malfunctions.
     - The rest can be monitored remotely from ECR.
   - Control: Log Book (which logbook? – CE engineer night order book).

B.3. Interview 3

Position: Project Engineer
Experience: Chief Engineer in DF Engine Ship and Diesel Engine Ship
Date of Interview: 30 May 2024
Location: AV Office Rotterdam

B.3.1. Scope of Interview

1. To Start Main Engine
2. Vessel Sailed

START THE MAIN ENGINE
Findings – General Questions:

1. Does this diagram give you a complete picture of your activities? What is missing?
    - Already giving complete picture of the process
    - Turning the engine location
        - Locally: Special Operations (afterhaul)
        - Remotely (ECR): Preferable
    - Steps of engine starting procedure (engine and operations specific)
        - Start the Engine (Locally/Remotely)
        - Situation 1: Monitor the engine condition on idle RPM
        - Situation 2: Increase the RPM of the engine to designated fixed level and monitor it
    - What they do during pre-starting inspection
        - Mechanical job (preparation stuff)
            - Stop condition
            - Oil lube
            - Fuel check
            - Air
            - Etc.
        - Visual check
    - What they do during the monitoring after starting the engine:
        - See the indicator and performance of the engine
            - In new engines, almost all of the information is given in ECR and LCP
            - However, information on LCP is limited compared to ECR. In ECR they can make trends of graphs based on their needs to analyze and monitor
            - In older engines, the indicators are located on the engine
        - Visual check
2. How long do you spend doing tasks inside the ER for a day?
    - Local Inspection Pre-Start Engine
        - Normal conditions: Time window is 1 hour before departure but practically the job can be done within 30 minutes. The reasons for a 1-hour time window
            - Official procedure written in the Log Book as well: the engine starting procedure begins 1 hour before departure.
            - However, in practice, it needs only 30 minutes.
        - Emergency conditions: 5 minutes

- Monitor the engine after starting
    - 5 minutes
    - Depends on the situation
    - Start the Engine (Locally/Remotely)
        - Situation 1: Monitor the engine condition on idle RPM (5 minutes)
        - Situation 2: Increase the RPM of the engine to a designated fixed level and monitor it (wait time to reach RPM + 5 minutes)

3. Do you spend more than that in case of problems? (If yes, what is the reason?)
4. What is the task or group of tasks on which you spend the most time in the ER during normal operating conditions?
    - Pre-starting inspection: 30 – 60 minutes
5. What is the task or group of tasks on which you spend the most time in the ER during maintenance tasks?
6. Which typical activities are hard to predict in terms of how long they will actually take (unpredictability of duration)?
    - Monitoring after engine starting
        - Waiting to warm up
        - Increase the RPM
7. Which task gives you the highest probability of creating a leak?
    - Critical aspect
        - Water hammering due to water cooling on the combustion engine crankshaft
            - Usually in diesel engines they can check visually by looking inside the crankshaft
            - Risk: Explosion – leakage
            - In current technology, there is a device or indicator to measure the condition inside the crankshaft that can determine whether there is water or not inside the crankshaft
            - How to prevent (safety measures):
                - New Engine: In the new engine, the system automatically starts with a very low RPM in the beginning which might reduce the damage if there is water inside the crankshaft
                - Old Engine: The old engine tends to directly work at high RPM in the beginning, leading to a higher damage possibility. Sometimes the crew can rotate the piston cylinder manually to reduce the risk
        - Oil in cylinder head
            - Poses the same risk as water hammering
            - Solved by the crew rotating the engine crankshaft manually to ensure that the oil is distributed uniformly towards the cylinder head sides
            - Turbocharger oil leakage
8. How can you tell whether a leak has occurred?
9. Under what conditions is your presence inside the engine room still required even when a leak happens? What is the effect on ship safety?

Idea:

1. Put the input valve on the outside of the engine chamber
    - Most of the tasks involve controlling or checking the input valve

    - Any input valve might not be contaminated by ammonia before combustion (ENSURE)
2. Put cameras inside with 4 points of view

VESSEL SAILED

Findings – General Questions:

1. Does this diagram give you a complete picture of your activities? What is missing?
    - Complete picture given
    - What they do in the bigger picture based on location
        - ER
            - Inspection
            - Monitor
            - Maintenance
        - ECR
            - Monitor
            - Control
    - Feedback on each step
        - Monitoring General (MS)
            - In a single space of ER (most ships are like that), 80% of the work is done inside there.
            - Some rooms and facilities are there (look again at Chapter 2 to see what things are inside the engine room)
            - Example:
                - Workspace
                - Spare part room
                - Etc.
            - Most of the time they stay inside the ECR to monitor it via the control panel and indicators
        - Daily inspection (morning & evening)
            - Fill in the Log book
                - So far it's a paper-based book
                - Developing digital log book – mind the new hazard (potential human error due to people not focusing on the visual check but relying/focusing heavily on the device)
            - Schedule
                - Morning – 08:00 – 09:00 (1 hour)
                - Before Lunch – 11:00 – 12:00 (1 hour UMS check)
                - Evening – 16:00 – 17:00 (1 hour UMS check before dinner)
        - UMS Check
            - Schedule
                - 22:00 (around 30 minutes)
            - Main task
                - Is to only check

            - If you find something wrong in UMS and need to make corrections, that must mean there were mistakes/errors during the daily inspection
            - Because something was missed during the inspection
    - Maneuvering & Mooring
        - Condition must be MMS (manned machinery space)
        - Standby inside ECR
            - Most things can be monitored & controlled
            - If anything happens, the CE and EoW can react and take action
        - Critical to ship safety

2. How long do you spend doing tasks inside the ER for a day?
    - Answered in no.1
3. Do you spend more than that in case of problems? (If yes, what is the reason?)
4. What is the task or group of tasks on which you spend the most time in the ER during normal operating conditions?
5. What is the task or group of tasks on which you spend the most time in the ER during maintenance tasks?
6. Which typical activities are hard to predict in terms of how long they will actually take (unpredictability of duration)?
7. Which task gives you the highest probability of creating a leak?
8. How can you tell whether a leak has occurred?
9. Under what conditions is your presence inside the engine room still required even when a leak happens? What is the effect on ship safety?

Idea:

1. Gas remote camera
    - More expensive
    - Might be gas-specific related – find out how it works!
2. Frequency drive ventilation
3. Location of ventilation
    - Crankcase – critical safety due to the possibility of leakage
    - Dependent on gas density
        - Lighter than air = CH_4
        - Almost equal to air = NH_3
4. PPE
    - Gas detector on each personnel
    - Gas mask for immediate safety measures if there is a massive leakage

B.4. Interview 4

Position: Project Engineer
Experience: 3rd Engineer in DF Engine Ship and Diesel Engine Ship
Date of Interview: 6 June 2024
Location: AV Office Rotterdam

B.4.1. Scope of Interview

1. Vessel Sailed + in-depth Maintenance

VESSEL SAILED

Findings – General Questions:

1. Does this diagram give you a complete picture of your activities? What is missing?
    - No feedback or correction
    - Running hours – noon-readings
        - Take running hours of the engine, level of tanks, consumption of the main engine & auxiliary engine – collected in Logbook
        - Shared with the office – to analyze (e.g., Fuel consumption to know the next time bunkering)
        - Performed inside the ER – flow meters (mostly inside the purifier room) – calculate how much the consumption
            - Not located inside the ECR
            - Only in ER (local component)
    - But mostly new vessels have
2. How long do you spend doing tasks inside the ER for a day?
    - Day starts with the morning meeting with the engineer crew
        - What happened during the night
        - What are the findings
        - Divide the schedule and routine jobs
    - Scheduled Inspections
        - Morning Inspection (09:00 – 10:00) – 30-60 minutes
            - Fill in the Logbook
            - Visual check
            - Indicator check
        - Evening Inspection (16:00 – 17:00) – 30-60 minutes
            - Fill in the Logbook
            - Visual check
            - Indicator check
        - Before lunch (11:45 – 12:00) – 15 minutes
            - Check whether we can leave the engine room unmanned or not
            - Similar to UMS but a quick one because you will leave only for 1 hour
            - No specific task to check
    - Running Hours
        - Collected in Logbook
        - Fuel consumption

        - Indicator check – flow meter (Local only)
            - Inside the purifier room
            - For diesel or DF engine
            - 5 minutes (max) – not that significant
    - Planned Maintenance
    - Corrective Maintenance
    - UMS Checklist (22:00 – 23:00) – 1 hour

3. Do you spend more than that in case of problems? (If yes, what is the reason?)
4. What is the task or group of tasks on which you spend the most time in the ER during normal operating conditions?
    - Maintenance (Corrective & Planned)
        - Whole day (80%-90% of the day will be inside the ER to have maintenance)
            - Sometimes it's simple like cleaning filters – but they usually add another simple maintenance
            - But sometimes it's overhauling the engine
            - So every day has a different time for performing maintenance based on the components/task
        - Every day
            - Each day is a different component
            - Or continuation of maintenance from another day (Spread big maintenance over days)
        - Most frequent maintenance components
            - Filters
            - Injectors
            - Etc (see transcription)
5. What is the task or group of tasks on which you spend the most time in the ER during maintenance tasks?
6. Which typical activities are hard to predict in terms of how long they will actually take (unpredictability of duration)?
    - Corrective Maintenance
        - Outside prediction and schedule
            - In planned maintenance, you can plan like 2 years ahead of time
        - Spare parts availability related
        - When you do planned maintenance, you can find other failures that require corrective maintenance
        - Frequency based on maintenance type
            - Small Maintenance – frequent
            - Big Maintenance – not frequent
7. Which task gives you the highest probability of creating a leak?
    - Maintenance – e.g., Filter change/inspection
        - Reasons
            - If it doesn't close properly enough it will leak

        - The gasket is usually under pressure for a long time (so its shape changes), so when you remove and put it back, it might lead to leakage
    - Steps of maintenance
        - Prerequisite activity (as safety precaution to isolate the equipment) – important to ensure safety during the maintenance (especially for rotating or pressurized parts)
            - Controlled by: Safety Manuals (SMS)
            - System:
            - Lock out – lock the equipment so it's impossible to start it (keep the key in person)
            - Tag out – put the tag "do not start this equipment"
            - Test out – test it out afterwards (is it isolated or not?)
            - If mechanical – e.g., can it be opened or not
            - If electrical – e.g., is there still voltage or not?
    - Resources and control for maintenance
        - For high-risk maintenance – Work Permit
            - Connected to risk assessment
            - Documents need to be checked and signed by Chief Engineer and Captain
            - Check if you have proper precautions before starting your job
            - Example of works that need Work permit: High voltage activity, high places, enclosed space, hot works (welding)
            - ER related: Overhaul a pump
            - Permit working on a pressurized system
            - Permit on electrical
            - And in some cases: permit for lifting

8. How can you tell whether a leak has occurred?
    - In terms of corrective maintenance due to components failures, it can be seen from
        - Visual inspection
        - Indicator check inside ECR or local indicator at ER
9. Under what conditions is your presence inside the engine room still required even when a leak happens? What is the effect on ship safety?
    - No reasons to be still inside the ER – because the engine stops
    - Can be controlled in ECR
        - But there will be an issue after switching off
            - Lose water pressure
        - So many alternatives to keep the ship safe
            - Ship can still be drifting
            - In hazard area, you can have a tugboat next to you
    - There is a procedure for ship safety if there is too much CO_2 inside ER (Inside the document SMS [Safety Management System?])
        - Because a lot of ERs use CO_2 for fire extinguishers

FRAM Thinking Questions:

1. Monitoring
    - Trigger: Schedule

- Task that can be affected by monitoring output
  - Corrective maintenance (if there are any failures)
- To improve safety
  - The more you can read out remotely – is safe (more remote readings) – for any type of fuel
    - But beware of new hazards
      - Behavioral issue – less check to actual condition through visual check
      - The more you have remote, the less people will look at the equipment itself – because you are in the ECR reading it
      - It still needs to be checked whether the remote reading corresponds with what is actually there
      - It might lead to more corrective jobs because things are not fixed before it becomes worse
- Comments on Remote monitoring
  - Pros
    - Support monitoring in ER isolation due to failure (leakage, fire, etc.)
  - Cons
    - Not enough POV to substitute visual inspection (amount of camera is not feasible)
    - The resolution of CCTV is not detailed enough to detect small failure (sometimes you see small things that you don't see on the camera)
- How to detect gas leakage
  - Gas detection sensor
    - Specifically located in the high-probability location for the leakage
    - **IDEA:** Having a gas detection camera could help to understand the leakage conditions and locations, for taking action
      - Imagine there are several alarms activated, it might be harder to determine the location of the problem (pinpoint)
      - But it can be seen on the indicator, but still...
- Delay effect
  - Not negatively affecting the other task especially corrective maintenance
    - Because there are other methods to detect corrective maintenance (indicator, sensors), so it's not significant
    - There are alarm systems that indicate the potential failure before the system breaks down
    - There are also backup mechanisms for some of the components such as pumps
    - You cannot pinpoint the moment if something breaks down during the inspection, so it's quite unpredictable
    - You can also detect the failure gradually by looking at the conditions through the indicator

2. UMS Checklist
   - Trigger: Schedule
   - Task that can be affected by monitoring output

        - Corrective maintenance (if there are any failures)
    - To improve safety
        - The more remote activity is safe
            - But beware of new hazards
                - Behavioral issue – less check to actual condition through visual check
    - Resources
        - Only one person goes inside, therefore you enter the ”dead man alarm system”
            - Before entering the ER, inform the bridge
            - The timer will be on, with a duration of around 12 minutes
            - If it reaches 12 minutes, the engineer should press the button again to extend to another 12 minutes (reset the time)
            - If after 2 minutes they don’t push the button, the ship will be alarmed (general alarm to engineer and bridge)

3. Routine Inspection
    - Trigger: Schedule
    - Task that can be affected by monitoring output
        - Corrective maintenance (if there are any failures)
        - Indicator check on fuel consumption, if there is any unusual behavior – corrective maintenance
    - To improve safety
        - The more remote activity is safe
            - But beware of new hazards
                - Behavioral issue – less check to actual condition through visual check
    - If finding something – report to Chief engineer / 2nd engineer
    - Task:
        - Check every corner and equipment (globally)
        - Check for leakages
        - Check pressures and temperatures
            - In old engines, you have the local indicator
            - In most new engines, it’s mostly digital – ECR
        - Write down in the Logbook
4. Planned Maintenance
    - Trigger: Maintenance schedule
    - Controlled by: Maintenance Schedule, Manufacturer manual, Safety procedure (SOLAS – Safety of Life at Sea)
    - Task that can be affected by monitoring output
        - During planned maintenance, crew might find another failure – corrective maintenance
    - Effect of delay
        - Delayed maintenance means working day extended and any other activity such as inspection is postponed
        - The delay might impact ship operation

    - This activity is a priority compared to inspection because the longer the maintenance, the longer its impact on ship operations
  - What causes spending longer time
    - Wrong installments on previous maintenance
    - Spare parts availability (especially for corrective maintenance)
    - Sometimes they can find something wrong that leads to corrective maintenance
  - Any ways to reduce time spent in the ER while doing tasks
    - Comment on reducing frequency maintenance by enhancing components reliability
      - Can't heavily only rely on the manufacturer to increase components quality
      - Sometimes the maintenance occurs before the scheduled maintenance – quality of the components is not lasting until the designated maintenance period
      - Sometimes they postponed the maintenance (drydock) because the condition is not suitable
        - Deviation of engine running hours with expected dry-docking schedule
      - It's a complex thing because it could be affected by
        - Fuel quality
        - Operational
        - Who is doing the maintenance
        - Crew
        - Maker/supplier of the engine service company
        - Third-party company
        - Spare parts used (OEM or not)
    - But reliability can be improved through
      - Vibration monitoring and proximity sensors
        - It can assess the conditions
        - Lead to predictive maintenance (condition-based maintenance)
        - Predict when something goes wrong
        - See project PRIMA (Pre-MA)
  - Most frequent:
    - On DF Engine – Pilot fuel filters that change once per month
    - Injectors
    - Valve clearances
    - Camshaft
    - **CHECK THIS ON THE MAINTENANCE COMPONENT LIST EXCEL**
  - Scheduled or Corrective maintenance might take more time than expected
    - The inspection after that might be postponed
    - The working hour is extended
    - Finishing the maintenance is the priority – because it can have an operational impact

5. Corrective Maintenance
  - Trigger: If failure (or potential failure) is detected
    - Not only during scheduled inspections
    - Can be detected using vibration measurement or any other indicators

      - Fuel consumption or any other indicator that shows another component not working properly
    - Find something – it goes to corrective
      - In inspection
      - Monitoring
        - Remote
        - Locally
      - UMS
      - Planned maintenance
  - Frequency: Unpredictable
  - Time: Unpredictable
  - Task
    - Create the job order – plans for improving the system or correcting the fault inside the system
    - Scheduling it themselves

General Findings:

1. There are different layouts to enter the ER and ECR
    - First layout (normal)
        - Deck – ECR – ER
        - Pass ECR first before going inside ER
    - Second layout
        - Deck – ER – ECR
        - Pass the ER first before entering ECR

Interview 5

Position: Vessel Manager
Experience: 2nd-3rd Engineer in DF Engine Ship and Diesel Engine Ship, and Designing the Retrofit of Normal Gas to Dual Fuel Engine
Date of Interview: 6 June 2024
Location: AV Office Rotterdam

Scope of Interview:

1. Engine Change Mode
2. In-depth Onboard Maintenance

ENGINE CHANGE MODE

Findings – General Questions:

1. Does this diagram give you a complete picture of your activities? What is missing?
    - Either Wartsila or M&K, it's more or less the same.
        - Gas to diesel instantly because it is a backup mode (emergency).
        - If something goes wrong, you can directly go back from gas to diesel or by any triggered alarm which will shut off the gas engine → automatically change over to diesel.
    - Safety measures → a lot of alarms.
        - SOGA = Shut Off of Gas Engine (Gas to Diesel Auto)
            - Changing from gas mode to diesel directly without stopping → no need to interrupt your engine operation.
        - Put measurements and sensors for the gas engine for safety measures.
    - The pre-requisite comment.
        - Generalization of the engine load level:
            - In newer Wartsila engines → reduce the load to <80%.
            - In older M&K engines → load needs to be >25%.
            - It depends on the design and manufacturer.
            - Location: Remote → Bridge.
        - Gas leak test:
            - Automatic test every time you change the mode.
            - Self-test of the fuel supply line from GVU (gas valve unit) to the engine.
        - The 30 minutes wait after using HFO to LFO:
            - Because of the fouling by the HFO (High Fuel Oil).
            - But the vessel usually uses MGO (Marine Gas Oil) → so no need to run for a certain time before changing to gas.
        - Reset the engine:
            - To solve the alarm related to the gas system.
            - Nitrogen pressure.
                - Used to purge your gas out of the system (in case of the alarm).
                - Push off the remaining gas to the safety area.
                - To have Nitrogen pressure inside the buffer tank which is 1 bar higher than the actual gas pressure.
        - What if you missed the Pre-requisite task?

        - The automated system won't allow switching over to gas → safety measures.
            - All of the pre-requisitions are needed to be able to switch to gas.
            - If not met → it will fail → get an alarm → not able to switch to gas mode.
    - Location: All is remote → no need to be done near the engine.
        - Visual inspection on Pre-requisition:
            - No need officially → can be done remotely from indicator check.
            - But sometimes, engineers preferred to do a visual check → only a few minutes (not an hour job) → to make a quick check (to see everything is okay: no leaking).
        - Changing the mode:
            - Always remote = Engine Control Room (ECR).
            - LCP = used to start the engine only (locally).
                - To check it directly.
                - But only when it's running on diesel.
                - Because usually, the ship starts on diesel, then changes to gas.

2. How long do you spend doing tasks inside the ER for a day?
    - Depending on the load:
        - The higher the load → longer to change from diesel mode to gas mode (up to 5 minutes).
        - Due to deviation (gap) difference of gas load and diesel load.
        - Gas to diesel = instant.
3. Do you spend more than that in case of problems? (If yes, what is the reason?)
4. What is the task or group of tasks which you spend the most time on the ER during normal operating conditions?
5. What is the task or group of tasks which you spend the most time on the ER during maintenance tasks?
6. Which typical activities are hard to predict in terms of how long they will actually take (unpredictability of duration)?
7. Which task gives you the highest probability to create a leak?
    - Already have the gas leak test:
        - During the leak test, you already supply a little bit of gas to the engine without consuming it (only pressurizing the system).
        - Gas valves per cylinder are not opening yet → during this test you are already checking for leaks.
        - If there is a leak, your system stops → can't change to gas mode because you need to solve your leakage.
            - Leakage gas alarm system purges with nitrogen indicating you have a leakage.
8. How can you tell whether a leak has occurred?
9. At what conditions is your presence inside the engine room still required even when a leak happens? What is the effect on ship safety?

FRAM Thinking Questions

1. Changing to engine mode
    - Trigger:
        - Alarm system → automatically triggers the change from gas to diesel.
        - Human decision → by doing pre-requisite.
            - Based on pre-requisition acceptance.
            - Diesel mode → cool down the engine because the temperature is lower.
        - Ship operations phases:
            - Depart = around 25% → still in diesel.
            - Sailing = won't below 25% → change to gas.
        - Changing to gas mode = Critical operations:
            - Before changing to the shaft generator (put all of the consume power to the main engine).
            - Ensure the change happens before changing to the shaft generator.
            - Why?
                - Fluctuation in RPM.
                - Tweaking the engine and doing something with the engine.
            - Risk if putting all the reliability to the main engine? If something goes wrong:
                - Cargo compressor on deck fails.
                - Supply pressure broke down.
                - Blackout (electricity).
                - Unannounced risk.
            - Solution:
                - Before changing, we are in special operations → put safety by putting reliability on the auxiliary engine.
                - Do the changeover.
                - When the main engine (DF) is stable in gas mode, change all the power supply to the main engine.
            - Risk to crew inside ER?
                - The risk is more associated with the whole ship operations.
                - There is no risk associated with the crew (due to leakage).
                - Because of the safety measures of the double-walled pipe.
            - Who performs the whole changeover?
                - Chief engineer does the decision making for the changeover → responsible.
                - EoW will do the pre-requisite.
                - But it is a combination.
            - Resources:
                - No specific, just used the panels (flip the switch) in the ECR → remote.
            - Conclusions:
                - No need to be inside of the ER → all of it are automated.
                - Old ship → yes need to do something in ER.

            - New ship → remotely.

ONBOARD MAINTENANCE

Findings

1. DF also consists of a diesel engine, so the maintenance for diesel engines is also applied to DF engines.
2. Pre-requisite of the maintenance:
    - Ensuring the gas-free:
        - In the crankcase, there is usually a gas slip alongside the piston and goes to your crankcase.
        - So if you want to open the crankcase:
            - Purge the crankcase with the Nitrogen (so many minutes) = around 10 minutes.
            - Purge with air because crew need to go in (20 minutes) → so the Nitrogen is out.
            - Gas measurement devices to check the gas concentration in the crankcase → during the purging check the gas measurement (if 0% LEL then it is safe to go inside).
            - Open the crankcase and leave it open for = 30 minutes (due to temperature as well).
            - Then you can enter the crankcase.
        - If you open the gaseous part → make sure no gas inside.
            - Trigger the flushing of the engine.
                - Emergency procedure = system automatically due the flushing.
                - Manual flush.
                - Easier.
                - Location: depends on the manufacturer.
                - Usually in the engine room but not always located on the engine.
                - In M&K located in ECC (engine control cabinet) → inside the ER.
        - Frequency:
            - Based on the component.
            - Not performed daily.
            - Based on running hours.
            - Based on breakdown/failures → corrective maintenance.
        - Control:
            - Specific document manual by the manufacturer/maker.
        - Time:
            - Depending on the size of the engine → depends on the number of flushings to be sure the crankcase volume is fueled with nitrogen.
            - A small engine might take 10 minutes at the specific pressure → provided by the guidelines (control document).
            - There is a calculation based on the volume and engine maker specific.
            - Sometimes you just purge until the gas measurement shows a value below LEL.
        - Resources:
            - Treat it as an enclosed space → permit.

- Go to an enclosed space.
- Ventilation.
- Oxygen measurement.
- Treat it like a normal tank.

C

Probability of Fatality Calculation: Python Code

The Python script is developed by Rustam Abubakirov and modified by Author

Link of the Script Developer Profile:

https://www.tudelft.nl/staff/r.abubakirov/?cHash=fe3cb9052a35d029f17812e72ea194ca

The calculation of P_{fat} when gas sensor success to detect gas leakage

```python
import math
import numpy as np
import matplotlib.pyplot as plt
from google.colab import files

#Find the approximate volume space of engine room on Coral Star/Sticho
V = 19*14*4             #m3

#Changes of 30-air per hour
v = V*30/3600           #m3/s

C_0 = 0                #kg/m3

#The variable that changing to find summation of IRPA is only 'd' (hole diameter)
d =  23          #mm

#Change the rhog if want to analyze LNG or NH3
#rhog CH4 = 6.5435 kg/m^3 (at 10 bar)
#rhog NH3 = 6.9525 kg/m^3 (at 10 bar)
rhog = 6.5435    #kg/m3  you may use https://www.engineering-4e.com/ch4-physical-properties-
    calculator for LNG / https://www.engineering-4e.com/nh3-physical-properties-calculator
    for NH3

#Determine the bar gauge pressure of fuel on Coral Star/Sticho
P = 10           #barg

t_I = 60         #s
t_exp = 600      #s
A = -15.6        #mg/m3
B = 1            #DIM-LESS
n = 2            #DIM-LESS

def Q_S(t):
  Q_S0 = 0.00014*pow(d,2)*math.sqrt(rhog*P)
  Q_SI = 0
  if t >= t_I:
    Q_Sc = Q_SI
  else:
    Q_Sc = Q_S0
  return Q_Sc

def C_t(Q_source, t_current, t):
  C_factors = []
  pos = 0
  for j in Q_source:
    C_factors.append(j/V*np.exp(v/V*t_current[pos]))
    pos+=1
  C_INT = np.trapz(C_factors, t_current)
  C_tc = (C_0+C_INT)*np.exp(-1*v/V*t)
  return C_tc

t_array = np.linspace(0,t_exp,t_exp+1)

t_current = []
Q_source = []
C_inside = []
P_fatality = []

for t in t_array:
  t_current.append(t)
  Q_source.append(Q_S(t))
  C_inside.append(C_t(Q_source,t_current,t))

```

```
  C_tcn = []
  for j in C_inside:
    C_tcn.append((j*1000000)**n)
  t_min = []
  for k in t_current:
    t_min.append(k/60)
  D_tc = np.trapz(C_tcn, t_min)
  Pr = A+B*np.log(D_tc)
  P_fc = 0.5*(1+math.erf((Pr-5)/np.sqrt(2)))
  P_fatality.append(P_fc)

C_mgm3 = [x*1000000 for x in C_inside]
C_ppm = [x*22.4/17.03 for x in C_mgm3]

fig, axs= plt.subplots(nrows=2, ncols=1,figsize=(10,7), facecolor="1")
plt.style.use('classic')
axs[0].grid(color='lightgrey', linestyle='-', linewidth=0.5, zorder=1)
axs[1].grid(color='lightgrey', linestyle='-', linewidth=0.5, zorder=1)
axs[0].plot(t_array, Q_source, c='k', linewidth=1)
axs[1].plot(t_array, C_ppm, c='k', linewidth=1)
plt.setp(axs[0], xlabel='Time,␣s', ylabel='Source␣outflow␣rate,␣kg/s')
plt.setp(axs[1], xlabel='Time,␣s', ylabel='Concentration␣inside,␣ppm')
plt.subplots_adjust(hspace = 0.25)
plt.savefig('ScenarioN.png')
plt.show()

print('\nNH3␣P_fat_succ:', float('%.3f' % P_fatality[t_exp]))
print('CH4␣max␣C␣above␣LFL:', "yes" if max(C_ppm) >= 50000 else "no")
```

The calculation of P_{fat} when gas sensor fails to detect gas leakage

```
t_I = 600          #s
t_exp = 600       #s
A = -15.6         #mg/m3
B = 1             #DIM-LESS
n = 2             #DIM-LESS

def Q_S(t):
  Q_S0 = 0.00014*pow(d,2)*math.sqrt(rhog*P)
  Q_SI = 0
  if t >= t_I:
    Q_Sc = Q_SI
  else:
    Q_Sc = Q_S0
  return Q_Sc

def C_t(Q_source, t_current, t):
  C_factors = []
  pos = 0
  for j in Q_source:
    C_factors.append(j/V*np.exp(v/V*t_current[pos]))
    pos+=1
  C_INT = np.trapz(C_factors, t_current)
  C_tc = (C_0+C_INT)*np.exp(-1*v/V*t)
  return C_tc

t_array = np.linspace(0,t_exp,t_exp+1)

t_current = []
Q_source = []
C_inside = []
P_fatality_fail = []

for t in t_array:
  t_current.append(t)
  Q_source.append(Q_S(t))
  C_inside.append(C_t(Q_source,t_current,t))

  C_tcn = []
  for j in C_inside:
    C_tcn.append((j*1000000)**n)
```

```
  t_min = []
  for k in t_current:
    t_min.append(k/60)
  D_tc = np.trapz(C_tcn, t_min)
  Pr = A+B*np.log(D_tc)
  P_fc = 0.5*(1+math.erf((Pr-5)/np.sqrt(2)))
  P_fatality_fail.append(P_fc)

C_mgm3 = [x*1000000 for x in C_inside]
C_ppm = [x*22.4/17.03 for x in C_mgm3]

fig, axs= plt.subplots(nrows=2, ncols=1,figsize=(10,7), facecolor="1")
plt.style.use('classic')
axs[0].grid(color='lightgrey', linestyle='-', linewidth=0.5, zorder=1)
axs[1].grid(color='lightgrey', linestyle='-', linewidth=0.5, zorder=1)
axs[0].plot(t_array, Q_source, c='k', linewidth=1)
axs[1].plot(t_array, C_ppm, c='k', linewidth=1)
plt.setp(axs[0], xlabel='Time,␣s', ylabel='Source␣outflow␣rate,␣kg/s')
plt.setp(axs[1], xlabel='Time,␣s', ylabel='Concentration␣inside,␣ppm')
plt.subplots_adjust(hspace = 0.25)
plt.savefig('ScenarioN.png')
plt.show()

print('\nNH3␣P_fat_fail:', float('%.3f' % P_fatality_fail[t_exp]))
print('CH4␣max␣C␣above␣LFL:', "yes" if max(C_ppm) >= 50000 else "no")
```

The calculation of the average of P_{fat}

```
P_gd = 0.01
P_fatsuc = 0
P_fatfail = 1

P_fat_avg = P_fatfail * P_gd + P_fatsuc * (1 - P_gd)
P_fat_avg
```

D

Python Result: Leak Outflow Rate and Concetration Level

D.1. The P_{fat} result of CH4

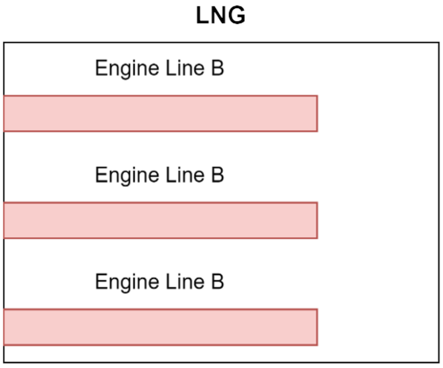

Figure D.1: The Engine room layout for CH4 engine room

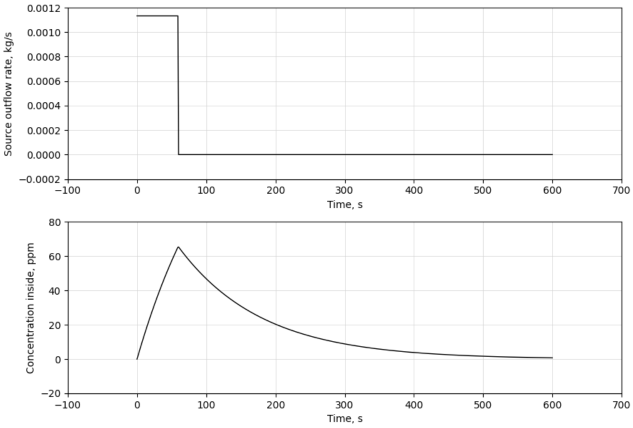

Figure D.2: The graph of the leak outflow rate (top) and concentration level (bottom) of CH4 at leak diameter 1 mm

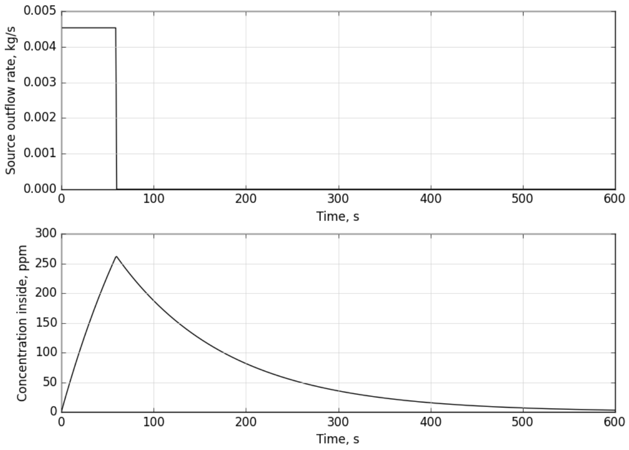

Figure D.3: The graph of the leak outflow rate (top) and concentration level (bottom) of CH4 at leak diameter 2 mm

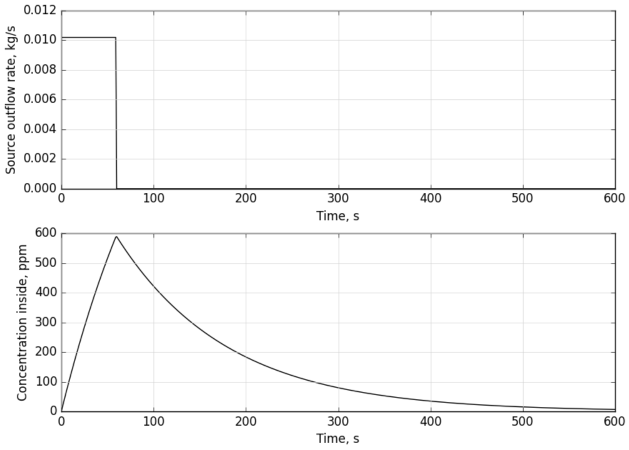

Figure D.4: The graph of the leak outflow rate (top) and concentration level (bottom) of CH4 at leak diameter 3 mm

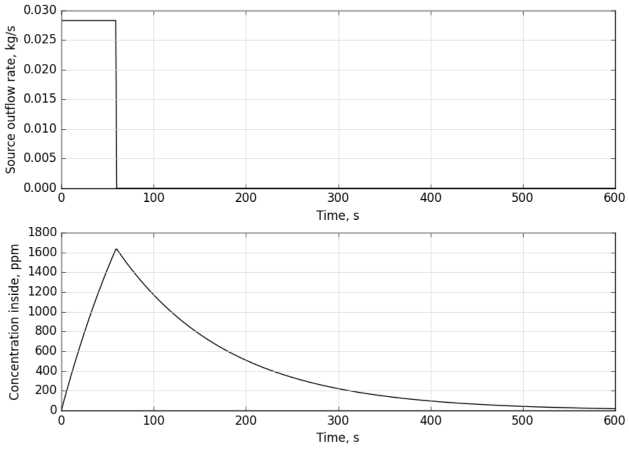

Figure D.5: The graph of the leak outflow rate (top) and concentration level (bottom) of CH4 at leak diameter 5 mm

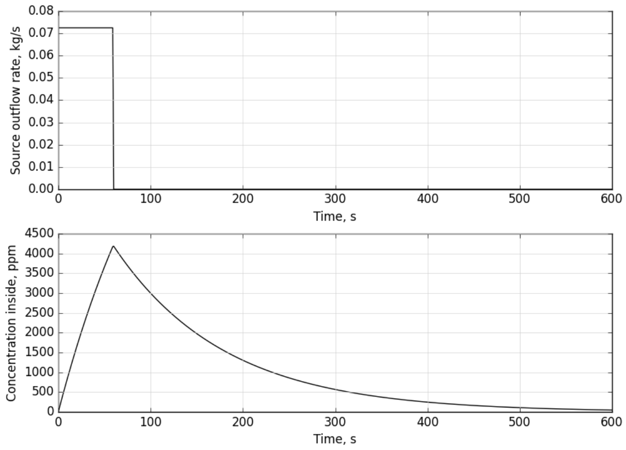

Figure D.6: The graph of the leak outflow rate (top) and concentration level (bottom) of CH4 at leak diameter 8 mm

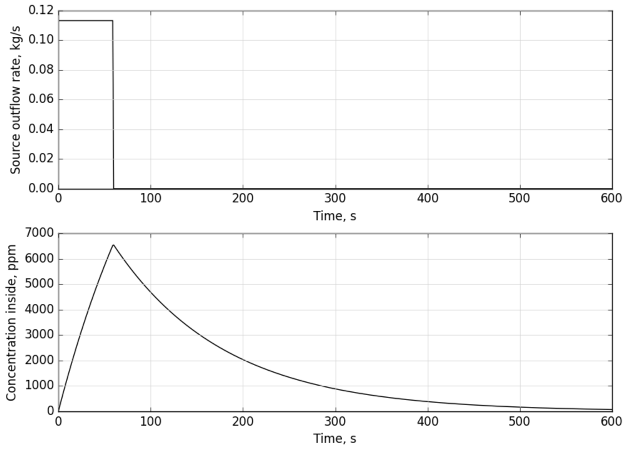

Figure D.7: The graph of the leak outflow rate (top) and concentration level (bottom) of CH4 at leak diameter 10 mm

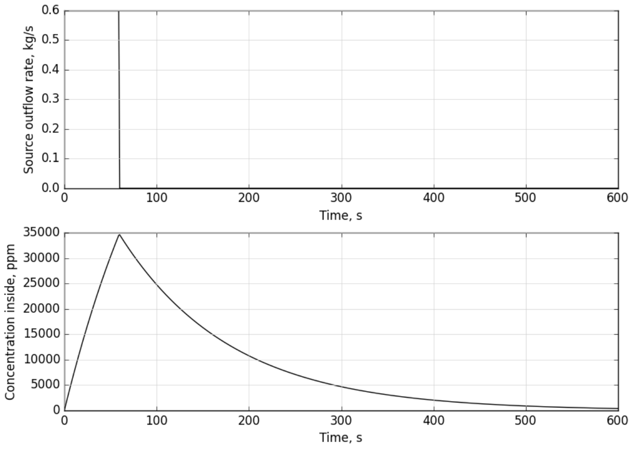

Figure D.8: The graph of the leak outflow rate (top) and concentration level (bottom) of CH4 at leak diameter 23 mm

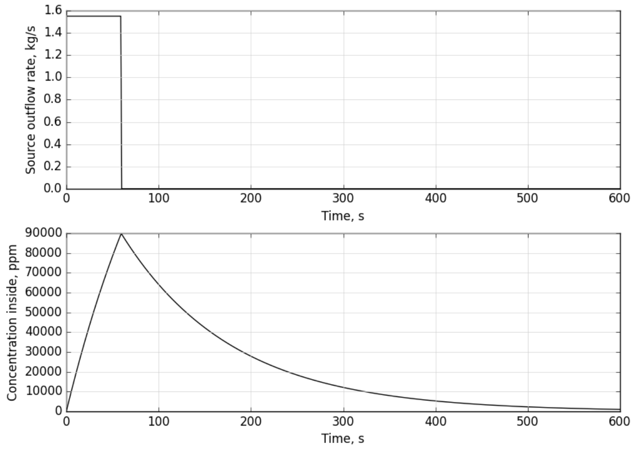

Figure D.9: The graph of the leak outflow rate (top) and concentration level (bottom) of CH4 at leak diameter 37 mm

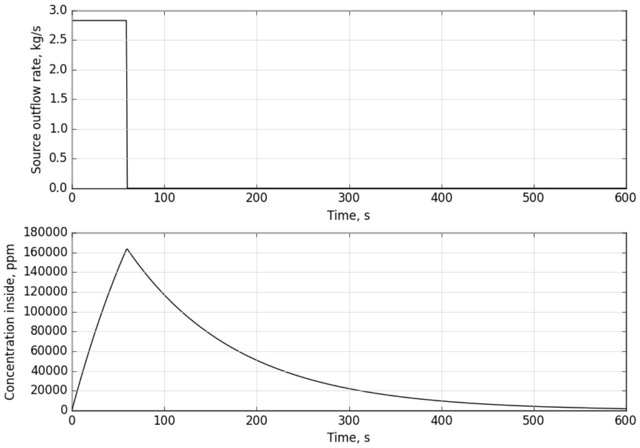

Figure D.10: The graph of the leak outflow rate (top) and concentration level (bottom) of CH4 at leak diameter 50 mm

D.2. The P_{fat} result of NH3 for Scenario 1

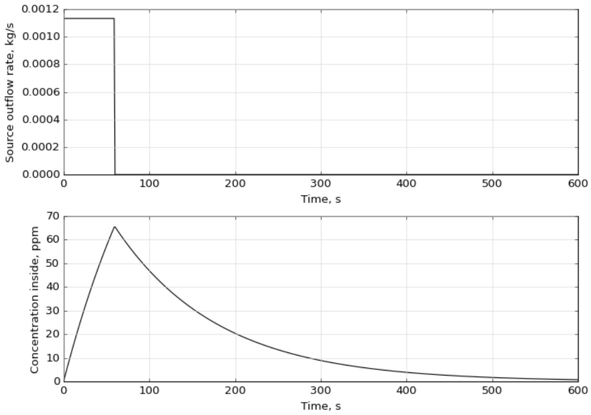

Figure D.11: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 1 mm when the gas sensor success detect the leakage

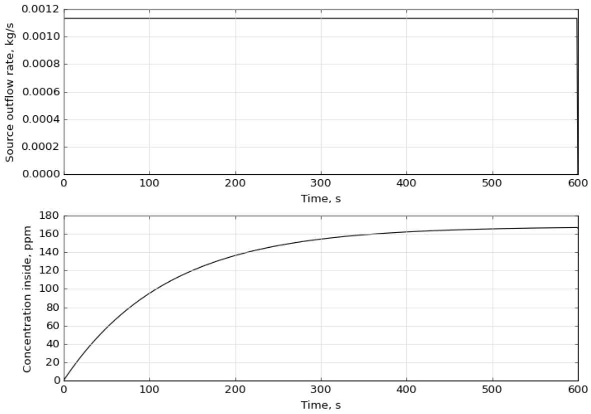

Figure D.12: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 1 mm when the gas sensor fails detect the leakage

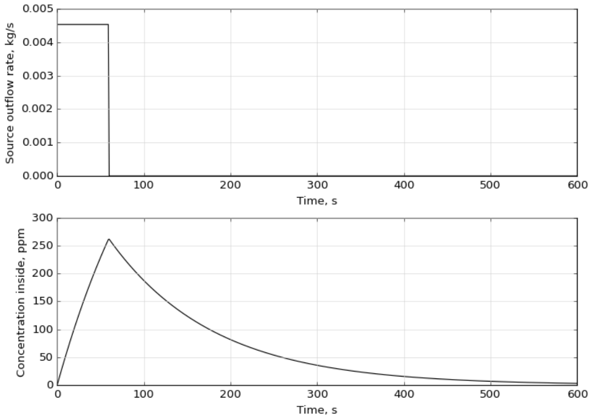

Figure D.13: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 2 mm when the gas sensor success detect the leakage

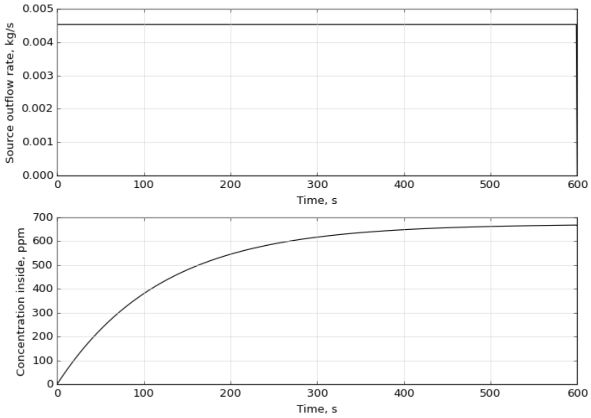

Figure D.14: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 2 mm when the gas sensor fails detect the leakage

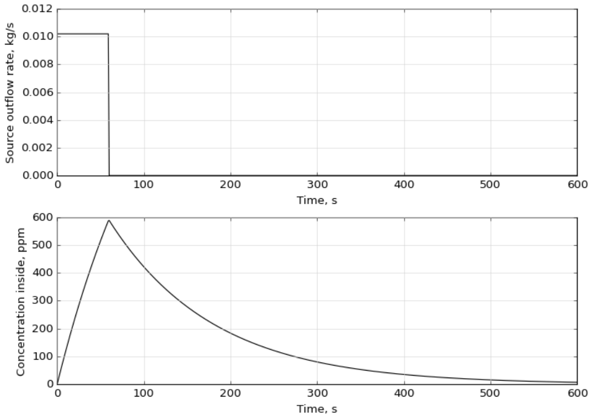

Figure D.15: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 3 mm when the gas sensor success detect the leakage

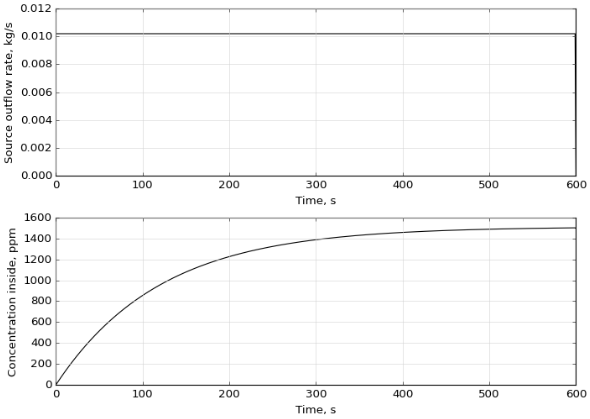

Figure D.16: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 3 mm when the gas sensor fails detect the leakage

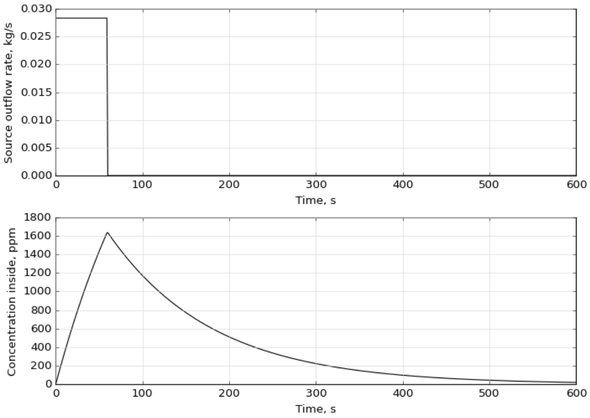

Figure D.17: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 5 mm when the gas sensor success detect the leakage

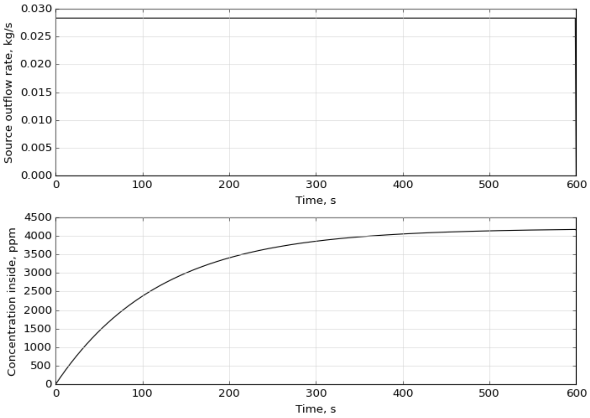

Figure D.18: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 5 mm when the gas sensor fails detect the leakage

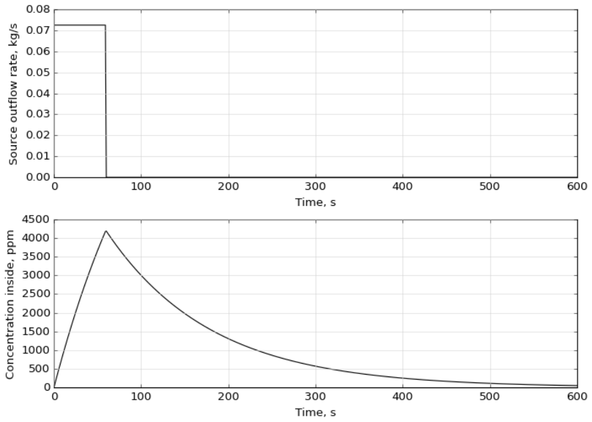

Figure D.19: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 8 mm when the gas sensor success detect the leakage

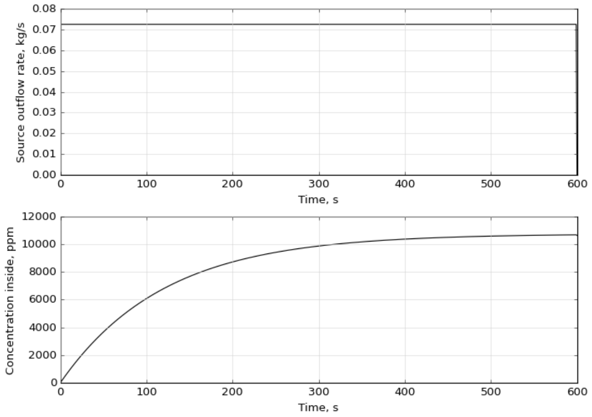

Figure D.20: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 8 mm when the gas sensor fails detect the leakage

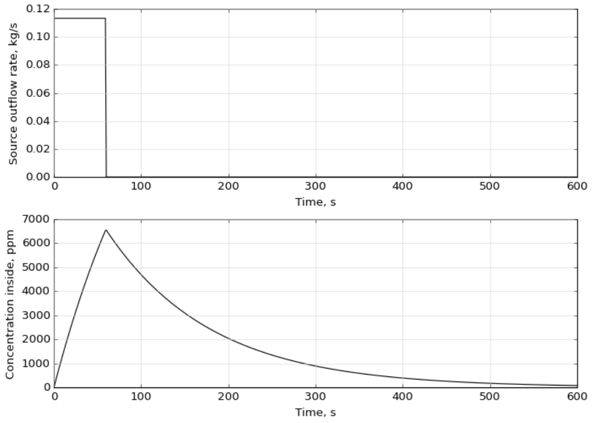

Figure D.21: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 10 mm when the gas sensor success detect the leakage

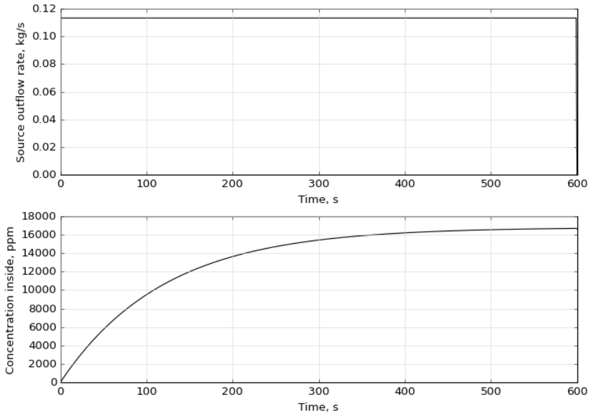

Figure D.22: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 10 mm when the gas sensor fails detect the leakage

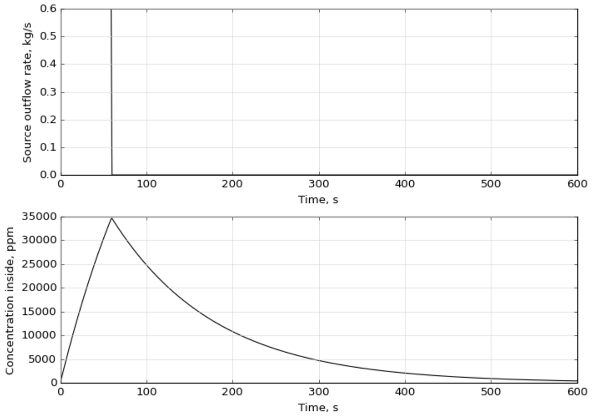

Figure D.23: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 23 mm when the gas sensor success detect the leakage

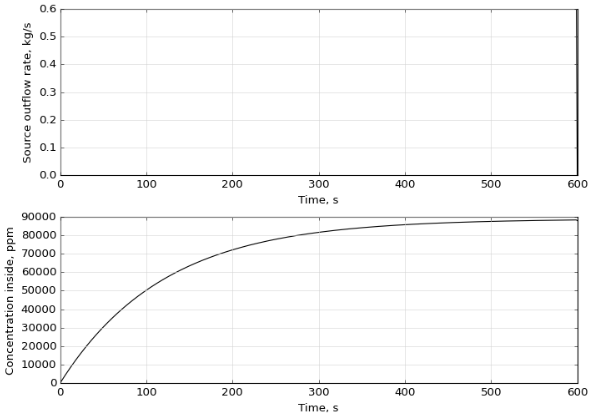

Figure D.24: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 23 mm when the gas sensor fails detect the leakage

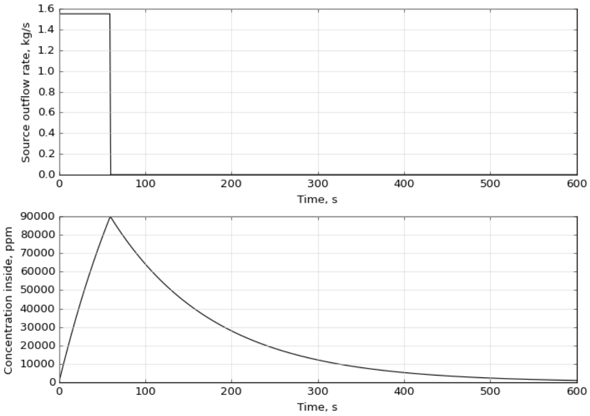

Figure D.25: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 37 mm when the gas sensor success detect the leakage

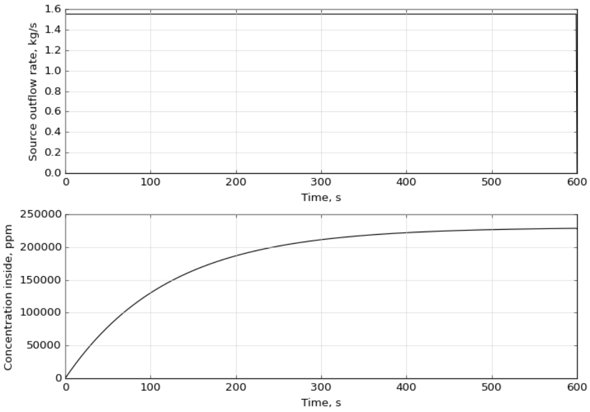

Figure D.26: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 37 mm when the gas sensor fails detect the leakage

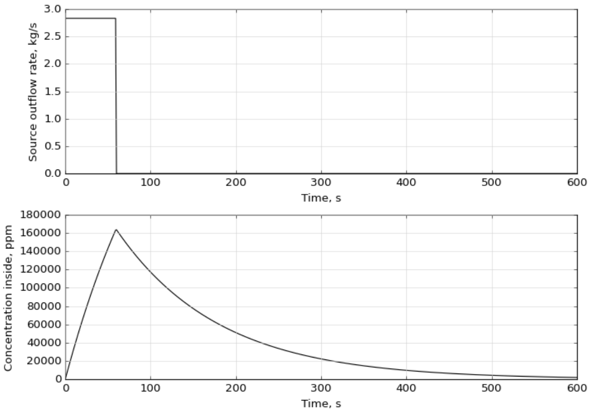

Figure D.27: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 50 mm when the gas sensor success detect the leakage

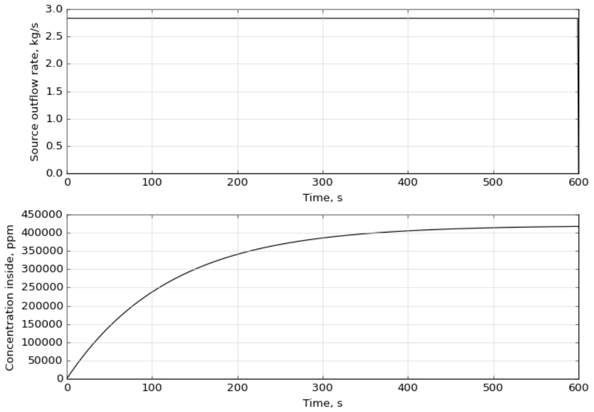

Figure D.28: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 50 mm when the gas sensor fails detect the leakage

D.3. The P_{fat} result of NH3 for Scenario 2

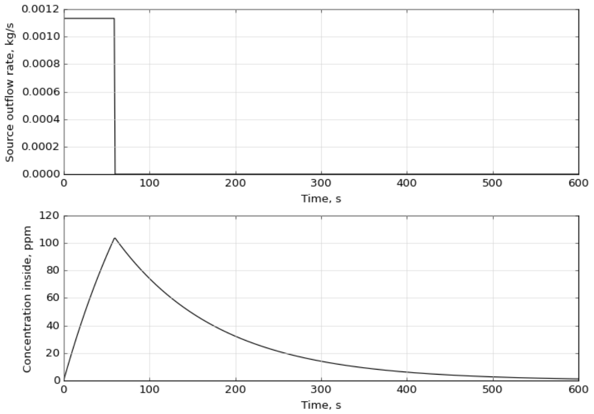

Figure D.29: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 1 mm when the gas sensor success detect the leakage

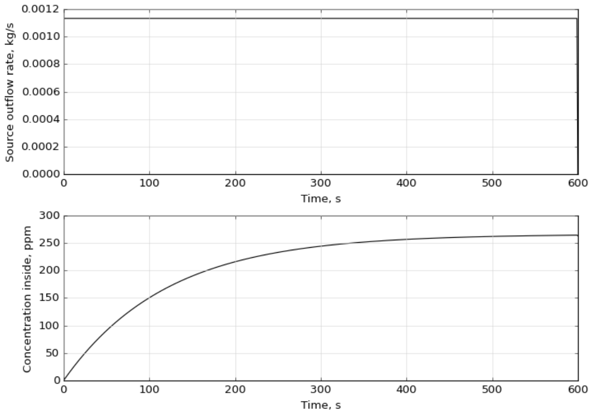

Figure D.30: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 1 mm when the gas sensor fails detect the leakage

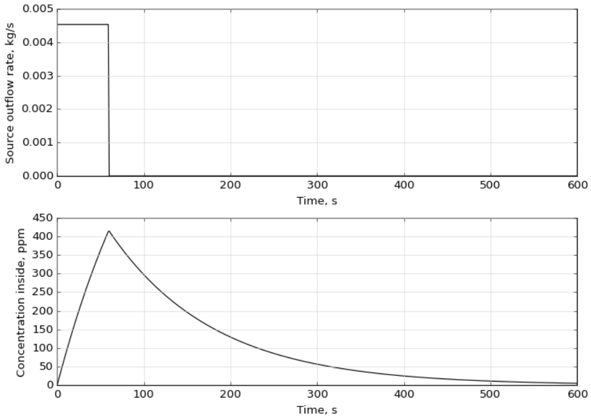

Figure D.31: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 2 mm when the gas sensor success detect the leakage

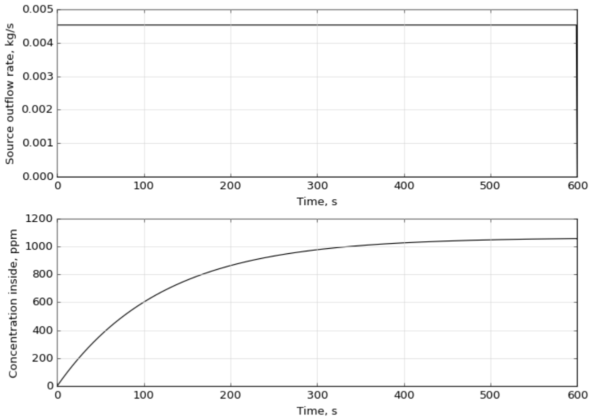

Figure D.32: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 2 mm when the gas sensor fails detect the leakage

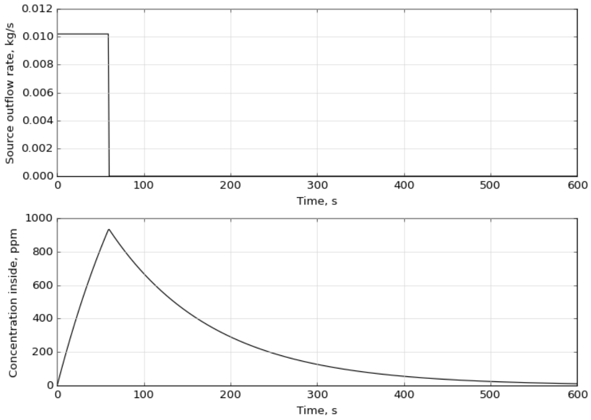

Figure D.33: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 3 mm when the gas sensor success detect the leakage

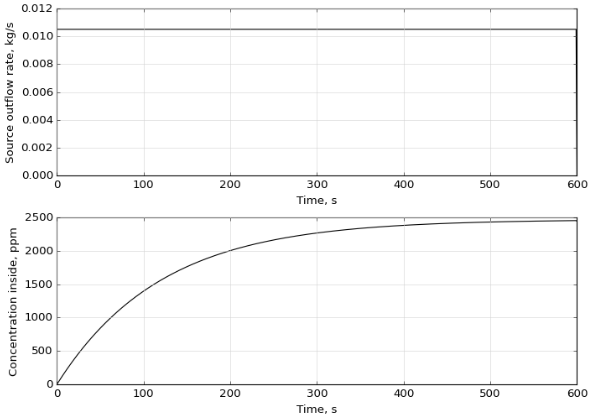

Figure D.34: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 3 mm when the gas sensor fails detect the leakage

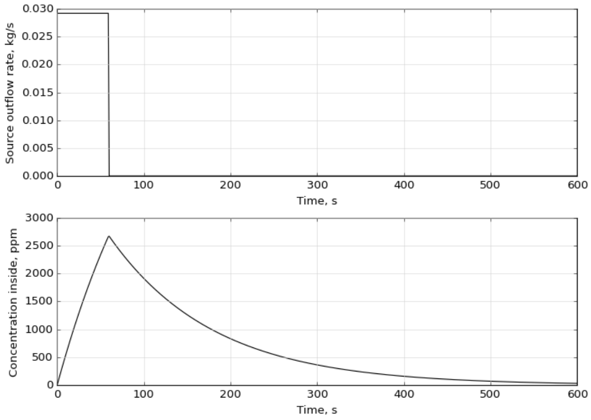

Figure D.35: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 5 mm when the gas sensor success detect the leakage

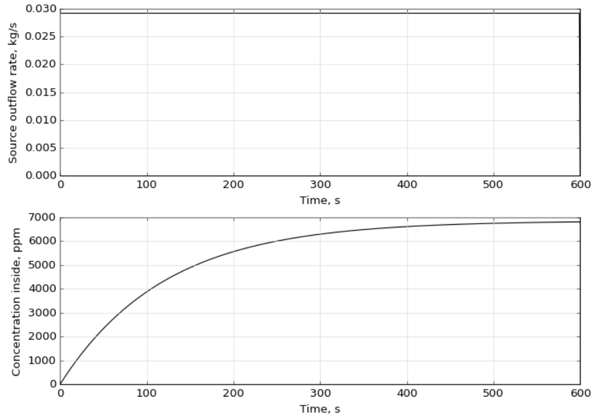

Figure D.36: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 5 mm when the gas sensor fails detect the leakage

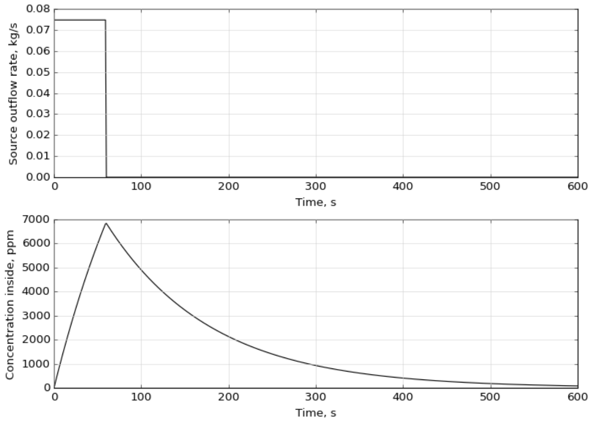

Figure D.37: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 8 mm when the gas sensor success detect the leakage

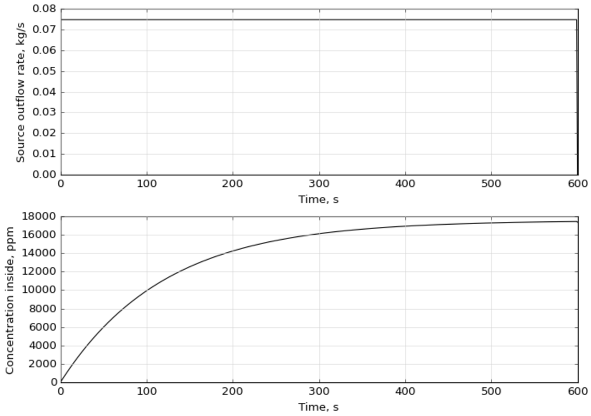

Figure D.38: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 8 mm when the gas sensor fails detect the leakage

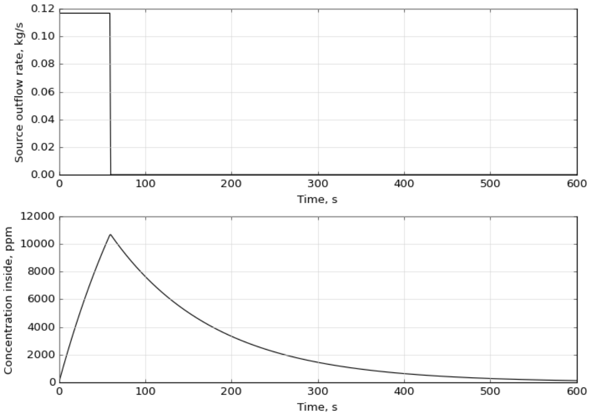

Figure D.39: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 10 mm when the gas sensor success detect the leakage

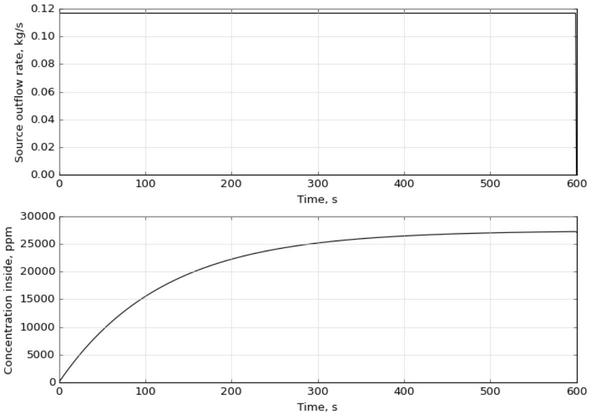

Figure D.40: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 10 mm when the gas sensor fails detect the leakage

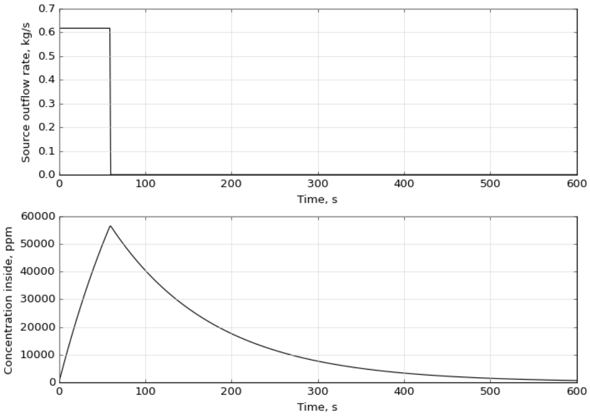

Figure D.41: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 23 mm when the gas sensor success detect the leakage

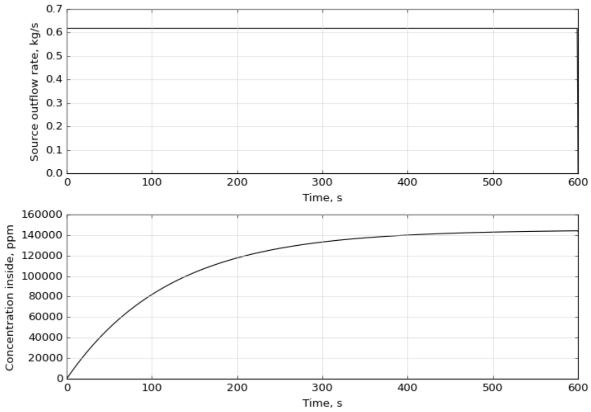

Figure D.42: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 23 mm when the gas sensor fails detect the leakage

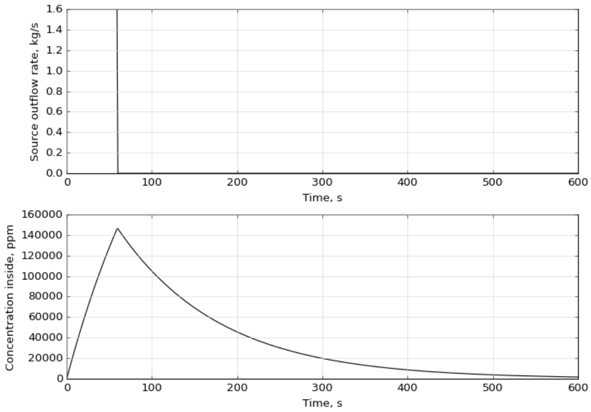

Figure D.43: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 37 mm when the gas sensor success detect the leakage

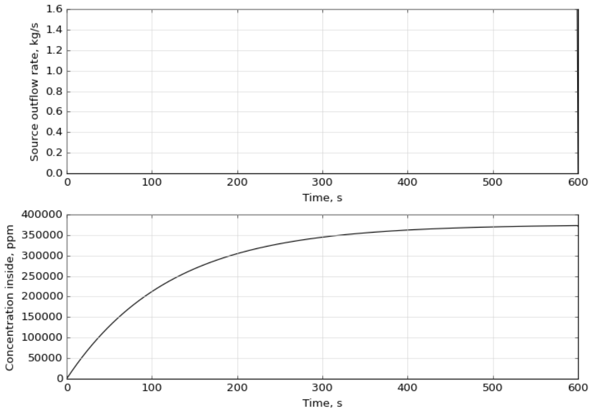

Figure D.44: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 37 mm when the gas sensor fails detect the leakage

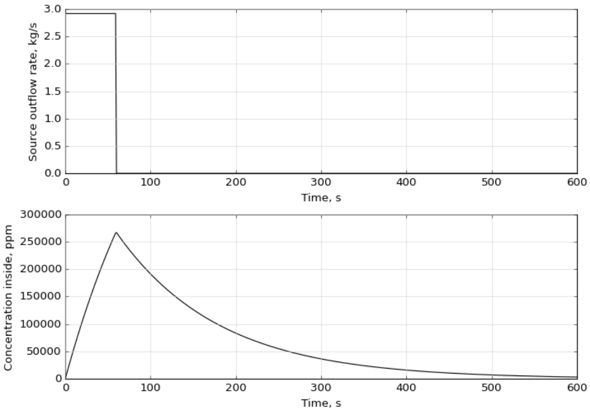

Figure D.45: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 50 mm when the gas sensor success detect the leakage

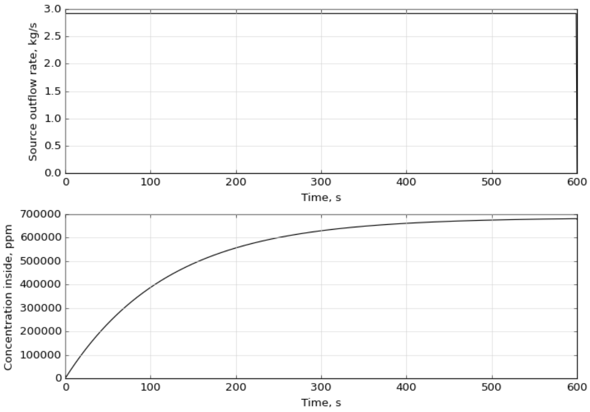

Figure D.46: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 50 mm when the gas sensor fails detect the leakage

D.4. The P_{fat} result of NH3 for Scenario 3

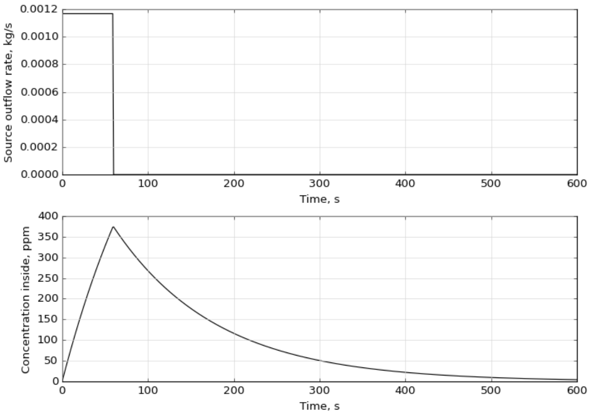

Figure D.47: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 1 mm when the gas sensor success detect the leakage

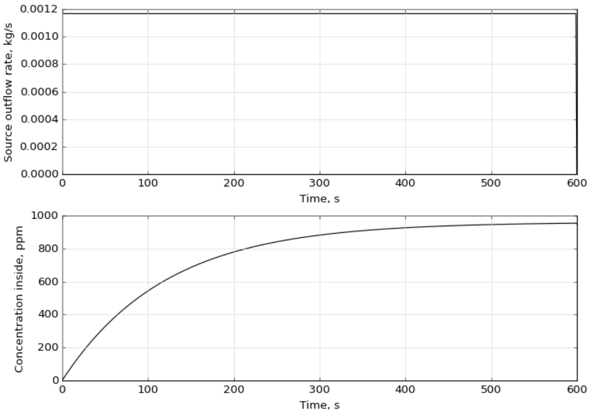

Figure D.48: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 1 mm when the gas sensor fails detect the leakage

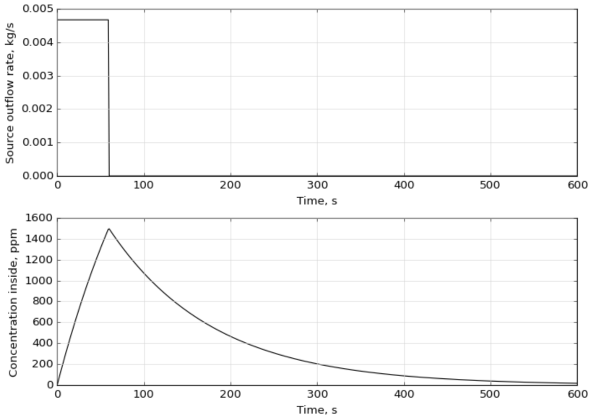

Figure D.49: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 2 mm when the gas sensor success detect the leakage

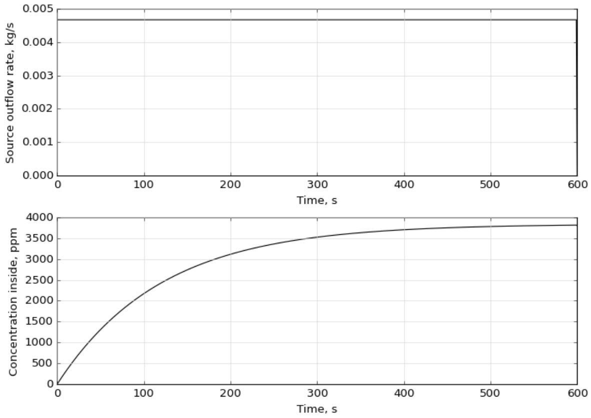

Figure D.50: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 2 mm when the gas sensor fails detect the leakage

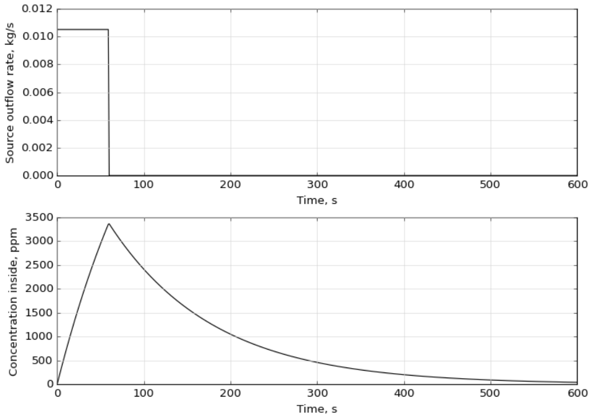

Figure D.51: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 3 mm when the gas sensor success detect the leakage

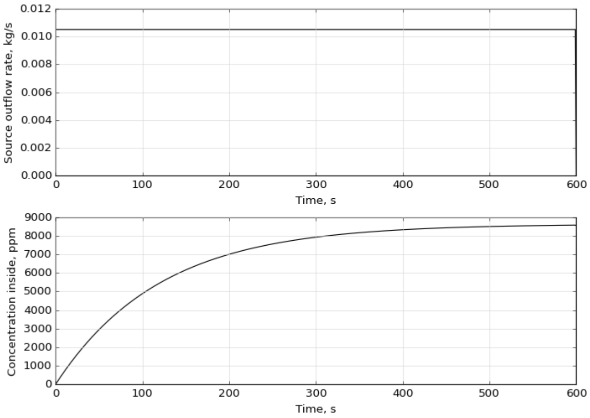

Figure D.52: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 3 mm when the gas sensor fails detect the leakage

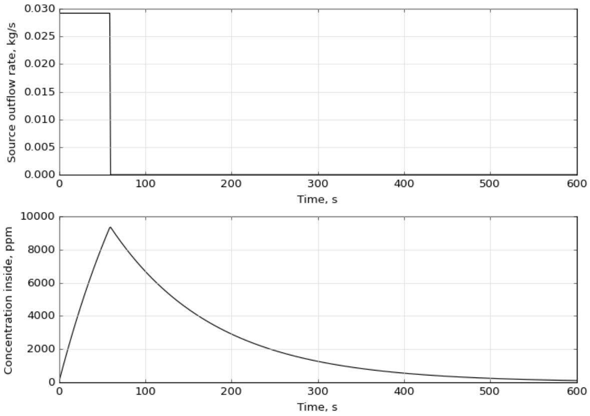

Figure D.53: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 5 mm when the gas sensor success detect the leakage

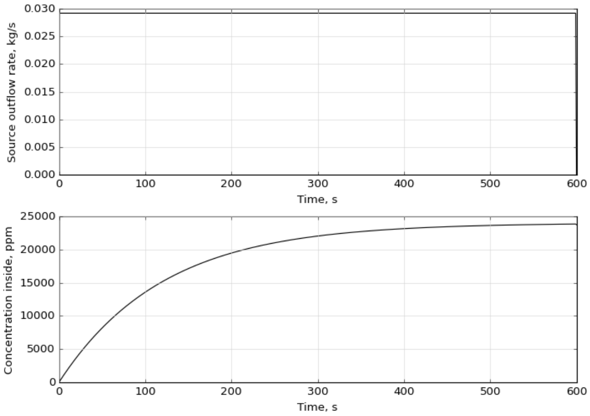

Figure D.54: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 5 mm when the gas sensor fails detect the leakage

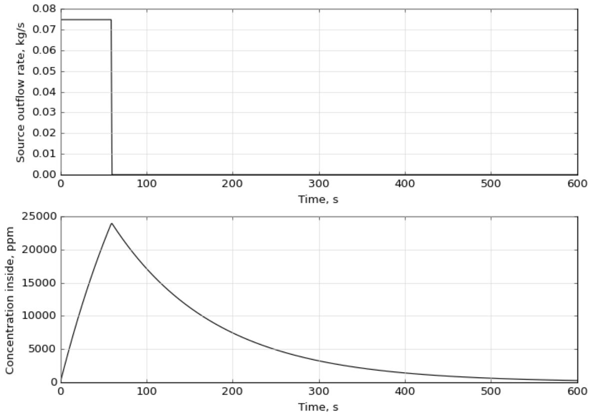

Figure D.55: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 8 mm when the gas sensor success detect the leakage

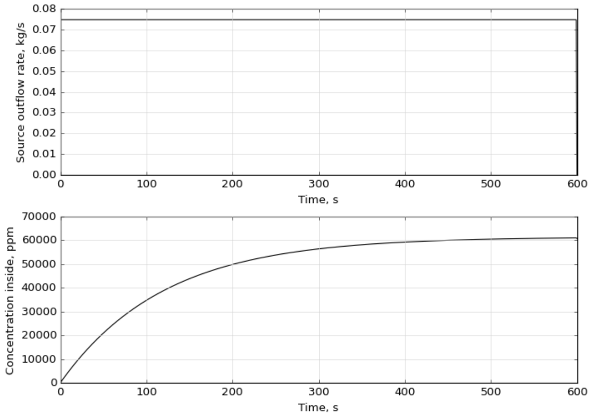

Figure D.56: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 8 mm when the gas sensor fails detect the leakage

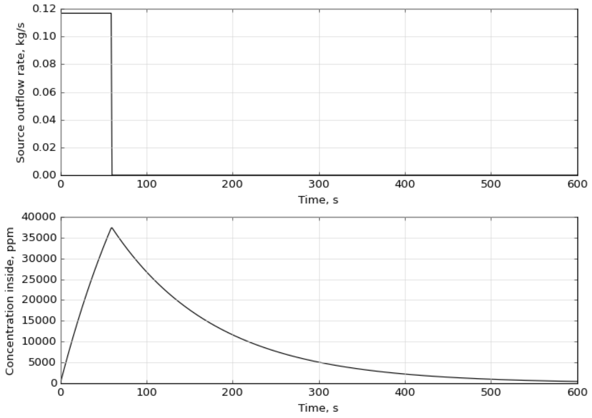

Figure D.57: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 10 mm when the gas sensor success detect the leakage

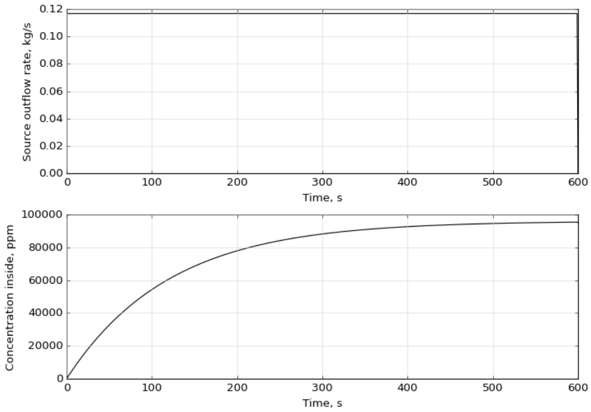

Figure D.58: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 10 mm when the gas sensor fails detect the leakage

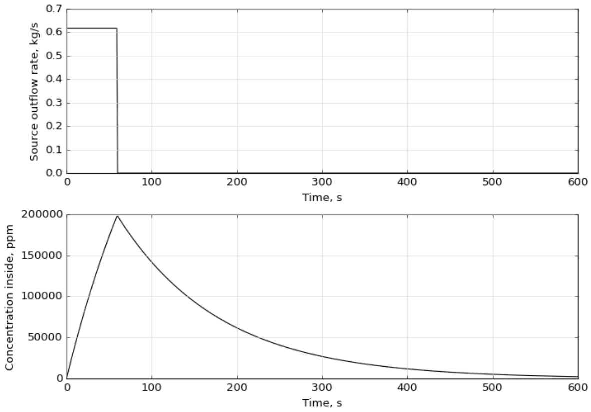

Figure D.59: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 23 mm when the gas sensor success detect the leakage

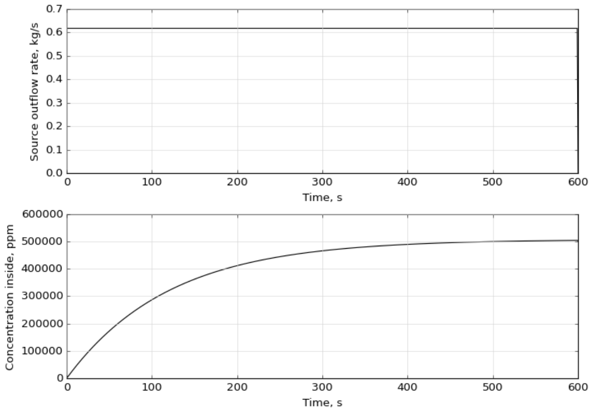

Figure D.60: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 23 mm when the gas sensor fails detect the leakage

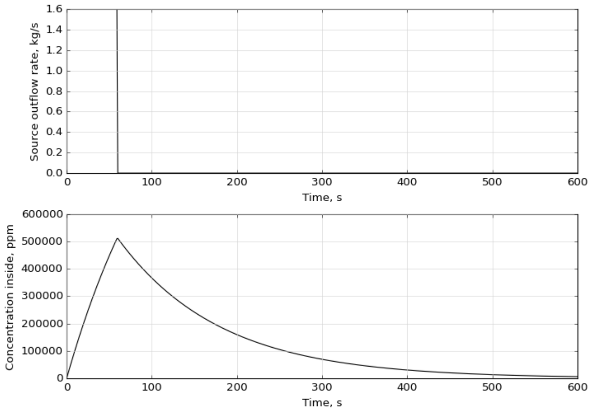

Figure D.61: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 37 mm when the gas sensor success detect the leakage

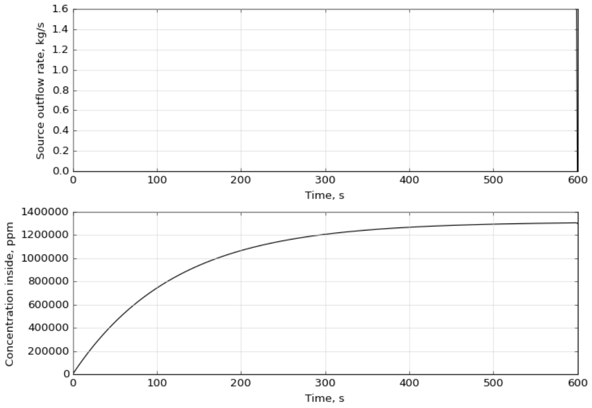

Figure D.62: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 37 mm when the gas sensor fails detect the leakage

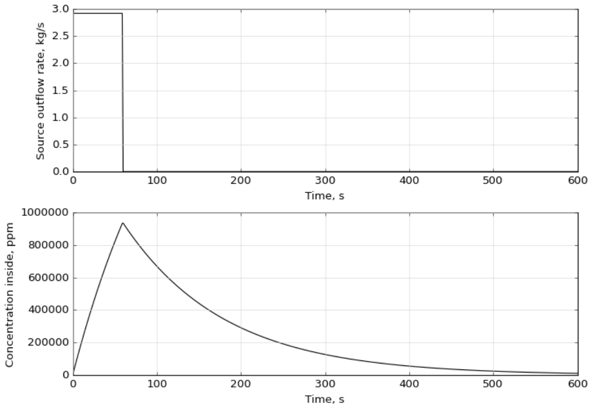

Figure D.63: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 50 mm when the gas sensor success detect the leakage

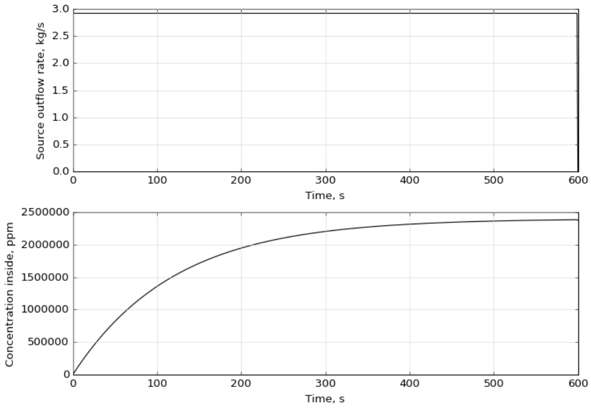

Figure D.64: The graph of the leak outflow rate (top) and concentration level (bottom) of NH3 at leak diameter 50 mm when the gas sensor fails detect the leakage