

University of Strathclyde

Department of Naval Architecture, Ocean, and Marine Engineering

**An Integrated Qualitative-
Quantitative Risk Assessment
Framework for the Determination of
Safety and Hazardous Zones on
Hydrogen-Fuelled Ships**

by

Insik Hwang

A thesis presented in fulfilment of the requirements for the degree
of Doctor of Philosophy

September

2026

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.50. Due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.

To my parents, Hongnam Hwang & Sunim Park

To my brother, Hyeon Pil Hwang

To my love, Yoongeun Kwon

ABSTRACT

The maritime industry is undergoing a transition towards decarbonisation, driven by the International Maritime Organization's net-zero emissions target. Among the candidate zero-carbon fuels, hydrogen has emerged as one of the most strategically significant, with ammonia receiving complementary attention as a hydrogen carrier suitable for onboard energy conversion. However, the practical deployment of hydrogen as a marine fuel remains constrained by unresolved safety challenges. Current regulations, most notably the IGF Code, prescribe distances for the placement of fuel system components but do not define the spatial extent of the safety and hazardous zones that bound the consequences of an accidental release. Although the principles of integrated and probabilistic risk assessment are well established in the offshore oil and gas industry, existing maritime studies have applied qualitative and quantitative methods in isolation, relied on deterministic worst-case assumptions, and treated environmental and operational parameters as fixed inputs.

This thesis addresses these gaps by developing a structured and integrated qualitative–quantitative risk assessment framework that adapts established risk assessment principles to the determination of safety and hazardous zones on hydrogen-fuelled ships. The framework comprises five phases, namely scenario and system definition, qualitative hazard identification and risk screening, quantitative risk assessment, risk integration, and general observations. Its originality lies in the structured procedural integration of these phases, through an explicit linkage between the qualitative and quantitative stages, a formal parametric scenario analysis sub-phase, a direct link between integrated risk results and the spatial determination of zones, and comparative risk profiling across fuel types under standardised conditions.

The framework is applied through two case studies. The first provides an overall demonstration of the framework for bunkering operations at the Port of Hamburg, establishing safety zones for liquefied natural gas (LNG), liquid ammonia (LNH₃), liquefied hydrogen (LH₂), and compressed gaseous hydrogen (GH₂) across three

bunkering methods and 76 parametric scenarios through the Population-Independent and Population-Dependent Analysis (PIDA-PDA) integrated parametric approach. Ammonia produced the largest safety zones, with an outer zone boundary of approximately 601 m under default conditions extending to approximately 924 m at the largest leaked fuel quantity, whereas liquefied hydrogen produced the smallest. The parameters governing the zones differed between fuels, and compressed hydrogen, despite its intermediate zone extent, presented the highest societal risk, indicating that a safety zone alone is insufficient to achieve tolerable risk for compressed hydrogen bunkering at the scale modelled.

The second case study provides an in-depth application of selected components of the framework to an onboard ammonia cracking system on an 18 m hydrogen fuel cell ferry. HAZID identified five release points, which were analysed through 75 transient CFD simulations using FLACS and STAR-CCM+ and evaluated probabilistically against a frequency criterion of 10^{-4} per year. The resulting toxic zones of approximately 7 m for the ammonia tank connection and 5 m for the cracking system, with no separate zone required at the remaining release points, replaced deterministic distances of several times the vessel length. The risk-informed zone confirmed the prescriptive requirement where the risk justified it and reduced it where it did not, and the zone definitions formed part of the basis on which approval of the vessel was obtained from the Korean Register.

The research establishes that risk-informed zones are both more practical and more discriminating than uniform prescriptive distances, and that zone determination must be accompanied by an explicit evaluation of risk tolerability. The framework provides ship designers, port authorities, classification societies, and regulatory bodies with a structured and transparent route for determining and demonstrating the adequacy of safety and hazardous zones, and its outputs offer technical input to the development of performance-based safety requirements for hydrogen-fuelled ships.

ACKNOWLEDGEMENTS

The completion of this PhD thesis marks the culmination of a long and challenging journey, one that would not have been possible without the guidance, support, and kindness of many individuals.

First and foremost, I would like to express my deepest gratitude to Dr. Byongug Jeong. He served as a compass for my research, providing clear direction and insightful discussions that shaped the very foundation of this work. His unwavering encouragement and support were the catalysts that allowed me to begin this journey. Whenever I felt lost during these three years, his mentorship helped me find my way back, making this research more successful and meaningful. Beyond academia, I am profoundly grateful to Dr. Jeong and his family for their warm hospitality and care. Their kindness made my life in Glasgow feel like a home away from home. Without it, my time here would have been far more difficult.

I am also deeply indebted to Professor Peilin Zhou for providing me with the invaluable opportunity to participate in various Horizon projects at the University of Strathclyde. These projects were a turning point in my professional development, allowing me to transition from a student into an independent researcher. I am truly grateful for his guidance, consideration, and, above all, his fairness throughout the process. Collaborative work within these projects significantly enhanced my ability to work in international teams and cooperate with global partners.

It has been a great privilege to study and work alongside my colleagues at NAOME. While I cannot mention everyone by name, I wish to express my sincere respect and gratitude for the support and camaraderie they have shown me.

My heart goes out to my family in Korea, whose steadfast support of my choices has been my greatest strength. I owe everything to my parents, Hongnam Hwang and Sunim Park, and my brother, Hyeonpil Hwang. Their solid support from afar gave me the resilience to persevere and complete this journey without ever giving up.

I would also like to express my deepest love and gratitude to Yoongeun Kwon. Her constant support and warm encouragement were the pillars that kept me steady through the many challenges I faced.

To those whose names are not explicitly mentioned here but who contributed to making my PhD years the happiest time of my life, I offer my sincere thanks. Your love and support are woven into the fabric of this achievement, and I could not have reached this milestone without you.

Finally, I wish to acknowledge that the ideas described in this thesis are not entirely my own. I am merely a practitioner applying the magnificent works of the great scholars who preceded me over the centuries to the maritime field. It is my sincere hope that this thesis serves as a bridge, passing on my knowledge and passion to new readers and future PhD candidates.

PUBLICATIONS

Journals

- **Hwang, I.**, Jeong, B., Jang, H., Kim, D. & Jee, J. (2025). An integrated qualitative–quantitative risk assessment for defining toxic and hazardous zones on hydrogen-fuelled ships with ammonia cracking systems. *Ocean Engineering*. 341, Part 1, 122475.
<https://doi.org/10.1016/j.oceaneng.2025.122475>
- **Hwang, I.**, Park, C. & Jeong, B. (2023). Life cycle cost analysis for Scotland short sea ferries. *Journal of Marine Science and Engineering*. 11, 2, 25, 424. <https://doi.org/10.3390/jmse11020424>
- **Hwang, I.**, Jeong, B., Zhou P., Wang, H., (2025), A PIDA-PDA Integrated Parametric Approach for Establishing Safety Zone for Hydrogen, Ammonia and LNG Bunkering Operations, *International Journal of Hydrogen Energy*. Volume 206. <https://doi.org/10.1016/j.ijhydene.2025.153212>
- Park, C., Jang, H., Jeong, B., Zhou, P., Wang, H., Mesbahi, A., **Hwang, I.**, Liu, Y. & Mujeeb-Ahmed, M. P. (2026). Regulatory gap analysis for risk-based design of liquefied hydrogen maritime transport vessels. *International Journal of Hydrogen Energy*. 217, 153840.
<https://doi.org/10.1016/j.ijhydene.2026.153840>
- Park C, **Hwang I**, Jang H, Jeong B, Ha S, Kim J, Jee J. Comparative Analysis of Marine Alternative Fuels for Offshore Supply Vessels. *Applied Sciences*. 2024; 14(23):11196.
<https://doi.org/10.3390/app142311196>
- Jang, H., Mujeeb-Ahmed, M. P., Wang, H., Park, C., **Hwang, I.**, Jeong, B., Zhou, P., Papadakis, A., Giannakis, A. & Sykaras, K. (2024). Safety evaluation on ammonia-fueled ship: Gas dispersion analysis through vent mast. *International Journal of Hydrogen Energy*. 83, 1060-1077.
<https://doi.org/10.1016/j.ijhydene.2024.03.351>
- Jang, H., Mujeeb-Ahmed, M. P., Wang, H., Park, C., **Hwang, I.**, Jeong, B., Zhou, P. & Mickeviciene, R. (2023). Regulatory gap analysis for risk

assessment of ammonia-fuelled ships. *Ocean Engineering*. 287, Part 2, 115751. <https://doi.org/10.1016/j.oceaneng.2023.115751>

Conferences

- **Hwang, I.**, Zhou, P., Jeong, B., Wang, H., Jang, H. & Palliparambil, M. A. M. (2024). Establishing safety zones for ammonia bunkering operations: A quantitative risk assessment. 7th International Conference on Maritime Technology and Engineering (MARTECH 2024). Lisbon, Portugal. <https://doi.org/10.1201/9781003508762-35>
- Yang, I., Jeong, B., Zhou, P., Wang, H., Mesbahi, A. P., **Hwang, I.**, Park, K., Jang, H., Choi, Y., Tsouvalis, N., Papadopoulos, C., Charalampakis, K., Kostidi, E., Papadakis, A., Vlachos, D., Sykaras, K. & Gergis, I. Hazard identification and risk assessment of compressed hydrogen as a marine fuel in SAFeCRAFT project. 20th International Congress of the International Maritime Association of the Mediterranean (IMAM 2025). Chania, Greece. https://doi.org/10.1007/978-3-031-73462-5_51
- Palliparambil, M. A. M., Jeong, B., Zhou, P., Jang, H., **Hwang, I.** & Wang, H. (2024). Numerical investigation of fire risk in ammonia tank leak incidents: Implications for ammonia-fueled vessels. 7th International Conference on Maritime Technology and Engineering (MARTECH 2024). Lisbon, Portugal. <https://doi.org/10.1201/9781003508762-38>

REPRESENTATIVE PROJECTS

- **NH3CRAFT [Research project]**

Safe and efficient storage of ammonia within ships (NH3CRAFT)

HORIZON-IA, European Commission, June. 2022 to May.2025

The project aim is to demonstrate for high-quantity on-board storage of NH₃ as marine fuel. (To partly collect related databases, not directly related to my PhD work).

- **LH2CRAFT [Research project]**

Safe and Efficient Marine Transportation of Liquid Hydrogen

(LH2CRAFT), European Commission June. 2023 to May.2027

The project aim is to develop long-term storage and long-distance transportation of Liquid Hydrogen (LH₂) for commercial vessels. (To partly collect related databases, not directly related to my PhD work).

- **SAFeCRAFT [Research project]**

Safe and Efficient Use of Sustainable Fuels in Maritime Transport

Applications (SAFeCRAFT), European Commission December. 2023 to November.2027

The project aim is to demonstrate and accelerate the adoption of Sustainable Alternative Fuels across diverse vessel types through four enabler technologies. (To partly collect related databases, not directly related to my PhD work).

CONTENTS

ABSTRACT	1
ACKNOWLEDGEMENTS.....	3
PUBLICATIONS.....	5
CONTENTS.....	8
LIST OF FIGURES.....	14
LIST OF TABLES.....	13
GLOSSARY	16
1 INTRODUCTION.....	18
1.1 Overview.....	18
1.2 Countermeasures.....	20
1.3 Motivations	22
1.4 Outline of the Thesis.....	24
2 AIM AND OBJECTIVES	26
2.1 Aim and objectives	26
2.2 Tasks	26
3 OVERVIEW OF SAFETY OF HYDROGEN-FUELLED SHIPS.....	32
3.1 Hazards characteristic of hydrogen	32
3.1.1 Physical and chemical properties of hydrogen.....	32
3.1.2 Historical hydrogen accidents and their implications	33
3.2 Potential risks associated with hydrogen-fuelled ship systems	38
3.2.1 Bunkering system.....	40
3.2.2 Hydrogen fuel tank.....	43
3.2.3 Fuel supply system	46
3.2.4 Fuel consumption machinery	48
4 LITERATURE REVIEW.....	51

4.1	Introduction to risk assessment methodologies	51
4.2	Qualitative risk assessment methods	52
4.3	Quantitative risk assessment methods	54
4.4	Review of applied research and case studies	57
4.5	Identified gaps	76
5	METHODOLOGY.....	79
5.1	Introduction.....	79
5.2	Analytical scope and focus	80
5.3	Overview of the integrated framework.....	84
5.3.1	Phase 1: Scenario and system definition	87
5.3.1.1	System boundaries and definition.....	87
5.3.1.2	Operational and environmental conditions characterisation....	88
5.3.1.3	Regulatory requirements and technical modelling assumptions 88	
5.3.2	Phase 2: Qualitative hazard identification and risk screening.....	89
5.3.2.1	Hazard identification.....	89
5.3.2.2	Hazard scenario prioritisation and risk screening	90
5.3.2.3	Identification of critical safety scenarios	90
5.3.3	Phase 3: Quantitative risk assessment	91
5.3.3.1	Failure frequency estimation.....	91
5.3.3.2	Consequence modelling	91
5.3.3.3	Parametric scenario analysis	92
5.3.4	Phase 4: Risk integration.....	93
5.3.4.1	Risk-informed zone determination.....	93
5.3.4.2	Risk acceptance criteria and vulnerability	94
5.3.4.3	Safety level verification	94
5.3.5	Phase 5: General observations.....	95

5.3.5.1	Comparative risk profiling	95
5.4	Summary	96
6	A PIDA-PDA Integrated parametric approach for establishing safety zone for hydrogen, ammonia and LNG bunkering operations	98
6.1	Background and scope	98
6.2	Case study	99
6.2.1	Phase 1- Scenario and system definition	101
6.2.1.1	System boundaries and definition	101
6.2.1.2	Operational and environmental conditions characterisation ..	103
6.2.1.3	Regulatory requirements and technical modelling assumptions	105
6.2.2	Phase 2- Qualitative hazard identification and risk screening	106
6.2.2.1	Hazard identification	107
6.2.2.2	Hazard scenario prioritisation and risk screening	107
6.2.2.3	Identification of critical safety scenarios	110
6.2.3	Phase 3- Quantitative risk assessment	110
6.2.3.1	Failure frequency estimation	110
6.2.3.2	Consequence modelling	112
6.2.3.3	Parametric scenario analysis	115
6.2.3.3.1	Changes in fuel supply time	121
6.2.3.3.2	Changes in fuel leakage quantity	122
6.2.3.3.3	Changes in wind speed	123
6.2.3.3.4	Changes in population density	124
6.2.4	Phase 4- Risk integration	125
6.2.4.1	Risk-informed zone determination	126
6.2.4.2	Risk acceptance criteria and vulnerability	127
6.2.4.3	Safety level verification	127

6.2.5	Phase 5- General observations	130
6.3	Discussion and novelty	134
6.3.1	Discussion of results.....	134
6.3.2	Novelty of the integrated PIDA-PDA approach.....	136
6.3.3	Novelty of the parametric comparative approach	138
6.3.4	Implications for industry and regulation	139
6.3.5	Limitations and future research	140
7	An integrated qualitative-quantitative risk assessment for defining toxic and hazardous zones on hydrogen-fuelled ships with ammonia cracking systems.....	141
7.1	Background and scope	141
7.2	Case study	143
7.2.1	Phase 1- Scenario and system definition	146
7.2.1.1	System boundaries and definition	146
7.2.1.2	Operational and environmental conditions characterisation..	148
7.2.1.3	Regulatory requirements and technical modelling assumptions	148
7.2.2	Phase 2- Qualitative hazard identification and risk screening	149
7.2.2.1	Hazard identification.....	149
7.2.2.2	Hazard scenario prioritisation and risk screening	150
7.2.2.3	Identification of critical safety scenarios	152
7.2.3	Phase 3- Quantitative risk assessment.....	153
7.2.3.1	Failure frequency estimation.....	153
7.2.3.2	Consequence modelling	155
7.2.3.3	Parametric scenario analysis	159
7.2.3.3.1	Bunkering connection (No. 1)	160
7.2.3.3.2	Ammonia tank (No. 2).....	164
7.2.3.3.3	Cracking system (No. 3)	167

7.2.3.3.4 Vent master (No. 4)	170
7.2.3.3.5 Fuel cell room vent (No. 5).....	173
7.2.4 Phase 4- Risk integration.....	176
7.2.4.1 Risk-informed zone determination.....	177
7.2.4.2 Risk acceptance criteria and vulnerability	177
7.2.4.3 Safety level verification	179
7.2.5 Phase 5- General observations	184
7.3 Discussion and novelty	185
7.3.1 Methodological contributions and key findings.....	185
7.3.2 Limitations and future research directions	187
7.3.3 Concluding remarks	187
8 DISCUSSION	189
8.1 Interpretation of findings	189
8.2 Positioning and contribution.....	191
8.3 Limitations and future research	193
8.4 Research objectives	194
8.5 Implications for practice and regulation	195
9 CONCLUSIONS	198
9.1 Principal conclusions	198
9.2 Concluding remarks.....	199
REFERENCES	201
A. APPENDIX.....	209
B. APPENDIX.....	213
I. CFD <i>simulation</i> for No. 1 bunkering leak, No. 2 ammonia tank leak, and No. 3 cracking system leak.....	213
i. Grid generation	213
ii. Boundary conditions	215

iii.	Gas detector installation.....	217
II.	CFD simulation for No. 4 vent master and No. 5 vent leak	217
i.	Grid generation	217
ii.	Boundary conditions	219
iii.	Gas detector installation.....	223

LIST OF FIGURES

Figure 2.1 Overview of objectives and tasks	27
Figure 3.1. Outline of system arrangement for hydrogen-fuelled ships (developed based on DNV handbook (DNV, 2026))	39
Figure 5.1 Outline of integrated risk assessment framework.....	86
Figure 6.1 Application of the five-phase risk assessment framework to the bunkering safety zone case study.....	100
Figure 6.2. P&ID for shore facility	102
Figure 6.3. P&ID for ship	103
Figure 6.4. Port of Hamburg (Hamburg.com, 2025)	104
Figure 6.5. Differential population density per site	105
Figure 6.6. Event tree for fuel leakage consequence	107
Figure 6.7. Event tree for fuel leakage time.....	108
Figure 6.8. Outline of Risk Assessment.....	125
Figure 7.1 Application of the integrated risk assessment framework to the onboard toxic and hazardous zone determination case study	145
Figure 7.2. 18 m ammonia-reformed hydrogen fuel cell 3D geometry	148
Figure 7.3. Process of qualitative risk assessment.....	150
Figure 7.4. General layout of the target vessel and leak analysis locations.....	152
Figure 7.5. Accidental scenarios for ammonia/hydrogen leaks (Nos. 1-5).....	153
Figure 7.6. Annual wind direction/wind speed statistics for the Busan area (as of 2022)) (Windfinder, 2023).	154
Figure 7.7. Rapid ignition potential of fuel leakage (OGP, 2010b).....	155
Figure 7.8. Consequence analysis process for accident scenarios	156
Figure 7.9. Simulation Results (2D XZ plot) for Scenario 1	162
Figure 7.10. Simulation Results (3D plot) for Scenario 1	163
Figure 7.11. Simulation Results (2D XZ plot) for Scenario 2	165
Figure 7.12. Simulation Results (3D plot) for Scenario 2	166
Figure 7.13. Simulation Results (2D XZ plot) for Scenario 3	168
Figure 7.14. Simulation Results (3D plot) for Scenario 3	169
Figure 7.15. Simulation Results for Scenario 4	173
Figure 7.16. Simulation Results for Scenario 5	176
Figure 7.17. Safety zone (toxic/hazardous zone) establishment process through risk assessment.....	177

Figure 7.18. Determination of safety distance for potential leaks during ammonia bunkering (No. 1).....	180
Figure 7.19. Determination of safety distance for potential leaks from the ammonia tank connection (No. 2)	181
Figure 7.20. Determination of safety distance for potential leaks from the cracking system (No. 3).....	182
Figure 7.21. Determination of safety distance for potential leaks from the hydrogen vent (No. 5).....	183
Figure 7.22. Overview of Hazardous Zone.....	183
Figure A.1 F-N curve of default scenarios.....	209
Figure A.2 Default simulation results	209
Figure A.3 Results for changing in bunkering time.....	210
Figure A.4 Results for changing in total leaked fuel quantity	210
Figure A.5 Results for changing in wind speed.....	211
Figure A.6 Results for changing in population.....	211
Figure A.7 Results for changing in population (F-N curve).....	212
Figure B.1. Gas Leak Simulation Grid Generated in FLACS	214
Figure B.2. Flash utility	215
Figure B.3. Boundary conditions applied to the CFD model.....	216
Figure B.4. Gas Leak Simulation Grid Generated in STAR-CCM+ (Scenarios 4 and 5)	219
Figure B.5. Boundary conditions applied to the gas leak CFD model.....	220

LIST OF TABLES

Table 3.1. Previous accident list related to hydrogen	34
Table 4.1. Past research	61
Table 6.1. Leakage frequency	111
Table 6.2. Fuel leaked quantity per scenario	115
Table 6.3. Input parameters	120
Table 6.4. Acceptable tolerance level of each scenario.	130
Table 6.5. Detailed boundaries for each scenario (metres).....	132
Table 7.1 Ship specifications	146
Table 7.2. Selection of leak risk locations and accident scenarios for the case ship (5 locations).....	151
Table 7.3. General information of the CFD modelling condition.....	158
Table 7.4 Summary of consequence analysis results.....	159
Table 7.5. Results of ammonia leak scenarios at the bunker connection.....	161
Table 7.6. Results of ammonia leak scenarios at the ammonia tank	164
Table 7.7. Results of ammonia leak scenarios at the cracking system	167
Table 7.8. Risk assessment matrix (5×5).....	178
Table 7.9. Frequency Index (occurrence frequency)	178
Table 7.10. Severity Index (impact)	179
Table B.1. Grid size and count by scenario	213
Table B.2. Boundary conditions	216
Table B.3 Boundary Conditions and Computational Setup.....	222

GLOSSARY

ABS	American Bureau of Shipping
ALARP	As Low As Reasonably Practicable
ALOHA	Areal Locations of Hazardous Atmospheres
BN	Bayesian Network
BV	Bureau Veritas
CAD	Computer-Aided Design
CCC	Sub-Committee on Carriage of Cargoes and Containers
CFD	Computational Fluid Dynamics
DNV	Det Norske Veritas
DQRA	Dynamic Quantitative Risk Assessment
DWT	Deadweight Tonnage
EAB	External Advisory Board
EMSA	European Maritime Safety Agency
EPE	Equivalent Potential Energy
ESD	Emergency Shutdown Device
ETA	Event Tree Analysis
FLACS	Flame Acceleration Simulator
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
F-N	Frequency–Number (of fatalities) curve
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
FTS	Facility-to-Ship
FVM	Finite Volume Method
GH₂	Compressed Gaseous Hydrogen
GHG	Greenhouse Gas
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HES	Health and Safety Executive
HIAD	Hydrogen Incident and Accident Database

IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organization
ISO	International Organization for Standardization
JAMET	Journal of Advanced Marine Engineering and Technology
JRC	Joint Research Centre
KR	Korean Register
LCA	Life Cycle Analysis
LFL	Lower Flammable Limit
LH₂	Liquefied (Liquid) Hydrogen
LNG	Liquefied Natural Gas
LNH₃	Liquid Ammonia
LPG	Liquefied Petroleum Gas
LR	Lloyd's Register
MEPC	Marine Environment Protection Committee
MSC	Maritime Safety Committee
OGP	International Association of Oil and Gas Producers
PDA	Population-Dependent Analysis
PHAST	Process Hazard Analysis Software Tool
PIDA	Population-Independent Analysis
QRA	Quantitative Risk Assessment
RANS	Reynolds-Averaged Navier-Stokes
SIMOPs	Simultaneous Operations
STAR-CCM+	Siemens Digital Industries Software (CFD platform)
STPA	System-Theoretic Process Analysis
STS	Ship-to-Ship
TEU	Twenty-foot Equivalent Unit
TTS	Truck-to-Ship
VCE	Vapour Cloud Explosion

1 INTRODUCTION

1.1 Overview

Maritime transport underpins the global economy, accounting for more than 80% of world trade by volume and reaching approximately 12,720 million tonnes in 2024, an increase of 2.2% on the previous year (UNCTAD, 2025, Reusser and Pérez Osses, 2021). Sustaining this scale of activity requires the consumption of vast quantities of marine fuel, and the resulting emissions footprint is now substantial. According to the Fourth IMO Greenhouse Gas Study, total shipping accounted for approximately 2.89% of global anthropogenic GHG emissions in 2018 (IMO, 2020a), a contribution that, in absolute terms, would rank international shipping among the seventh-largest emitters worldwide and is comparable to the total national emissions of Germany (UNFCCC, 2022). The decarbonisation of the maritime sector has therefore emerged as an unavoidable global priority. Yet, in contrast to land-based transport, where electrification has become the dominant decarbonisation pathway, the maritime industry cannot rely on the same solution. Ocean-going vessels demand orders of magnitude greater energy quantities and operate beyond the reach of conventional charging infrastructure (Reusser and Pérez Osses, 2021).

In response to these challenges, both regional and international regulators have introduced increasingly stringent policy frameworks designed to compel the maritime sector towards decarbonisation. At the regional level, the European Union committed to reducing GHG emissions by at least 55% by 2030 through the Fit for 55 package, officially adopted by the European Commission on 14 July 2021 (European Commission, 2021). Within this package, FuelEU Maritime, applying from 2025, mandates a phased reduction in the GHG intensity of marine fuels of up to 80% by 2050 relative to a 2020 baseline, and explicitly excludes fossil fuels from its certification process (European Commission, 2023). At the international level, the International Maritime Organization (IMO) adopted its revised GHG Strategy at MEPC 80 in July 2023, setting indicative checkpoints of a 20% emission

reduction by 2030 and 70% by 2040 against 2008 levels, and ultimately targeting net-zero emissions by or around 2050 (IMO, 2023b). Crucially, the same Strategy stipulates that zero or near-zero GHG emission technologies, fuels and/or energy sources should represent at least 5%, striving for 10%, of the energy used by international shipping by 2030.

In order to comply with these targets, ship operators are under increasing pressure to commit to zero-emission fuel pathways, since the ultimate 2050 goal cannot be achieved through energy-efficiency measures, route optimisation, or wind-assisted propulsion alone. Among the candidate zero-carbon fuels, hydrogen has emerged as one of the most strategically significant for ocean-going maritime applications, offering a high gravimetric energy density of approximately 120 MJ/kg, roughly three times that of conventional marine diesel oil, and delivering high conversion efficiency with zero operational CO₂ or SO_x emissions when used in fuel cells. Ammonia receives complementary attention as both a marine fuel in its own right and a hydrogen carrier suitable for onboard energy conversion, offering the practical advantage of being liquid at ambient pressure when cooled to approximately -33 °C, which enables storage and transportation using technology closely analogous to existing LPG infrastructure (Diamantakis et al., 2026). Other candidates have been actively explored but face inherent limitations. Methanol is commercially available and easily handled at ambient conditions, but remains a transitional solution as it is not intrinsically zero-carbon (Phogat et al., 2025). Battery-electric propulsion has proven viable for short-range coastal operations but is rendered impractical for deep-sea trading vessels by the energy-density limitations of current battery technology, where the required energy quantities are two to three orders of magnitude greater. The growing industrial commitment to hydrogen-based pathways is reflected in a rapidly expanding order book of hydrogen- and ammonia-fuelled demonstration projects (DNV, 2022).

Acknowledging the strategic importance of these fuels, both the United Kingdom and the European Union have adopted formal hydrogen strategies that directly support maritime applications. The UK's Hydrogen Strategy, originally published in 2021 and reaffirmed in 2023, sets an ambition of up to 10 GW of low-carbon hydrogen production capacity by 2030, with at least half delivered through

electrolytic production, and identifies the maritime and ports sector as a key end-use sector for hydrogen-derived fuels (Department for Energy Security and Net Zero, 2025). Similarly, the European Commission's Hydrogen Strategy outlined a target of 40 GW of electrolyser capacity within the EU by 2030, with the European Maritime Safety Agency (EMSA) tasked with providing technical guidance on the safe deployment of alternative fuels in shipping (European Commission, 2020). These policy frameworks collectively create a strong institutional impetus for accelerating the practical adoption of hydrogen-derived fuels in the maritime sector, and underscore the importance of ensuring that the safety and regulatory infrastructure needed to support these fuels is developed in parallel with their commercial deployment.

1.2 Countermeasures

The adoption of hydrogen and ammonia as marine fuels is not proceeding in a regulatory vacuum. Over the past decade, international regulatory bodies and classification societies have developed a series of frameworks intended to govern the safe use of low-flashpoint fuels in maritime applications, and these frameworks have progressively extended to cover hydrogen-derived fuels. The primary international instrument in this area is the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels, commonly known as the IGF Code, which was adopted by the IMO in 2015 and entered into force in January 2017 (Maritime Safety Committee, 2016). The IGF Code established performance-based safety requirements for ships using natural gas as fuel, and included provisions intended to be progressively extended to other low-flashpoint fuels, recognising that future alternative fuels would require similar regulatory attention. Subsequent amendments and interim guidelines, including the Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel (MSC.1/Circ.1621, 2020) (IMO, 2020b), the Interim Guidelines for Ships Using Fuel Cells (MSC.1/Circ.1647, 2022) (IMO, 2022), and the Interim Guidelines for the Safety of Ships Using LPG Fuels (MSC.1/Circ.1666, 2023) (IMO, 2023a), have progressively expanded the regulatory coverage to encompass a broader range of alternative energy systems.

With respect to hydrogen as a marine fuel, the regulatory development is currently in an active and rapidly maturing phase. The IMO Sub-Committee on Carriage of Cargoes and Containers (CCC) finalised the draft Interim Guidelines for the Safety of Ships Using Hydrogen as Fuel at its eleventh session (CCC 11) in September 2025, and these guidelines are scheduled for adoption at the 111th session of the Maritime Safety Committee (MSC 111) in May 2026. The interim guidelines provide a first set of prescriptive and goal-based requirements covering fuel storage arrangements, fuel supply system design, gas detection and ventilation, bunkering operations, and fire-fighting arrangements for both compressed gaseous hydrogen and liquefied hydrogen as fuel (DNV, 2025). In parallel, ammonia has received complementary regulatory attention reflecting its dual role as a marine fuel in its own right and as a hydrogen carrier suitable for onboard energy conversion. The draft Interim Guidelines for the Safety of Ships Using Ammonia as Fuel were approved at MSC 109 in December 2024, and the Interim Safety Guidelines for Ships Using Ammonia Cargo as Fuel, supplementing Chapter 16 of the IGC Code, were finalised at CCC 11 in September 2025 with a view to adoption at MSC 111 (IMO, 2024). Major classification societies including DNV, Lloyd's Register, Bureau Veritas, and the Korean Register have additionally developed their own class notations and safety guidelines for hydrogen-fuelled and ammonia-fuelled ship concepts (Jang et al., 2023), and these typically require designers to demonstrate compliance through a combination of prescriptive technical requirements and risk-based approaches where prescriptive guidance is absent or insufficient.

At the national and regional level, the United Kingdom and the European Union have taken proactive measures to advance the safety regulatory environment for hydrogen-derived fuels in ports and maritime operations. The UK's Clean Maritime Plan highlighted the need to develop hydrogen-specific safety protocols, emergency response procedures, and bunkering facility standards that go beyond what existing LNG-based guidance can offer (Transport, 2019). In the European context, EMSA has published technical studies on the risks and safety of hydrogen and ammonia as marine fuels, providing guidance to member state maritime administrations on the application of risk-based approaches for approving novel fuel system designs.

Classification societies have similarly developed their own technical standards and approval frameworks for hydrogen-fuelled ships, which in many cases require ship designers to conduct a qualitative risk assessment study (HAZID, HAZOP and FMEA) and, in more advanced cases, a quantitative risk assessment (QRA) prior to design approval (EMSA, 2025). Yet, as the following section will show, this architecture remains demonstrably incomplete in one practically critical respect that directly governs the deployability of hydrogen-fuelled ships.

1.3 Motivations

Despite the considerable progress documented in the preceding section, the existing regulatory architecture exhibits two complementary deficiencies that, taken together, constitute the principal motivation for the present research. The first concerns the prescriptive provisions of the existing codes themselves. The IGF Code does prescribe certain quantitative distances for the installation and structural arrangement of fuel-system components, such as a minimum of 10 m between a pressure-relief valve outlet and the nearest air intake, with classification societies specifying further values such as 15 m (KR) or up to B or 25 m (LR and ABS) under particular conditions, and hull-dimensional formulae such as $B/10$ and $B/15$ are provided for the location of fuel storage tanks within the ship's structure (Jang et al., 2023). These provisions, however, govern the geometric separation of fuel-system equipment and the structural placement of fuel containment, not the spatial extent of the safety and hazardous zones that bound the consequences of an accidental release. For the determination of such zones, the IGF Code defines safety and exclusion areas in qualitative and prescriptive terms only, requiring that 'adequate' separation be maintained or that ignition sources be 'kept away' from hazardous areas, without prescribing the specific spatial extent that such zones must encompass for hydrogen and the ammonia systems associated with onboard hydrogen production.

The second deficiency concerns the regulatory provisions for risk assessment. Both the IGF Code framework and the class society guidelines explicitly require designers to conduct hazard identification and, increasingly, quantitative risk

assessment where prescriptive guidance is absent or insufficient (EMSA, 2023). However, the practical execution of such assessments in current industry practice exhibits two fundamental limitations. First, qualitative and quantitative methods are typically applied in isolation rather than in an integrated manner, with the insights generated by qualitative HAZID studies seldom informing the parameter selection, scenario definition, or modelling boundaries of the subsequent quantitative analysis. Second, the quantitative analyses themselves rely predominantly on deterministic worst-case assumptions, which generate hazard footprints that are physically conservative but operationally unrealistic, and on environmentally fixed input parameters that conceal the substantial sensitivity of the results to wind, leak rate, and population exposure conditions.

The practical consequence of this regulatory gap is significant. Ship designers developing hydrogen or ammonia-fuelled vessel concepts face an ill-defined approval pathway when it comes to demonstrating the adequacy of safety zones and hazardous zone designations. In the absence of code-specified distances, designers are required to conduct project-specific risk assessments, which may be evaluated differently by different classification societies and flag state administrations. This creates inconsistency across the industry and introduces a degree of technical and commercial uncertainty that may disincentivise early adopters. Moreover, as the number of hydrogen and ammonia vessel projects grows, the absence of a coherent and harmonised quantitative framework for safety zone determination becomes an increasingly urgent practical problem for both the industry and the regulators responsible for overseeing it.

These gaps collectively define the principal motivation for the present research, and this thesis advances three corresponding methodological contributions. The first, which forms the overarching contribution, is the integration of qualitative and quantitative risk assessment into a single unified framework, in which structured hazard identification directly informs the scenario definition and parameter selection of the subsequent consequence and frequency analyses, thereby ensuring that no credible hazard scenario is treated in isolation. Two further contributions operate within this unified framework and address its principal weaknesses identified above. The second is the use of sensitivity-driven parametric analysis for

data-sparse hydrogen risk assessment, which acknowledges the limited empirical incident record for hydrogen-derived fuels and which incorporates population-dependent considerations that translate physical hazard footprints into practically deployable safety zones. The third is the systematic introduction of probabilistic risk evaluation into the determination of hazardous zones, which moves beyond the worst-case deterministic assumptions embedded in current practice and which thereby enables the practical determination of hazardous zones for small hydrogen-fuelled vessels on which conservative, prescriptive approaches would otherwise be operationally prohibitive.

1.4 Outline of the Thesis

The thesis is organised into nine chapters, the structure of which reflects the sequential development of the research from problem identification through methodological development to case study application and synthesis of findings.

Chapter 1, the present chapter, provides the contextual background for the research by tracing the regulatory and industrial drivers behind the maritime energy transition, surveying the current regulatory landscape governing hydrogen and ammonia as marine fuels, and articulating the specific motivations that underpin the research.

Chapter 2 defines the overarching aim and objectives of the thesis and presents the structured set of research tasks developed to achieve them. The chapter provides an explicit mapping between the identified research gaps and the corresponding tasks, establishing the logical framework within which the subsequent research is conducted.

Chapter 3 provides a systematic overview of the safety characteristics of hydrogen as a marine fuel, examining the physical and chemical properties of hydrogen that are directly relevant to maritime hazard assessment. This chapter characterises the principal hazard types associated with hydrogen-fuelled ships, including fire and explosion, and discusses the implications of these hazards for the various operational contexts addressed in this thesis, including bunkering and onboard fuel processing.

Chapter 4 presents a critical literature review of existing risk assessment approaches applied to LNG, ammonia, and hydrogen systems in maritime and port environments. The review traces the methodological evolution of the field, identifies the specific limitations of existing approaches, and derives the research gaps that motivate the methodological framework proposed in this thesis.

Chapter 5 presents the integrated risk assessment methodology developed in this thesis. The chapter describes the overall system modelling approach, the accident scenario definition process, and the quantitative methods employed for frequency analysis, consequence analysis, and risk integration.

Chapter 6 presents the first case study application of the developed methodology, examining the establishment of bunkering safety zones for hydrogen, ammonia, and LNG under comparative parametric conditions. The case study demonstrates the versatility of the PIDA-PDA approach across different fuel types and operational environments and provides a quantitative basis for evaluating the adequacy of current prescriptive safety zone guidelines.

Chapter 7 presents the second case study, in which the integrated qualitative-quantitative risk assessment framework is applied to the determination of toxic and hazardous zones for an onboard ammonia cracking system on a hydrogen-fuelled ship. This case study demonstrates the applicability of the integrated methodology to complex dual-hazard onboard environments and provides evidence-based support for the safety design of small hydrogen-fuelled vessels equipped with ammonia fuel processing systems.

Chapter 8 provides a critical discussion of the research findings, positioning the proposed framework against established risk assessment practice, reflecting on its contribution, limitations, and applicability, and providing recommendations. The chapter also examines how the findings support the identified research objectives and considers the implications for future risk assessment practices and performance-based safety regulations for hydrogen-fuelled ships.

Chapter 9 presents the principal conclusions of the thesis. The chapter concludes with remarks on the contribution of this thesis to the safe adoption of hydrogen as a marine fuel.

2 AIM AND OBJECTIVES

2.1 Aim and objectives

The overall aim of this thesis is to contribute to enhancing the safety of hydrogen-fuelled ships by developing a structured and integrated risk assessment framework that adapts and applies established risk assessment principles to the determination of safety and hazardous zones, thereby supporting safety-informed design and operational decision-making.

- (1) To identify technical and research gaps in the risk assessment of hydrogen-fuelled ships through a critical review of existing studies, risk assessment approaches, and relevant regulatory frameworks.
- (2) To develop a structured and integrated risk assessment framework that adapts established risk assessment principles to the determination of safety and hazardous zones for hydrogen-fuelled ships.
- (3) To demonstrate the applicability of the proposed framework through two representative case studies, comprising an overall demonstration of the framework and an in-depth application of selected components.
- (4) To provide key recommendations for safe design and risk assessment practices, based on the findings obtained from the application of the proposed methodology.

2.2 Tasks

To address the research aim and objectives outlined, a set of research tasks was defined and implemented, as illustrated in Figure 2.1 and described below.

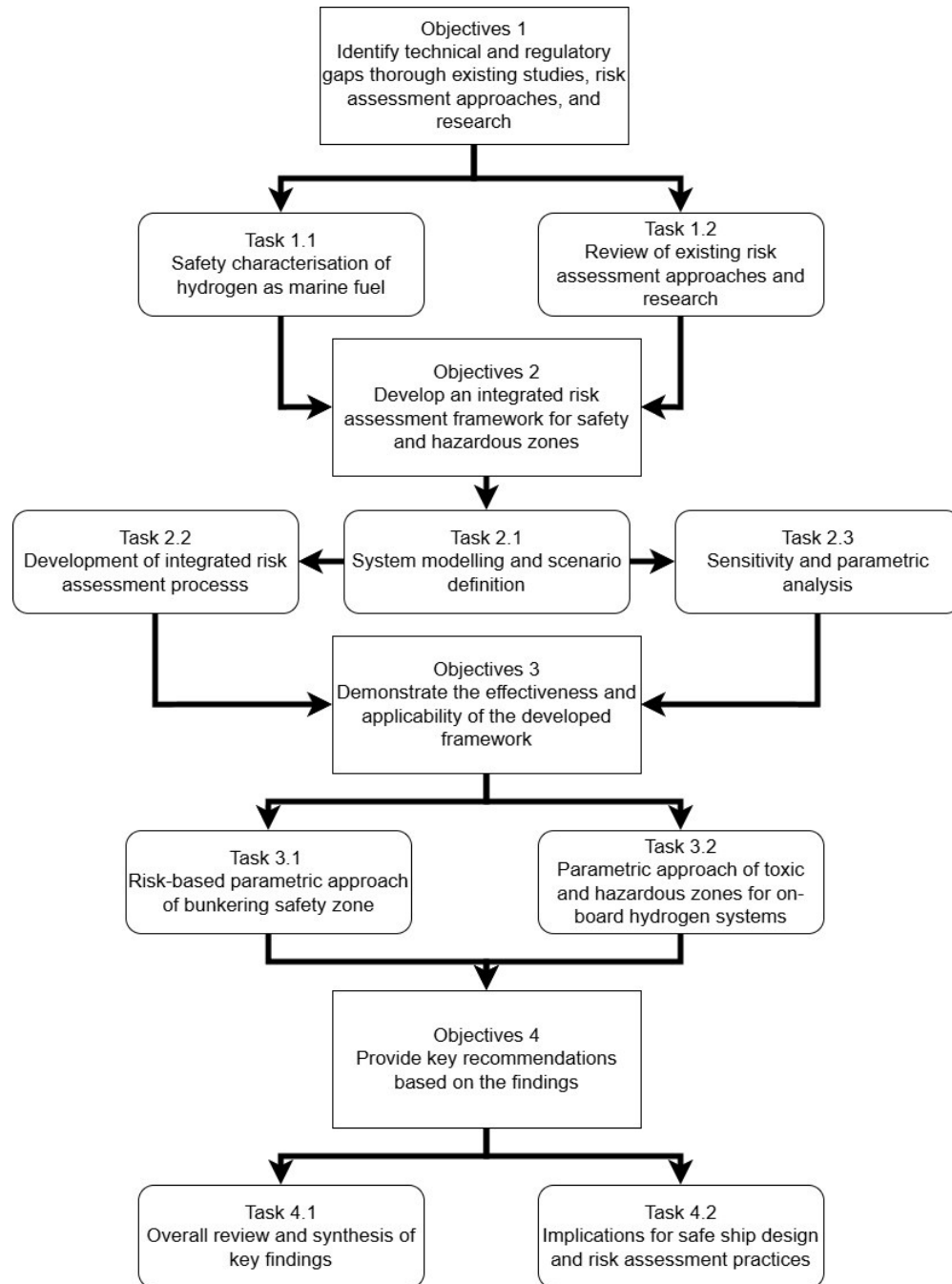


Figure 2.1 Overview of objectives and tasks

Task 1.1 Safety characterisation of hydrogen as a marine fuel

A fundamental requirement for the development of a structured safety assessment framework was a clear understanding of the unique physical and chemical hazards of hydrogen, which differ significantly from those of

conventional marine fuels. The safety characteristics of hydrogen as a marine fuel were examined in order to identify the key hazards and vulnerable aspects that require detailed consideration. Particular attention was given to hydrogen-specific properties, such as its wide flammability range, low ignition energy, and cryogenic effects, as well as the implications of these characteristics for marine applications. This task provided a fundamental understanding of the safety challenges associated with hydrogen-fuelled ships and bunkering operations, and established the basis for subsequent risk assessment activities.

Task 1.2 Critical review of existing risk assessment approaches and regulations

To determine whether current practices are sufficient for hydrogen-fuelled ships, a review of existing safety assessment approaches and relevant regulatory frameworks was required. To translate identified research gaps into a technical foundation for risk quantification, a critical review of literature was conducted focusing on existing safety assessment approaches applied to hydrogen-fuelled ships and other low-flashpoint fuel systems, including current international safety regulations such as the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) and various classification society rules. Through this critical review, technical, research and regulatory gaps were identified, highlighting the limitations of existing practices and motivating the need for a more integrated risk assessment framework.

Task 2.1 System modelling and scenario definition

To address the research gaps identified in the preceding tasks, it was necessary to establish a structured and clearly defined basis for the proposed framework. To overcome the limitations of conventional safety assessments, a structured and integrated framework was therefore proposed, beginning with system modelling and accident scenario definition. Accordingly, as the first step in developing the integrated risk assessment framework, system modelling and representative accident scenarios were defined to establish clear system boundaries and identify credible hazardous events. Hydrogen-fuelled systems were numerically modelled, and relevant accidental release scenarios were selected based on the

key findings from the identified research gaps. This task provided the foundation for the subsequent quantitative risk analysis.

Task 2.2 Development of integrated risk assessment process

Given the inherent limitations of fragmented risk assessment methodologies and the need for greater precision in safety zone determination, an integrated risk assessment process was developed. The developed process enabled a more consistent and transparent assessment of safety risks. This task constituted the central element of the methodological development, focusing on integrating consequence analysis, probabilistic considerations, and fatality risk evaluation within a unified framework to provide a robust and systematic basis for the precise determination of safety and hazardous zones.

Task 2.3 Sensitivity and parametric analysis

Recognising the uncertainties inherent in probabilistic analyses due to the scarcity of historical accident data and the inherent complexity of novel fuel systems, sensitivity and parametric analyses were prioritised to ensure methodological robustness such analyses were performed to identify the parameters that have the greatest impact on risk levels and to evaluate how variations in these parameters affect the assessment results. The task demonstrated a systematic approach for conducting such analyses and highlighted how the findings could support robust safety assessments and informed decision-making.

Task 3.1 Case study 1: Comparative risk assessment of bunkering safety zones for hydrogen and alternative marine fuels

The versatility of the proposed methodology and its capacity to inform regulatory standards were demonstrated through a comparative analysis of bunkering safety zones for various energy carriers. Accordingly, by applying the developed risk assessment methodology, the required extent of bunkering safety zones was evaluated under different operational and environmental conditions.

The influence of key parameters on safety zone dimensions was analysed, and the results were compared with existing regulatory practices and guidelines.

Task 3.2 Case study 2: Probabilistic approach to toxic and hazardous zone determination for onboard ammonia cracking systems on hydrogen-fuelled ships

Onboard ammonia cracking systems introduce additional complexity due to the simultaneous presence of flammable hydrogen and toxic ammonia under complex shipboard conditions. This combination of multiple hazard types necessitates a more detailed and probabilistic approach to understand the interaction between system configuration, operational parameters, and environmental factors. The developed methodology was further applied to assess toxic and hazardous zones associated with an onboard ammonia cracking system. The results provided insights into how system design, operating conditions, and environmental factors influence the extent of these zones, thereby demonstrating the applicability of the integrated risk assessment framework to onboard safety evaluations.

Task 4.1 Overall review and synthesis of key findings

The synthesis of research outcomes was necessitated by the requirement to provide a holistic interpretation of the developed methodology and its practical implications. The results obtained from the development and application of the integrated risk assessment methodology and key findings from the case studies were reviewed and synthesised. This task focused on consolidating the key methodological insights and safety findings derived from the case studies, with an emphasis on their consistency and broader applicability.

Task 4.2 Implications for safe ship design and risk assessment practices

To translate the methodological and analytical findings into practical relevance, based on the key findings, the implications for safe ship design and risk assessment practices were systematically examined. The final task was to discuss how the outcomes of the developed methodology could support safety-

informed design decisions, risk evaluation, and regulatory considerations for hydrogen-fuelled ships.

3 OVERVIEW OF SAFETY OF HYDROGEN-FUELLED SHIPS

The purpose of this chapter is to provide an overview of the safety challenges associated with hydrogen-fuelled ships and to highlight the importance of systematic safety evaluation. This chapter aims to establish the motivation for the research presented in this thesis by examining existing safety perceptions related to hydrogen as a marine fuel, together with current rules, regulations, standards, and guidelines governing its application. Particular emphasis is placed on identifying the limitations and shortcomings of existing approaches, thereby highlighting opportunities for improvement.

3.1 Hazards characteristic of hydrogen

3.1.1 Physical and chemical properties of hydrogen

The development of hydrogen-fuelled ships was primarily motivated by increasingly stringent environmental requirements rather than purely economic or technical drivers. In particular, the need to reduce greenhouse gas emissions and local air pollutants has accelerated the exploration of hydrogen as a zero-carbon energy carrier for marine applications. Although hydrogen offers significant environmental advantages at the point of use, its implementation as a marine fuel introduces distinct technological and safety challenges.

Hydrogen is a colourless, odourless, non-toxic, and non-corrosive substance increasingly adopted as a carbon-neutral energy carrier for zero-emission ship propulsion. In maritime applications, hydrogen may be stored either as compressed gaseous hydrogen (CGH₂) in high-pressure cylinders or as liquid hydrogen (LH₂) in cryogenic tanks. LH₂ is characterised by an extremely low normal boiling temperature (approximately -253°C at atmospheric pressure), which necessitates highly insulated cryogenic storage and processing systems to maintain the liquid below its boiling threshold (Zhao et al., 2024). Following an unintended release,

hydrogen rapidly vaporises (for LH₂) and mixes with ambient air. As it warms, its density becomes far lower than air, promoting strong buoyant rise. Nevertheless, prior to full dispersion, hydrogen can form a flammable cloud when mixed with air (Depken et al., 2024).

Such uncontrolled hydrogen release may present multiple, concurrent hazards. First, hydrogen is a powerful flammability-driven hazard because it has a very wide flammable range in air and a very low minimum ignition energy, meaning that even small ignition sources can trigger combustion once a flammable mixture forms. Depending on release conditions and confinement, ignition may manifest as a jet flame, flash fire, or an explosion involving overpressure. Second, although hydrogen is not toxic, it can act as an asphyxiant by displacing oxygen in confined spaces, which is a relevant concern for ship compartments, trunks, and machinery spaces. Third, for LH₂ systems, the cryogenic nature of the fluid introduces additional physical hazards such as cryogenic burns and material embrittlement, and the rapid phase change from liquid to gas results in a very large volumetric expansion (on the order of hundreds of times), which can intensify dispersion dynamics and increase the likelihood of flammable mixture formation if not properly managed by isolation, ventilation, and controlled venting arrangements.

Most importantly, the physical consequences of a hydrogen release are considerably more severe than those of conventional LNG. The phase change from liquid to gas for hydrogen results in a volumetric expansion of approximately 848 times, which is significantly higher than the 600-fold expansion characteristic of LNG. This rapid expansion intensifies the dispersion dynamics and substantially increases the likelihood of forming large flammable mixtures, necessitating more rigorous isolation, ventilation, and controlled venting arrangements in the ship's safety design (ISO, 2026).

3.1.2 Historical hydrogen accidents and their implications

In the safety design of hydrogen-fuelled ships, a fundamental distinction must be made between leaks occurring in 'below-deck/internal spaces' and those occurring

'on-deck/outside the hull'. For internal spaces, such as fuel preparation rooms or cofferdams, the current maritime safety framework (notably the IGF Code) prescribes a multi-layered defence system. These include mechanical ventilation systems, fixed gas detection arrangements, and automated fire-extinguishing systems. These measures are designed to detect leaks at an early stage, control gas concentrations, and confine the consequences of an incident within specific boundaries of the vessel's internal structure.

In this context, reviewing the history of hydrogen-related accidents is essential to gain technical insights into the safety management of hydrogen-fuelled ships. While the maritime industry has only recently begun to deploy hydrogen as a primary fuel, the history of hydrogen-related events has reported various critical incidents. Some of these resulted in significant asset loss and casualties, providing a cautionary baseline for the development of safety-informed designs.

Table 3.1. Previous accident list related to hydrogen

Year	Location	Facility	Incident type	Primary Cause	Damage / Consequences
2022	Port of Hastings, Australia	Suiso Frontier (ocean-going LH ₂ carrier)	Brief flame propagation/ discharge from the GCU vent outlet	Incorrect solenoid valve voltage (240 V vs 24 V) leading to GCU damper failure.	No injuries, Potential for port-wide fire, Exposed vulnerability of vent systems.
2017	Plymouth, UK	Nortrade r (general cargo ship)	Two hydrogen explosions by shipments	Hydrogen gas generated from cargo (non-ferrous metals, alkalinity of the cargo, and moisture)	1 injury, extensive damage to the vessel (out of service for two months)

2012	Saint-Quay-Portrieux, France	Electric-powered canoe	Explosion without a flame	Hydrogen emitted from the dry batteries	1 injury, boat destroyed
2000	On the sea, Mediterranean Sea	THOR EMILIE (Cargo ship)	Explosion caused by chemically generated hydrogen	Natural hydrogen generation by the chemical reaction of zinc skimming and moisture or water	6 fatalities, total loss of ship
1983	Canada, North America	Shipping container of a ship	Hydrogen gas release	Chemical reaction of phosphorus pentoxide with wine	Damage of containers

The historical marine cases presented in Table 3.1 reveal several important patterns regarding the nature of hydrogen-related accidents in maritime environments. A fundamental observation is that hydrogen releases, particularly those occurring on open decks, in port areas, or within semi-enclosed ship spaces, rarely remain as benign dispersion events. Instead, they frequently escalate into high-consequence fires or explosions, driven by rapid formation of flammable hydrogen–air mixtures once hydrogen contacts air and the presence of numerous credible ignition mechanisms in marine operations (e.g., electrical equipment, static discharge, hot surfaces, and mechanical sparks). Consequently, the accident footprint is often not confined to the immediate leak point. Events may involve explosion overpressure, flash fire, or jet-flame-like behaviour, with secondary hazards such as thermal radiation, debris/projectile effects, and cascading damage to adjacent compartments

or assets. Furthermore, several cases illustrate that the hazardous consequences can extend beyond the vessel boundary and affect surrounding port infrastructure, nearby ships, and third-party personnel.

(1) Predominance of fire and explosion consequences

The marine incidents demonstrate that hydrogen generation or release can transition rapidly to explosion even when the initiating event is not a hydrogen fuel system failure in the conventional sense. In multiple maritime cases, hydrogen, which was produced unintentionally through chemical reactions, was found within spaces that may be partially confined, enabling the formation of flammable mixtures and subsequent ignition. As evidenced by the THOR EMILIE (2000) (JRC, 2026t) and the Plymouth Port, UK (2017) (JRC, 2026v) cases, hydrogen accumulation frequently leads to devastating explosions rather than simple fire events. In the case of the THOR EMILIE, the transition from hydrogen generation to a catastrophic explosion resulted in the total loss of the ship and six fatalities.

Unlike land-based industrial leaks, maritime incidents often involve ‘unintended’ hydrogen generation (e.g., from non-ferrous cargo or battery emissions), where the lack of dedicated detection leads to delayed response. However, even in advanced vessels like the Suiso Frontier (2022) (JRC, 2026u), the brief flame discharge at the vent stack confirms that hydrogen can ignite almost instantaneously upon release due to its exceptionally low minimum ignition energy. These instances prove that the margin for active mitigation is nearly non-existent, necessitating a ‘safety-by-design’ approach through separation distances.

(2) Spatial scalability and environmental impacts

A key distinction of the hydrogen incidents recorded is the spatial scalability of their consequences. The impact of these accidents is rarely confined to the point of origin. Instead, they impose significant threats to the surrounding environment and third-party infrastructure, escalating the consequences.

- Total Loss and Environmental Hazard: The THOR EMILIE (2000) and the 2012 Electric Canoe incidents both resulted in the total destruction of the vessels. In a port or narrow channel, such a total loss involving a large-scale

hydrogen carrier could block navigation or cause cascading fires in adjacent berths.

- External Boundary Vulnerability: The potential for a ‘port-wide fire’ noted in the Suiso Frontier (2022) case underscores that hazards from vent masts or bunkering manifolds are not confined to the ship’s deck. The high buoyancy of hydrogen means that thermal radiation from a vent fire can directly threaten nearby port cranes, infrastructure, and personnel.
- Container and hold-related hazards: The shipping-container case shows that even when a release originates within containerised cargo, overpressure and damage can extend beyond the immediate package boundary, requiring the risk owner to consider adjacent containers, ship structures, and personnel in surrounding spaces.

In conclusion, the reviewed maritime cases indicate that hydrogen-related events at sea and in port environments can escalate rapidly and produce consequences that are not necessarily confined to the initial release location. Across the cases, hydrogen is frequently generated or released under conditions where mixing with air occurs quickly, and where ignition sources are readily available, resulting in outcomes that include explosions and severe structural damage. Even when the initiating mechanism is not a failure of a dedicated hydrogen fuel system, maritime operations can still create credible pathways for hydrogen hazards to develop, such as unintended hydrogen generation from cargo–moisture reactions and hydrogen accumulation associated with electrical power systems.

A further observation is that the consequences in maritime settings can extend beyond a single compartment or package. Containerised cargo and shipboard spaces may act as partially confined volumes that enable hydrogen accumulation and overpressure, leading to damage propagating to adjacent areas. In port-area contexts, the proximity of other vessels, terminal infrastructure, and third-party personnel increases the potential for broader disruption, even when the originating event occurs on a single vessel or within a specific cargo unit. Collectively, these cases highlight that the maritime hydrogen hazard is characterised by (i) rapid escalation once hydrogen–air mixtures form, (ii) strong sensitivity to confinement and congestion at the point of release or generation, and (iii) the potential for

consequences to affect neighbouring assets and operations beyond the immediate source.

3.2 Potential risks associated with hydrogen-fuelled ship systems

In general, hydrogen is utilised to generate propulsion power or electrical energy onboard ships. This can be achieved through various energy conversion technologies, including dual-fuel engines, multi-fuel internal combustion engines, and fuel cell systems. Owing to its unique physicochemical properties compared with conventional fossil fuels, including LNG, hydrogen presents safety characteristics that are considerably more sensitive and safety-critical. Its low ignition energy, wide flammability range, and high diffusivity, together with the potential requirement for high-pressure or cryogenic storage, necessitate dedicated fuel containment and processing systems. Accordingly, careful consideration must be given to the configuration and operating conditions of hydrogen fuel systems, including pressure levels, storage methods, and supply arrangements.

To enable safe and efficient operation, hydrogen-fuelled ships must therefore incorporate specialised process systems. Broadly, the onboard hydrogen fuel system comprises four main subsystems: the bunkering system, the hydrogen storage system (including suitable segregation and piping arrangements), the fuel gas supply system, and the propulsion or power generation system, such as a dual-fuel engine or fuel cell system. Figure 3.1 presents an outline of the system diagram for hydrogen-fuelled ships, illustrating the functional relationship among the four main subsystems and the associated safety and monitoring systems. The diagram was developed based on the generic block diagrams for compressed gas hydrogen and liquid hydrogen fuel systems presented in the DNV Handbook for Hydrogen-Fuelled Vessels (DNV, 2026).

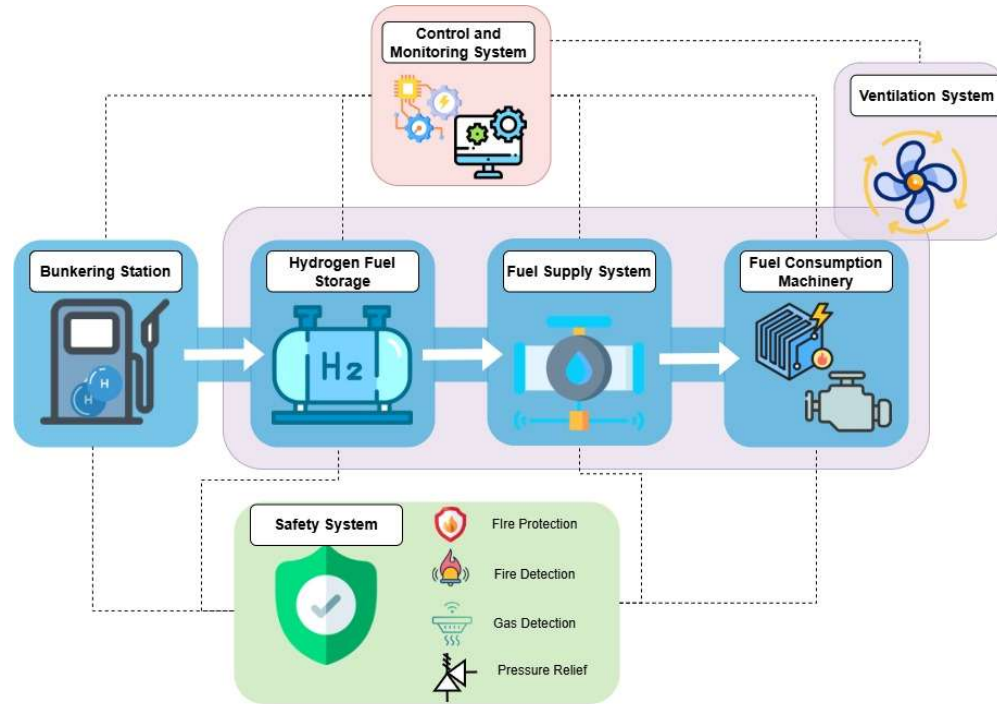


Figure 3.1. Outline of system arrangement for hydrogen-fuelled ships (developed based on DNV handbook (DNV, 2026))

Since operational experience with hydrogen handling in marine applications is still scarce, accident evidence from land-based hydrogen handling systems provides a useful reference for identifying relevant hazards and failure scenarios. For this purpose, the Hydrogen Incidents and Accidents Database (HIAD 2.1), maintained by the Joint Research Centre (JRC) of the European Commission, was used as the primary source of accident information (JRC, 2026a). The HIAD database systematically records hydrogen-related incidents across industrial, transport, and energy applications worldwide. From this database, 18 events were selected on the basis of their relevance to the four onboard subsystems identified above, and are discussed in the following sections to illustrate the characteristic hazard mechanisms and failure modes associated with each stage of the hydrogen fuel chain.

3.2.1 Bunkering system

The bunkering system constitutes one of the most safety-critical subsystems of a hydrogen-fuelled ship, as it involves the transfer of hydrogen from an external supply source to the onboard storage tanks. JRC cases offer a useful basis for anticipating potential failure mechanisms and consequence pathways relevant to future marine bunkering operations. Unlike land-based experience, bunkering in the marine sector involves handling large quantities under controlled but potentially vulnerable conditions. Incident records from hydrogen transfer and refuelling operations show that even short-duration events at the transfer stage can result in immediate hazardous outcomes, including high-pressure gas release, explosive ignition, equipment damage, and injury to personnel in the vicinity. For example, Event ID 1102, during refuelling of a train, failure of a ferrule fitting caused a 450 bar hydrogen release lasting only a few seconds, yet still resulted in hearing injuries and a secondary escape-related injury (JRC, 2026o). In another case, Event ID 1138, rupture of a hydrogen transfer hose during gaseous hydrogen transfer led to explosive ignition, after which the remaining hydrogen in the trailer was allowed to burn off (JRC, 2026q).

In addition to technical system considerations, bunkering is inherently complex from an operational perspective. Bunkering is not an autonomous or isolated process. Rather, it requires coordinated actions among ship crews, fuel suppliers, port authorities, and regulatory bodies. During bunkering operations, concurrent port activities such as cargo handling, passenger movements, or maintenance work may take place in close proximity to the transfer interface. The accident database further indicates that failures are not limited to component integrity alone, but may also arise from operational misalignment and interface mismanagement between different actors and systems. A representative example is Event ID 911, in which a tube trailer pulled away after transfer while the fill line had not been properly stowed or verified clear, causing mechanical loading on the manifold and a subsequent hydrogen leak (JRC, 2026h). Another case, Event ID 1089, involved erroneous connection of a hydrogen trailer to a compressed-air network because of missing or unclear labelling, resulting in hydrogen being introduced into the wrong

system, followed by explosion and burn-off (JRC, 2026m). These cases demonstrate that hydrogen transfer safety depends not only on equipment reliability but also on clear connection management, procedural discipline, and effective communication among personnel involved in the operation.

In general, hydrogen bunkering may take place in different configurations, such as ship-to-ship, truck-to-ship, or shore-to-ship transfer, depending on the infrastructure available. Regardless of the configuration, the bunkering system typically includes transfer hoses or loading arms, connection interfaces, isolation valves, emergency shut-down (ESD) systems, pressure and temperature monitoring devices, and venting arrangements. The design and arrangement of these components must ensure safe transfer under normal operating conditions, while also mitigating the consequences of potential accidental releases. Experience from hydrogen transfer systems shows that the performance of these components under actual operating conditions, including repeated cycling, transportation, vibration, and low-temperature service, is particularly important. In Event ID 702, one refuelling hose developed cracks and leaked after only 130 filling cycles during a durability test (JRC, 2026e), while another dispenser leak occurred in Event ID 463 at a break-away coupling only when the hydrogen temperature decreased to the pre-cooled range of approximately -33 to -40 °C, despite previous leak tests at ambient temperature (JRC, 2026c).

From a safety perspective, the most vulnerable points in the bunkering process are commonly located at the transfer interfaces and connection points. These include hose connections, flanges, quick-connect couplings, and valve assemblies, where mechanical failure, improper coupling, or human error may result in unintended hydrogen release. The selected accident cases strongly support this observation. Minor but safety-relevant hydrogen releases have been reported from dispenser hoses, break-away couplings, and threaded or ferrule fittings, while more severe events have arisen from hose rupture or misconnections during active transfer. In the train refuelling case, the failed ferrule fitting had reportedly been added on site and not fully tested after transport, indicating how seemingly small modifications at the interface can undermine system integrity. Similarly, the hose rupture event during transfer illustrates that failure of a single flexible connection can rapidly

escalate from release to ignition when excess-flow limitation or equivalent mitigation is absent.

In addition, the dynamic nature of bunkering operations, such as pressure fluctuations, transient flow conditions, repeated coupling and decoupling, transportation-induced vibration, and potential misalignment between supply and receiving systems, may increase the likelihood of leak scenarios. This is reflected in several incidents. The dispenser hose leak in Event ID 702 emerged after repeated filling cycles during durability testing, while the dispenser leak in Event ID 463 was associated with low-temperature conditions during fuelling. The train refuelling incident also suggests that component condition may be affected by transportation and installation history, since the dispenser had been moved between locations before the release event. Together, these cases indicate that bunkering risk cannot be assessed solely on the basis of nominal design pressure, but must also account for transient operating conditions and the cumulative degradation imposed on interface components over time.

The characteristics of hydrogen further influence bunkering safety considerations. Due to its low ignition energy and wide flammability limits, even small leaks may create hazardous atmospheres if ignited. High-pressure gaseous hydrogen systems may generate high-velocity jet releases, while cryogenic liquid hydrogen systems introduce additional concerns related to rapid phase change, cold embrittlement of materials, and the formation of flammable vapour clouds. Although not every release escalates to fire or explosion, the incident evidence shows that escalation can occur abruptly when hydrogen is released under transfer conditions. In Event ID 1138, hose rupture during transfer led directly to explosive ignition and sustained burning. In Event ID 1089, the accidental introduction of hydrogen into a non-intended system generated an explosive atmosphere and subsequent ignition. Even where ignition did not occur, as in Events ID 702, 463, 911, and 1102, the incidents still required shutdown, isolation, repair, or emergency response, confirming that unignited releases during transfer remain operationally significant and must be treated as credible hazardous scenarios.

Another important aspect of bunkering safety is the presence and distribution of personnel in the vicinity of the transfer operation. Unlike many onboard systems

that are located within controlled machinery spaces, bunkering activities may involve crew members, port personnel, and other operators within relatively open and accessible areas. As a result, the definition of safety and hazardous zones becomes a critical design and operational consideration. The reviewed incidents support this need. Personnel were close enough to hear and respond to hydrogen leakage in several cases, and in the train refuelling event the acoustic and physical effects of the high-pressure release caused actual injury. More broadly, the cases indicate that the hazard footprint of bunkering extends beyond equipment damage alone, encompassing human exposure during connection, disconnection, inspection, and emergency intervention. This reinforces the need for conservative safety zoning, controlled personnel access, and operational segregation during hydrogen bunkering.

3.2.2 Hydrogen fuel tank

The hydrogen fuel tank system is designed to ensure the safe containment of fuel under high-pressure or cryogenic conditions, depending on the required storage state, either in compressed gaseous form (CGH₂) at high pressure or in liquefied form (LH₂) at cryogenic temperatures. Compressed hydrogen storage typically involves high-pressure cylinders or composite tanks designed to withstand pressures that may reach several hundred bar. In contrast, liquid hydrogen storage relies on cryogenic tanks designed to maintain extremely low temperatures. Such tanks are generally double-walled and equipped with advanced insulation systems to minimise heat ingress and reduce boil-off. However, accident records indicate that safe containment depends not only on nominal design pressure or storage concept, but also on the integrity of local pressure-boundary details such as flanges, bolts, neck assemblies, plugs, seals, and attached pipework. Failures in these localised elements have led to both unignited releases and major explosions, despite the primary storage concept itself being intended for high-integrity containment. For example, in Event ID 1091, a leak from the liquid withdrawal valve of a liquid hydrogen storage tank was traced to the use of incorrect bolts, which resulted in insufficient flange tightening and the loss of approximately 40 kg of hydrogen (JRC,

2026n). In Event ID 1161, a release from a high-pressure storage vessel at a hydrogen refuelling station was associated with differences in thread engagement and rupture of the O-ring and back-up ring in the vessel neck assembly (JRC, 2026s).

From a ship design perspective, hydrogen fuel tanks often occupy larger volumes relative to the equivalent energy content of conventional fuels. This lower volumetric energy density may necessitate dedicated tank compartments and increased safety distances from critical areas. For smaller vessels in particular, spatial limitations can significantly influence tank placement and integration with other onboard systems. In addition, the hydrogen fuel tank system must incorporate monitoring and safety devices such as pressure sensors, temperature sensors, level indicators, and emergency shut-down interfaces. These elements contribute to maintaining safe operating conditions and enable timely detection of abnormal situations. The interaction between the tank system and downstream fuel supply components further emphasises the importance of viewing the hydrogen fuel tank as part of an integrated fuel chain rather than as an isolated storage unit. This systems view is strongly supported by accident evidence. In the Oslo hydrogen refuelling station explosion (Event ID 884), hydrogen leaked from the interface between a high-pressure storage tank and connected piping due to two untightened bolts on the gasketed connection (JRC, 2026g). Although the defect originated in assembly, the event escalated through the connected storage and distribution arrangement, eventually forming an explosive cloud and causing a detonation strong enough to damage buildings about 65 m away and trigger airbag deployment in nearby vehicles. The case illustrates that fuel tank safety cannot be considered independently from attached manifolds, sealing arrangements, pressure cycling history, and leak detection logic.

The reviewed storage-related incidents also show that degradation or vulnerability may remain latent for long periods before failure becomes apparent. In Event ID 884, the improperly tightened bolts reportedly remained in service for more than two years under pressures up to 900 bar before fatigue associated with repeated refuelling pressure oscillations led to gasket failure and release. This is particularly relevant for hydrogen fuel tank systems on ships, where repeated bunkering, thermal cycling, vibration, and operational transients may progressively weaken

sealing performance or threaded interfaces even when the tank itself remains structurally sound. Likewise, the release in Event ID 1161 suggests that installation-induced damage to sealing components can undermine containment without any fundamental weakness in the metal pressure-retaining parts. These events therefore highlight the need to treat joint integrity, assembly control, and inspection of auxiliary sealing components as central aspects of hydrogen fuel tank safety.

The accident records further indicate that storage-related hazards are not limited to internal pressure containment alone, but also include external mechanical threats and post-accident response challenges. In Event ID 1103, a hydrogen fuel cell bus collided with a low bridge, causing rooftop hydrogen tanks to be sheared off (JRC, 2026p). Although the automatic safety valves functioned as intended and only a small residual release occurred, the incident exposed an important secondary vulnerability. Emergency responders initially failed to recognise that the tanks were not fully empty and also did not notice damage to the high-voltage electrical system until noted by the bus operation engineer. This case is especially relevant for shipboard applications, where storage tank location, structural protection, and accessibility for emergency intervention must be carefully considered. It shows that even where the storage tanks themselves retain most of their hydrogen successfully, accident consequences may still depend on the clarity of tank status indication, isolation performance, and emergency response understanding.

A more severe example of storage-related escalation is provided by Event ID 707, in which a leak from a hydrogen storage tank in a ceramic factory caused an explosion, resulting in significant off-site damage, multiple minor public injuries, evacuation, and interruption of road and rail traffic (JRC, 2026f). Although this was an industrial stationary-storage event rather than a transport application, it demonstrates that the hydrogen fuel tank system should not be viewed merely as a passive containment unit. Once containment is lost, the inventory stored within the tank may generate consequences extending well beyond the immediate installation boundary.

Overall, these incidents show that hydrogen fuel tank safety depends on more than the nominal strength of the storage vessel itself. The practical safety performance of the tank system is shaped by several interdependent factors, including the

integrity of flanges, plugs, seals, bolts, and connected interfaces, the quality of assembly and maintenance practices, the effects of repeated pressure cycling and operational loads, and the ability of monitoring and emergency systems to identify and manage abnormal conditions before escalation occurs. Accordingly, the hydrogen fuel tank should be treated as an integrated storage and containment system whose risk profile is influenced by both internal design features and its interaction with the wider fuel handling chain.

3.2.3 Fuel supply system

The fuel supply system functions as the interface between the hydrogen fuel tanks and the propulsion or power generation units. Its primary role is to condition and supply hydrogen at the required pressure, temperature, and flow rate to the end-use equipment while maintaining safe and controlled operating conditions. Shore accident records show that hazardous events may originate not only from the storage tanks themselves, but also from downstream supply components such as flexible hoses, joints, valves, compressors, buffer vessels, and supply pipelines.

Depending on the storage type and propulsion technology, the configuration of the fuel supply system may vary considerably. In all configurations, however, the high-pressure hydrogen stored in the tanks must be reduced to appropriate operating pressures before entering engines or fuel cells. This pressure regulation process must be carefully controlled to prevent excessive temperature changes, pressure surges, or unintended releases. For liquid hydrogen systems, the management of boil-off gas and phase transition effects becomes an integral part of the supply system, and temperature control, insulation continuity, and proper venting arrangements are therefore essential to ensure stable and safe fuel delivery.

The sensitivity of the fuel supply system to control failures is illustrated by Event ID 1044, in which pressure fluctuations in the lubricating oil system of a hydrogen compressor, combined with improper operator response, caused abnormal shutdown of the compressor and interlocked stoppage of the hydrogen feed pump (JRC, 2026l). Because the outlet valve was not closed in time and two check valves failed, high-pressure hydrogen flowed into a low-design-pressure buffer tank,

leading to overpressure, tank burst, explosion, and subsequent fire. This case demonstrates that the fuel supply system must be assessed as a dynamic control chain in which the behaviour of compressors, the response of valves, and the reliability of interlocks are all safety-critical.

Given hydrogen's small molecular size and high diffusivity, leakage prevention and detection are particularly important within the fuel supply system. Piping arrangements may incorporate double-walled piping or ventilated enclosures to reduce the consequences of hydrogen leakage. Leak detection systems, emergency shut-down systems, and interlocking mechanisms are typically integrated to enable rapid isolation under abnormal conditions. This design emphasis is supported by Event ID 976, in which hydrogen leaked from a hose joint of a flexible pipe in the engine compartment of a prototype hydrogen vehicle equipped with onboard liquid hydrogen storage (JRC, 2026k). The leaked hydrogen ignited, and the resulting fire also involved brake oil. The corrective actions identified after the event included changes in piping layout, avoidance of hot surfaces near hydrogen piping and fastening parts, installation of a vent duct to discharge leaked hydrogen in a safe direction, and improved fitting design and fastening management.

A further important lesson concerns the routing and confinement of hydrogen supply pipework. Event ID 973 involved hydrogen supplied through a pipeline running in a trench below a furnace in a metal powder plant (JRC, 2026j). A corroded section of the hydrogen pipeline released gas into the covered trench, where it accumulated before ignition, after which the explosion dispersed combustible material and escalated the event. Although this was an industrial process plant rather than a marine fuel system, it demonstrates how hydrogen released from degraded pipework may remain undetected in enclosed or poorly ventilated spaces until ignition occurs. Additionally, Event ID 267, which involved an explosion during testing of hydrogen feeding to an engine, reinforces that the fuel supply system should not be regarded as a passive transfer line but as an active process system requiring careful control during both normal operation and testing (JRC, 2026b).

Taken together, these accident cases demonstrate that the hydrogen fuel supply system should be regarded as a safety-critical process chain rather than merely a

fuel transfer path between storage and the end-use unit. As illustrated by Event ID 1044, the behaviour of compressors, valves, and interlocks may critically influence whether an abnormal condition remains controlled or escalates into a major accident. More broadly, the safety performance of the fuel supply system depends on the integrity of joints and fittings, the reliability of control and isolation functions, the adequacy of piping layout and ventilation, and the management of abnormal or test-related operating conditions. For marine applications, this highlights the need for careful arrangement design, effective enclosure and ventilation strategies, segregation from ignition sources, and rapid leak detection and isolation throughout the full supply pathway.

3.2.4 Fuel consumption machinery

The fuel consumption machinery represents the final stage of the onboard hydrogen fuel chain, where the stored and conditioned hydrogen is ultimately converted into useful mechanical or electrical energy. In hydrogen-fuelled ships, this function may be provided by hydrogen-capable internal combustion engines, such as dual-fuel or multi-fuel engines, or by fuel cell systems. In both cases, this subsystem differs from upstream fuel storage and supply arrangements because hydrogen is handled in the immediate vicinity of energy conversion equipment, where thermal loads, electrical components, ignition sources, confined installation spaces, and machinery restart or load-change conditions may directly influence accident development.

For hydrogen internal combustion engines, safe operation depends on careful control of fuel admission, mixture formation, ignition timing, and combustion stability. Hydrogen's low ignition energy, high flame speed, and wide flammability range make the machinery particularly sensitive to abnormal combustion phenomena such as pre-ignition, backfiring, or ignition of leaked hydrogen in the vicinity of the engine. This is illustrated by Event ID 594, in which a leak of hydrogen gas was followed by an explosion when a ramjet engine, loaded with air, oxygen, and hydrogen, was started for a preliminary combustion test (JRC, 2026d). The explosion destroyed the test facilities, showing how rapidly hydrogen-related

ignition within or around propulsion machinery can escalate when fuel admission and ignition are not tightly controlled.

Fuel cell-based machinery presents a different but equally important safety challenge. Since electricity is generated electrochemically rather than through combustion, the main risk is not abnormal combustion inside the prime mover itself, but hydrogen leakage, accumulation, and delayed ignition within the fuel cell compartment or adjacent enclosures. Event ID 1152 provides a relevant example (JRC, 2026r). After refuelling, a hydrogen fuel cell city bus was restarted, and an explosion occurred in the fuel cell compartment approximately 11 seconds later, causing serious injuries to three persons. Reports associated with the event suggested that similar buses were later found to have small hydrogen leaks, possibly linked to loose bolts on hydrogen fuel lines, which prompted fleet-wide inspection and corrective action. Likewise, Event ID 971 involved an explosion of a fuel cell forklift during driving, resulting in one fatality and six minor injuries, although the exact cause was not specified in the available sources (JRC, 2026i). Together, these cases indicate that hydrogen consumption machinery can remain vulnerable even after apparently normal fuelling or during routine operation, particularly when small undetected leaks persist near enclosed equipment spaces.

Taken together, these accident cases suggest several recurring hazard characteristics for hydrogen fuel consumption machinery. First, the final consumption stage is located close to machinery, electrical devices, hot surfaces, and restart sequences, meaning that even relatively small hydrogen releases may encounter ignition opportunities before they are detected or dispersed. Second, the transition from normal operation to start-up, restart, test, or transient conditions appears particularly important, as these phases may involve changing pressures, altered ventilation patterns, temporary sealing weaknesses, or abnormal control responses. Third, the confinement of hydrogen within machinery rooms, engine enclosures, or fuel cell compartments can increase the likelihood of gas accumulation and subsequent explosion, especially where leak detection or ventilation performance is insufficient. Accordingly, the main safety concerns at this stage are not limited to the fuel conversion technology itself, but also include

enclosure integrity, tightness of hydrogen lines and fittings, ventilation effectiveness, ignition source control, and safe shutdown or restart logic.

For marine applications, these findings imply that hydrogen fuel consumption machinery should be treated as a highly integrated safety-critical subsystem rather than merely as the endpoint of fuel use. Particular attention should be paid to the segregation of engines or fuel cell modules from other ship spaces, the avoidance of hydrogen accumulation within enclosed machinery areas, the reliability of leak detection and ventilation systems, and the integration of shutdown and restart interlocks with the wider fuel supply chain. In addition, the arrangement of equipment should minimise the proximity of hydrogen-containing components to potential ignition sources, while also ensuring accessibility for inspection and maintenance. Since maritime operational experience remains limited, accident experience from analogous land-based applications provides a useful basis for identifying credible accident mechanisms and design precautions relevant to shipboard hydrogen consumption machinery.

In conclusion, the accident evidence reviewed in this chapter shows that hydrogen-fuelled ship design requires more than compliance with general design principles or isolated technical safeguards. Since each subsystem of the hydrogen fuel chain presents its own characteristic hazards and escalation potential, safe design should be established through detailed risk assessment addressing subsystem-specific and integrated system-level interactions. This need is further reinforced by the current limitations of prescriptive regulations for hydrogen applications in shipping, as well as the still limited operational experience available from practical marine deployment. In this context, risk assessment is not only a supporting design tool but a central means of compensating for regulatory gaps and uncertainties in emerging hydrogen technologies. This is also consistent with the intent of existing regulatory frameworks, which explicitly recognise the importance of risk-based evaluation for identifying hazards, verifying safety measures, and demonstrating an acceptable level of safety. Therefore, the design of hydrogen-fuelled ships should rely on a structured and detailed risk assessment process to enable safe system integration, support evidence-based design decisions, and ensure that appropriate protective measures are incorporated throughout the entire hydrogen fuel chain.

4 LITERATURE REVIEW

4.1 Introduction to risk assessment methodologies

Risk assessment methodologies provide the basis for examining how hazardous events may originate, escalate, and result in harmful consequences. As new fuel technologies are introduced into marine applications, the need for effective risk assessment methodologies has become increasingly important to support safe design, operational planning, and regulatory compliance. The safety assessment of hydrogen-fuelled ships requires more than a general recognition of hydrogen hazards. Although the hazardous properties of hydrogen are well established, the principal challenge in marine applications lies in how these hazards are systematically assessed and translated into practical design and operational decisions. In this context, risk assessment is not merely a regulatory requirement, but also a critical decision-making tool for addressing the uncertainties associated with emerging fuel technologies.

In general, risk is commonly understood as a function of the likelihood of an event and the severity of its consequences. Accordingly, risk assessment aims to identify relevant hazards, examine how they may lead to undesired events, and evaluate their potential impacts on personnel, assets, and the environment (IMO, 2002). In maritime systems, such assessment has traditionally been approached using both qualitative and quantitative methodologies, each contributing in different ways depending on the purpose, scope, and maturity of the system under consideration.

In this context, risk assessment has been bifurcated into qualitative and quantitative approaches. Qualitative methodologies rely on the heuristic judgement of subject matter experts to identify relevant accident scenarios (Aven, 2016). However, because operational experience with hydrogen and ammonia is still in its infancy, the scarcity of empirical data introduces substantial epistemic uncertainty. This makes it difficult to apply conventional experience-based practices with high confidence. Conversely, quantitative risk assessment (QRA) utilises numerical models to estimate consequence severity and event likelihood. Yet, the efficacy of

QRA is frequently hindered by the paucity of practical data and the limitation of time and resources, which often forces researchers to adopt static, "worst-case" assumptions (Schaad et al., 2025).

Recent literature on hydrogen bunkering safety zones and ammonia-fuelled systems reveals a significant methodological fragmentation. Many studies focus on isolated components, such as purely physical dispersion or simplified frequency analysis, without a coherent integration of operational variables. This lack of a parametric link frequently yields disproportionately severe or unrealistic safety requirements, which may impede the practical implementation of alternative fuel technologies. Consequently, there is an urgent need to move beyond traditional, fragmented assessments towards a more integrated framework. Against this background, this chapter reviews the principal risk assessment methodologies relevant to hydrogen-fuelled ships, with particular attention to their functions, strengths, limitations, and applicability to marine safety problems. The review first examines qualitative and quantitative risk assessment methods, followed by their application in marine-related studies. Based on this review, the main methodological gaps are identified and the requirements for an integrated risk assessment framework are discussed, thereby providing the conceptual basis for the framework developed in the subsequent methodology chapter.

4.2 Qualitative risk assessment methods

Qualitative risk assessment serves as an initial means of identifying hazards, understanding accident scenarios, and examining system vulnerabilities before detailed numerical analysis is undertaken. This approach relies on the heuristic nature of the process, drawing upon the collective judgement and practical experience of subject matter experts (SMEs) (Haugen and Kristiansen, 2022). In maritime applications, these methods have been extensively applied to complex or developing systems, particularly where design concepts are still evolving and sufficient operational data are not yet available. Their role is especially important in alternative-fuel ship systems, where the introduction of new fuels and

technologies creates uncertainties that cannot always be addressed through existing prescriptive rules alone.

A number of qualitative techniques have been applied in the maritime and process safety literature (ABS, 2020). Among the most commonly used are Hazard Identification (HAZID), Hazard and Operability Study (HAZOP), Failure Mode and Effects Analysis (FMEA), and Failure Mode, Effects and Criticality Analysis (FMECA). In more complex systems, complementary approaches such as System-Theoretic Process Analysis (STPA) have also been used to address control-related hazards that may not be fully captured by conventional component-oriented techniques (Leveson, 2016).

HAZID is commonly used during the early design stage as a high-level technique for identifying major hazards and potential accident scenarios associated with a proposed system. Its principal objective is to support design improvement by revealing safety-critical issues that require further consideration at an early stage. HAZOP, by contrast, is generally performed during the basic or detailed design stage and is concerned primarily with hazards arising from system operation and process deviations. By applying structured guide words, HAZOP enables the systematic examination of deviations from intended operating conditions and their potential implications for safety and operability. FMEA and FMECA are typically conducted during the detailed design stage to determine whether the failure of individual components may propagate into functional failures at the subsystem or system level. As bottom-up techniques, they focus on component-level failure modes and their effects, thereby helping to identify critical failures that may affect the overall safety and reliability of the system.

The main strength of qualitative risk assessment lies in its flexibility and practicality. These methods can be used even when detailed numerical data are unavailable, and they enable the incorporation of multidisciplinary expertise from design, operation, maintenance, and safety management. At the same time, qualitative methods also have recognised limitations. Their outcomes depend strongly on the knowledge, experience, and judgement of the experts involved, which may introduce subjectivity and reduce consistency between studies (Anthony Cox Jr, 2008). This issue becomes more pronounced when the system under consideration is novel and

direct operational experience is limited. Previous literature has therefore pointed out that qualitative methods may be problematic when assessing systems for which knowledge and experience remain insufficient, and that the results may be difficult to generalise or translate into high-credibility quantitative prediction without further analytical support (Goerlandt and Montewka, 2015). Furthermore, qualitative methods do not inherently provide numerical spatial information. While they can identify that a hose rupture may occur during bunkering, they cannot quantify the physical extent of the resulting impact radius (Duong et al., 2024b). Consequently, relying solely on qualitative judgement for the consequence may lead to inconsistent safety requirements that are either insufficiently protective or, conversely, so conservative as to result in operationally unrealistic overestimation or underestimation (Anthony Cox Jr, 2008).

For this reason, qualitative risk assessment is generally regarded as an essential foundation rather than a complete basis for final safety evaluation. Its principal contribution lies in identifying hazards, screening accident scenarios, and highlighting critical subsystems and failure pathways that warrant more detailed investigation.

4.3 Quantitative risk assessment methods

Quantitative risk assessment (QRA) provides a more explicit and measurable basis for safety evaluation by estimating the likelihood and consequences of hazardous events through analytical calculations, numerical modelling, and simulation-based approaches (Lees, 2012). Unlike qualitative methods, which rely primarily on structured expert judgement, quantitative methods seek to produce objective and reproducible outputs that support design comparison, safety verification, and risk-informed decision-making. In the marine sector, QRA has been increasingly applied to complex and novel fuel systems, particularly in cases where prescriptive regulations alone are insufficient to demonstrate the adequacy of a proposed design. By converting identified hazards into measurable indicators such as event frequency, hazardous distance, toxic exposure range, individual risk, and societal

risk, QRA enables descriptive accident scenarios to be translated into quantifiable spatial and risk-based metrics (Moon et al., 2025).

In general, quantitative risk assessment in marine applications distinguishes between two core elements, frequency and consequence (ABS, 2020). Frequency analysis is used to estimate how often an undesired event may occur, while consequence analysis is used to assess the physical effects and potential harm resulting from that event (ISO, 2019). This distinction is well established in risk studies, where leak occurrence and the subsequent effects of fire, explosion, or toxic exposure are often analysed through separate but connected stages. In practice, this structure provides the basis for a wide range of QRA frameworks applied to low-flashpoint fuel systems and hazardous gas handling operations (Duong et al., 2024a).

For frequency analysis, a number of probabilistic techniques have been employed in the literature. Among the most common are Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Bayesian networks (BN), and related probabilistic models (Ferdous et al., 2011). FTA is typically used to trace the logical combinations of failures that may lead to an initiating event (Vesely et al., 1981), whereas ETA is used to examine how such initiating events may develop into different accident outcomes depending on the success or failure of subsequent barriers and system responses. Bayesian-network-based approaches have also been used because of their flexibility in probability updating and causal diagnosis (Li et al., 2023).

For consequence analysis, computational tools are used to quantify the physical effects associated with hazardous releases. In the marine sector, a range of modelling approaches has been applied to assess the behaviour of released fuels, including phenomenological models and Computational Fluid Dynamics (CFD) (DNV, 2026). Phenomenological models are based on simplified analytical equations and are commonly used for the rapid estimation of discharge rates, pool evaporation, and gas dispersion (Lees, 2012). Although they are computationally efficient, their applicability may be limited in situations involving complex geometries, confined spaces, or strong interaction with surrounding structures (Duong et al., 2024b). By contrast, CFD has become one of the most widely used tools for analysing gas dispersion, flammable cloud formation, thermal effects, and toxic concentration distribution, particularly for low-flashpoint and gaseous fuels.

By solving the Navier–Stokes equations in three-dimensional space, CFD enables a more detailed representation of fluid flow and release behaviour under realistic conditions (Versteeg, 2007). This is especially important for capturing fuel-specific physical behaviour, such as the high buoyancy of hydrogen, particularly in obstructed environments such as ship decks, enclosed spaces, or port terminals. CFD is therefore particularly valuable where the geometry of the ship, ventilation conditions, confinement effects, and environmental variables such as wind speed and direction have a strong influence on the resulting hazard footprint. Because of this capability, CFD has been widely adopted in studies related to hazardous zone determination, fuel leakage consequences, and safety-distance evaluation for LNG, ammonia, and hydrogen applications.

Beyond standalone frequency or consequence analysis, marine QRA studies often combine multiple methods within a structured framework. In complex ship and offshore systems, so-called selective quantitative risk assessment has frequently been used, in which only pre-identified critical scenarios, subsystems, or operating conditions are taken forward for detailed quantitative analysis after an initial screening stage (Jeong et al., 2018). This approach has been applied extensively in LNG-related marine and offshore studies, where quantitative modelling is focused on those scenarios considered most relevant or safety-critical. Such selective application reflects the practical reality that fully comprehensive quantification of all possible accident scenarios is often neither feasible nor necessary (Spouge, 1999).

In addition to conventional QRA tools, a variety of specialised or integrated quantitative approaches have been reported in the literature depending on the hazard type and study objective. These include probabilistic seismic risk analysis, fire, explosion, and poisoning probability models, Monte Carlo simulation, and human risk models such as population-independent and population-dependent analysis. Some studies have also used dedicated tools such as HyRAM for hydrogen refuelling applications, while others have developed bespoke integrated models to reflect the particular characteristics of marine fuel systems. This indicates that quantitative risk assessment in the marine sector is not based on a single standard

tool, but rather on a family of analytical methods selected according to the nature of the fuel, the hazard mechanism, and the intended risk metric.

A major strength of quantitative methods is that they can provide explicit and measurable outputs that are difficult to obtain from qualitative assessment alone. These outputs may include release frequency, toxic or flammable dispersion range, overpressure extent, fatality risk, and formal risk metrics such as individual or societal risk. Such quantified information is particularly important where the objective is to compare design alternatives, determine safety distances, define hazardous zones, or justify deviations from prescriptive requirements. Previous literature has therefore highlighted the value of quantitative methods in establishing more objective and transparent safety evaluations for low-flashpoint fuel systems.

At the same time, quantitative risk assessment also faces recognised limitations. Its reliability depends strongly on the availability and quality of input data, including failure frequencies, leak scenarios, operating conditions, and environmental assumptions (Schaad et al., 2025). For emerging marine fuel systems such as hydrogen, these data are often limited, uncertain, or highly case-specific (West et al., 2022). As a result, quantitative studies may rely on assumptions, simplified probability structures, or fixed boundary conditions that constrain the broader applicability of the results.

4.4 Review of applied research and case studies

The maturity of risk assessment practice varies considerably across safety-critical industries, and the marine sector is comparatively less advanced in this respect than the offshore oil and gas industry. In the offshore sector, integrated risk assessment has long been institutionalised as an established engineering practice. Regulatory regimes introduced after the Piper Alpha disaster require operators to demonstrate through a safety case that major accident hazards have been identified, assessed, and reduced to a level as low as reasonably practicable (Cullen, 1990, HSE, 2001). Industry standards further specify how hazard identification, frequency analysis, consequence modelling, and risk evaluation are to be combined within a single assessment process. NORSOK Z-013 defines requirements for offshore risk

assessment, including a probabilistic procedure for explosion risk analysis in which CFD is employed for ventilation, dispersion, and explosion calculations (NORSOK, 2024), while ISO 17776 provides a structured process for managing major accident hazards during the design of offshore installations (ISO, 2016). These frameworks are supported by standardised failure frequency and ignition probability datasets accumulated over decades of operational experience (OGP, 2010a), and by extensive methodological guidance for offshore and process applications (Vinnem, 2007, CCPS, 2010, Spouge, 1999).

Nevertheless, these established approaches are formulated at a highly generalised level. They were developed for large fixed installations handling well-characterised hydrocarbons, and their procedures, failure data, and acceptance criteria presuppose long operational histories and stable installation-level hazard profiles. They do not, in themselves, prescribe how an integrated assessment should be configured for the determination of safety and hazardous zones for ships and bunkering operations, where releases are transient, the exposed population varies with port activity, and the physical behaviour of hydrogen and ammonia differs markedly from that of conventional hydrocarbons. In the maritime domain itself, risk assessment practice remains comparatively immature, and even its conceptual foundations continue to be debated (Goerlandt and Montewka, 2015). Although the qualitative and quantitative methods reviewed in the preceding sections have each been introduced to marine applications individually, a unified framework that systematically combines them within a single assessment process has yet to be established in maritime practice.

Against this background, the remainder of this section reviews how risk assessment has been applied in practice within the marine sector, where operational experience has accumulated unevenly across fuels. The practical application of risk assessment has expanded significantly with the adoption of low-flashpoint and hazardous fuels across marine and related industrial sectors. Within this context, Liquefied Natural Gas (LNG) serves as an important methodological benchmark. Although the chemical properties of LNG differ from those of hydrogen and ammonia, it represents the first low-flashpoint fuel to achieve relatively widespread commercialisation and regulatory standardisation under the IMO IGF Code. For

this reason, reviewing the evolution of LNG risk assessment provides an important basis for understanding how safety methodologies have been introduced, adapted, and refined for other fuels, including the more demanding and less mature case of hydrogen.

Accordingly, a review of applied research cannot rely on hydrogen cases alone. A substantial proportion of the available literature has instead been developed around LNG-related applications, particularly in marine contexts such as bunkering, onboard storage and supply systems, hazardous zone determination, and consequence-based safety evaluation. Although LNG and hydrogen differ significantly in their chemical and physical properties, LNG studies remain highly relevant from a methodological perspective because they demonstrate how risk assessment methods have been applied in practice to low-flashpoint fuel systems. Reviewing these studies therefore provides an important foundation for understanding both the development of current approaches and the limitations that emerge when such methods are used to support practical safety decisions.

Furthermore, it is also important to review research on ammonia applications. Although ammonia has distinct chemical and physical properties compared with hydrogen, it represents another emerging low-flashpoint fuel context in marine applications and, in some areas, demonstrates a comparatively more established level of technical and methodological maturity than hydrogen. From the perspective of introducing risk assessment methods to new fuel systems and identifying their practical limitations, ammonia-related studies provide a useful intermediate reference between the more established LNG literature and the still limited hydrogen-focused literature. This is particularly relevant because applied research on ammonia has frequently addressed the determination of toxic and hazardous zones, offering important insights into how risk assessment methodologies can be adapted for fuels associated not only with fire and explosion hazards but also with significant environmental and human health impacts. While LNG and hydrogen studies have primarily focused on flammability-related consequences, ammonia studies have more explicitly incorporated toxicological thresholds, such as AEGL (Acute Exposure Guideline Levels) and ERPG (Emergency Response Planning Guidelines), into spatial risk evaluation. Reviewing how these methodologies have

been calibrated and applied in ammonia-related marine cases therefore helps to clarify the strengths and limitations of current fragmented approaches, while also providing a useful methodological basis for the present study, which ultimately aims to develop an integrated risk assessment framework capable of addressing diverse hazard profiles.

Table 4.1. Past research

No.	Ref.	Aim	Method	Case study	Identified Gaps	Key findings	Contributions	Limitation
1)	(Jeon g et al., 2020)	Introduce an enhanced approach to establishing safe zone for LNG bunkering	Enhanced version of quantitative risk assessment, probabilistic analysis and consequence analysis, FLACS	Truck-to-ship operation, 50,000 DWT bulk carrier, onboard bunkering system	Previous studies used a deterministic approach, overlooking probability, thus failing to capture the full risk of LNG bunkering.	The actual possibility hazards to the number of humans should be considered for setting a safety zone	Indicate an appropriate safety zone level that is practically applicable within the industry.	Does not consider parametric value
2)	(Ane ziris et al., 2022)	Performing a quantitative risk assessment for ship-to-ship bunkering in Greek ports	Quantitative assessment, FTA, ETA, SOCRATES	Ship-to-ship operation, 800 m ³ capacity of LNG supply to a passenger ship	There are limited analyses conducted for ship-to-ship LNG bunkering.	Flash fire by facility rupture leads to serious consequences	Applies QRA to LNG ship-to-ship bunkering by quantifying release probabilities and consequences, and assessing impacts on nearby populations.	There is uncertainty regarding the required data regarding accidental LNG release
3)	(Wu et al.,	Propose an integrated	Probabilistic graphic model,	Assess the potential	An integrated model for dynamic risk	domino effects and accident	Scenario and sensitivity analyses	Focus on domino

	2021)	quantitative risk assessment model based on Bayesian-Catastrophe-EPE for LNG bunkering and storage	Bayesian-Catastrophe-EPE model	energy release in uncontrolled condition based on both physical and chemical energies	analysis of LNG bunkering and storage is still lacking, highlighting the need for a comprehensive risk assessment approach.	escalations during LNG bunkering and storage are considerable and need to be further controlled	confirm the proposed integrated framework as an effective alternative for LNG bunkering and storage risk assessment.	effects and accident escalations, but does not propose the probability and consequence of each factor.
4)	(Nubli et al., 2022)	Presents the phenomenon related to accidental LNG release with discuss procedures for modelling and analysis of possible consequences.	CFD simulation, KFX, FLACS	LNG release on open deck from FGSS for gas dispersion and vapour cloud explosion	There is a lack of validated and mesh-sensitive CFD models for accurately analysing LNG explosion scenarios, due to the impracticality of full-scale experiments.	The implementation of CFD codes in the gas release and VCE simulations is useful since it is cheaper and saves a lot of time.	Integrating probabilistic methods with CFD to enhance scenario realism and by applying VCE simulation to optimise equipment layout in gas processing facilities.	The study remains the apply CFD to LNG release from ship while considering limited parameters.

5)	(Ventikos et al., 2022)	present and analyse a QRA methodology that is novel to the LNG bunkering	ALOHA (Areal Locations of Hazardous Atmospheres), FSA (Formal Safety Assessment)	Port of Piraeus (Greece), Truck-to-ship and ship-to-ship operation	Lacking a unified consequence model and structured methodology, especially a QRA approach tailored to LNG bunkering.	The risk entailed in STS operation is substantially higher than TTS	Provide practical insights for safer STS/TTS operations by applying a modular QRA framework.	Does not consider parametric value
6)	(Fan et al., 2023)	LNG Bunkering, Present a BN based DQRA methodology for LNG bunkering SIMOPs	Dynamic quantitative risk assessment, Bayesian network	Truck-to-ship operation, Shanghai port, PCTC, 200 m ³ of LNG,	The application of BN in DRA for LNG bunkering has not yet been thoroughly explored.	BN has advantages in handling the dynamic risks of LNG bunkering SIMOPs	The proposed DQRA model reflects real LNG bunkering operations by accounting for the timing of SIMOP event activations and deactivations.	The reliability of based data doubts due to a lack of suitable data collection from the industry of LNG bunkering.
7)	(Wang et al.,	LNG fuel system, Employ Formal Safety	Probability analysis, Formal safety assessment	LNG bunkering vessel with	Few studies have explored the safety and design of LNG	Leakage is one of the primary risks of a LNG	Demonstrates that the FSA method is effective for	The effectiveness of the risk

	2024)	Assessment (FSA) to LNG fuel system and address the safety analysis and design enhancement		Loading process, navigation process, bunkering process, and anchoring process	fuel systems, and the FSA approach has yet to be applied in this context.	bunkering vessel and fire and explosion accidents lead to serious consequence	identifying and reducing operational risks in LNG bunkering vessels.	control options is not presented.
8)	(Shao et al., 2022)	Present the findings and methodology of HAZID study for LNG fuelled fishing ship	Qualitative risk assessment, HAZID	HAZID workshop (Conceptual design of LNG fuelled small fishing ship, LNG fuel tank design, and fuel gas supply system)	Lack of HAZID Study of LNG fuelled fishing ship	The fire and explosion caused by gas leakage of connection parts (valves/flanges) are the most risk factors.	Provide a reference for the conceptual design of future alternative-fuel vessels.	Remains repeating the well-known methodology, HAZID study
9)	(Li and	Ensure the safety of LNG fuel	HAZID, CFD (FLACS)	Truck-to-ship operation, 24	Reliable LNG bunkering by tank	The leakage can occur in truck	Offers LNG tank truck bunkering and	Remains repeating the

	Liu, 2023)	bunkering operation of the LNG trucks at port		m ³ of LNG transport, leakage from three different size of hole (full hole, half hole and 1/10 hole) to identify combustible concentration	truck is essential to meet the fuelling needs of new and retrofitted ships.	hose joints due to various accidents, and a 25m range of restricted area can control the risk within an acceptable range.	proposes practical safety measures, such as restricted zones and equipment checks, based on quantitative leak analysis.	well-known methodology, HAZID study and CFD simulation for risk control option
10)	(Ianne et al., 2019)	Develop a quantitative assessment tool to support decision-making in the early process design of LNG	Consequence-based method for quantitative inherent safety assessment by an approaching relying on KPIs	Port-to-ship and ship-to-ship operation, Assess the inherent safety of bunkering options by a specific set of KPIs with the	The marine use of LNG lacks standardisation, with inconsistent safety regulations and limited data on infrastructure safety performance.	The LNG loading pumps located in the shore facility are the least inherently safe equipment, and shore-to-ship operation can	Support selecting future LNG-based processes and enhancing the safety of key bunkering system components.	There is a limitation to reduce the risk and recommend risk control option

		bunkering technologies		unit potential hazard index and the unit inherent hazard index		lead to the worst-case scenarios.		
11)	(Kim et al., 2022)	Propose the establishment of safety zones for ammonia bunkering while selecting a case ship.	Event tree, DNV Phast, PIDA, PDA	Truck-to-ship operation, 30 G/T ammonia fuel electric propulsion ship	Safety zones for ammonia bunkering have not yet been established, leaving uncertainty for upcoming ammonia-fuelled ships.	Leak rate effects to the dangerous range	Builds on previous LNG bunkering research by applying its approach to ammonia-fuelled ships, offering insights for developing safety standards for low-flashpoint fuel bunkering.	Does not consider environment factors such as wind speed and wind direction
12)	(Yan g and Lam,	Evaluate the operational risk associated with accidental	DNV Phast (Unified Dispersion Model), Sensitivity analysis	Port of Singapore, small, medium and large	Lack of research on how supply, release, and meteorological conditions affect	Release scale, wind speed, and hose diameter	The first to quantify the sensitivity of multiple factors affecting ammonia	Handle only gas dispersion not fire and explosion by

	2024)	ammonia release during ammonia bunkering operations		release (different sizes of hole and hose rupture)	ammonia bunkering risks, including sensitivity analysis and footprint-based risk comparisons.	are important factors	bunkering risk across various release scales	ammonia leakage
13)	(Duo ng et al., 2024 a)	Evaluating the impact of operational variables on ammonia cloud dispersion during accidental releases in bunkering operations.	EFFECTS	Truck-to-ship operation, 37,000L of ammonia storage vessel	Lack of generalisable safety zone guidelines and comprehensive risk assessments for truck-to-ship ammonia bunkering, especially under varied operational conditions like SIMOPs.	Hole size, ambient temperature, and wind speed affect the dispersion results. The hole size, leakage time, and amount of ammonia release linear with lethality of toxicity	Providing new insights into how key operational parameters influence ammonia dispersion over seawater and identifying potential risk reductions through parameter adjustments.	Handle only gas dispersion not fire and explosion by ammonia leakage

14)	(Fan et al., 2022)	Present a QRA framework based on BN for ammonia bunkering operations.	Extended event tree, ALOHA, Bayesian network models,	Ship-to-ship operation, 2,500 m ³ of ammonia transfer	There is no risk assessment framework using Bayesian Networks exists for quantifying ammonia bunkering risks in maritime operations.	The toxicity of ammonia contributes more than flammability to total risk	Demonstrates the applicability of Bayesian Networks in ammonia bunkering risk assessment by identifying dominant risk factors.	Consider individual risks only and ignoring the actual location environmental factors
15)	(Duong et al., 2023)	Proposes challenges and recommendations for good safety practices during the ammonia bunkering process.	Research and regulation review	Terminal-to-ship, ship-to-ship, truck-to-ship operations	The lack of integrated scientific research, regulatory clarity, and risk-based safety zone frameworks for ammonia bunkering, particularly under complex conditions like SIMOPs.	Volume, duration of leakage and weather conditions impact significantly to safety zone results	Advances ammonia bunkering safety by identifying and integrating key dispersion factors, addressing overlooked external variables.	Synthesise existing studies without generating new quantitative data

16)	(Ng et al., 2023)	Assess the operational parameters that affect the dispersion of ammonia clouds over the sea surface	DNV Phast	Ship-to-ship operation, 17,500 m ³ of ammonia carrier to 14,800 TEU container ship	There is limited understanding of safe ammonia bunkering practices and how ammonia disperses across the sea surface in the event of an accidental release.	Refrigerated storage of ammonia is the most effective in reducing operational risk.	Address how key operational parameters influence ammonia dispersion over seawater, offering practical guidance for designing effective control and mitigation measures in bunkering operations.	Unclear the impact of sensitivity for each factor to different release scales
17)	(Tofalos et al., 2020)	Contribute improvement of safety by investigating the safety of LNG and LH ₂ fuelled vessels during a process of bunkering	Quantitative risk assessment process	80,000 DWT bulk carrier, truck-to-ship and terminal-to-ship operation	A lack of systematic and comparative risk assessment studies for LNG and LH ₂ bunkering operations, despite regulatory gaps and high-risk levels in their fuel systems.	Redesign for hydrogen bunkering system and double wall piping and automatic leak detection system	Provides a comparative risk analysis of LNG and LH ₂ bunkering, establishes exclusion zones based on formal criteria, and identifies key	The results were not confirmed by formal software. Practical location and environmental

							operational factors affecting safety.	conditions are not considered
18)	(Feng et al., 2021)	Quantitative risk assessment to judge the acceptability of the risks and puts forward risk control measures and delimits the bunkering restricted area	HAZID, quantitative risk assessment, FLACS	2,000 DWT hydrogen powered ship,	A lack of clarity on the acceptability of risks and appropriate mitigation measures for hydrogen bunkering operations, particularly for hydrogen-powered ships in their early development stage.	Recommended the risk mitigation options to reduce frequency of leakage	Provides a quantitative risk assessment for hydrogen shore-based bunkering, proposes practical safety zones and separation distances	The failure data for recommendation methods are insufficient
19)	(Choi and Jeon, 2023)	Identify and mitigate the risks associated with hydrogen, particularly at	CFD (SOLIDWORKS, Pyrosim)	20t ammonia fuelled electric propulsion vessel	Direct hose leak scenarios of compressed hydrogen fuelled ships during	The length of the hydrogen plume increases while the width narrows until stabilises with	Offer understanding into how hydrogen gas plumes behave under varying wind directions and speeds, especially in open,	Only consider hydrogen gas dispersion

		the bunker station.			bunkering have not yet been studied.	the following wind direction	unobstructed environments.	
20)	(Fan et al., 2024)	Compare the safety of the three liquefied gas fuels during bunkering.	CFD (Fire Dynamics Simulator, FDS)	208,000 DWT bulk carrier, 2 scenarios for 0.3 m ³ / 100 kg leakage each with LNG, LH ₂ , LNH ₃	A lack of studies comparing the evaporation and dispersion behaviours of LNG, LH ₂ , and LNH ₃ under identical conditions.	Considering evaporation and dispersion, LNH ₃ is far more severe than LNG and LH ₂	Provide a detailed analysis of the dispersion behaviour of three marine liquefied gas fuels following release accidents during bunkering, conducted using CFD simulations.	The possibility fire and explosion of leaked fuel was not considered.
21)	(Hu et al., 2024)	Perform a numerical evaluation of fuel toxicity risks during routine vessel operations and	Integration of a QRA framework with Bayesian probability estimation and CFD simulations (ANSYS FLUENT)	A 50-ton coastal ammonia-powered harbour tug.	Critical lack of historical operational accident data for ammonia-powered vessels and a research focus previously limited	Operational accidents pose a higher risk than marine accidents, although both remain within acceptable	Offers a theoretical foundation for risk prevention systems and assists in calculating precise safety zones for ship personnel.	The study is confined to a specific tugboat vessel. Further research is required on internal

		potential marine accidents	using a dose-response model,		to bunkering scenarios.	ALARP (As Low As Reasonably Practicable) safety thresholds.		ammonia leakage risks within engine room environments.
22)	(Zhe ng et al., 2024)	To evaluate potential failure points in ammonia storage systems by applying a sophisticated hybrid FMEA framework.	FMEA integrated with Probabilistic Linguistic Terms (PLTs), a consensus-reaching process (CRP), and an improved GLDS method for prioritisation.	An industrial 10,000-ton ammonia storage tank and its associated refrigeration infrastructure.	Traditional FMEA methodologies struggle with modelling the uncertainty of subjective evaluation and fail to ensure consensus among diverse experts.	'Condenser cooling water pump failure' and 'failure of level transfer' were identified as the most critical risks to facility safety.	Enhances the reliability of risk prioritisation by effectively managing linguistic uncertainty and improving expert consensus.	The model lacks specific guidelines for the initial identification of failure modes, requiring tools like HAZID/HAZ OP as a supplement.
23)	(Dan asa et	To estimate the consequences	Utilisation of ALOHA software	A urea fertiliser	Necessity for comprehensive	Accidental releases during	Provides an essential reference for	The analysis is centred on a

	al., 2019)	and determine the risk level of accidental industrial ammonia releases.	for toxic plume forecasting and QGIS for spatial mapping of population impacts and evacuation factors.	manufacturing site located in Indonesia.	modelling that combines spatial population data with atmospheric conditions to predict casualties in chemical accidents.	the night are significantly more catastrophic (impacting 41.7 km ²) due to high atmospheric stability inhibiting gas dispersion.	governmental and industrial stakeholders to establish robust emergency response plans (ERP).	specific worst-case leakage scenario involving the failure of large storage vessels.
--	-------------------	--	--	--	--	---	---	---

As summarised in Table 4.1, the reviewed studies demonstrate that risk assessment research for low-flashpoint and hazardous fuels has expanded significantly across LNG, ammonia, and hydrogen applications, with LNG-related bunkering studies forming the most established body of work. Methodologically, the literature shows a progressive transition from qualitative screening tools, such as HAZID and HAZOP, towards more quantitative and consequence-oriented approaches, including FTA, ETA, Bayesian network models, CFD, PHAST, and integrated QRA frameworks. This progression indicates that while earlier studies primarily focused on identifying major accident scenarios and confirming operational feasibility, contemporary research increasingly seeks to quantify safety zones, restricted areas, toxic footprints, and operational risk levels under precisely defined release conditions.

Nevertheless, a critical synthesis of the analysed cases reveals that this technical progression has not always resulted in true methodological integration. Instead, qualitative techniques and quantitative simulations have frequently been applied in isolation rather than within a coherent and synergistic framework. This limitation is particularly pronounced in hydrogen and ammonia applications, where the scarcity of historical failure records and operational data leads to a heavy dependence on expert judgement during qualitative assessments, while simultaneously constraining the reliability of quantitative simulations through uncertain or weakly supported failure-rate assumptions. Consequently, data scarcity remains a key bottleneck that limits the statistical confidence, robustness, and broader applicability of the resulting risk profiles.

A clear pattern emerging from the reviewed studies is that LNG has served as the principal methodological reference for subsequent ammonia and hydrogen research. Many LNG studies addressing truck-to-ship, ship-to-ship, and terminal-based bunkering have demonstrated the applicability of probabilistic frequency analysis, consequence modelling, and CFD for evaluating exclusion zones and operational risk. However, even within the comparatively mature LNG literature, many studies remain case-specific, focusing on individual ports, specific transfer arrangements, or predefined leak scenarios. Several studies also lack parametric treatment, fail to

sufficiently examine environmental variability, or rely on limited underlying accident data, which constrains the broader applicability of their findings.

This case-specific tendency is also evident in more recent ammonia and hydrogen studies, where the applicability of results is often confined to particular vessel types, terminal geometries, or isolated operating conditions. For instance, the study on the first Korean ammonia fuel cell ship (Kim et al., 2022) provided a useful foundation for toxicity-based safety zone determination, but its limited treatment of fluctuating wind speed and direction reduced the extent to which the results could capture realistic environmental variability. Likewise, comparative analyses between liquid hydrogen and LNG (Tofalos et al., 2020) established credible fire and explosion scenarios, yet the absence of empirical validation continues to limit the robustness and transferability of the resulting safety distances across different maritime settings.

Furthermore, despite the diversity of tools applied, many studies still treat frequency analysis, consequence analysis, and human exposure assessment as separate tasks rather than as components of a single integrated framework. This fragmentation is closely linked to another recurring limitation, the widespread reliance on deterministic worst-case assumptions. Although the use of maximum release rates and unfavourable meteorological conditions provides a conservative safety margin, it often leads to disproportionately severe and operationally unrealistic safety zones (Aneziris et al., 2022). In restricted port areas, where space optimisation is critical, such expansive exclusion zones can impose impractical operational constraints and may ultimately hinder the commercial feasibility and early adoption of carbon-neutral fuel technologies.

To address these methodological shortcomings, recent research has increasingly moved towards more integrated frameworks, most notably the Population-Independent Analysis (PIDA) and Population-Dependent Analysis (PDA) approach proposed by Jeong (Jeong et al., 2020). By synthesising the physical hazard footprint with actual population distribution and exposure information, this methodology moves beyond traditional consequence-only models and provides a more realistic basis for estimating human risk under practical operating conditions.

Overall, the reviewed studies demonstrate that while substantial progress has been made in applying risk assessment methods to alternative fuel systems, recurring limitations related to case-specific assumptions, incomplete treatment of uncertainty, and the fragmented application of methods remain unresolved. These patterns highlight the necessity for a parametric integrated framework that can satisfy both regulatory rigour and operational feasibility.

4.5 Identified gaps

Based on the review of existing literature and applied case studies, several important gaps remain in the risk assessment of low-flashpoint and hazardous fuels. These gaps are not merely a result of a lack of analytical tools, but rather stem from the fragmented way in which existing methods are selected, combined, and interpreted. As the practice of the offshore oil and gas industry demonstrates, the underlying principles of integrated and probabilistic risk assessment are well established in other industries. However, the gaps identified below remain unresolved challenges in adapting and combining these established principles for hydrogen-fuelled maritime applications, where transient operations, novel fuel behaviour, and scarce operational data alter the conditions under which such methods can be applied. As a result, the current body of research often provides useful case-specific findings, but does not always offer a sufficiently consistent, transferable, or practically applicable basis for supporting broader safety and design decisions. In particular, three critical gaps can be identified.

The first major gap is the methodological fragmentation between qualitative hazard identification and quantitative risk evaluation. In many previous studies, qualitative methods such as HAZID, HAZOP, and FMEA have been applied mainly as preliminary tools for hazard screening and scenario selection, while quantitative methods such as CFD, FTA, ETA, PHAST, or QRA have been used separately to estimate consequences, event frequencies, or safety distances. Although both categories of methods provide valuable insights, they have frequently been applied as isolated stages rather than as components of a coherent and integrated assessment process.

This disconnect reduces the consistency of the overall risk assessment. In particular, the insights obtained during qualitative hazard identification are often not systematically transferred into the assumptions, parameter selection, and modelling boundaries used in quantitative simulations. As a result, important operational contexts, system-specific interactions, and realistic accident pathways may not be sufficiently reflected in subsequent consequence or frequency analysis. The literature therefore suggests that the main limitation is not the absence of either qualitative or quantitative tools, but the lack of an integrated assessment framework that coherently connects qualitative hazard identification and quantitative risk evaluation.

The second major gap is the strong dependence on deterministic worst-case assumptions. A large proportion of the reviewed studies assessed safety on the basis of maximum release rates, the most unfavourable meteorological conditions, or highly conservative boundary assumptions. While such approaches may be useful for establishing precautionary safety margins, they often do not sufficiently distinguish between extreme scenarios and representative operating conditions. As a result, many studies have produced disproportionately severe or operationally unrealistic safety zones, toxic impact areas, or exclusion distances.

This over-conservative tendency is particularly problematic in marine and port applications, where space optimisation and operational practicality are critical. Excessively large exclusion zones may impose severe restrictions on bunkering operations, port layouts, and surrounding activities, thereby reducing the practical feasibility of alternative fuel implementation. A major reason for this bias is that many existing studies treat physical consequence assessment in isolation, without adequately incorporating the probability of occurrence, scenario likelihood, or actual population exposure. Consequently, the resulting risk boundaries often reflect upper-bound hazard footprints rather than balanced and risk-informed safety requirements.

The third major gap lies in the limited treatment of environmental variability and parametric uncertainty. Gas dispersion, fire development, and explosion consequences are highly sensitive to environmental and operational parameters such as wind speed, wind direction, atmospheric stability, release scale, congestion,

and ventilation conditions. However, many existing studies have treated these factors as fixed inputs or have examined them only within a narrow range of assumptions. This limitation is especially significant in hydrogen- and ammonia-related studies, where empirical failure data and operational experience remain limited and modelling assumptions therefore play a more influential role in shaping the final results.

The absence of a robust parametric approach reduces both the reliability and the general applicability of the resulting safety assessments. Where only a limited number of scenarios are considered, it becomes difficult to determine whether the findings are broadly representative or merely specific to the selected assumptions. In addition, the scarcity of historical failure data for emerging fuels means that both qualitative and quantitative stages of assessment remain affected by substantial uncertainty. This not only weakens the statistical confidence of the resulting risk profiles, but also limits the ability to compare different fuels or operational arrangements on a consistent basis. The literature therefore indicates a clear need for approaches that can systematically examine the influence of varying environmental and operational parameters, rather than relying solely on static and highly case-specific conditions.

Overall, the reviewed literature demonstrates that substantial progress has been made in applying risk assessment methods to LNG, ammonia, and hydrogen systems. Nevertheless, it also confirms that existing approaches remain constrained by methodological fragmentation, deterministic over-conservatism, and insufficient integration of environmental and parametric variability. These limitations reduce the consistency, realism, and broader applicability of current safety assessments, particularly for emerging marine fuel systems. Addressing these limitations requires a structured framework that adapts and integrates established methods for the maritime context, which is the task undertaken in the following chapter.

5 METHODOLOGY

5.1 Introduction

As identified in the preceding literature review, current risk assessment practices for alternative marine fuel systems exhibit three principal shortcomings that collectively motivate the development of a structured risk assessment framework tailored to hydrogen-fuelled maritime applications. First, there is a persistent disconnect between qualitative hazard identification and quantitative numerical simulation, in which the two analytical stages are applied in isolation rather than through coherent integration. This fragmentation means that the operational contexts captured during hazard identification are not accurately reflected in the subsequent safety outcomes. Second, the prevailing reliance on static worst-case assumptions fails to account for the parametric variability inherent in real operating conditions, such as fluctuations in leak characteristics, system pressures, and dynamic environmental factors. Third, the case-specific nature of most existing studies confines their findings to particular vessel types, terminal geometries, or isolated operating conditions, limiting the generalisability of their conclusions. These limitations collectively highlight the need for a more structured, integrated, and generalisable risk assessment framework.

This chapter presents the methodology developed to address the identified gaps. The proposed framework provides a standardised tool that is structured into five sequential and interconnected phases. It is designed to transition systematically from initial system definition through qualitative hazard screening and quantitative risk modelling to integrated risk evaluation and comparative observation. Each phase builds upon the outputs of the preceding phase, ensuring a coherent analytical progression from the identification of credible hazardous scenarios to the determination of risk-informed safety requirements.

A key characteristic of this framework is its generalisability. Rather than being constrained to a single fuel type, system configuration, or application context, the methodology provides a common procedural structure within which different case

studies can be conducted under consistent analytical logic. The following sections first clarify the analytical scope and focus of the case studies to which this framework is applied, then present the overall structure of the integrated framework, followed by a detailed description of each of the five phases.

5.2 Analytical scope and focus

Before proceeding to the detailed description of each phase, it is necessary to clarify the analytical scope of the case studies to which this framework is applied. The risk assessment presented in this thesis focuses specifically on external fuel release scenarios, that is, releases occurring outside the enclosed hull structure of the vessel, including on open decks, at bunkering interfaces, around external pipe runs, and from topside equipment. This section provides the rationale for this focus.

In ship design, fuel releases occurring inside compartments or below-deck spaces can, in principle, be managed through multiple layers of engineered safeguards. These typically include mechanical ventilation systems designed to prevent gas accumulation, fixed gas detection arrangements for early warning and emergency shutdown, gas-tight and enclosed space boundaries to confine hazardous atmospheres, fixed fire-fighting equipment, A-60 grade fire protection materials, and a range of sensors including flame detectors and heat detectors (IMO, 2016). Taken together, these measures provide a multi-layered defence system that is capable of detecting leaks at an early stage, controlling gas concentrations within defined limits, and confining the consequences of an incident within specific structural boundaries of the vessel. Even in the event of a major internal release, the physical extent of the hazardous effects can be contained within the ship structure, and the escalation potential can be managed through the coordinated action of these safeguards.

Importantly, these internal safeguard requirements are already codified in quantitative terms within the existing regulatory framework. The IGF Code and associated classification society rules specify prescriptive requirements for internal fuel-handling spaces with considerable precision, including minimum ventilation capacity of 30 air changes per hour for single-wall fuel pipe installations, gas

detection alarm thresholds at 20% of the lower flammability limit (LFL) with automatic shutdown at 40% LFL, and detailed specifications for A-60 grade fire-rated boundaries, gas-tight enclosures, and emergency shutdown arrangements. Comparative analyses of classification society rules have confirmed that, while some differences exist between individual class requirements, the prescriptive coverage for internal spaces is broadly comprehensive and provides a well-defined baseline for design compliance (Jang et al., 2023). Consequently, the safety of internal fuel-handling spaces can, to a large extent, be addressed through demonstrating compliance with these existing prescriptive standards, without necessarily requiring a full risk-based assessment.

External releases present a fundamentally different risk profile. A fuel release in an open or semi-open environment results in immediate and direct contact between the released substance and the surrounding atmosphere, with no engineered confinement to limit the spatial extent of the hazardous effects. The application of active mitigation measures, such as forced ventilation or controlled gas sensing, is physically limited in an open-air environment. As a result, the consequences of an external release cannot be confined within the boundaries of the vessel but may extend into the surrounding environment, potentially affecting adjacent vessels, port infrastructure, and personnel in the wider area (Jang et al., 2024).

The significance of external releases has changed fundamentally with the transition from conventional fossil fuels to alternative low-flashpoint and hazardous fuels. Under the traditional fossil fuel paradigm, external fuel spills were primarily an environmental concern (ITOPF, 2025). The probability of fire or explosion from a conventional fuel spill in an open environment was comparatively low, and the dominant risk was pollution rather than thermal or toxic harm to personnel. For LNG, the situation was somewhat different in that gas accumulation from an evaporating pool could potentially form a flammable cloud. However, in open spaces, the natural buoyancy and rapid dispersion of methane vapour was generally regarded as a favourable safety characteristic, as it reduced the likelihood of sustained flammable concentrations in the vicinity of the release (Ha and Lee, 2026).

Hydrogen introduces a qualitatively different external release risk. Its exceptionally wide flammability range (4% to 75% by volume), extremely low minimum ignition

energy (approximately 0.017 mJ, which is nearly two orders of magnitude lower than that of methane), high flame speed, and strong buoyancy mean that an atmospheric release of hydrogen is far more likely to result in ignition than a comparable release of LNG or conventional fuels (Molkov, 2012). Furthermore, for high-pressure storage systems, research has demonstrated that sudden hydrogen release can produce spontaneous ignition through shock-induced heating of the ambient air at the leak point, without the need for any external ignition source. This phenomenon has no practical equivalent in LNG or conventional fuel systems and represents a fundamentally different ignition mechanism that is specific to high-pressure hydrogen releases in open environments (Astbury and Hawksworth, 2007).

The review of historical accident data confirms this assessment across both maritime and land-based contexts. Within the maritime environment, the recorded cases examined in Chapter 3, including the THOR EMILIE explosion (2000, six fatalities, total loss), the UK port hydrogen explosions (2017), and the Suiso Frontier vent flame event (2022), demonstrate that hydrogen releases in marine settings rarely remain as benign dispersion events and frequently escalate into fire or explosion. Crucially, evidence from land-based hydrogen facilities reinforces the same pattern. The Gangneung hydrogen storage facility explosion (2019, two fatalities, complete facility destruction), the Sandvika hydrogen refuelling station explosion (2019, blast damage extending over 100 metres), and the Santa Clara tube trailer fire (2019, total equipment loss) all involved atmospheric hydrogen releases that resulted in immediate or near-immediate ignition and significant consequences. Taken together, these maritime and land-based cases provide converging evidence that hydrogen, once released to the open atmosphere, exhibits a consistently high probability of ignition and rapid escalation to fire or explosion, regardless of the specific industrial setting.

Ammonia presents a complementary but equally critical concern. Although ammonia has a comparatively narrow flammability range and higher ignition energy than hydrogen, its principal external hazard is acute toxicity. Ammonia is immediately dangerous to life and health at relatively low atmospheric concentrations, and the gas dispersion from an external release can produce toxic footprints that extend well beyond the immediate vicinity of the release point.

Unlike hydrogen, where the dominant concern is fire and explosion, ammonia releases pose a direct inhalation hazard that can cause severe injury or fatality at distances that may reach into populated areas surrounding the vessel or port (Jang et al., 2024).

Consequently, the external release of alternative marine fuels represents a hazard category in which the consequences are no longer confined to the vessel itself but may extend to the surrounding maritime and urban environment. This represents a fundamental departure from the conventional fuel paradigm, where external releases were primarily managed as environmental incidents. For hydrogen and ammonia, external releases have the potential to cause direct harm to human life across areas that may encompass neighbouring vessels, port facilities, and, in the case of bunkering operations in or near urban ports, adjacent city districts.

It is also notable that this category of release scenario corresponds precisely to the area of greatest regulatory uncertainty. As discussed above, the current international regulatory framework provides relatively detailed and quantitative prescriptive requirements for internal fuel-handling spaces, covering ventilation rates, gas detection thresholds, fire protection standards, and compartment design. By contrast, for external safety distances, bunkering exclusion zones, and the spatial delineation of hazardous zones in open-air environments, the available prescriptive guidance is either absent or insufficiently defined in quantitative terms. The IGF Code, for example, does not specify explicit numerical safety distances for bunkering operations or external release scenarios, instead relying on general provisions that require risk-based assessment without providing detailed criteria or methodology. This asymmetry between the relatively mature regulatory coverage of internal spaces and the significant gaps in external safety distance requirements further reinforces the need for a risk-based assessment framework specifically focused on external release scenarios.

For these reasons, the case studies presented in Chapters 6 and 7 focus on external fuel release scenarios. Chapter 6 examines the bunkering interface, where fuel is transferred between supply and receiving vessels in an open or semi-open environment. Chapter 7 examines the vent master release from an ammonia cracking system, where processed gas is discharged to the external atmosphere. In

both cases, the absence of engineered confinement, the direct atmospheric exposure of the released fuel, and the potential for off-ship consequences define the analytical scope of the assessment.

5.3 Overview of the integrated framework

The integrated risk assessment framework developed in this study consists of five phases: Scenario and System Definition, Qualitative Hazard Identification and Risk Screening, Quantitative Risk Assessment, Risk Integration, and General Observations. The rationale for this structure follows the well-established logic of risk assessment as formalised in the IMO Formal Safety Assessment (FSA) guidelines (IMO, 2018) and ISO 31000 (ISO, 2018), whilst extending it to accommodate the parametric and comparative requirements identified in the literature review.

As the literature review has shown, the difficulty lies not in a shortage of analytical tools but in their fragmented and case-specific application, and although academic studies have increasingly combined qualitative and quantitative methods, they do not yet provide a procedure that can be applied to the determination of safety and hazardous zones for an individual vessel or bunkering operation. The same limitation is visible on the regulatory side. The FSA guidelines were developed to support the IMO rule-making process and therefore operate at the fleet scale, assessing the collective risk of entire ship categories rather than the design of an individual vessel. ISO 31000 provides general risk management principles applicable across industries but does not prescribe an operational assessment procedure. Neither instrument, however, provides a directly deployable procedure for determining safety and hazardous zones for an individual hydrogen-fuelled vessel or bunkering operation.

The proposed framework addresses this gap in two respects. First, whereas conventional practice proceeds in a largely one-directional sequence, the framework establishes an explicit procedural linkage between its qualitative and quantitative stages. This arrangement preserves consistency between the qualitative and quantitative stages throughout the assessment. Second, the framework embeds

parametric scenario analysis as a formal sub-phase, links the integrated risk results directly to the spatial determination of safety and hazardous zones, and supports comparative risk profiling across fuel types under standardised conditions. While the constituent techniques of each sub-phase are available from established practice, the originality of the framework lies in this structured procedural integration, which converts the general requirements of existing instruments into an operational end-to-end procedure for the determination of safety and hazardous zones in hydrogen-fuelled maritime applications.

Phase 1 establishes the physical, operational, and regulatory boundaries of the system under consideration. Phase 2 applies structured qualitative techniques to identify credible hazardous scenarios and to screen these scenarios according to their potential severity and relevance. Phase 3 undertakes the quantitative evaluation of the screened scenarios through parametric consequence modelling and failure frequency estimation, producing spatial hazard footprints for each scenario. Phase 4 synthesises the frequency and consequence outputs into integrated risk measures, evaluates these against established acceptance criteria predetermined in Phase 1 and, where appropriate, against the qualitative risk matrix applied in Phase 2, and verifies the resulting safety levels. Phase 5 draws together the findings from the preceding phases to produce comparative risk profiles, assess regulatory compliance, and formulate risk-informed recommendations.

This sequential structure ensures that the framework progresses from broad system-level scoping to increasingly focused and quantitative analysis. At the same time, the outputs of each phase provide traceable inputs to the subsequent phase, maintaining analytical coherence throughout the assessment process. The overall methodology is outlined in Figure 5.1, followed by a detailed description of each phase.

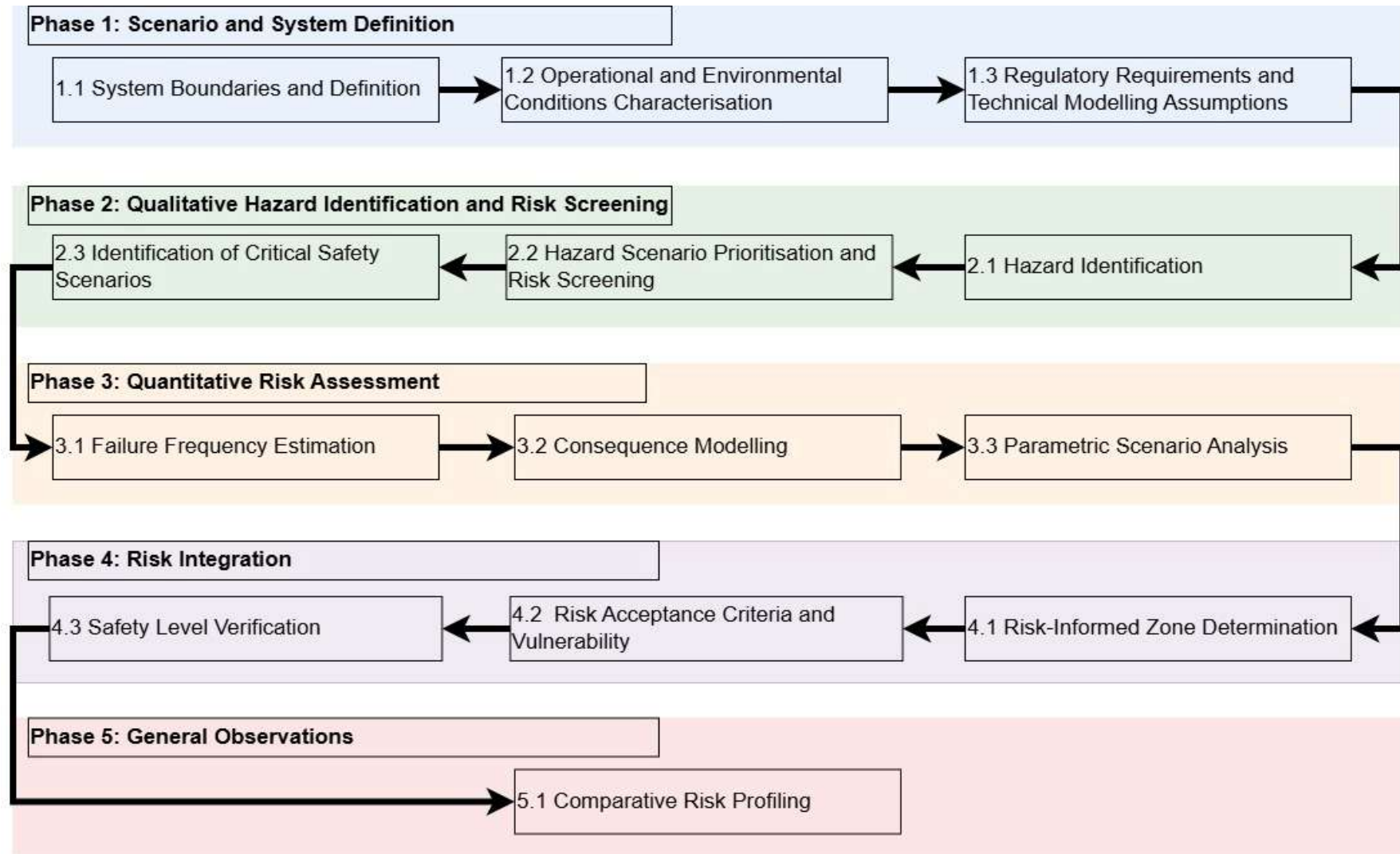


Figure 5.1 Outline of integrated risk assessment framework

5.3.1 Phase 1: Scenario and system definition

The first phase of the framework establishes the foundational basis upon which the entire risk assessment is constructed. Its purpose is to define, with sufficient clarity and precision, what system is being assessed, under what conditions, and against which regulatory and technical benchmarks. Without a clearly defined system boundary and a well-characterised set of operating conditions, the subsequent phases of hazard identification and quantitative modelling cannot proceed on a consistent or reproducible basis.

5.3.1.1 *System boundaries and definition*

The first step involves delineating the physical and functional boundaries of the system under assessment. This includes the identification of the vessel type, its fuel system architecture, the spatial arrangement of fuel-handling equipment, and the interface between the ship and its operating environment. In the context of this thesis, system boundaries are defined for two distinct application contexts. For bunkering operations, the boundary encompasses the fuel transfer interface, manifold connections, and surrounding areas exposed to accidental releases. For onboard fuel systems, the boundary includes fuel storage, fuel preparation, and fuel supply arrangements within the vessel structure, with particular attention to the points at which processed or vented gases are discharged to the external environment.

System definition also involves the specification of fuel types to be considered. In the present study, liquefied natural gas (LNG), liquefied hydrogen (LH₂), compressed gaseous hydrogen (GH₂), and liquefied ammonia (LNH₃) are included as target fuels, reflecting the current range of alternative marine fuels under active consideration by the industry. Each fuel is characterised by its specific physical and chemical properties, including boiling point, flammability range, ignition energy, toxicity thresholds, and phase behaviour under relevant operating pressures and temperatures. These properties form the basis for subsequent consequence modelling and directly influence the selection of appropriate hazard metrics and safety criteria.

5.3.1.2 Operational and environmental conditions characterisation

The second step characterises the operational and environmental conditions that govern the behaviour of accidental releases and their potential consequences. This involves the definition of parameters such as operating pressure and temperature of the fuel system, ambient temperature and atmospheric stability class, wind speed and direction, and the duration and mode of fuel transfer operations. These parameters are not fixed at single values but are defined as ranges or representative conditions to support the parametric analysis undertaken in Phase 3.

For bunkering operations, the characterisation also includes the specification of bunkering location, surrounding infrastructure geometry, and population distribution in the vicinity of the transfer point. For onboard systems, it includes the ventilation arrangements, compartment geometry, and the proximity of fuel-handling equipment to accommodation and machinery spaces. The selection of environmental parameters is informed by representative meteorological data and by the operational profiles typical of the vessel type under consideration.

5.3.1.3 Regulatory requirements and technical modelling assumptions

The third step identifies the applicable regulatory requirements and establishes the technical assumptions that underpin the subsequent analysis. This includes a review of the relevant provisions of the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code), applicable classification society rules, and any fuel-specific standards or guidelines. The purpose of this review is twofold. First, it identifies the prescriptive requirements that must be satisfied as a baseline. Second, it identifies areas where prescriptive rules are absent or insufficiently defined, thereby justifying the application of risk-based assessment.

In addition to regulatory requirements, this step also establishes the risk acceptance criteria to be used in Phase 4 for evaluating the integrated risk results. These criteria typically include individual risk thresholds, expressed as the annual probability of fatality at a given location. For the present study, the individual risk criteria adopted are consistent with those recommended by recognised standards, such as the DNV guidelines for quantitative risk assessment, with threshold levels of 1×10^{-5} , 1×10^{-6} , and 1×10^{-7} per year. By defining these criteria at the system definition stage rather than at the evaluation stage, the framework ensures that the assessment is conducted

against a predetermined and transparent benchmark, thereby avoiding post-hoc adjustment of acceptability thresholds.

Technical modelling assumptions, such as leak hole sizes, leak directions, ignition probabilities, isolation response times, and discharge models, are also specified at this stage. These assumptions provide the common analytical basis for the parametric scenarios developed in Phase 3 and are documented explicitly to ensure transparency and reproducibility.

5.3.2 Phase 2: Qualitative hazard identification and risk screening

The second phase of the framework applies structured qualitative techniques to identify the credible hazardous scenarios that warrant further quantitative analysis. This phase serves as the analytical bridge between the system definition established in Phase 1 and the numerical modelling undertaken in Phase 3. Its purpose is to ensure that the subsequent quantitative effort is directed towards the most safety-critical scenarios, rather than being applied indiscriminately to all conceivable failure modes.

5.3.2.1 Hazard identification

Hazard identification is conducted using established systematic techniques, principally Hazard Identification (HAZID), Hazard and Operability Study (HAZOP) and, where appropriate, Failure Mode and Effects Analysis (FMEA). These techniques draw upon the collective judgement and experience of subject matter experts to identify potential sources of hazardous releases, their causes, and the possible consequences. For hydrogen-fuelled ship systems, this process requires particular attention to failure modes that are specific to or exacerbated by the properties of the fuel. For liquefied hydrogen systems, these include cryogenic leakage, rapid phase transition upon contact with surrounding structures or seawater, and hydrogen embrittlement of containment materials. For compressed gaseous hydrogen systems, the primary concerns include high-pressure gas release from storage vessels operating at pressures of 300 bar or above, spontaneous ignition through shock-induced heating at the leak point, and the rapid formation of

flammable atmospheres owing to the exceptionally wide flammability range and low ignition energy of hydrogen.

The hazard identification process is structured around the system boundaries and operational conditions defined in Phase 1. For bunkering operations, the focus is on the fuel transfer interface and associated pipework, manifold connections, hose assemblies, and emergency shutdown systems. For onboard systems, the identification extends to fuel storage tanks, fuel preparation rooms, gas valve units, venting arrangements, and the interfaces between fuel-handling spaces and adjacent ship compartments.

5.3.2.2 Hazard scenario prioritisation and risk screening

Following the identification of hazards, the resulting scenarios are prioritised and screened to determine which require detailed quantitative assessment. This screening is typically performed using a qualitative risk matrix, in which each scenario is assigned a qualitative rating for both likelihood and consequence severity. Scenarios that fall within the higher-risk categories are carried forward to Phase 3, while those assessed as negligible or adequately addressed by existing prescriptive measures may be screened out with appropriate justification.

The screening process also considers the type of consequence associated with each scenario. For flammable fuels such as hydrogen and LNG, the relevant consequence types include jet fire, pool fire, flash fire, and vapour cloud explosion. For toxic fuels such as ammonia, the consequence assessment must additionally account for toxic gas dispersion and the associated health effects on exposed personnel. This distinction is important because it influences the selection of appropriate consequence models and safety criteria in subsequent phases.

5.3.2.3 Identification of critical safety scenarios

The final output of Phase 2 is a defined set of critical safety scenarios that are taken forward for quantitative analysis in Phase 3. Each scenario is characterised by its initiating event, the nature of the release, the fuel involved, the location of the release point, and the expected consequence type. This set of scenarios constitutes the analytical scope of the subsequent quantitative assessment and ensures that the modelling effort is concentrated on the scenarios of greatest safety significance.

5.3.3 Phase 3: Quantitative risk assessment

The third phase constitutes the core quantitative component of the framework, in which the critical scenarios identified in Phase 2 are subjected to detailed numerical analysis. This phase produces two principal outputs: the physical extent of the hazardous effects associated with each scenario, and the estimated frequency of occurrence of each scenario. Together, these outputs provide the necessary inputs for the risk integration performed in Phase 4.

5.3.3.1 Failure frequency estimation

Failure frequency estimation quantifies the frequency of the initiating leak event and the frequency of progression to each final consequence outcome. This phase does not consider the frequency of the initiating leak event in isolation. It instead combines the initiating leak frequency, the leak quantity, and the ignition probability of the released fuel to calculate the frequency with which the final consequence of a fuel leakage accident occurs.

The frequency of the initiating leak event is derived from published failure rate databases applicable to the type of equipment and operating conditions under consideration. Where direct historical data for hydrogen systems are unavailable, the estimation is based on other reliable data drawn from low-flashpoint fuels of comparable characteristics, such as LNG. Ignition probabilities, isolation success rates, and ventilation effectiveness are similarly drawn from recognised data sources and are applied consistently across all scenarios to ensure comparability.

A critical aspect of the frequency estimation is the treatment of uncertainty arising from the limited operational experience with hydrogen marine systems. Where data are sparse, conservative but reasonable assumptions are adopted and their influence on the results is assessed through sensitivity analysis. This treatment ensures that the frequency estimates, while acknowledging data limitations, remain grounded in the best available evidence.

5.3.3.2 Consequence modelling

Consequence modelling is used to quantify the physical effects of accidental releases, including gas dispersion, thermal radiation from fires, overpressure from

explosions, and toxic concentration distributions. The objective is to characterise the spatial extent and severity of each hazard outcome so that the resulting footprints can be carried forward into the parametric and risk integration phases.

The specific modelling tools employed depend on the nature of the scenario and the required level of spatial resolution. For scenarios involving complex geometries, confinement effects, or near-field dispersion behaviour, Computational Fluid Dynamics (CFD) is used to provide high-fidelity three-dimensional simulation of gas release, dispersion, and combustion. For scenarios where the release occurs in relatively open or unobstructed environments, phenomenological models or integral dispersion models may be used to provide computationally efficient estimates of hazard distances. The selection of modelling approach for each scenario is documented and justified on a case-by-case basis within the individual case studies presented in subsequent chapters.

5.3.3.3 Parametric scenario analysis

This sub-phase integrates the outputs of the failure frequency estimation and the consequence modelling to generate results across a wide range of scenarios. Rather than relying on a single set of fixed conditions, the frequency and consequence calculations are repeated across a systematically varied range of input parameters, such as leak hole size, operating pressure, wind speed, atmospheric stability class, leak direction, and fuel type. This process examines the sensitivity of safety outcomes to changes in individual input variables and identifies which factors exert the most critical influence on the resulting hazard footprint.

The combined outputs of the consequence modelling and the failure frequency estimation are used to delineate the spatial hazard footprint for each scenario. The hazard footprint represents the spatial area within which the physical effects of an accidental release exceed a defined threshold. For fire scenarios, this threshold is typically expressed in terms of thermal radiation intensity. For explosion scenarios, it is expressed in terms of overpressure.

The delineation of hazard footprints for each parametric combination of conditions produces a set of spatially referenced consequence envelopes. These envelopes provide the basis for the risk integration in Phase 4, where the frequency and

consequence dimensions are combined to define the spatial areas used to evaluate the resulting risk levels against the acceptance criteria established in Phase 1.

5.3.4 Phase 4: Risk integration

The fourth phase brings together the separate strands of quantitative analysis produced in Phase 3 to form a unified assessment of risk. The frequency and consequence outputs are first organised into an integrated spatial representation of risk around the release source. The acceptable extent of this risk is then established against predetermined criteria, and the corresponding safety level is verified for each scenario. In this way, the phase translates the dispersed parametric results into a coherent and defensible basis for defining safety and hazardous zones.

5.3.4.1 Risk-informed zone determination

This sub-phase synthesises the frequency and consequence results generated in Phase 3 to express the spatial extent of risk in an integrated form. Whereas the preceding phase produces the outcomes of individual scenarios, this sub-phase organises the consequence values against their corresponding accident frequencies so that the full set of results can be interpreted at a glance.

Risk synthesis is performed by combining the estimated frequency of each scenario with its corresponding spatial consequence footprint. For each point in space surrounding the release source, the individual risk contribution from each scenario is calculated as the product of the scenario frequency and the conditional probability of harm at that location. The total risk at any given point is then obtained by summing the contributions from all relevant scenarios, producing an integrated spatial representation of risk around the release source.

The synthesis accounts for all parametric variations considered in Phase 3, thereby reflecting the full range of operating conditions, release characteristics, and environmental influences. This integrated treatment ensures that the resulting risk distribution is not dominated by any single extreme scenario but instead represents the aggregated risk from all credible combinations of conditions.

5.3.4.2 Risk acceptance criteria and vulnerability

Building on the spatially integrated risk representation produced in the preceding sub-phase, this sub-phase establishes the extent to which the assessed risk is acceptable. The specific form of this evaluation depends on the risk metric adopted for the case study under consideration. In the first case study, the acceptable extent is determined through Population-Dependent Analysis (PDA), which incorporates the population exposed at each location. In the second case study, it is determined through the HAZID risk matrix, which classifies each scenario according to its likelihood and consequence severity.

Where individual risk is the governing metric, the evaluation adopts a tiered spatial classification. Locations where the individual risk exceeds the upper threshold are classified as unacceptable and require either design modification or the imposition of access restrictions, while locations where the risk falls below the lower threshold are classified as broadly acceptable. Locations falling between the two thresholds are subject to the ALARP (As Low As Reasonably Practicable) principle, under which additional risk reduction measures are required unless it can be demonstrated that the cost of further mitigation is grossly disproportionate to the safety benefit achieved.

Regardless of the metric employed, this evaluation produces a quantitative and defensible basis for distinguishing acceptable from unacceptable regions. By grounding the classification in explicit acceptance criteria and integrated risk evidence rather than in deterministic consequence distances alone, this sub-phase ensures that the resulting safety requirements reflect the combined contributions of multiple scenarios, varying release conditions, and probabilistic frequency estimates.

5.3.4.3 Safety level verification

The final sub-phase of Phase 4 designates the acceptable spatial extent for each scenario in accordance with the criteria established in the preceding sub-phase. This involves comparing the spatial extent of each risk zone with the physical layout of the system. Where the assessed risk exceeds the accepted threshold at locations where personnel may be present, the analysis identifies the need for additional risk control measures, design modifications, or operational restrictions.

Safety level verification also provides the basis for determining safety zones and exclusion distances. By identifying the boundary at which the individual risk falls below the accepted threshold, the framework produces a quantitative and defensible basis for safety zone delineation that is directly traceable to the underlying risk assessment.

5.3.5 Phase 5: General observations

The fifth and final phase draws together the results of the preceding phases to produce broader safety insights that extend beyond the individual case study. While Phases 1 through 4 are primarily concerned with the systematic execution of the risk assessment for a specific system and set of conditions, Phase 5 provides the interpretive context necessary to translate the technical results into actionable guidance for design, regulation, and operational practice.

5.3.5.1 *Comparative risk profiling*

Where the framework has been applied to multiple fuel types or system configurations under comparable conditions, comparative risk profiling is used to examine the relative safety performance of each option. This involves the side-by-side comparison of integrated risk results, hazard footprints, and safety zone extents derived from the same methodological framework and, where possible, from standardised boundary conditions. The comparative approach is a central feature of this thesis, as it enables the identification of fuel-specific risk characteristics that may not be apparent from isolated assessments. For example, the comparison may reveal that one fuel type produces a larger hazardous footprint for fire scenarios but a smaller footprint for toxic dispersion, or that the required safety zone for bunkering varies substantially between fuels even under identical operating conditions.

The results of the risk assessment are reviewed in the context of applicable regulatory requirements and practical implementation constraints. This review examines the extent to which the findings are consistent with existing prescriptive rules, identifies areas where current regulations may be insufficient or overly

conservative, and assesses the practical feasibility of implementing the risk-informed safety measures in real operational environments. The applicability review also considers the transferability of the results to other vessel types, port configurations, or operating conditions beyond those directly assessed in the case studies.

Based on the integrated analysis and comparative observations, risk-informed recommendations are formulated for ship designers, port authorities, and regulatory bodies. These recommendations address the delineation of safety zones, the specification of exclusion distances, the design of ventilation and gas detection systems, and the development of operational procedures for fuel handling and bunkering. The recommendations are grounded in the quantitative risk evidence produced by the framework and are intended to support decision-making that balances safety requirements with operational feasibility.

5.4 Summary

This chapter has presented the integrated risk assessment framework developed in this thesis to address the methodological gaps identified in the literature review. The framework is structured into five sequential phases: Scenario and System Definition, Qualitative Hazard Identification and Risk Screening, Quantitative Risk Assessment, Risk Integration, and General Observations. Each phase contributes a distinct analytical function, and together they provide a coherent and traceable pathway from initial system characterisation to the formulation of risk-informed safety requirements.

A distinguishing feature of the methodology is its focus on external fuel release scenarios, as justified in previous section. The transition from conventional fossil fuels to hydrogen and ammonia has fundamentally altered the risk profile of external releases, transforming what was historically an environmental concern into a direct threat to human life that may extend well beyond the vessel boundary. This focus is further supported by the asymmetry in the current regulatory framework, where internal fuel-handling spaces are governed by detailed prescriptive

requirements, while external safety distances and exclusion zones remain insufficiently defined in quantitative terms.

The five-phase structure provides a common procedural logic that can be applied across different fuel types, system configurations, and operational contexts, while the specific analytical tools and input data are selected on a case-by-case basis to reflect the characteristics of each application. This combination of methodological consistency and analytical flexibility distinguishes the proposed framework from the fragmented, case-specific approaches that currently dominate the literature.

The application of this framework to two representative case studies is presented in the following chapters. Chapter 6 applies the framework to the establishment of safety zones for hydrogen, ammonia, and LNG bunkering operations. Chapter 7 applies the framework to the definition of toxic and hazardous zones on hydrogen-fuelled ships with ammonia cracking systems. Together, these case studies demonstrate the effectiveness and versatility of the proposed methodology in addressing the safety challenges associated with hydrogen-fuelled ships.

6 A PIDA-PDA Integrated parametric approach for establishing safety zone for hydrogen, ammonia and LNG bunkering operations

6.1 Background and scope

This chapter presents the first of two case studies in which the integrated risk assessment framework developed in Chapter 5 is applied to a specific engineering problem. Specifically, this study addresses the quantitative determination of bunkering safety zones for three alternative marine fuels, liquefied natural gas (LNG), ammonia (NH₃), and hydrogen (H₂). The case study is based on the work published in the peer-reviewed journal paper by Hwang et al. (2026), "A PIDA-PDA Integrated Parametric Approach for Establishing Safety Zone for Hydrogen, Ammonia and LNG Bunkering Operations," International Journal of Hydrogen Energy, and presents the application of the integrated methodology within the overarching thesis framework (Hwang et al., 2026).

Bunkering represents one of the most operationally critical phases in alternative fuel handling, during which large volumes of hazardous substances are transferred between shore facilities or vessels in port environments characterised by significant personnel exposure (Fan et al., 2021). Despite the recognised urgency of establishing clear and defensible safety zones for such operations, existing regulatory provisions remain prescriptive, fragmented, and predominantly based on deterministic worst-case assumptions. This observation applies most notably to the IGF Code and its associated classification society guidance. These approaches fail to capture the influence of fuel-specific physical properties, environmental variability, or the probabilistic contribution of varying operational conditions to the overall risk profile. The result is either excessively conservative exclusion zones that constrain port operations and impede fuel adoption, or insufficiently differentiated guidance that does not reflect the genuinely distinct hazard profiles of LNG, ammonia, and hydrogen.

To address these deficiencies, this chapter presents the full application of the thesis methodology across all five phases. The methodology integrates consequence and frequency analyses within a parametric comparative framework, culminating in the application of Population-Independent Analysis (PIDA) and Population-Dependent Analysis (PDA) to produce risk-informed safety zones.

6.2 Case study

The risks associated with ammonia and hydrogen bunkering operations are shaped by both the frequency and severity of potential hazardous events. In the current maritime context, the frequency of such events remains inadequately characterised, compounded by the unpredictable nature of real-world port operations and the limited operational history of these emerging fuel systems. Given the scarcity of comprehensive historical incident data for alternative fuels, it is challenging to anticipate and eliminate all possible risk pathways in advance. Accordingly, this study systematically characterises both the likelihood and the consequences of potential accidents through an integrated analytical workflow. The primary analytical tool employed was DNV PHAST software, a leading commercially available platform for chemical process incident analysis, which is widely adopted in the process safety industry and has been extensively validated against experimental release data. PHAST simulates the full progression of a chemical release, from the initial leak through cloud or pool formation to dispersion. The software calculates consequence parameters including gas concentration levels, fire thermal radiation, toxicity exposure, and explosion overpressure (DNV, 2021). Both consequence and frequency analyses were performed within this software to map the spatial distribution of spill impacts and evaluate the probability and severity of potential accidents. Figure 6.1 illustrates how each of the five phases of the integrated risk assessment framework is operationalised in this case study, mapping the specific analytical inputs, modelling procedures, and outputs onto the general framework structure established in Chapter **Error! Reference source not found.**.

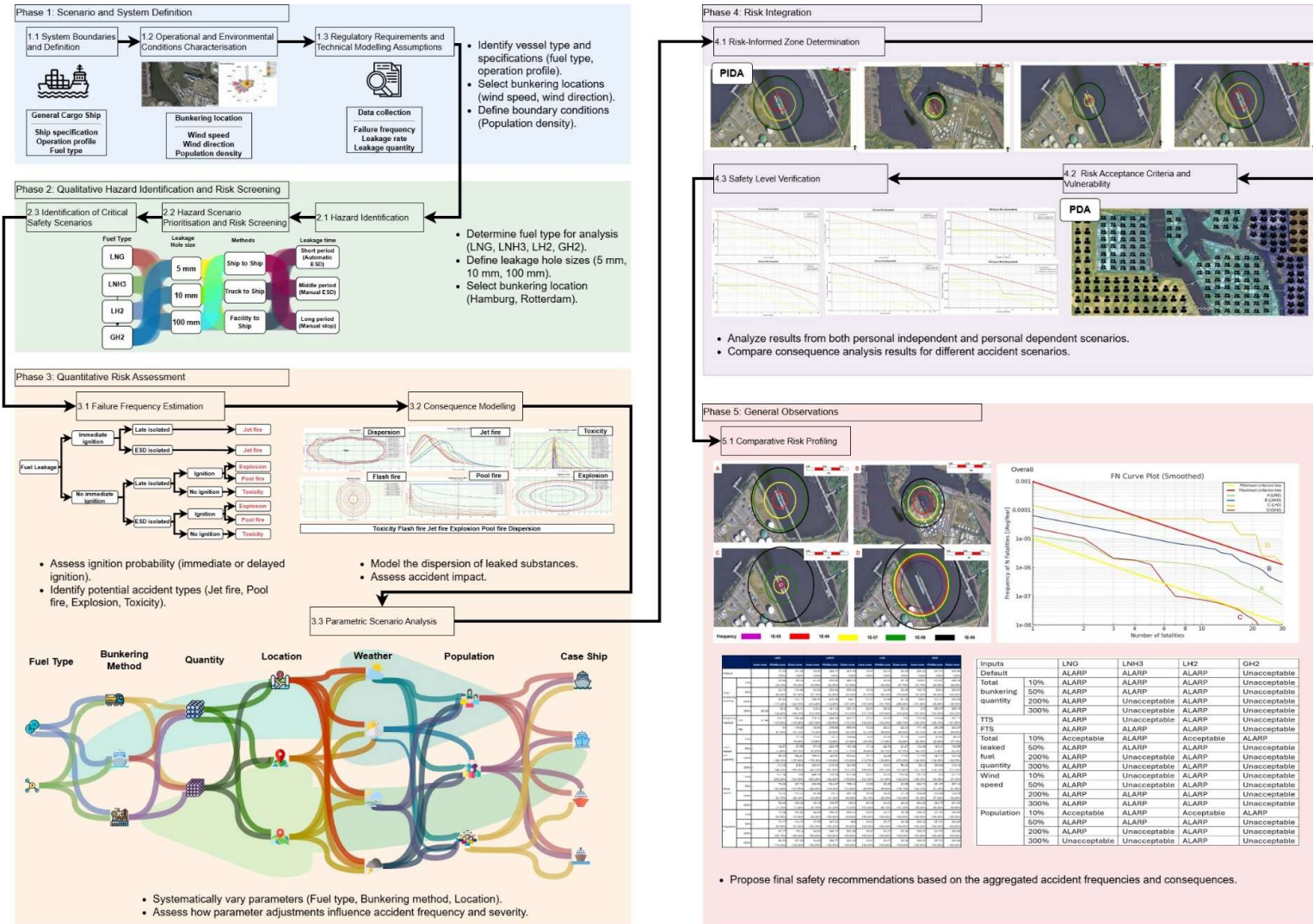


Figure 6.1 Application of the five-phase risk assessment framework to the bunkering safety zone case study

6.2.1 Phase 1- Scenario and system definition

The initial phase establishes the physical and operational boundaries within which the risk assessment is conducted. This includes determining the key parametric factors that influence the outcome of potential bunkering incidents, thereby providing the necessary foundation for all subsequent quantitative analyses.

At this stage, critical aspects of the assessment are established, including ship specifications, operational profiles, fuel types under consideration, and the leakage frequency characteristics of the bunkering system. Reliable leakage frequency data remain scarce for ammonia- and hydrogen-fuelled vessels owing to their limited operational history (Aneziris et al., 2022). This scarcity extends even to LNG-fuelled ships when considered in the context of comparative risk assessment across multiple fuel types. Accordingly, this phase places particular emphasis on the identification of credible accident scenarios and the parametric factors that most significantly influence their outcomes. Among the most important of these factors is the configuration of the bunkering operation itself. Fuel leakage during bunkering operations typically results in direct exposure to the atmosphere, allowing the leaked substance to disperse over a broad area and potentially affect the surrounding port environment. Key system parameters established at this stage include the proximity of the bunkering site to populated or sensitive areas, meteorological conditions (particularly wind speed and direction), population density within the affected zone, the composition and physical configuration of bunkering facility components, and the volume of fuel being transferred.

6.2.1.1 System boundaries and definition

In this study, the case fuels would be supplied in liquid form from shore facilities. When the case ship berths at port, the three hoses are connected from a shore facility to the ship, which is the fuel supply hose, vapour return hose, and purging nitrogen supply hose. While the shore facility supplies low-flash fuel to the ship, the vapour from the ship would return to the shore facility to avoid direct ventilation to the atmosphere. LNG keeps in liquid under $-162\text{ }^{\circ}\text{C}$ under the atmosphere pressure

(Kogbara et al., 2013). For the supply of fuel, low-pressure pump and high-pressure

Insik Hwang, University of Strathclyde, September. 2026 101

pump increase the pressure to 1 bar. Under compressed storage conditions using a Type C tank, ammonia is maintained in liquid form at around 10 bar and 20 °C (Zacharakis-Jutz, 2013) while storage and supply pressure would be 12 bar with the same temperature. Hydrogen can have two different methods of storage, liquid form and gaseous form. For liquid form, the hydrogen stays under -252 °C which is much lower than LNG, under the atmosphere pressure (Elberry et al., 2021, Zheng et al., 2021). Gaseous hydrogen requires a high pressure of 700 bar at around 21 °C.

Figure 6.2 is the P&ID for the fuel supply facility from the shoreside. The stored fuel in a storage tank is transferred to the ship through pumps. It consists of pump, compressor, pipes, valves, and flanges and considers a similar pipe diameter to the ship's pipe, which is 150A to the fuel supply line and 100A to the BOG line.

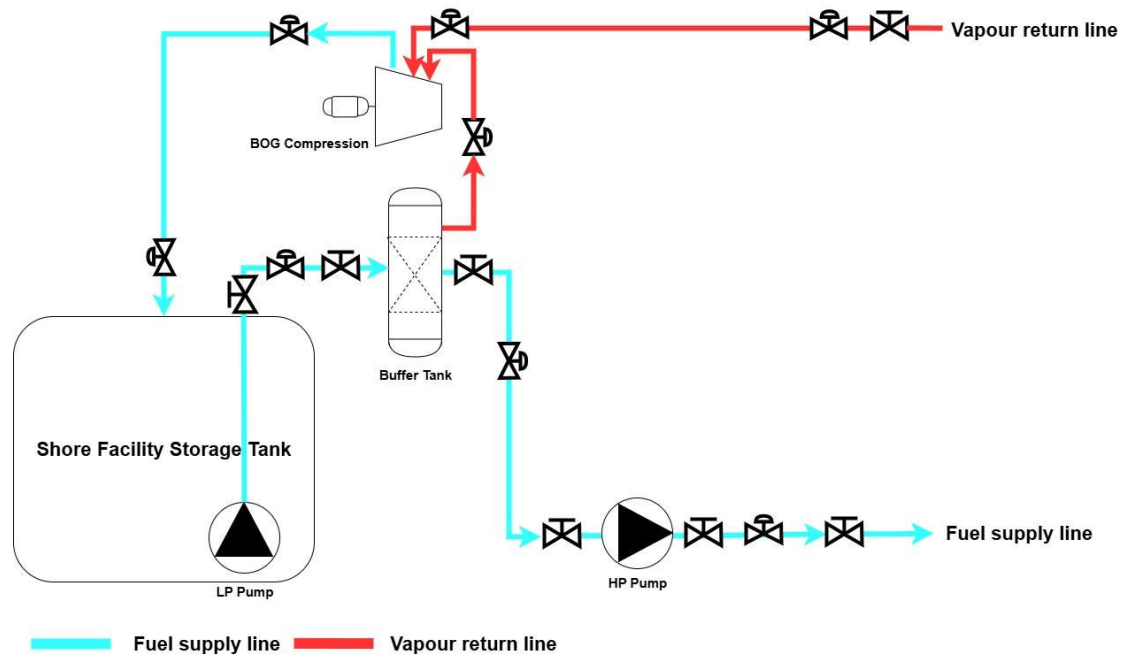


Figure 6.2. P&ID for shore facility

For the ship's side, Figure 6.3 below presents the P&ID of the bunkering system of the demonstrator ship. This study focuses on fuel supply line and vapour return line including fuel tanks on deck because the consequence of direct fuel leakage to atmospheres is the scope of this study.

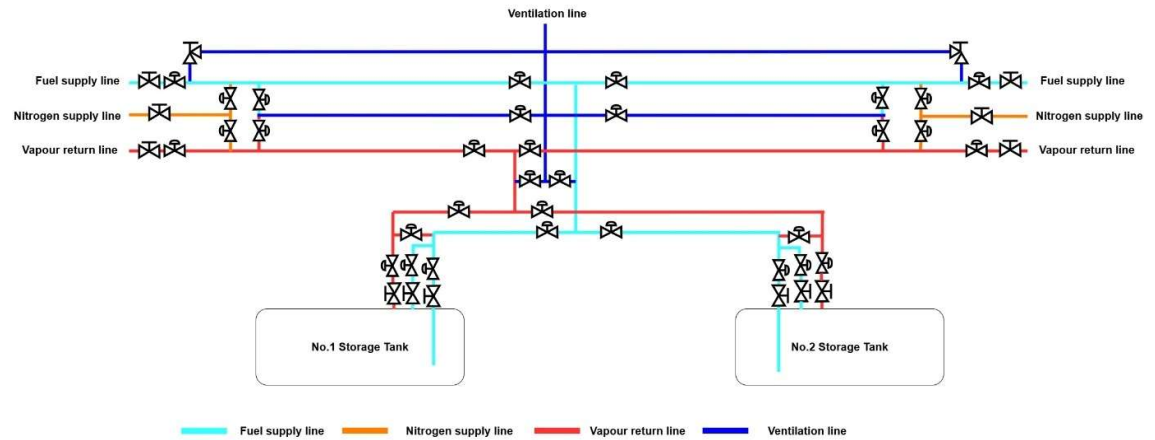


Figure 6.3. P&ID for ship

6.2.1.2 Operational and environmental conditions characterisation

The loading limit was considered that the value shall be limited to 98% to consider the case of external fire. The vessel operation scenario is assigned by the author. The ship consumes 150 m³ of fuel in a day and one round voyage is around 5 days. In other words, every 5 days, 73 times in a year, the ship needs to receive low-flash fuel for 6.5 hours which is 5 hours with a fuel supply rate of 150 m³/h and 1.5 hours of margin time. Briefly, the bunkering facilities operate 474.5 hours in a year.

Based on the bunkering location, the dispersion would be different, affected by different wind speeds and wind directions. As all of LNG, ammonia and hydrogen are low-flash fuel, they turn into gaseous form rapidly from liquid form and generate vapour clouds which spread widely and affect a wide range of areas. The direction of vapour cloud dispersion depends on the wind direction and the range of vapour cloud would be different by wind speed. The population density of bunkering location is one important parameter to analyse the consequence of accidents. Although, the alternative fuel is leaked and spread the massive range of areas with vapour cloud, the impact could be less if few of human exist within. On the other hand, it can be cause massive fatalities when the vapour cloud cover the high population density areas near ports such as residential area, shopping area, stadium, shopping mall or even the cruise ship berths near the bunkering ship.

A port, Port of Hamburg, was selected with a high possibility of alternative fuel bunkering ready in Europe, where is to define the impacts caused by alternative fuel leaks during bunkering locations. The differences in weather conditions, such as

wind speed and direction, population density, and distance from the city centre area, will show the various cases of impacts of fuel leakage accidents.

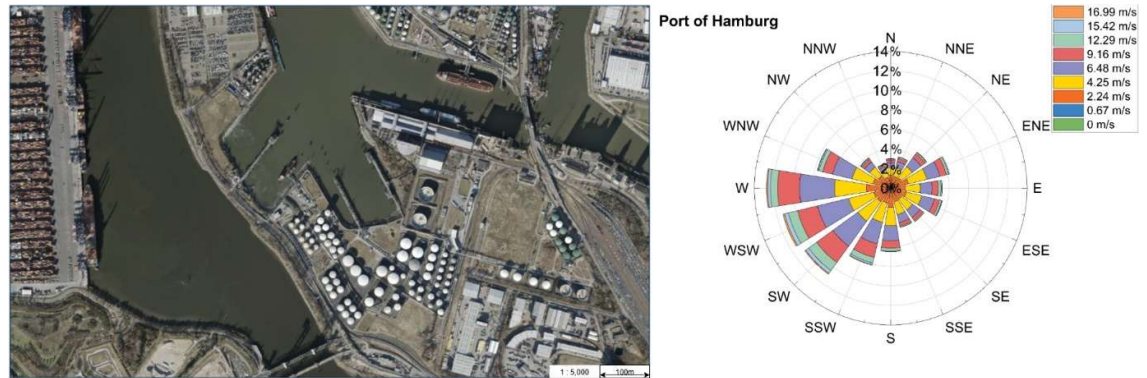


Figure 6.4. Port of Hamburg (Hamburg.com, 2025)

Hamburg (Figure 6.4**Error! Reference source not found.**) boasts an approximate population of 1,853,935 residents and the mean population density per square kilometre is documented at 2,455 (Statista, 2024). Fuel leakage incidents during bunkering have ramifications that extend beyond the vessel itself, encompassing its immediate surroundings. The extent of damage ensuing from such accidents correlates directly with the number of individuals present within the affected vicinity, rendering the population density of the accident area an influential determinant of the accident's outcome. It can be asserted that if a fuel spill transpires in the absence of individuals in the vicinity, potential consequences like fire, explosions, or adverse health effects due to toxicity are mitigated.

The predominant annual wind trajectory in Hamburg aligns with the west-south-west direction, characterised by notable occurrences of winds veering towards W, WSW, and SW azimuths, encompassing a substantial portion, around 30 % of the 16 distinct directions of wind rose (meteoblue, 2024). The prevailing wind velocities predominantly adhere to a 6.48 m/s range, with subsequent levels following at 4.25 m/s and 9.16 m/s as shown in Figure 6.4**Error! Reference source not found.**

The weighting of the population is assumed by the author, the average population density (100%) is assumed for residential and working areas, while the city centre, anticipated to accommodate a higher transient population than the norm, is

categorised as a denser 120%. Conversely, the harbour area, characterised by a mix of transitory populations, was designated at 50%, reflecting half of the average density. This adjustment takes into account the dispersion of workers engaged in ship operations, cargo handling, and port management, as well as passengers traversing passenger ships, spanning diverse areas due to the general port's characteristics. For areas such as Car parking and bulk storage, which are expected to host minimal transient populations in sprawling areas, a 10% assumption was assigned to each. The assignment of population is displayed in Figure 6.5

Reference source not found..

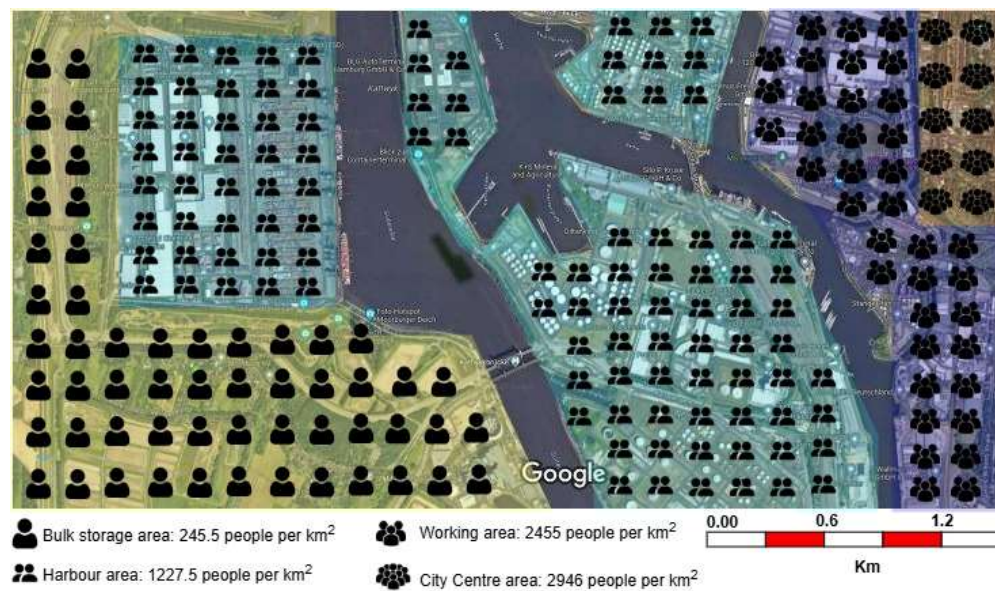


Figure 6.5. Differential population density per site

6.2.1.3 Regulatory requirements and technical modelling assumptions

ISO/TS 18683:2021 recommends establishing safety zones around LNG bunkering stations to minimise ignition risks and threats to human life during bunkering (ISO, 2021). It suggests restricting access to all personnel, except for essential workers, within the safety zone to minimise potential casualties in case of an actual accident. This ISO standard advises setting the safety zone range using either deterministic or probabilistic risk assessment methods based on the worst-case scenario.

However, when applying a deterministic method, the risk from low flash fuel leakage is evaluated based on the worst-case scenario without considering the likelihood of occurrence. As a result, the accident impact area may be significantly

large and impractical. Therefore, in this study a quantitative risk assessment using a probabilistic approach was applied to establish a more reliable safety zone for low flash fuel bunkering for the vessel. The criteria for defining the safety (or danger) zone are described in Section 6.2.4.2.

The credibility of the parametric comparative framework is supported by two complementary studies that collectively address both technical consistency and methodological grounding. The research conducted by DNV (DNV, 2021) supports the tool selection, risk criteria, and consequence modelling approach for the same hazardous substance. The same quantitative risk assessment software (DNV PHAST) and identical individual risk thresholds (1E-05, 1E-06, and 1E-07 per year) were applied. Although that study did not provide explicit numerical values for safety-zone diameters, it clearly demonstrated that the ammonia bunkering concept was evaluated against these frequency-based acceptance criteria, thereby offering a qualitative benchmark supporting the plausibility of the present results. The methodological foundation of this work builds upon the LNG bunkering study by Jeong et al. (Jeong et al., 2020), which demonstrated the effectiveness of the integrated PIDA-PDA approach forming the basis of the comparative assessment. This combination enables not only the reproduction of the DNV risk-criteria framework but also the probabilistic integration of population effects, providing a scientifically consistent and cross-referenced modelling basis. These two reference studies ensure that the developed model remains both theoretically grounded and practically aligned with internationally accepted quantitative risk-assessment practices.

6.2.2 Phase 2- Qualitative hazard identification and risk screening

The second phase develops the leakage scenario matrix that serves as the structured input for all downstream quantitative calculations. Credible hazardous scenarios are identified and the boundary conditions for quantitative modelling are defined at this stage.

6.2.2.1 Hazard identification

The vapour clouds of LNG and hydrogen are highly flammable and explosive. LNG has a lower flammability limit (LFL) of 5%, while hydrogen has a lower explosive limit (LEL) of 4% (Vilchez et al., 2013, Dutta, 2014). The ammonia vapour cloud has a relatively high LFL of 13.3% (Coronado et al., 2012). However, ammonia presents significant toxicity, with exposure to concentrations exceeding 30 ppm for more than 15 minutes capable of causing severe health effects (Padappayil and Borger, 2023). In this study, a toxic load of $1.3E+08 \text{ ppm}^n \times \text{min}$ is considered the threshold at which 99.9% of exposed individuals would experience instantaneous fatality. Accordingly, the risk assessment in this study addresses the fatalities caused by toxicity, fire, and explosion resulting from leaked ammonia affecting the ship's crew and third parties.

6.2.2.2 Hazard scenario prioritisation and risk screening

For each scenario, the accidental event progression is modelled through an event tree structure that distinguishes between immediate ignition, late isolation followed by delayed ignition, ESD-isolated delayed ignition, and no-ignition outcomes as shown in Figure 6.6. Detailed descriptions of each pathway are provided below.

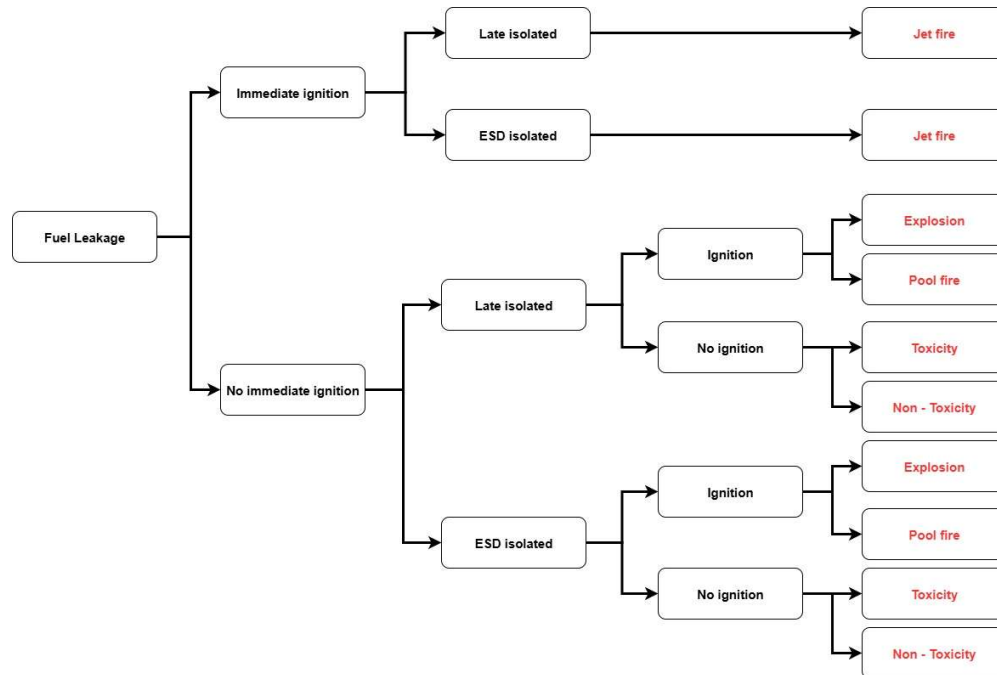


Figure 6.6. Event tree for fuel leakage consequence

The event tree for the fuel leakage scenarios shown in Figure 6.7 **Error! Reference source not found.** is constructed by the author based on the fuel leak scenarios by DNV (DNV, 2013). In case leakage happens during bunkering, the sensors detect fuel leakage to activate the automatic shutdown process in 5 seconds (Short term leakage). If the automatic shutdown is not activated, a crew or a watchkeeper has to shut down the bunkering supply system manually, where 30 seconds is required to activate manual emergency shutdown (Middle term leakage). When the emergency shutdown is not activated, the manual shutdown process is needed that takes 180 seconds (Long term leakage). By considering three different leakage durations and their corresponding calculated percentages, the total leakage period is determined to be 22.395 seconds.

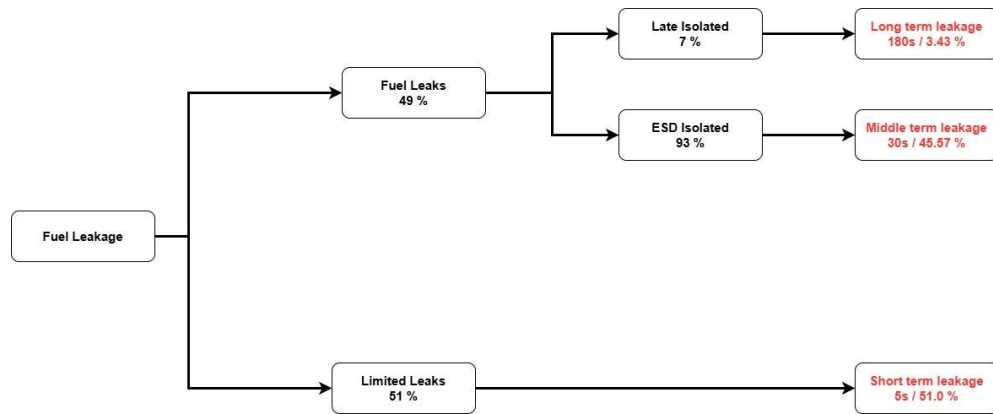


Figure 6.7. Event tree for fuel leakage time

Fuel release refers to the unintended discharge of low-flash fuels such as LNG, hydrogen, or ammonia into the atmosphere due to system failures during bunkering operations. The leak size and release rate vary based on the failure and the system's response. In this study, leak sizes are grouped into three representative categories for various analyses.

- Small leaks (1-5 mm) represented by a 5 mm hole
- Moderate leaks (5-10 mm) represented by a 10 mm hole
- Large leaks (50-150 mm) represented by a 100 mm hole

In the case of a fuel leakage event, several pathways are possible depending on whether ignition occurs immediately or not, as well as the effectiveness of the

isolation response. The flow of events is determined by a sequence of potential outcomes, each with associated consequences, such as fire, explosion, or toxicity.

Immediate Ignition: If the fuel leakage leads to immediate ignition (due to static discharge, spark, etc.), two scenarios arise based on the isolation response:

- Late Isolation: If the response to isolate the leak is delayed, the event likely results in a jet fire.
- ESD Isolation: If the Emergency Shutdown Device (ESD) activates and isolates the leak promptly, the outcome is still a jet fire, though potentially more contained than in the late isolation case.

No Immediate Ignition: If the leak does not result in immediate ignition, the event flow splits based on isolation response and whether ignition occurs at a later stage:

1) Late Isolation: Ignition Occurs: If ignition occurs after some delay, the outcomes could be an explosion or a pool fire, depending on the fuel's behaviour (e.g., LNG forming a pool, hydrogen's diffusivity leading to an explosion).

No Ignition: If ignition does not occur, the fuel continues to disperse, potentially resulting in toxicity due to gas exposure.

2) ESD Isolation: Ignition Occurs: Even after isolation, delayed ignition can still lead to either an explosion or a pool fire, though the extent may be reduced due to quicker isolation.

No Ignition: If no ignition occurs after isolation, the primary concern becomes the release of toxic gas, leading to toxicity risks.

Each of these pathways highlights the importance of the speed and effectiveness of the isolation response (either through ESD or manual intervention), as well as the occurrence of ignition. Immediate or delayed ignition determines whether fire, explosion, or toxicity becomes the dominant risk. This event analysis emphasises that prompt and reliable safety measures like ESD can significantly reduce the severity of the outcomes, though the risks of fire, explosion, or toxicity remain high in certain conditions.

6.2.2.3 Identification of critical safety scenarios

In this study, four fuel types are considered: LNG, liquefied ammonia (LNH₃), liquefied hydrogen (LH₂), and compressed gaseous hydrogen (GH₂). For each fuel, three representative leakage hole sizes are examined. Specifically, 5 mm, 10 mm, and 100 mm hole diameters are selected, corresponding to minor, moderate, and major release events respectively. These parameters are selected to capture a realistic range of accident severities while maintaining consistency with general industrial practice and the failure mode profiles typical of bunkering system components. The bunkering location is selected based on its operational significance and the representativeness of its environmental characteristics, including wind speed and direction variability, which exert a substantial influence on the dispersion behaviour of gaseous and cryogenic releases. These scenario definitions provide the complete, structured inventory from which all frequency and consequence calculations are derived, ensuring methodological coherence across the full assessment.

The potential fuel leakage is assumed from three different sizes, which are 5 mm, 10 mm and 100 mm size holes. The sizes of leakage hole present small cracks, normal failure and catastrophic rupture. The leakage frequency of each hole size is independent so, the possibility of leakage accidents can be one size hole leakage, or all three size leakage. With these considerations, more various possibilities and consequences of accidents would be considered.

6.2.3 Phase 3- Quantitative risk assessment

Phase 3 encompasses the full quantitative characterisation of risk through frequency, consequence, and parametric analysis.

6.2.3.1 Failure frequency estimation

The first sub-step of Phase 3 quantifies the frequency of each defined leakage scenario occurring during bunkering operations. Leakage frequencies were estimated based on system failure data derived from the DNV System Failure Frequency Database (DNV, 2013), with reference to comparable LNG operational

records supplemented by expert-informed assumptions for ammonia and hydrogen, where fuel-specific data are not yet available. The risk frequency calculation considers the operation schedule, operation profile, and P&ID, which includes fuel supply amount, bunkering time and bunkering period. The bunkering facility and line do not operate continuously. These facilities are only operated when receiving fuels, and the bunkering period and supply amounts are determined by vessel operation profile and schedule.

Based on Figure 6.2 and Figure 6.3, the details of different components and leak frequencies are provided in Table 6.1. The calculation of leak frequency for each component is derived from established schematic diagrams of the fuel supply facility at the shore and the vessel receiving the fuel. It is calculated based on a database from DNV (DNV, 2013). As the bunkering operation in a year is around 475 hours, the leakage frequency considers the time rate. Three different sizes of holes were considered as a source of leakage which means the leakage occurred by crack. To represent standards of crack, 5 mm, 10 mm, and 100 mm are selected.

Table 6.1. Leakage frequency

	Component	Size and Number	Frequency (per year)		
			5 mm	10 mm	100 mm
Shore side	Buffer tank	150A ×1EA	3.22E-05	2.37E-05	8.80E-06
	LP Pump	150A ×1EA	8.53E-05	3.17E-05	5.76E-06
	HP Pump	150A×1EA	8.53E-05	3.17E-05	5.76E-06
	Pipe	150A×200m	1.81E-05	6.71E-05	1.22E-05
	Manual Valve	150A×7EA	1.21E-05	5.79E-06	1.39E-06
	Actuated Valve	150A×8EA	7.82E-05	2.41E-05	3.48E-06
	Flange	150A×30EA	4.06E-05	1.47E-05	2.59E-06
Ship side	Manual Valve	150A×10EA	1.73E-05	8.27E-06	1.98E-06
	Manual Valve	100A×4EA	5.78E-06	2.77E-06	1.62E-06

	Actuated Valve	150A×30EA	2.93E-04	9.02E-05	1.31E-05
	Pipe	150A×150m	1.36E-04	5.03E-05	9.16E-06
	Pipe	100A×60m	6.53E-05	2.42E-05	2.15E-06
	Flange	150A×80EA	1.08E-04	3.91E-05	6.91E-06
	Flange	100A×8EA	9.12E-06	3.30E-06	3.49E-06

A: Pipe nominal diameter (mm) EA: each

The frequency for each fuel type under different conditions is estimated based on accessible data, particularly of LNG. Since there is limited historical data for emerging fuels like hydrogen and ammonia, assumptions based on comparable data are made to enhance the robustness of the analysis. By visually representing these zones, stakeholders can better understand the probability of each scenario, helping to prioritise safety measures and allocate resources accordingly.

6.2.3.2 Consequence modelling

The second sub-step of Phase 3 evaluates the physical consequences of each leakage scenario, modelling the spatial extent and severity of the resulting hazard footprints. This analysis models the dispersion and behaviour of hazardous substances, such as toxic clouds, flammable vapours, and explosive plumes, assessing their impact on human health, property, and the environment. The severity of incidents involving different fuels is compared across LNG, ammonia, liquid hydrogen, and compressed hydrogen to determine the factors that contribute most to severe outcomes. In this analysis, six key hazards are considered: pool fires, jet fires, flash fires, explosions, toxicity, and dispersion.

- **Pool Fire:** Pool fires occur when a liquid fuel leak forms a flammable pool, which ignites and burns. This scenario is common with liquified fuel spills, as these substances can spread on the surface and catch fire. Pool fires can cause widespread thermal radiation, damaging nearby infrastructure and posing significant risks to personnel. It is assumed that exposure to heat flux of 4 kW/m² or higher could lead to fatalities (Raj, 2008), and exposure to 37.5 kW/m² would result in 99.9% fatalities ((HSE), 2025), based on basic fatality possibility of the DNV Phast software.

- **Jet Fire:** Jet fires are associated with high-pressure leaks, such as from compressed hydrogen or liquid hydrogen. When ignited, these leaks produce highly concentrated, intense flames that are localised but can lead to severe damage and injury. Jet fires are particularly dangerous due to their rapid spread and difficulty in containment. The heat flux resulting in fatalities from a jet fire is comparable to that of a pool fire. It is assumed that exposure to a heat flux of 4 kW/m² or more could cause fatalities, while exposure to 37.5 kW/m² would lead to a 99.9% fatality rate, as outlined in the fatality assumptions of the DNV Phast software.
- **Flash Fire:** Flash fires can occur when a flammable vapour cloud, formed by the dispersion of leaked fuel, ignites and burns rapidly. Hydrogen leaks, especially in confined areas or poorly ventilated locations, are particularly prone to flash fires due to hydrogen's wide flammability range and low ignition energy. The spread of flash fires can be extensive, but they typically burn for a short duration.
- **Explosion:** Explosions are a major concern for fuels which have high explosiveness. When a vapour cloud or gas ignites in an enclosed or semi-enclosed space, it can lead to vapour cloud explosions, producing shockwaves and causing severe damage to structures and harm to individuals within the blast radius. This makes explosion risk a critical factor in assessing the safety of hydrogen bunkering. According to the suggestion by software, any individual within a range where overpressure exceeds 0.02 bar is considered to suffer fatal injuries. Exposure to 0.2 bar or higher is assumed to result in 99.9% fatalities (Freeman, 1990).
- **Toxicity:** Inhalation of air containing concentrations of low-flash fuels at 1,300 ppm or higher can lead to fatal injury. Since hydrogen is non-toxic to humans and disperses rapidly in the atmosphere(Energy, n.d), the likelihood of asphyxiation resulting from hydrogen leakage is considered negligible. Toxicity is particularly relevant in the case of ammonia leaks, where concentrations exceeding 30 ppm more than 15 minutes can cause severe health effects(Jang et al., 2023). Based on the probit-based toxic load evaluation implemented in PHAST software, a dose level of 1.3E+08 ppmⁿ

×min corresponds to a fatality probability greater than 99.9% for ammonia exposure.

By modelling each of these hazards across different leakage scenarios, the analysis provides an overall view of the risks posed by various fuels. Maps and dispersion models are used to visually represent the spread of fire, explosion, and toxic gas under varying conditions, offering a detailed comparison between fuel types. The consequence analysis results are essential for determining the severity and range of potential accidents, aiding in the establishment of safety zones and the development of mitigation strategies. This approach ensures that the most critical factors, including toxicity, explosiveness, or dispersion, are accounted for when assessing the overall risk of alternative fuel bunkering operations.

The insights gained from this analysis can assist in designing new plants, modifying existing operational procedures, or implementing other mitigation measures. To analyse the impact of potential accidents, the Probit analysis method was applied. This enables the estimation of the extent of human casualties for each type of accident, as summarised in the preceding hazard descriptions. Since a conservative calculation method was adopted, the predicted casualties may appear somewhat higher than they would in reality. The conservative approach in this study implies that worst-case figures were intentionally considered. When the reference database provided a range of possible values, the author selected the more severe figures to ensure a safety-oriented and precautionary assessment.

The fuel leakage rate would be different based on fuel density kg/m^3 , leakage hole size, and initial leakage pressure. The simple fuel leakage rate equation is conducted from DNV reference (DNV, 2013). In this study, the different equation is needed for liquid material and gaseous material. The LNG, LNH_3 , LH_2 are calculated based on liquid material leakage equation, **Error! Reference source not found.**, and GH_2 is calculated based on gaseous material leakage rate **Error! Reference source not found.**

$$Q_L = 2.1 \times 10^{-4} d^2 \sqrt{\rho_L P_L}$$

Equation 6.1. Equation for liquid fuel leakage rate calculation (DNV, 2013).

where,

d : hole diameter (mm)

ρ_L : liquid density (kg/m^3)

P_L : initial pressure of liquid (bar gauge)

For LNG, liquid density is assumed as 460 kg/m^3 (UNITROVE, 2025), in -162°C , 1 bar. The liquid density of ammonia is assumed as 610 kg/m^3 (ToolBox, 2025) under storage temperature 20°C and 12 bar. Liquid hydrogen has 70.8 kg/m^3 (Dagdougui et al., 2018) of density, and the storage temperature is considering as -251.95°C under 1 bar.

$$Q_g = 1.4 \times 10^{-4} d^2 \sqrt{\rho_g P_g}$$

Equation 6.2. Equation for gaseous fuel leakage rate calculation (DNV, 2013).

where,

d : hole diameter (mm)

ρ_g : initial density of gas (kg/m^3)

P_g : initial pressure of gas (bar gauge)

The 39.75 kg/m^3 (Kolthoum et al.) of density is assumed for gaseous hydrogen density under 20°C with 700 bar. From calculated leakage rate, the total leakage quantity per hole size with general leakage time is calculated in Table 6.2

Error! Reference source not found..

Table 6.2. Fuel leaked quantity per scenario

Fuel type	Leakage quantity per hole size (d) (kg)		
	5 mm	10 mm	100 mm
LNG	2.52	10.09	1008.67
LNH ₃	10.06	40.24	4023.70
LH ₂	0.99	3.96	395.72
GH ₂	13.07	52.30	5229.94

6.2.3.3 Parametric scenario analysis

The final sub-step of Phase 3 introduces the parametric variation into the quantitative analysis. Rather than relying on a single set of fixed conditions, the

frequency and consequence calculations performed in the preceding sub-steps are repeated across a systematically varied range of input parameters. In this case study, the parameters subject to variation include fuel supply time, fuel leakage quantity, wind speed, and population density.

This process generates a distribution of results that captures the sensitivity of safety zone dimensions to each governing variable. By identifying the parameters that exert the greatest influence on accident severity, the parametric analysis provides the necessary foundation for the risk integration performed in Phase 4. The systematic exploration of input conditions also addresses the scarcity of extensive operational data for alternative fuel bunkering systems, enabling the identification of general trends and patterns that would not be apparent from a single-condition assessment.

The core focus of this study lies in conducting a parametric analysis. By systematically comparing the original figures, the parameters under consideration demonstrate their significance and critical impact on the results. Adjusting the input parameters yields varying outputs, which underscores the necessity of systematically organising inputs and corresponding outputs to identify the most influential factors and better understand their interrelationships. The inherent complexity of the system, coupled with diverse operational methods, renders it challenging to intuitively predict the criticality of each parameter without such a structured approach.

(a) Default scenarios

The default scenarios are a crucial baseline for comparison, providing a reference point to evaluate the impact of varying parameters. The scenario would be a standard of changing input parameters and output results. To ensure a reliable basis for comparison, the default values for each fuel type were calculated and designated as standard values for further comparative analysis. This approach allows for a structured assessment of parameter variations and their influence on the overall outcomes.

(b) Fuel type

LNG is a prominent fuel type representing alternative energy sources within the marine industry. It is widely utilised as both fuel and cargo, with its safety standards being generally well-established and accepted. Compared to other alternative fuels such as hydrogen and ammonia, the storage, transfer systems, and associated technologies for LNG are relatively advanced and mature. A significant number of LNG-powered ships are currently in operation, solidifying its position as an established fuel option in the marine sector. The severity and risks associated with LNG can be better understood when compared with other fuel types.

Ammonia and hydrogen, on the other hand, are gaining attention as potential zero-emission fuels for the maritime industry. However, their current adoption is limited, with only a small number of ships utilising these fuels. Ammonia and hydrogen require more precise storage and handling due to their high toxicity and flammability. The distinct properties of each fuel type result in varying levels of severity even under similar leakage scenarios. Additionally, differences in storage temperatures and pressures significantly influence leakage rates, which, in turn, affect the total leakage quantity and associated risks.

(c) Bunkering method

There are three primary methods for supplying fuel to ships: Ship-to-Ship (STS), Truck-to-Ship (TTS), and Facility-to-Ship (FTS). The choice of fuel supply method depends on various factors considered by shipowners and fuel suppliers, including, but not limited to, the required fuel quantity, the location of the operation, and the availability of resources. In this study, the supply systems for all three methods are analysed under the assumption that they include the same components. However, the fuel supply rate differs among the methods due to system-specific limitations in pipe and pump sizes. These differences in supply rates not only impact the quantity of fuel leakage but also influence the total time required for fuel transfer, thereby extending the annual operation time of the ship.

The extended annual operation time has a direct correlation with the frequency of potential fuel leakage incidents. Since bunkering facilities do not operate continuously 24 hours a day, seven days a week, an increase in operation time leads to a higher frequency of fuel transfer activities, which in turn raises the likelihood

of accidents. Thus, the characteristics of each supply method must be carefully considered to assess their operational and safety implications.

(d) Quantity (bunkering volume / ship size)

In general, larger ships demand a significantly greater quantity of fuel compared to smaller vessels, resulting in variations in the total fuel supply time based on the ship's size and required fuel capacity. These variations, when considered alongside the selected bunkering method, contribute to differences in the overall fuel supply duration. Adjustments in fuel supply time subsequently influence the annual operational utilisation of bunkering facilities, thereby affecting the overall frequency of accidental occurrences. Such changes are anticipated to have a substantial impact on the severity of the outcomes associated with fuel supply operations.

The insights gained from analysing variations in total fuel supply input are expected to provide a deeper understanding of the underlying dynamics. When incorporated into future studies through general trend analyses, these findings can offer more effective and intuitive interpretations of the relationships and patterns observed. Such extensive analyses will facilitate the refinement of operational strategies and the development of enhanced safety protocols, ensuring improved efficiency and risk management.

(e) Wind speed

Leaked fuel disperses in the atmosphere, carried by the wind, and its diffusion behaviour varies depending on the specific characteristics of the fuel. If the fuel exhibits toxic properties, strong winds may help disperse the hazardous substances more rapidly to under the critical limits, potentially reducing the severity of the incident. However, in the case of fuels with high flammability and explosive tendencies, increased wind speed can expand the affected area, exacerbating the consequences of fire and explosion hazards. This indicates that even under identical leakage conditions, the resulting impact can differ significantly depending on the environmental conditions and the inherent properties of the fuel.

Unlike conventional fossil fuels, which generally share similar characteristics, alternative energy sources exhibit substantial variations in their physical and

chemical properties. Given these differences, a parametric analysis of severity based on wind speed and fuel properties is necessary to quantify the extent to which wind speed influences the overall severity of an incident. By incorporating the distinct characteristics of each fuel type, such an analysis will provide valuable insights into the potential risks and their mitigation strategies under varying environmental conditions.

In this study, PHAST does not explicitly account for the probability of individual wind speeds. Rather, it incorporates the overall wind distribution and directional patterns derived from the input wind rose data. Accordingly, in the wind speed parametric study, the overall wind speed values were systematically adjusted to evaluate their effect on the resulting safety distances. In this framework, the safety zone is determined based on generalised conditions rather than short-term variations, ensuring that the derived boundary represents a realistic and representative outcome.

(f) Population density

Even if an identical fuel leakage incident occurs and affects the same spatial range, the overall severity of the incident inevitably increases if a greater number of people are present within the affected area. In general, when establishing a bunkering safety zone, access is restricted for personnel who are not essential to the bunkering operation. However, in the case of alternative fuels that have the potential to cause severe impacts over a wide area, the entire ship may fall within the bunkering safety zone. This implies that all individuals onboard would be within the hazard zone and exposed to the consequences of the incident.

Even when assuming the same accident scenario, the number of individuals present within the affected area can determine whether the pre-established safety zone remains within an acceptable risk threshold or if it exceeds permissible limits. This highlights the necessity of re-evaluating safety zone boundaries based on fuel properties and potential exposure levels, ensuring that they remain adequate for mitigating risks associated with large-scale fuel leakage incidents.

A parametric study was conducted by systematically varying the default figure settings to identify the extent to which each input parameter influences the results.

The key influencing factors were categorised into total fuel supply volume, fuel supply method, fuel leakage quantity, wind speed, and population density. To assess the sensitivity of these parameters, each baseline value was set at 100%, and subsequent simulations were performed with modified values of 10%, 50%, 200%, and 300% of the original input as shown in **Error! Reference source not found..** To avoid providing duplicate information, the Geographic Information System (GIS) for each simulation is provided in the A. APPENDIX.

Table 6.3. Input parameters

Parameters	Default figure		Changed figure			
			10%	50%	200%	300%
Leakage frequency depends on supply fuel quantity (per year)	5 mm	2.12E-02	3.48E-04	7.01E-04	2.03E-03	2.93E-03
	10 mm	7.69E-03	1.26E-04	2.54E-04	7.37E-04	1.06E-03
	100 mm	1.80E-03	2.96E-05	5.96E-05	1.73E-04	2.49E-04
Leakage fuel quantity (LNG) (kg)	5 mm	2.52	0.25	1.26	5.04	7.57
	10 mm	10.09	1.01	5.04	20.17	30.26
	100 mm	1008.67	100.87	504.34	2017.34	3026.01
Leakage fuel quantity (LNH ₃) (kg)	5 mm	10.06	1.01	5.03	20.12	30.18
	10 mm	40.24	4.02	20.12	80.47	120.71
	100 mm	4023.7	402.37	2011.85	8047.41	12071.1
Leakage fuel quantity (LH ₂) (kg)	5 mm	0.99	0.1	0.49	1.98	2.97
	10 mm	3.96	0.4	1.98	7.91	11.87
	100 mm	395.72	39.57	197.86	791.44	1187.16
Leakage fuel quantity (GH ₂) (kg)	5 mm	13.07	1.31	6.54	26.15	39.22

	10 mm	52.3	5.23	26.15	104.6	156.9
	100 mm	5229.94	522.99	2614.97	10459.9	15689.8
Population density (per km ²)	Harbour area	1227.5	122.75	613.75	2455	3682.5
	Product area	245.5	24.55	122.75	491	736.5
	Person onboard	30	3	15	60	90
Wind speed range (m/s)	G	0	0	0	0	0
	F	1.5	0.15	0.75	3	4.5
	E	5	0.5	2.5	10	15
	D	9.5	0.95	4.75	19	28.5
	C/D	14.5	1.45	7.25	29	43.5
	C	20.5	2.05	10.25	41	61.5
	B/C	27.5	2.75	13.75	55	82.5
	B	34.5	3.45	17.25	69	103.5
	A	38	3.8	19	76	114
Parameters	Default figure		Changed figure			
Leakage frequency per supply method (TTS)	5 mm	2.12E-02	3.58E-03			
	10 mm	7.69E-03	1.30E-03			
	100 mm	1.80E-03	3.04E-04			
Leakage frequency per supply method (FTS)	5 mm	2.12E-02	7.07E-04			
	10 mm	7.69E-03	2.56E-04			
	100 mm	1.80E-03	6.01E-05			

6.2.3.3.1 Changes in fuel supply time

Variations in the total fuel supply volume directly impact the duration of the bunkering process. Since data on the frequency of fuel leakage incidents due to component failures is based on continuous system operation over a one-year period, any deviation from full-year usage must be considered when assessing its effect on

leakage frequency. To summarise, the different fuel supply quantity changes the total operational time of the system influences the expected frequency of failure events.

Additionally, the total fuel supply duration is affected by changes in the fuel supply flow rate. For instance, the Truck-to-Ship (TTS) method, which operates at a lower flow rate compared to Ship-to-Ship (STS) bunkering, requires approximately 25% more time to deliver the same amount of fuel as STS. In contrast, the Facility-to-Ship (FTS) method, which operates at twice the flow rate of TTS, significantly reduces the total fuel supply time. These differences in bunkering methods highlight the influence of flow rate variations on operational duration and potential risk exposure. The variation in fuel supply duration significantly impacts the overall results, with the magnitude of change differing depending on the fuel type as shown in **Error! Reference source not found..** For A. LNG, values for the inner zone are not distinctly observed. However, in the middle zone, the minimum and maximum variations reach approximately 60 metres, while in the outer zone, the expansion is close to 100 metres. In contrast, B. LNH₃ exhibits a much larger variation. The inner, middle, and outer zones all show an increase of approximately 200 metres, which is significantly greater than the variations observed for other fuel types. For hydrogen-based fuels, both C. LH₂ and D. GH₂ show relatively smaller changes. In C. LH₂, the outer zone expands by approximately 70 metres, whereas the middle zone increases by only 2 metres. Similarly, for D. GH₂, the expansion varies across zones, with the maximum increase reaching 70 metres and the minimum around 5 metres. Given that the inner zone's minimum range starts at 140 metres and the outer zone extends up to 260 metres, the relative increase in range is smaller compared to B. LNH₃. This indicates that while GH₂ experiences some expansion, its impact is less pronounced than that of ammonia.

6.2.3.3.2 Changes in fuel leakage quantity

Variations in fuel leakage quantity are generally expected to have a significant impact on the overall severity of the results. Even if a failure occurs in a component or system, the absence of fuel leakage would mean that the malfunction remains confined to the equipment itself without causing further damage to the surrounding environment. However, in the event of fuel leakage, there is a heightened risk of

cascading incidents, including fire, explosions, and toxic exposure, which could lead to severe human casualties and extensive property damage. Given these considerations, it is crucial to conduct a detailed parametric analysis to quantify the effect of different leakage volumes on accident severity. The increase in leakage quantity significantly expands hazard zones, with variations depending on fuel type and leakage volume. A.LNG shows a notable increase, with its middle zone expanding from 42.87 metres (50% leakage) to 113.32 metres (300%), and the outer zone surpassing 200 metres. B.LNH₃ experiences the most dramatic expansion, with the inner zone growing from 11.87 metres (10%) to 230.01 metres (300%) and the outer zone increasing by over 700 metres. C.LH₂ shows a moderate increase, with its outer zone expanding by 70 metres at 200% leakage but slightly decreasing at 300%, suggesting dispersion variations. D.GH₂ exhibits significant expansion, especially in the middle (82.61m to 399.08m) and outer zones (98.01m to 410.42m). Overall, B.LNH₃ shows the largest hazard zone expansion, followed by GH₂, while LNG and LH₂ exhibit moderate increases. These findings highlight the critical role of fuel type and leakage volume in hazard assessment and safety planning.

6.2.3.3.3 Changes in wind speed

Wind speed is a key factor influencing the dispersion range of leaked fuel. Strong winds can carry the leaked fuel over a greater distance, directly affecting the severity of an incident. When fuel remains concentrated in a specific area without adequate dispersion, the risk of severe accidents, including fire, explosion, or toxic exposure, increases significantly. Therefore, understanding the role of wind speed is crucial in assessing accident severity and implementing effective safety measures. The influence of wind speed on hazard zones differs based on fuel type, affecting both dispersion behaviour and accident severity. A.LNG shows a notable reduction in hazard zones as wind speed increases, with the middle zone contracting from 157.14 metres (10%) to 59.63 metres (300%), and the outer zone decreasing from 233.00 metres (10%) to 109.32 metres (300%). B.LNH₃ experiences the most significant decline, as its inner zone shrinks from 496.18 metres (10%) to 39.18 metres (300%), and the outer zone reduces by over 400 metres, from 875.68 metres (10%) to 439.90 metres (300%). This suggests that ammonia disperses efficiently under strong winds, lowering high-concentration areas but potentially spreading lower concentrations over a broader range. C.LH₂ exhibits relatively minor changes,

with the middle zone maintaining a range of approximately 23-25 metres, while the outer zone contracts significantly from 113.95 metres (10%) to 26.64 metres (300%), indicating that wind primarily influences long-range dispersion. D.GH₂, however, remains mostly unchanged across all wind speeds, with its inner, middle, and outer zones showing consistent values around 207m, 250m, and 257m, respectively, suggesting that gaseous hydrogen disperses widely regardless of wind conditions. Overall, B.LNH₃ and A.LNG show the most pronounced reduction in hazard zones with increasing wind speeds, while D.GH₂ remains largely stable. These results emphasise the crucial role of wind speed in fuel dispersion dynamics and its impact on safety planning and risk management.

6.2.3.3.4 Changes in population density

Population density is not expected to significantly impact the PIDA (Population-Independent Analysis) boundary but is anticipated to have a considerable effect on the PDA (Population-Dependent Analysis). While the spatial extent of fuel dispersion remains unchanged regardless of population density, the absolute number of individuals within the affected area plays a crucial role in determining the severity of the incident. A lower population density within the hazard zone may lessen overall consequences, whereas a higher density could lead to more severe outcomes due to increased human exposure. Additionally, safety zones are established to restrict unnecessary personnel from entering hazardous areas. However, fluctuations in the number of individuals within these zones highlight the risks associated with insufficient access control. If safety measures fail to regulate entry effectively, the severity of an incident could escalate significantly, underscoring the need for strict enforcement of access restrictions and emergency preparedness protocols to minimise human exposure and mitigate risks. Changes in population density do not significantly affect the boundary size but rather influence the severity of potential consequences within the affected zones. A.LNG shows a moderate increase in the boundaries of accident, with the middle zone rising from 72.34 metres (10%) to 88.53 metres (300%) and the outer zone increasing from 105.83m (10%) to 197.03m (300%), indicating that while the boundary remains stable, a higher population density amplifies the potential impact. B.LNH₃, on the other hand, maintains relatively stable values across all zones, with the inner zone fluctuating slightly around 94.09m – 94.83m, and the middle and outer zones

remaining nearly unchanged at approximately 387m – 390m and 600 metres – 601 metres, respectively. C.LH₂ and D.GH₂ show no significant variations across different density levels, reinforcing the idea that population density does not alter the dispersion range but rather affects the overall risk level within the hazard zones. These findings suggest that while boundary sizes remain consistent, the number of affected individuals increases with population density, making safety measures and emergency planning particularly critical in densely populated areas.

6.2.4 Phase 4- Risk integration

Phase 4 integrates the frequency, consequence, and parametric analysis results produced in Phase 3 to derive the final bunkering safety zone recommendations for each fuel type and operational configuration. The integration is performed through two complementary analytical tools, Population-Independent Analysis (PIDA) and Population-Dependent Analysis (PDA), which are applied sequentially to produce risk-informed safety zones.

Figure 6.8 presents an outline of the risk assessment process. Each event type is individually simulated, and its corresponding consequence is calculated. The frequency and consequence results are then combined to derive the overall safety distance for each case.

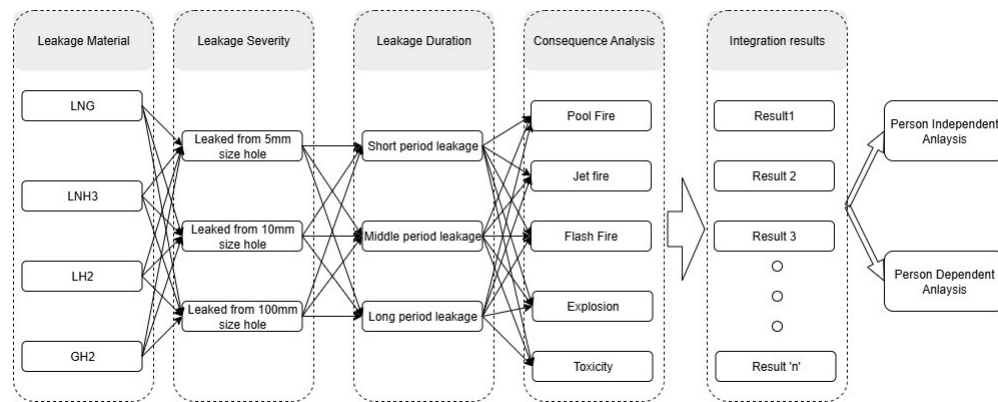


Figure 6.8. Outline of Risk Assessment

6.2.4.1 Risk-informed zone determination

Population-Independent Analysis (PIDA) is applied first to establish the spatial boundaries of the safety zone. By integrating critical distances from all credible scenarios with their corresponding frequency data, PIDA produces exceedance frequency contour plots that identify the maximum radius within which individual risk levels exceed defined acceptance criteria. The contour plots provide a spatially precise representation of hazard boundaries that is independent of local population characteristics, ensuring that the defined zones are robust against the widest range of potential accidents.

The purpose of establishing a safety zone for bunkering is to restrict access to the danger zone for all individuals except essential personnel, thereby minimising potential human casualties from accidents that may occur during bunkering operation. Additionally, it aims to strengthen safety equipment within the danger zone to prevent possible accidents.

The critical distance for each scenario was combined with its occurrence frequency, and the combined scenario results were re-ordered from the lowest to the highest risk range. The critical distance closest to the acceptable accident frequency was then established as the bunkering safety zone for the vessel. The safety zone from these results is displayed on the bunkering GIS map.

The DNV Safeti software was employed to model and calculate the range of influence, generating results displayed on a geographical map with the combined frequency analysis and consequence analysis. The consequence analysis presents the border on the map to show the boundary of an accident. It is considered that the fatality occurred within the boundaries of toxicity, fire and explosions caused by fuel leaks. The accident frequencies are displayed in the period of each accident, where the different colours of border lines show each accidental case.

Building on the considerations outlined above, the default figure simulations are performed for four different types of fuels. These default values serve as the baseline for the subsequent parametric analysis, allowing for a systematic assessment of how variations in each parameter influence the results. By comparing

the changes in output values corresponding to different parameter adjustments, the analysis identifies the factors that have a critical impact on the overall outcomes.

Overall, B. LNH₃ exhibits the widest affected area, followed by D. GH₂, A. LNG, and finally C. LH₂, which has the smallest range. However, when analysing the Inner Zone, D. GH₂ demonstrates the largest affected area. This observation can be attributed to the high storage pressure of compressed hydrogen, which, upon leakage, has a high potential for fire and explosion in the atmosphere.

In contrast, C exhibits the smallest affected range across all zones. Although it shares a similarly high fire and explosion risk under atmospheric conditions with D, the fact that it is released in liquid form and has a lower storage pressure contributes to its more limited dispersion range. This distinction highlights the significant influence of fuel state and storage conditions on the extent of the hazard zones.

6.2.4.2 Risk acceptance criteria and vulnerability

By considering all possible events, the analysis categorises the risk zones into different levels to visualise the likelihood of incidents based on the risk acceptance criteria suggested by DNV (DNV, 2021).

- The inner zone represents the highest-risk areas, typically surrounding the bunkering station, where incidents are most likely to occur. The individual risk is up to 1E-05 per year.
- The middle zone covers moderate-risk (up to 1E-06 frequency per year) areas where incidents are possible but less frequent.
- The outer zone includes areas with the lowest risk, which have up to 1E-07 individual risk, further away from the bunkering site and less likely to be impacted by spill incidents.

The vulnerability criteria applied in this assessment correspond to the fatality thresholds defined in the previous section, the heat flux, overpressure, and toxic load levels at which fatalities are assumed to occur.

6.2.4.3 Safety level verification

Population-Dependent Analysis (PDA) is then applied to evaluate the acceptability of the safety zones established by PIDA. PDA introduces population density and human exposure into the assessment, translating the physical hazard footprint into

F-N curves that represent the frequency of incidents against the number of potential fatalities. Where the F-N curve falls within the acceptable region defined by the risk acceptance criteria, the PIDA-derived safety zone is confirmed as adequate. Where it exceeds the tolerance threshold, the safety zone boundary requires adjustment. The combined outputs of PIDA and PDA provide the basis for the final safety zone determination. PIDA defines the physical upper bound of the hazard, while PDA verifies whether that bound is sufficient to achieve acceptable societal risk levels for the specific operational context. This sequential structure ensures that the resulting safety zones are both scientifically defensible and practically deployable.

From the perspective of PDA (Population-Dependent Analysis), assessing the severity of the results requires focusing on the F-N Curve rather than the boundaries displayed on a map. The F-N Curve is a graphical representation used in risk assessment to illustrate the relationship between the frequency of an incident and the number of fatalities it may cause. It is commonly used in quantitative risk assessment to evaluate societal risk levels. The F-N Curve is typically divided into three risk regions: Unacceptable, ALARP (As Low As Reasonably Practicable), and Acceptable. The Unacceptable region represents the highest level of risk, where immediate mitigation is required as the frequency and severity of incidents exceed tolerable limits. The ALARP region is an intermediate zone where risk reduction is necessary if it is feasible and cost-effective, ensuring that hazards are minimised to a reasonable extent. The Acceptable region signifies a low-risk level where no further mitigation is required, as the risk is considered tolerable. By utilising the F-N Curve, it becomes possible to quantify fatality rates, which cannot be determined solely through PIDA (Population-Independent Analysis). While PIDA provides insight into fuel dispersion and hazard zones, PDA, through the F-N Curve, offers a more detailed understanding of the actual human impact by correlating population exposure with potential fatalities. This approach enables a more precise evaluation of risk and helps in implementing effective safety measures. The F-N curves illustrating the effects of population density variations are presented in the A. APPENDIX.

In addition, an F-N curve considering the possibility of each scenario occurring was presented. An F-N curve represents the frequency of incidents resulting in N or

more fatalities. It is a useful tool for illustrating accident statistics, predicting risk levels, and establishing criterion lines for acceptable societal risk. The curve is based on the fundamental risk concept, where risk is defined as the product of frequency and consequence, commonly expressed as the expected number of fatalities per year (Häring, 2016). In this study, the cumulative F-N Curves are used to show the cumulative frequency of events leading to N or more fatalities on the y-axis. While A.LNG was initially expected to exhibit the lowest risk, slightly lower values were observed for C.LH₂. Contrary to the common assumption that B.LNH₃ would present the highest severity, D.GH₂ emerged as the most critical scenario. The high diffusivity of hydrogen is reflected in the curve's rapid decline beyond a certain threshold. Consequently, if D.GH₂ is considered for marine fuel applications, the establishment of a safety zone alone may be insufficient to achieve an acceptable risk level, and additional safety barriers or enhanced protective measures may be required. The F-N curve illustration is provided in the A. APPENDIX.

As shown in Table 6.4, the **Error! Reference source not found.** F-N Curve analysis of 76 parametric scenarios reveals that D.GH₂ poses the highest risk, frequently falling into the Unacceptable region, even under default conditions, and worsening with higher bunkering quantities, leakage amounts, and population density. B.LNH₃ also exhibits significant risk fluctuations, becoming Unacceptable at higher fuel volumes and low wind speeds, indicating the need for stricter safety measures. A.LNG and C.LH₂ remain predominantly within the ALARP region, with C.LH₂ occasionally reaching the Acceptable range at low leakage and population levels. Wind speed plays a crucial role in reducing localised hazards, as higher speeds generally shift results towards ALARP, whereas low wind speeds lead to more Unacceptable classifications for B.LNH₃ and GH₂. Population density significantly influences risk severity, with higher densities (300%) pushing A.LNG, B.LNH₃, and D.GH₂ into Unacceptable zones, emphasising the need for strict access control and emergency planning. Overall, the results highlight the necessity for enhanced safety protocols, particularly for D.GH₂ and B.LNH₃, under high-risk conditions such as large fuel volumes, extensive leakage, low wind speeds, and high population density.

Table 6.4. Acceptable tolerance level of each scenario.

Inputs		LNG	LNH ₃	LH ₂	GH ₂
Default		ALARP	ALARP	ALARP	Unacceptable
Total bunkering quantity	10%	ALARP	ALARP	ALARP	Unacceptable
	50%	ALARP	ALARP	ALARP	Unacceptable
	200%	ALARP	Unacceptable	ALARP	Unacceptable
	300%	ALARP	Unacceptable	ALARP	Unacceptable
TTS		ALARP	Unacceptable	ALARP	Unacceptable
FTS		ALARP	ALARP	ALARP	Unacceptable
Total leaked fuel quantity	10%	Acceptable	ALARP	Acceptable	ALARP
	50%	ALARP	ALARP	ALARP	Unacceptable
	200%	ALARP	Unacceptable	ALARP	Unacceptable
	300%	ALARP	Unacceptable	ALARP	Unacceptable
Wind speed	10%	ALARP	Unacceptable	ALARP	Unacceptable
	50%	ALARP	Unacceptable	ALARP	Unacceptable
	200%	ALARP	ALARP	ALARP	Unacceptable
	300%	ALARP	ALARP	ALARP	Unacceptable
Population	10%	Acceptable	ALARP	Acceptable	ALARP
	50%	ALARP	ALARP	ALARP	Unacceptable
	200%	ALARP	Unacceptable	ALARP	Unacceptable
	300%	Unacceptable	Unacceptable	ALARP	Unacceptable

6.2.5 Phase 5- General observations

The final phase consolidates the findings from the preceding analyses to derive observations that extend beyond the specific case study configuration. This phase is concerned with identifying general trends and patterns across the parametric results and translating the quantitative outputs into insights relevant to regulatory development and operational practice.

In this case study, Phase 5 examines the comparative behaviour of the four fuel types across the full range of parametric conditions to identify which variables exert

the most consistent influence on safety zone dimensions. The phase also evaluates the extent to which the PIDA-PDA derived safety zones differ from those implied by existing prescriptive regulatory guidance, thereby providing a basis for assessing the adequacy of current provisions. Where the results reveal systematic patterns that are not specific to the particular port configuration or vessel type examined, these are identified as candidates for generalisation to broader operational contexts. The detailed findings of this phase are presented below, and their implications are discussed in Section 6.3.

The present analysis of parametric variations for A.LNG, B.LNH₃, C.LH₂, and D.GH₂ demonstrates pronounced differences in hazard zone expansion and overall risk profiles as organised in Table 6.5. B.LNH₃ and D.GH₂ exhibit the greatest susceptibility to increases in bunkering quantity and fuel leakage volume, with B.LNH₃ surpassing 900 metres in the outer zone at 300% leakage, and D.GH₂ extending beyond 410 metres under similar conditions. In contrast, A.LNG and C.LH₂ consistently remain within the ALARP region, indicating more moderate expansions despite changes in operational parameters.

Notably, wind speed emerges as a critical factor in mitigating dispersion-related risks, particularly for A.LNG and B.LNH₃, both of which show substantial reductions in hazard zones under higher wind speeds (300%). Conversely, D.GH₂ remains relatively unaffected, suggesting inherently broad dispersion characteristics that necessitate stringent risk management strategies. Although population density does not markedly alter the spatial boundaries of hazard zones, it can significantly amplify overall risk severity by increasing the number of exposed individuals.

These findings underscore the importance of fuel-specific safety protocols, robust containment measures, and detailed emergency response plans. In particular, B.LNH₃ and D.GH₂, demand heightened safeguards under conditions of elevated bunkering volume, substantial fuel leakage, and low wind speed. By tailoring risk mitigation strategies to each fuel's unique properties, stakeholders can more effectively maintain safe and reliable bunkering operations.

Table 6.5. Detailed boundaries for each scenario (metres)

		LNG			LNH ₃			LH ₂			GH ₂		
		Inner zone	Middle zone	Outer zone	Inner zone	Middle zone	Outer zone	Inner zone	Middle zone	Outer zone	Inner zone	Middle zone	Outer zone
Default		-	77.33 (100%)	141.26 (100%)	94.83 (100%)	386.77 (100%)	601.49 (100%)	19.81 (100%)	25.27 (100%)	26.38 (100%)	206.32 (100%)	257.91 (100%)	263.86 (100%)
Total bunkering quantity	10%	-	35.64 (46.1%)	99.14 (70.2%)	41.25 (43.5%)	250.92 (64.9%)	490.18 (81.5%)	-	23.33 (92.3%)	25.78 (97.7%)	139.67 (67.7%)	212.67 (82.5%)	260.29 (98.6%)
	50%	-	62.16 (80.4%)	114.48 (81.0%)	64.24 (67.7%)	324.62 (83.9%)	559.26 (93.0%)	16.93 (85.5%)	24.89 (98.5%)	26.48 (100.4%)	169.72 (82.3%)	254.3 (98.6%)	264.63 (100.3%)
	200%	-	90.62 (117.2%)	174.77 (123.7%)	206.95 (218.2%)	433.36 (112.0%)	645.7 (107.4%)	21.27 (107.4%)	25.69 (101.7%)	67.28 (255.0%)	209.5 (101.5%)	257.51 (99.8%)	263.06 (99.7%)
	300%	25.68	96.20 (124.4%)	192.41 (136.2%)	240.2 (253.3%)	481.18 (124.4%)	681.31 (113.3%)	22.01 (111.1%)	25.92 (102.6%)	92.44 (350.4%)	212.00 (102.8%)	259.97 (100.8%)	265.15 (100.5%)
Bunkering method	TTS	37.66	103.22 (133.5%)	198.44 (140.5%)	216.15 (227.9%)	496.86 (128.5%)	692.27 (115.1%)	23.07 (103.0%)	26.03 (103.0%)	102.00 (386.7%)	210.98 (102.3%)	258.94 (100.4%)	267.71 (101.5%)
	FTS	-	64.00 (82.8%)	115.06 (81.5%)	69.53 (73.3%)	335.58 (86.8%)	559.54 (93.0%)	16.93 (85.5%)	25.21 (99.8%)	26.34 (99.8%)	171.45 (83.1%)	253.95 (98.5%)	263.07 (99.8%)
Total leaked fuel quantity	10%	-	-	21.23 (15.0%)	11.87 (12.5%)	70.57 (18.2%)	209.43 (34.8%)	8.01 (40.4%)	10.58 (41.9%)	11.13 (42.2%)	53.97 (26.2%)	82.61 (32.0%)	98.01 (37.1%)
	50%	-	42.87 (55.4%)	97.55 (69.1%)	57.45 (60.6%)	268.75 (69.5%)	451.88 (75.1%)	17.12 (86.4%)	22.76 (90.1%)	24.27 (92.0%)	133.08 (64.5%)	189.31 (73.4%)	196.55 (74.5%)
	200%	-	99.03 (128.1%)	194.42 (137.6%)	169.05 (178.3%)	543.62 (140.6%)	803.45 (133.6%)	23.72 (119.7%)	34.49 (136.5%)	72.97 (276.6%)	272.92 (132.3%)	341.32 (132.3%)	350.04 (132.7%)
	300%	-	113.32 (146.5%)	238.8 (169.0%)	230.01 (242.5%)	649.36 (167.9%)	924.56 (153.7%)	33.4 (168.6%)	40.81 (161.5%)	58.66 (222.4%)	321.20 (155.7%)	399.08 (154.7%)	410.42 (155.5%)
Wind speed	10%	-	157.14 (203.2%)	233.00 (164.9%)	496.18 (523.2%)	720.24 (186.2%)	875.68 (145.6%)	20.07 (101.3%)	23.23 (91.9%)	113.95 (432.0%)	207.13 (100.4%)	250.00 (96.9%)	257.11 (97.4%)
	50%	-	79.98 (103.4%)	187.74 (132.9%)	236.52 (249.4%)	534.87 (138.3%)	755.19 (125.6%)	19.59 (98.9%)	25.25 (99.9%)	83.55 (316.7%)	206.73 (100.2%)	251.57 (97.5%)	257.12 (97.4%)

Ch 6. Safety zones establish for bunkering operations

	200%	-	73.25 (94.7%)	113.52 (80.4%)	65.64 (69.2%)	237.20 (61.3%)	481.16 (80.0%)	19.03 (96.1%)	24.82 (98.2%)	27.16 (103.0%)	204.89 (99.3%)	250.68 (97.2%)	259.09 (98.2%)
	300%	-	59.63 (77.1%)	109.32 (77.4%)	39.18 (41.3%)	160.57 (41.5%)	439.9 (73.1%)	20.16 (101.8%)	24.93 (98.7%)	26.64 (101.0%)	204.26 (99.0%)	252.75 (98.0%)	261.05 (98.9%)
Population	10%	-	72.34 (93.5%)	105.83 (74.9%)	94.09 (99.2%)	390.31 (100.9%)	600.51 (99.8%)	19.81 (100.0%)	25.27 (100.0%)	26.38 (100.0%)	206.32 (100.0%)	257.91 (100.0%)	263.86 (100.0%)
	50%	-	74.17 (95.9%)	114.47 (81.0%)	97.05 (102.3%)	387.61 (100.2%)	600.00 (99.8%)	19.81 (100.0%)	25.27 (100.0%)	26.38 (100.0%)	206.32 (100.0%)	257.91 (100.0%)	263.86 (100.0%)
	200%	-	81.77 (105.7%)	181.40 (128.4%)	94.83 (100.0%)	386.77 (100.0%)	601.49 (100.0%)	19.81 (100.0%)	25.27 (100.0%)	26.38 (100.0%)	206.32 (100.0%)	257.91 (100.0%)	263.86 (100.0%)
	300%	-	88.53 (114.5%)	197.03 (139.5%)	94.83 (100.0%)	386.77 (100.0%)	601.49 (100.0%)	19.81 (100.0%)	25.27 (100.0%)	26.38 (100.0%)	206.32 (100.0%)	257.91 (100.0%)	263.86 (100.0%)

6.3 Discussion and novelty

6.3.1 Discussion of results

The findings of this case study reinforce the value of combining Population-Independent Analysis (PIDA) and Population-Dependent Analysis (PDA) within a unified framework to address the distinctly different hazard profiles posed by LNG, ammonia, and hydrogen bunkering. By first quantifying worst-case spatial hazard boundaries through PIDA and subsequently refining those boundaries through population density and exposure data via PDA, the methodology accommodates the full range of parametric variation across leak diameters, bunkering methods, and environmental conditions. Several key patterns emerge from the integrated results.

For LNG (A), hazard zones expand with increasing leak volume, reaching a maximum outer zone boundary of approximately 238 m under large leak conditions, with low wind speed scenarios producing comparable results at approximately 233 m. These findings confirm that LNG, while not without risk, benefits from a comparatively well-characterised hazard profile that is amenable to probabilistic zone determination.

For liquefied ammonia (LNH₃, B), the study produces the most severe risk outcomes of any fuel type considered. Under large leak conditions, representing 300% of the default leakage quantity, the outer zone boundary extends to approximately 924 m, substantially exceeding the hazard radii of all other fuels examined. Under low wind speed conditions, the hazard range expands to as much as five times the default value, confirming that wind speed is the single most critical environmental variable governing ammonia bunkering risk. This result has direct operational implications. Ammonia bunkering operations should be subject to meteorological monitoring protocols, and worst-case toxic exclusion zones must account for near-calm atmospheric stability classes rather than being anchored to average wind conditions.

For liquefied hydrogen (LH₂, C), the outer zone boundary under low wind conditions expands to approximately 113 m, representing a 430% increase over the default value, yet all LH₂ scenarios remain within PDA acceptable limits. This result reflects the dual character of LH₂ risk. While its physical hazard footprint can be substantial under adverse meteorological conditions, the relatively low storage pressure and limited dispersion under normal wind conditions moderate the societal risk to acceptable levels, provided that ESD systems and secondary containment measures are properly maintained.

For compressed gaseous hydrogen (GH₂, D), the results are the most consistently severe from a societal risk perspective. Despite exhibiting relatively modest spatial variation across the parametric range (up to 150% of the default zone extent), GH₂ scenarios exceed PDA tolerance thresholds in the majority of cases examined. This reflects the dominant influence of high storage pressure on the initial release characteristics of GH₂, which produces high-velocity jet releases capable of rapid vapour cloud formation over extended distances. The implication is that GH₂ bunkering operations at the scale and configuration modelled represent a more persistent challenge to regulatory compliance than either LH₂ or LNG, and may require enhanced physical separation or secondary barrier systems to achieve acceptable risk levels.

Taken together, these findings confirm that leak quantity and wind speed exert comparable and substantial influences on accident severity across fuel types, with wind speed playing a particularly critical role in driving toxic dispersion for ammonia and expanding the spatial hazard envelope for liquefied hydrogen. This result underscores the inadequacy of single-condition assessments and validates the parametric approach as the appropriate methodological basis for alternative fuel bunkering risk analysis.

6.3.2 Novelty of the integrated PIDA-PDA approach

The primary methodological novelty of this case study lies in the integrated application of PIDA and PDA as mutually reinforcing and sequentially structured tools for bunkering safety zone delineation. This approach builds directly upon the foundational PIDA and PDA concepts established in the LNG safety literature, and notably the work by Jeong (Jeong et al., 2020) upon which this thesis builds. Whilst both analyses have been employed separately in the LNG bunkering safety literature, no prior study has formally integrated them into a structured, two-tier approach applied simultaneously across four energy carriers, namely LNG, LNH₃, LH₂, and GH₂, and three bunkering methods, namely STS, TTS, and FTS, under systematic parametric variation. The integration directly addresses the two principal deficiencies of existing approaches that were identified in the literature review. These are the over-conservatism of deterministic consequence-based methods, and the neglect of human exposure distribution in purely probabilistic models.

The novelty of the PIDA-PDA approach lies in the structured way in which established risk metrics are linked to safety zone determination. Individual risk contours, F-N curves, and fatality estimates have long been employed in maritime and offshore quantitative risk assessment, and their use in this approach ensures that the results remain grounded in accepted practice. What is new is the function these metrics perform. In conventional practice, an F-N curve is used to judge whether the societal risk of an activity or installation is tolerable, and its outcome is not directly connected to the sizing of a spatial boundary. In the present approach, the F-N curve produced by PDA verifies whether the zone boundary derived from PIDA remains acceptable under the site-specific population conditions, and it triggers an adjustment of that boundary where the tolerance threshold is exceeded. The same metrics are thereby redirected from an acceptance judgement of the overall activity towards the verification of a previously derived spatial boundary. This structured linkage distinguishes the PIDA-PDA approach from conventional quantitative risk assessment methods and makes it preferable for zone determination, as it yields boundaries that are both defensible against the full

probabilistic scenario range and demonstrably tolerable for the population actually exposed.

Deterministic methods, as applied in much of the existing bunkering safety literature, establish exclusion zone boundaries based on the worst-case physical impact of a single, maximally severe leakage event. While this approach is computationally straightforward and regulatory precedent exists for it, most notably in ISO/TS 18683:2021 (ISO, 2021), it systematically overestimates the practical risk by treating a high-consequence, low-probability event as the design basis for permanent operational exclusion zones. In space-constrained port environments, this can generate requirements that are physically impractical to implement and that may inadvertently constrain the adoption of otherwise viable alternative fuels.

Purely probabilistic models, by contrast, can underweight the consequence dimension of risk by focusing attention on the statistical frequency of events without adequately characterising the spatial distribution of their physical effects in relation to actual personnel locations. The result is a risk profile that is statistically defensible but insufficiently attentive to the human consequences of individual high-severity scenarios.

The integrated PIDA-PDA approach resolves this tension by operating in two analytically distinct but complementary stages. PIDA first establishes the physical upper-bound hazard. Specifically, it defines the spatial extent within which individual risk levels exceed defined acceptance criteria (1×10^{-5} , 1×10^{-6} , and 1×10^{-7} per year) across the full probabilistic distribution of credible scenarios. This provides a scientifically defensible maximum boundary that is independent of local demographic factors and therefore applicable across diverse port environments. PDA then refines this boundary by introducing the actual population density and operational occupancy of the specific bunkering site, translating the physical hazard footprint into a human-centric F-N risk metric. Where the local population is sparse, the PDA boundary may be meaningfully smaller than the PIDA contour, enabling less restrictive access controls without compromising safety. Where personnel density is high, such as near cruise terminals or active working wharves, PDA may require enhanced measures even within PIDA-acceptable zones.

This complementary structure generates practically deployable safety zones that balance protection with operability, offering direct utility for port layout planning, ship design, and regulatory framework development. The framework demonstrates greater realism than either deterministic or purely probabilistic approaches considered in isolation, and its outputs are directly actionable by the range of stakeholders, including port authorities, ship designers, operators, and regulators, who must collectively manage bunkering risk in the maritime environment.

6.3.3 Novelty of the parametric comparative approach

The second principal novelty of this case study is the systematic, simultaneous comparison of LNG, LNH₃, LH₂, and GH₂ under identical operational and environmental conditions through a unified parametric framework. As established in the literature review, prior bunkering risk assessments have almost exclusively treated these fuels in isolation or under substantially different modelling assumptions, preventing the derivation of consistent and actionable conclusions regarding their relative safety performance. The present study is the first to generate a directly comparable, cross-fuel bunkering safety dataset under a single, consistently applied methodological framework.

The parametric structure of the analysis, in which each input parameter is systematically varied while others are held at their default values, provides a transparent and reproducible basis for identifying the controlling variables for each fuel type. This is of particular value in the current operational context, where extensive empirical data for alternative fuel bunkering remain limited. The scenario-based parametric approach serves as a critical interim tool for managing risk under data-scarce conditions, enabling practitioners to identify and prioritise the most influential risk factors across a range of plausible conditions. As real-world operational data accumulate from early alternative fuel deployments, the parametric inputs can be progressively refined to produce increasingly accurate and fuel-specific risk profiles.

Beyond its immediate analytical utility, the parametric comparative framework establishes the methodological infrastructure for developing a preliminary risk

database that shipowners, shipyards, and port operators can use as a reference for rough-order-magnitude safety zone estimation prior to detailed, site-specific assessments. Such a database is an identified gap in the current regulatory environment, and the present results provide its direct empirical foundation.

6.3.4 Implications for industry and regulation

Several key implications of this study for the maritime industry and its regulatory frameworks are identified.

- **Preliminary risk database.** The quantitative results provide the groundwork for a preliminary risk database that shipowners and shipyards can use for rough-order safety zone estimation based on fuel type and bunkering capacity. Such a database would be instrumental for pre-design and retrofitting decisions prior to more detailed, case-specific risk assessments.
- **Regulatory development.** The comparative findings provide an evidence base for shaping future fuel-specific regulations. Since LNG bunkering safety regulations are comparatively well-developed, the present results enable the translation of LNG risk criteria into equivalent standards for ammonia, liquefied hydrogen, and compressed hydrogen. Quantifying the conditions under which each alternative fuel can achieve risk levels comparable to or lower than LNG supports the development of proportionate and operationally defensible safety requirements.
- **Bunkering practice improvements.** The results support a shift towards enhanced bunkering practices for high-risk configurations. In particular, ammonia bunkering, given its potential for large-scale fatalities from toxic dispersion over distances exceeding 600 m under adverse conditions, warrants the introduction of secondary containment barriers or semi-confined bunkering station designs, robust meteorological monitoring and operational delay protocols, and enhanced ESD actuation requirements. For compressed hydrogen, physical separation from high-occupancy areas and reinforced secondary barrier systems are indicated by the PDA results.

6.3.5 Limitations and future research

Notwithstanding its contributions, this study is subject to limitations that inform the direction of future research. First, the leakage scenario matrix, while representative of the credible range of bunkering accidents, is based on the selected probability-driven values and does not exhaustively enumerate all possible leakage configurations. Second, leakage frequency estimates are derived primarily from LNG operational data and adapted for ammonia and hydrogen through comparative assumptions. These estimates may differ significantly from fuel-specific values as dedicated operational data accumulate for emerging fuel systems, whose handling properties and failure modes are in several respects distinct from those of LNG.

Future research should prioritise three directions. Operational dataset expansion is required to reduce the epistemic uncertainty currently inherent in leakage frequency estimates for hydrogen and ammonia systems. Refinement of ignition probability models specific to these fuels is necessary, particularly for hydrogen, where the wide flammability range and low minimum ignition energy produce ignition probability profiles that differ materially from those of LNG. Finally, full-scale experimental validation of model predictions against field measurements from operational alternative fuel bunkering facilities is essential to facilitate the regulatory adoption of the PIDA-PDA methodology and to strengthen confidence in the safety zone boundaries it produces.

These limitations notwithstanding, the integrated PIDA-PDA parametric framework developed and demonstrated in this case study provides a robust, scalable, and evidence-based tool for establishing bunkering safety zones for alternative marine fuels. It offers direct utility for the port layout, ship design, and regulatory planning decisions that will determine the pace and safety of the maritime industry's transition towards sustainable decarbonisation.

7 An integrated qualitative-quantitative risk assessment for defining toxic and hazardous zones on hydrogen-fuelled ships with ammonia cracking systems.

7.1 Background and scope

This chapter presents the second of two case studies in which the integrated risk assessment framework developed in Chapter 5 is applied to a specific engineering problem. The problem addressed is the quantitative determination of toxic and hazardous zones for an onboard hydrogen and ammonia fuel system installed on a small hydrogen-fuelled ship. The case study is based on the work published in the peer-reviewed journal paper by Hwang et al. (2025), "An Integrated Qualitative–Quantitative Risk Assessment for Defining Toxic and Hazardous Zones on Hydrogen-Fuelled Ships with Ammonia Cracking Systems," *Ocean Engineering*, and presents the application of the integrated methodology within the overarching thesis framework (Hwang et al., 2025).

Ammonia and hydrogen are increasingly gaining attention in the marine industry as potential carbon-neutral fuels, aligning with the growing decarbonisation demands. However, ammonia's toxicity, corrosiveness, and fire and explosion hazards, along with hydrogen's high flammability, pose significant safety concerns when these fuels are used for ships. Since 2017, ships with a gross tonnage of 500 and above using low flashpoint fuels are subject to the IGF Code and class regulations (IMO, 2016). The IGF Code was initially designed for LNG as a marine fuel, resulting in notable safety discrepancies when applied to other low flashpoint fuels, particularly hydrogen and ammonia. Despite significant regulatory advancements, certain aspects of current regulations still fall short of providing practical guidelines for ensuring the safe use of ammonia and hydrogen as marine fuels. The existing regulations outline the hazardous zones for potential leak points in ammonia and hydrogen systems onboard. However, these guidelines present two critical design issues. The specified extents of hazardous zones are impractical for small vessels, being too extensive for application. Furthermore, the guidelines do not identify all potential leak points, leaving designers facing considerable design

challenges and confusion. In the context of hazardous zone assessment, deterministic approaches have historically been the default methodology. Deterministic models typically assume extreme conditions such as maximum release rates, unfavourable meteorological conditions, and worst-case failure scenarios, which can lead to overly conservative and impractically large hazard zones. The overly conservative nature of deterministic analysis does not account for the varying probabilities of different conditions occurring simultaneously, thereby lacking nuance and specificity in risk assessment. Such conservatism can nevertheless be justified for a novel technology, where uncertainty remains high across many aspects of system behaviour and a worst-case basis offers a margin of safety against what is not yet fully understood. Small vessels, however, present a different situation. Owing to their spatial and physical constraints, they are frequently unable to accommodate the zone extents that a deterministic analysis requires, and where this is the case the transition to an alternative fuel becomes impossible in practice rather than merely difficult.

To address these deficiencies, this chapter presents an in-depth application of selected components of the integrated framework developed in Chapter 5. The component examined in depth is the consequence modelling of Phase 3, which is carried out through CFD simulation on two independent platforms across five distinct release points. The qualitative hazard identification of Phase 2 draws on the outcomes of a HAZID study conducted within the vessel development programme, which were made available as the input to the present assessment, and the risk integration of Phase 4 is applied in a simplified form based on a frequency acceptance criterion. This division of roles, in which Chapter 6 provides the overall demonstration of the framework and this chapter examines selected components in depth, avoids unnecessary overlap and allows each study to contribute distinct evidence on the applicability of the framework. The methodology integrates qualitative hazard identification with probabilistic analysis and CFD-based consequence modelling within a coherent framework, combining the detailed physical representation of CFD and the risk assessment capabilities of probabilistic analysis to produce practical toxic and hazardous zone definitions for a real case vessel. The detailed correspondence between each phase of the thesis framework

and the analytical activities undertaken in this case study is illustrated in **Error! Reference source not found.** and elaborated in the following sections.

7.2 Case study

The risks associated with ammonia and hydrogen onboard systems are shaped by both the frequency and severity of potential hazardous events. In the current maritime context, the frequency of such events remains inadequately characterised, compounded by the complex nature of shipboard operations and the limited operational history of these emerging fuel systems. Given the scarcity of extensive historical incident data for alternative marine fuels, it is challenging to anticipate and eliminate all possible risk pathways in advance. Accordingly, while efforts to reduce the likelihood of accidents are important, this study places greater emphasis on systematically characterising and mitigating the consequences of accidents should they occur.

The primary analytical tools employed in this case study are FLACS (Flame Acceleration Simulator, developed by Gexcon) and STAR-CCM+ (Siemens Digital Industries Software), which are leading commercially available computational fluid dynamics (CFD) platforms for the simulation of gas dispersion, fire, and explosion scenarios. FLACS was selected for its unique capability to model the flashing evaporation of superheated liquid ammonia releases, a physical phenomenon in which pressurised liquid partially vaporises upon depressurisation to atmospheric conditions and generates a dense aerosol cloud. This behaviour is critical to the accurate prediction of ammonia dispersion from liquid releases and cannot be adequately captured by simple gas-phase dispersion models. STAR-CCM+ was employed for gaseous ammonia and hydrogen vent releases, where the lower-velocity, buoyancy-driven nature of the flow is better suited to this platform's finite-volume gas-phase solver. Both consequence and frequency analyses were performed within this combined simulation framework to map the spatial distribution of toxic and flammable gas concentrations and to evaluate the probability and severity of potential accidents.

Figure 7.1 **Error! Reference source not found.** provides a visual summary of the methodology framework as implemented for the toxic and hazardous zone case study. The figure maps the integrated risk assessment framework developed in Chapter 5 onto the specific analytical activities undertaken in this case study. For each phase and sub-step, the corresponding inputs, modelling tools, and deliverables are presented alongside the general framework structure, offering a consolidated overview of the analytical process before the detailed account that follows in the subsequent sections.

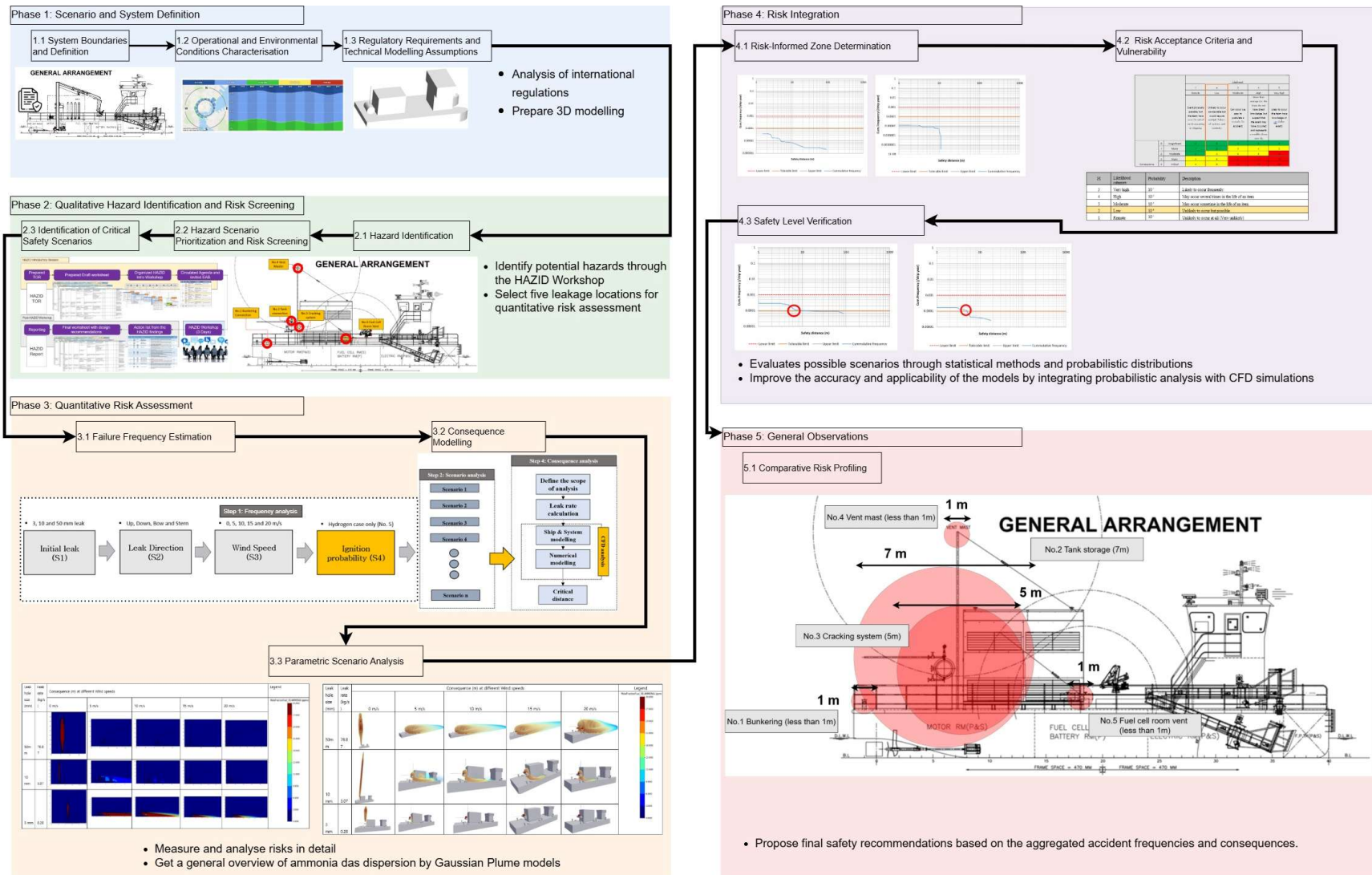


Figure 7.1 Application of the integrated risk assessment framework to the onboard toxic and hazardous zone determination case study

7.2.1 Phase 1- Scenario and system definition

The initial phase establishes the physical, operational, and regulatory boundaries within which the risk assessment is conducted. This provides the necessary foundation for all subsequent analytical activities.

7.2.1.1 *System boundaries and definition*

In this sub-step, relevant data were collected through the examination of materials such as ship design drawings, system operation modes, safety schematics, route/navigational patterns, and the surrounding environment. Table 7.1 shows the general ship specification. The detailed analysis of the entire ammonia system of the target vessel and the identification of potential risks were conducted. The primary tasks undertaken include the identification of potential hazards associated with the use of ammonia as a ship fuel, the analysis of international regulations and classification rules pertaining to ammonia-powered vessels, the understanding and analysis of the target vessel and the ammonia system, and the preparation of 3D modelling based on drawings related to the target vessel.

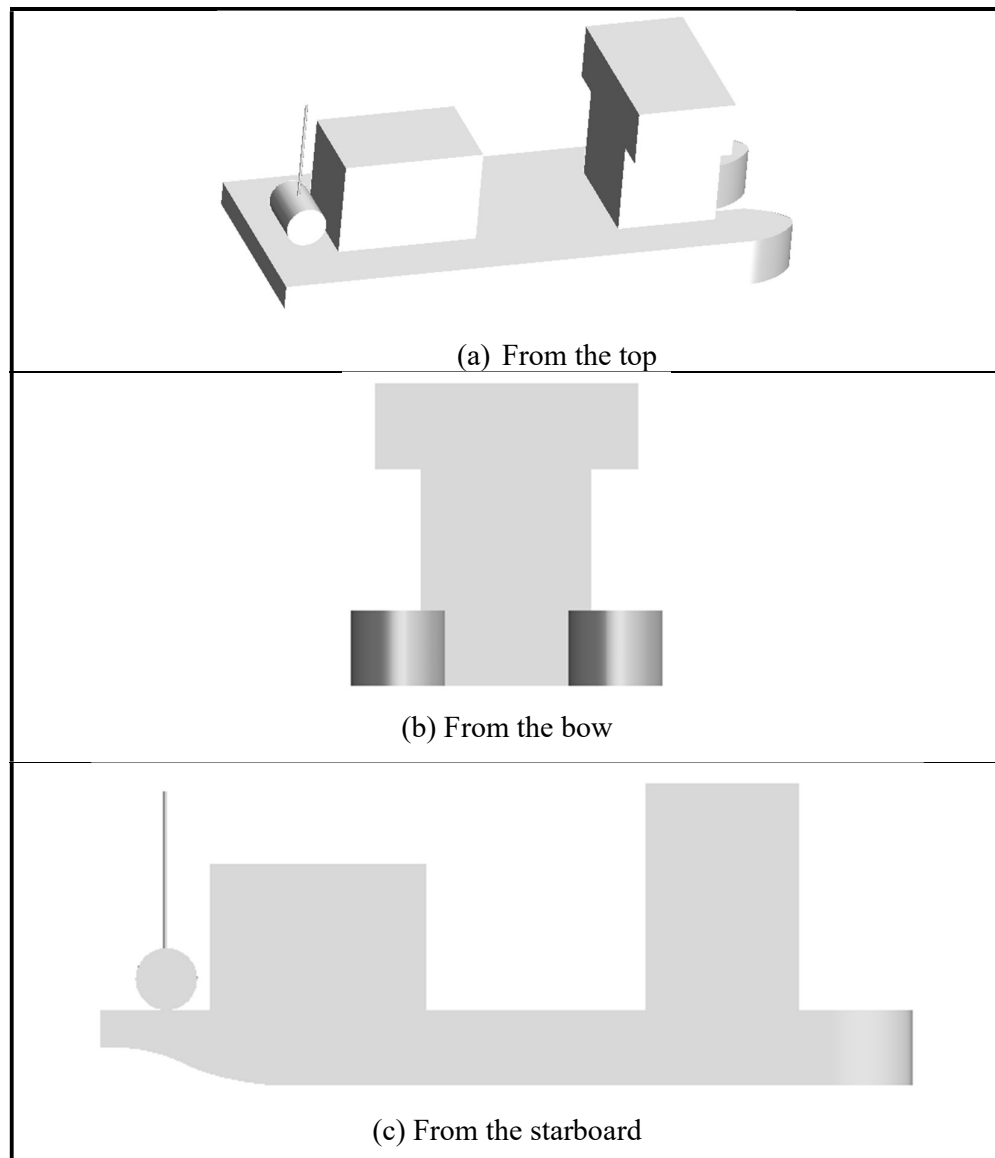
These tasks represent the initial steps in thoroughly analysing the ammonia system of the case ship, aiming to identify and understand potential risks and comply with relevant international regulations and classification rules.

Table 7.1 Ship specifications

Main particulars	Symbols	Full scale
Length overall	$L_{OA}(m)$	18.5
Length between the perpendiculars	$L_{BP}(m)$	18.0
Breadth (MDL.)	$B(m)$	7.00
Depth (MDL.)	$D(m)$	1.80
Draft	$T(m)$	1.00

The preparation of 3D models based on target vessel drawings facilitates a more detailed examination of the vessel's components and configurations, contributing to the overall risk assessment process.

Based on the proposed general layout, Computer-Aided Design (CAD) modelling was performed for the 3D structure of the vessel. The software used for this task was SOLIDWORKS, developed by Dassault Systèmes SolidWorks Corp. The design, as illustrated in Figure 7.2 **Error! Reference source not found.**, was created by referencing the general arrangement and machinery room layout provided by the K engineering company.



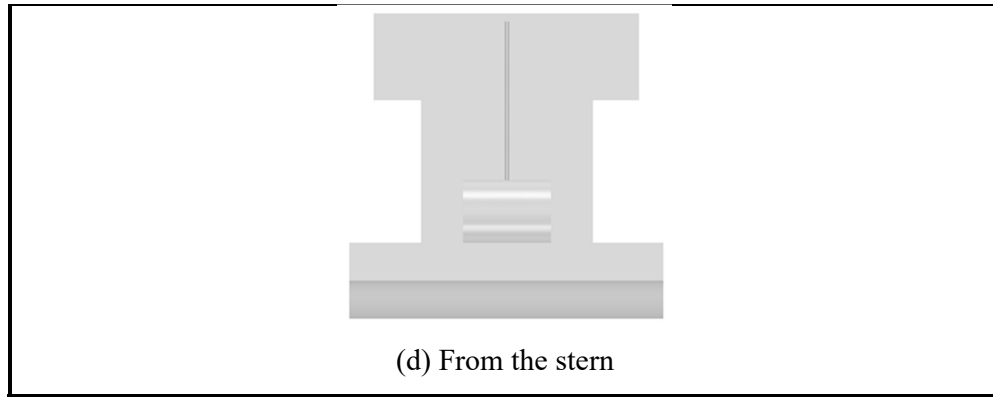


Figure 7.2. 18 m ammonia-reformed hydrogen fuel cell 3D geometry

7.2.1.2 Operational and environmental conditions characterisation

The case vessel is an 18 m harbour service vessel intended for operation in the coastal waters of the Busan region. Its operational modes, route patterns, and the surrounding port environment were characterised from the design documentation collected in the preceding sub-step. The environmental conditions most relevant to the dispersion analysis are dominated by the local wind climate. Annual wind statistics for the Busan region were therefore adopted as the environmental basis of the assessment, and the corresponding probability distribution of wind speeds is derived in the following section as part of the frequency estimation.

7.2.1.3 Regulatory requirements and technical modelling assumptions

The regulatory boundaries of the assessment are defined by the IGF Code and the Korean Register's Rules for Low Flashpoint Fuel Ships, which govern the design of the ammonia fuel system and its safety arrangements on the case vessel.

The assessment focuses on determining the maximum extent of the toxic and hazardous zones resulting from the leakage of ammonia and hydrogen under various environmental conditions. The scope of the dispersion analysis comprises three elements, namely the confirmation of the dispersion behaviour of leaked ammonia gas together with the examination of its spatial concentration distribution, the quantification of the toxic zone for the leaked gas with areas reaching concentrations of 30 ppm or higher treated as toxic zones, and the designation of hazardous zones for hydrogen leakage with concentrations of 4 % or more indicating the flammable range.

7.2.2 Phase 2- Qualitative hazard identification and risk screening

The second phase of the framework applies structured qualitative techniques to identify the credible hazardous scenarios that warrant detailed quantitative analysis. For the case vessel, a Hazard Identification (HAZID) study was carried out within the vessel development programme, and its outcomes were made available as the qualitative input to the present assessment. HAZID was adopted as the primary qualitative tool because of its suitability for identifying major hazard sources and associated accident scenarios at the system design level. On the basis of these outcomes, the screening of leak locations and the definition of the accident scenarios taken forward to Phase 3 were performed through a review of the vessel design documentation.

7.2.2.1 Hazard identification

The HAZID (Hazard Identification) process begins with the preparation of the Terms of Reference (TOR), which outlines the scope and objectives of the HAZID session. Following this, a draft worksheet is prepared, detailing potential hazards, causes, consequences, and safety measures to be considered. To ensure that all participants are well-informed about the process, an introductory workshop is organised. During this workshop, the agenda is circulated, and members of the External Advisory Board (EAB) are invited to participate in the upcoming activities.

The core of the HAZID process is a three-day workshop, where stakeholders engage in detailed discussions to identify hazards, assess associated risks, and explore potential safety measures. This collaborative effort ensures a thorough examination of possible risks and leads to the creation of an action list based on the workshop findings. This list details the specific actions needed to address the identified risks.

After the workshop, the worksheet is finalised, incorporating design recommendations that address the identified hazards. The process culminates in the generation of a HAZID report, which summarises all findings, recommendations, and the actions to be taken. This structured and iterative approach ensures that all potential hazards are identified and mitigated during the design phase, leading to

safer outcomes in the final implementation. The overall process of qualitative risk assessment is given in Figure 7.3.

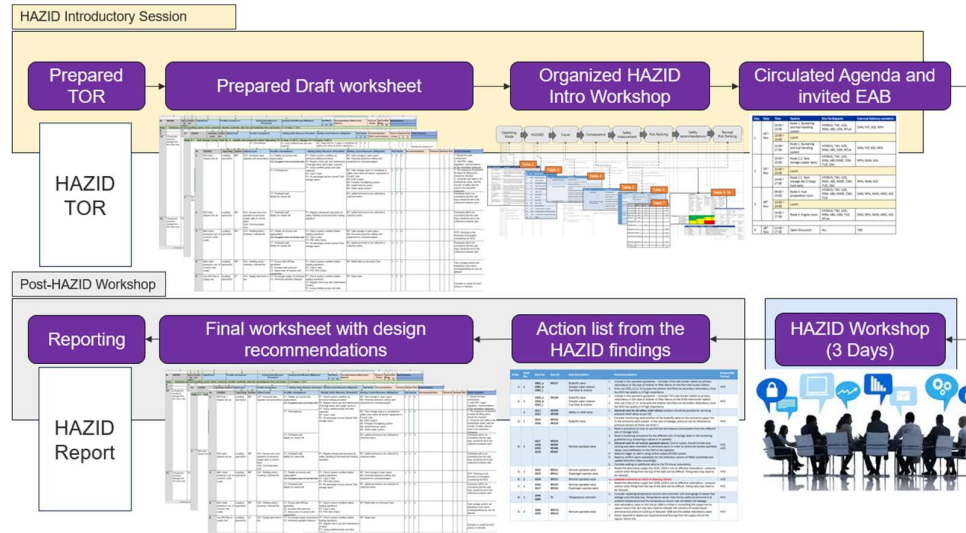


Figure 7.3. Process of qualitative risk assessment.

The outcome of this process relevant to the present assessment is the set of locations within the ammonia and hydrogen fuel system at which a release was judged credible, together with the associated operating conditions.

7.2.2.2 Hazard scenario prioritisation and risk screening

The locations identified through the HAZID study were reviewed against the detailed design documentation of the case vessel, including the arrangement of the ammonia bunkering equipment, the ammonia storage tank, the cracking system, and the hydrogen fuel cell installation, together with the operating mode and the operating pressure of each system.

The HAZID study confirmed the most critical locations susceptible to ammonia and hydrogen leakage. As a result, the five locations summarised in Table 7.2 were identified as leakage risk zones and selected for quantitative risk assessment. The location of these zones is indicated on the general layout diagram in Figure 7.4. It is worth noting that the Vent Master (ammonia leakage, No. 4) is situated near the bow of the target vessel and is designed based on the IGF Code and the Korean Register's rules for low-flashpoint fuel ships to ensure compliance.

Table 7.2. Selection of leak risk locations and accident scenarios for the case ship (5 locations)

No.	Leak location	Operating conditions	Accidental scenarios
1	Bunkering Connection	(DIA : 2 INCH (50A) PRESSURE : 20 BAR)	During ammonia bunkering, there is a risk of toxicity due to a large amount of ammonia leaking due to rupture of piping equipment, etc.
2	Tank Connection	(DIA : 2 INCH (50A) PRESSURE : 20 BAR)	Risk of toxicity due to leakage of large amounts of ammonia due to rupture of fuel supply pipes and piping systems of adjacent fuel tanks.
3	Cracking System	(DIA : 1/2 INCH (12.7A) PRESSURE : 20 BAR)	Risk of toxicity due to ammonia leakage due to rupture of the piping device at the inlet end of the ammonia reformer.
4	Ammonia Tank Vent Master	(DIA : 2 INCH (50A) PRESSURE : 20 BAR)	Risk of toxicity due to the release of a large amount of ammonia gas into the atmosphere due to the operation of the pressure relief valve due to overpressure in the ammonia tank.
5	Fuel Cell Room Vent	Speed 7 m/s, 0.28 m leak diameter	Due to hydrogen leakage in the fuel cell room, there is a risk of fire/explosion as hydrogen is exposed to the atmosphere through mechanical ventilation on the exposed deck.

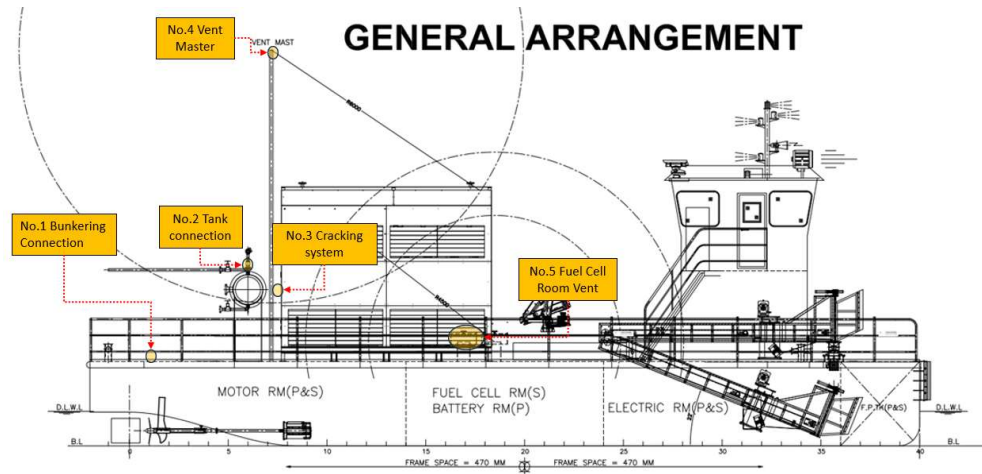


Figure 7.4. General layout of the target vessel and leak analysis locations.

Liquid ammonia, once leaked, rapidly vaporises and disperses in the atmosphere, reaching a wide area. Ammonia, particularly as a highly toxic substance, can have lethal effects even at extremely low concentrations upon inhalation. In the event of a leakage on the main vessel, the toxic gas could potentially spread several kilometres. Moreover, both ammonia and hydrogen are flammable gases, posing a significant risk of fire and explosion when dispersed in the atmosphere.

For each retained location, the substance and the physical state of the anticipated release were then determined, since these govern the dominant hazard type and, in turn, the consequence criteria applied in Phase 3. Locations Nos. 1 to 3 involve the release of pressurised liquid ammonia from the bunkering connection, the tank connection, and the cracking system, for which the dominant hazard is toxic exposure. Location No. 4 involves the release of gaseous ammonia to the atmosphere through the vent master, for which the dominant hazard is likewise toxic exposure, although the release mechanism differs. Location No. 5 involves the release of gaseous hydrogen through the fuel cell room ventilation outlet, for which the toxic hazard is negligible and the dominant hazard is fire and explosion.

7.2.2.3 *Identification of critical safety scenarios*

The extent of gas dispersion during a leak can vary significantly depending on the ambient atmospheric conditions. Therefore, for accident scenarios (Nos.1 to 4), various scenarios were established by considering the leakage amount (S1), leakage

direction (S2), and wind speed (S3), as depicted in Figure 7.5 **Error! Reference source not found..**

Additionally, for hydrogen leakage through the fuel cell room ventilation system (No.5), ignition potential was considered in addition to the existing scenarios. This is because, while the risk of toxicity is negligible for hydrogen leakage, the risk of fire/explosion is high. Hence, the possibility of ignition by considering fire/explosion due to ignition was further taken into account for hydrogen leaks.

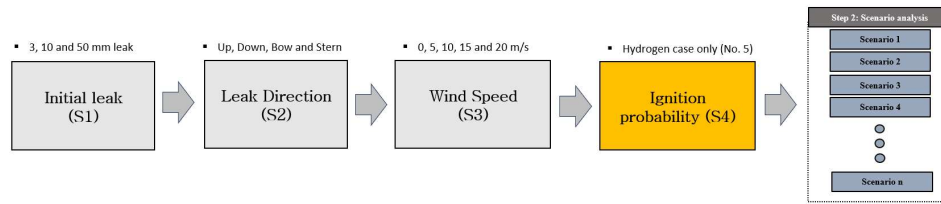


Figure 7.5. Accidental scenarios for ammonia/hydrogen leaks (Nos. 1-5)

7.2.3 Phase 3- Quantitative risk assessment

The third phase constitutes the core quantitative component of the framework, producing estimates of both the physical extent of hazardous effects and the frequency of occurrence of each identified scenario. Leak frequencies for each of the five locations were estimated using generic component failure rate data, with adjustments applied to reflect the specific operating conditions and component types relevant to the ammonia fuel system of the case vessel.

7.2.3.1 Failure frequency estimation

The data were derived from the System Failure Frequency Database provided by DNV (DNV, 2013). The DNV data, originally developed based on data collected by the Health and Safety Executive (HSE) following the Piper Alpha incident, is widely utilised in risk assessment in the oil/gas industry.

For ammonia leakage (S1), the frequency is based on the occurrence of accidents leading to gas/liquid leakage due to various leak hole sizes. The ammonia leakage

frequency due to system failure was calculated based on three representative leak hole sizes (3 mm, 10 mm, 50 mm (complete rupture)).

In the case of ammonia leakage through equipment rupture (S2), it was assumed that rupture could occur in four directions (up, down, left, right) with equal probability, resulting in an assignment of 25% probability to each direction.

Various scenarios for different wind speeds (S3) were calculated using annual wind speed statistics for the Busan region, as shown in Figure 7.6. Wind direction probabilities were not separately considered due to the relative appearance of wind direction depending on the vessel's navigation location. However, CFD simulations were conducted based on the most hazardous conditions.

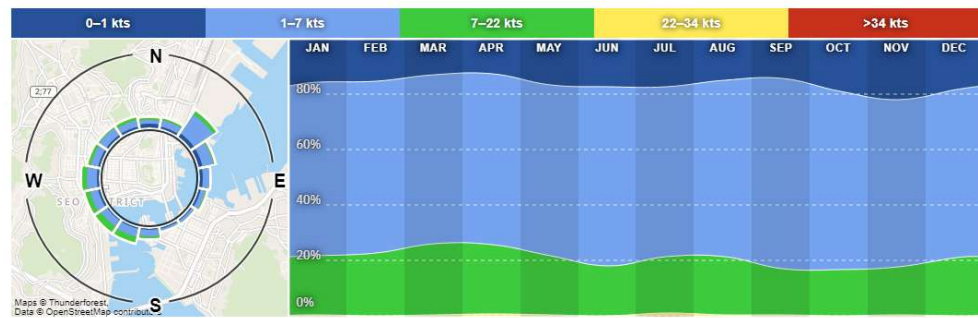


Figure 7.6. Annual wind direction/wind speed statistics for the Busan area (as of 2022) (Windfinder, 2023).

The ignition probability (S4) is defined as the phase where ignition occurs during the process of hydrogen leakage starting on the exposed deck and the subsequent formation and dispersion of flammable gas after a certain time. In this case, there is a high probability of ignition by ignition sources at locations other than the discharge point, leading to the potential for flash fires, pool fires, or explosions. For delayed ignition, OGP (2010b) provides ignition probabilities for a total of 30 different scenarios. This study adopts the first scenario, addressing ignition through leakage via the transfer pipeline of liquid flammable fuel, which is most similar to bunkering on the target vessel. The probability of delayed ignition for this scenario varies with the leakage rate per hour and is defined through Figure 7.7.

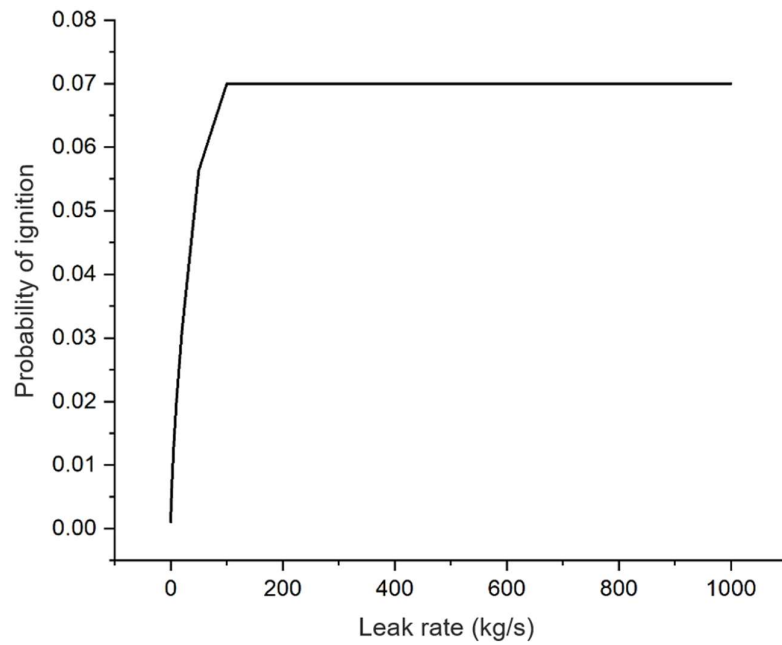


Figure 7.7. Rapid ignition potential of fuel leakage (OGP, 2010b)

7.2.3.2 Consequence modelling

The accident scenarios established in Phase 2 were evaluated for toxicity and hazard ranges through Computational Fluid Dynamics (CFD) simulations. The consequence analysis process, as depicted in Figure 7.8, was conducted to assess the extent of the toxic and hazardous zones.

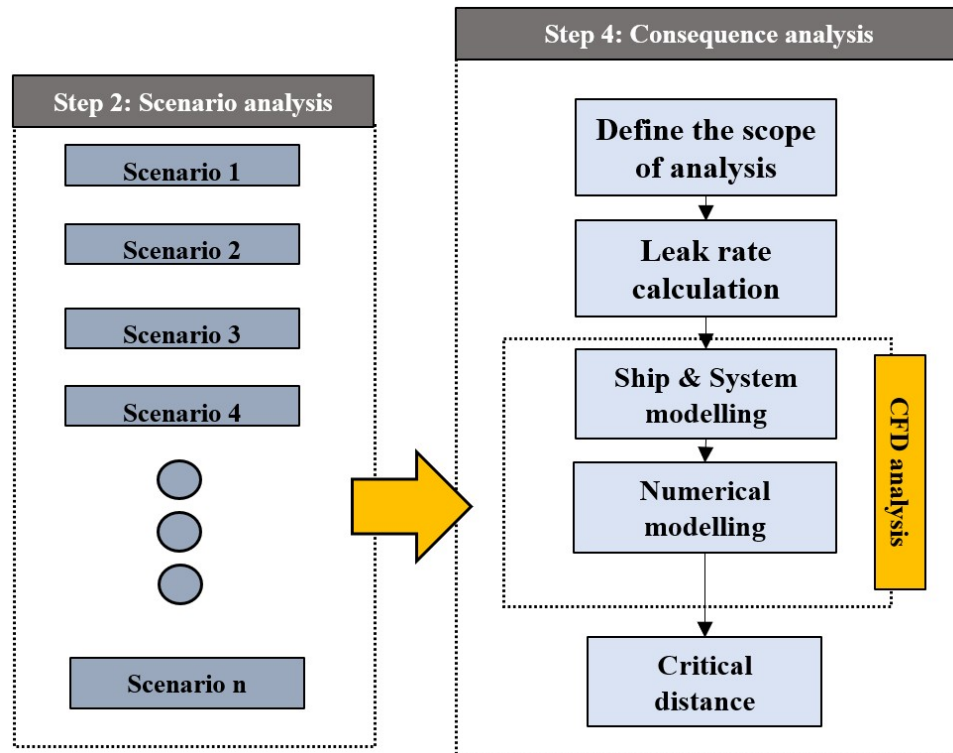


Figure 7.8. Consequence analysis process for accident scenarios

Liquid ammonia leaks (Nos. 1–3). This category covers the scenarios in which liquid ammonia leaks into the atmosphere from the bunkering connection, the tank connection, and the cracking system. The leakage rate and quantity vary based on the size of the leak and the success of response measures post-leakage. In this study, the maximum size of the piping system in the ammonia system of the target vessel was calculated to be 50 mm. To adopt a conservative perspective, various leak sizes were simplified into three categories: 1–3 mm leaks represented as 3 mm hole leaks, 3–10 mm leaks considered as 10 mm hole leaks, and 10–50 mm leaks regarded as 50 mm hole leaks.

The assumed density of ammonia is 682 kg/m^3 , and the leakage pressure is considered the normal pressure during ammonia bunkering, which is 20 bar. A discharge coefficient (Cd) of 0.75 was used based on a typical sharp orifice. Using the following equation, the leakage rate at the initial leak point was calculated for ammonia liquid leakage scenarios (No. 1–3), considering different leak hole sizes.

Using Eq. (7.1), the analysis initiates with the calculation of leak rates in representative leak holes and the operating conditions for bunkering. The parameters used in this calculation are based on the data for the case ship.

$$Q = C \times A \times \sqrt{2 \times \rho \times p_g} \quad \text{Eq. (7.1)}$$

Where Q is the leak rate [kg/s], C is the discharge coefficient, A is the cross-sectional area of the leak point [m²], ρ is the density of fuel [kg/m³], and P_g is the gauge pressure inside the pipe [Pa].

Gaseous ammonia leak (No. 4). The calculation was conducted according to the method specified in Chapter 7, Section 703, "Pressure Release Devices," of the Korean Register's Rules for Low Flashpoint Fuel Ships (KR). Using a pipe size of 50 mm as the reference, the maximum discharge capacity was determined to be 0.21 m³/s.

Hydrogen leak (No.5) For the fuel cell room, with an area of 0.06 m², two mechanical ventilation devices are installed, each providing a ventilation capacity of 9 m³/min. Typically, one device is in continuous operation, considering ventilation requirements 30 times per hour. Therefore, the exhaust velocity of the ventilation devices was designed to be 3 m/s.

The liquid ammonia release scenarios (Nos. 1–3) were simulated in FLACS, in which the atmospheric dispersion of ammonia is computed from the Reynolds-averaged Navier-Stokes equations with the standard k- ϵ turbulence model and Favre-averaged governing equations discretised by the finite volume method. Because pressurised liquid ammonia partially vaporises upon release, the Flash utility of FLACS was applied to represent the two-phase near-field jet, and the end of the near-field region, at which the liquid fraction has fully changed phase, was used as the starting point of the gas dispersion calculation. The computational domains were discretised with structured Cartesian grids with a minimum cell size of 0.6 m, and all release cases were solved as transient simulations with gas detectors placed at critical monitoring locations.

A grid sensitivity study was performed for each FLACS scenario using coarse, medium, and refined grids, corresponding to 16,275, 24,360, and 36,036 cells for the bunkering scenario, 46,332, 86,592, and 195,888 cells for the tank scenario, and 52,635, 101,840, and 178,948 cells for the cracking system scenario. Gas concentrations were monitored at three locations in each domain, and the medium and refined grids produced closely matching concentration histories while the coarse grid diverged at the downstream monitoring locations. The medium grid was therefore adopted for the production simulations.

The gaseous ammonia and hydrogen release scenarios (Nos. 4 and 5) were simulated in STAR-CCM+ using an automatically generated hexahedral mesh of approximately 4,500,000 cells, produced with the Surface Remesher and Trimmed Cell Mesher tools and locally refined around the vent master and the fuel cell room vent. Grid independence was confirmed through a sensitivity study with approximately 2,000,000, 3,200,000, and 4,500,000 cells. The domain boundaries were prescribed as velocity inlets to impose the wind conditions, the hull was treated as a no-slip wall, and the release points were represented by mass flow inlet conditions with an ammonia mass flow rate of 0.21 kg/s for scenario No. 4 and a hydrogen discharge speed of 3 m/s for scenario No. 5. Turbulence was modelled with the Realizable k- ϵ Two-Layer model, and the SIMPLE algorithm was used for pressure-velocity coupling.

In total, 75 transient production simulations were performed across the two platforms, comprising 45 FLACS cases spanning three leak locations, three hole sizes, and five wind speeds, and 30 STAR-CCM+ cases spanning two release conditions for the vent master and four hydrogen concentrations for the fuel cell room vent under the same five wind speeds. These were supplemented by twelve grid-sensitivity simulations. The full account of the numerical modelling methods, boundary conditions, and grid sensitivity results is provided in Appendix B.

All accidental scenarios, with the estimates of gas leak rates, are investigated to assess the critical boundary of gas dispersion by means of CFD method, FLACS Ver. 10.5. Table 7.3 presents the general setup information for the simulation.

Table 7.3. General information of the CFD modelling condition.

Analysis Duration	Leakage Duration	Wind Build-up Time	Reference Height of the Wind	Ambient Temperature
110 Seconds	90 Seconds	10 Seconds	10 m	20 °C
Simulation Volume Sizes [m]	Boundary Condition [X,Y,Z]	Courant-Friedrichs-Levy Number	Grid Size [minimum]	Grid Size [maximum]
(2000, 2000, 200)	Wind(Outflow) & Nozzle(Inflow)	CFLC:10 CFLV:1	0.5 m	40 m

Different safety evaluators and flag states have different views on determining the tolerable level of the gas concentration in air. This study adopts two different criteria.

- Criterion 1: half-LFL (lower flammable limit) equivalent to 2.5 % of airborne gas concentration by volume
- Criterion 2: full-LFL equivalent to 5.0 % of airborne gas concentration by volume

Given this, the critical distances/areas are defined to be the lengths/scopes within those gas concentration levels. Hence, the CFD simulation makes it possible to observe gas dispersion behaviours at different scenarios, and thereby to determine critical distances and areas. The measured critical distance and area are, then, used to indicate the extent of the hazardous zone when combined with the frequency analysis results during the next phase of risk assessment.

7.2.3.3 *Parametric scenario analysis*

The final sub-step of Phase 3 introduces the parametric variation into the quantitative analysis. Rather than relying on a single set of fixed conditions, the consequence calculations were repeated across a systematically varied range of input parameters. For each of the five leak locations, the leak hole size or the release concentration was varied together with five wind speeds ranging from 0 m/s to 20 m/s, and the resulting dispersion behaviour was evaluated case by case. Table 7.4 summarises the results of the consequence analysis for each scenario.

Table 7.4 Summary of consequence analysis results

Scenarios	Leak hole size (mm)	Leak rate (kg/s)	Consequence (m) at different Wind speeds				
			0 m/s	5 m/s	10 m/s	15 m/s	20 m/s
	50 mm	76.87	3	91.5	54	36	22
	10 mm	3.07	5	4.5	4	2.8	2

No.1 Bunkering	3 mm	0.28	10	2.5	2	1.5	1.5
No.2 Tank system	50 mm	76.87	7	86	66	46	26
	10 mm	3.07	5	5	4	3	1
	3 mm	0.28	3	1	1	1	1
No. 3 Cracking system	12.7 mm	4.96	7	18	13	6	6
	10 mm	3.07	5	5	4	3.5	3
	3 mm	0.28	3	1	1	1	1
No. 4 Vent master	30 ppm	0.21	0.03	0.05	0.07	0.07	0.07
	100% ammonia	0.21	0.7	1.6	5.3	6	8
Scenarios	H ₂ Concentration	Discharge speed (m/s)	Consequence (m) at different Wind speeds				
			0 m/s	5 m/s	10 m/s	15 m/s	20 m/s
No. 5 H₂ gas Vent	100%	3 m/s	1.6	10	11	11	7.3
	50%	3 m/s	1.1	10	7.7	3.8	3.3
	25%	3 m/s	0.7	7.3	3.4	2.8	2.3
	10%	3 m/s	3	3.5	0.7	0.7	0.6

7.2.3.3.1 Bunkering connection (No. 1)

Table 7.5 presents a quantitative analysis of potential ammonia leakage scenarios at the bunker connection point. Figure 7.9 and Figure 7.10 illustrate the ammonia dispersion patterns in 2D and 3D plots, respectively. The table summarises the leak rates (kg/s), frequencies (per year), and the consequence distances (m) exceeding 30 ppm of ammonia concentration under various wind speeds (0 m/s, 5 m/s, 10 m/s, 15 m/s, 20 m/s) based on leak hole sizes of 50 mm, 10 mm, and 3 mm.

For the 50 mm hole, with a significant leak rate of 76.87 kg/s, the dispersion distance is limited to 3 metres under calm conditions. However, as wind speed increases, the dispersion range expands drastically, reaching 91.5 metres at 5 m/s. It then decreases to 54 metres at 10 m/s, 36 metres at 15 m/s, and 22 metres at 20 m/s. This trend indicates that large-scale leaks can initially disperse over a wide area as wind speed increases, but further increases in wind speed gradually reduce the affected distance.

For the 10 mm hole, the leak rate decreases to 3.07 kg/s. In windless conditions, the dispersion reaches 5 metres. As the wind speed rises, the dispersion range gradually decreases to 4.5 metres at 5 m/s, 4 metres at 10 m/s, 2.8 metres at 15 m/s, and 2 metres at 20 m/s. This demonstrates that moderate leaks are significantly influenced by wind, which acts to limit the dispersion range.

For the 3 mm hole, the leak rate is minimal at 0.28 kg/s. Without wind, the ammonia spreads up to 10 metres. However, with increasing wind speed, the dispersion distance rapidly decreases to 2.5 metres at 5 m/s, 2 metres at 10 m/s, and 1.5 metres at both 15 m/s and 20 m/s. This indicates that small leaks are quickly diluted by wind, substantially reducing the impact area.

Large leaks have the potential to disperse over a wide area, especially under moderate wind conditions. Conversely, medium and small leaks show limited dispersion as wind speed increases, though they can still pose significant risks in confined or poorly ventilated environments.

Table 7.5. Results of ammonia leak scenarios at the bunker connection

Leak hole size (mm)	Leak rate (kg/s)	Frequency (/year)	Consequence (m) at different Wind speeds				
			0 m/s	5 m/s	10 m/s	15 m/s	20 m/s
50 mm	76.87	1.39E-05	3.0	91.5	54.0	36.0	22.0
10 mm	3.07	3.74E-05	5.0	4.5	4.0	2.8	2.0
3 mm	0.28	9.99E-05	10.0	2.5	2.0	1.5	1.5

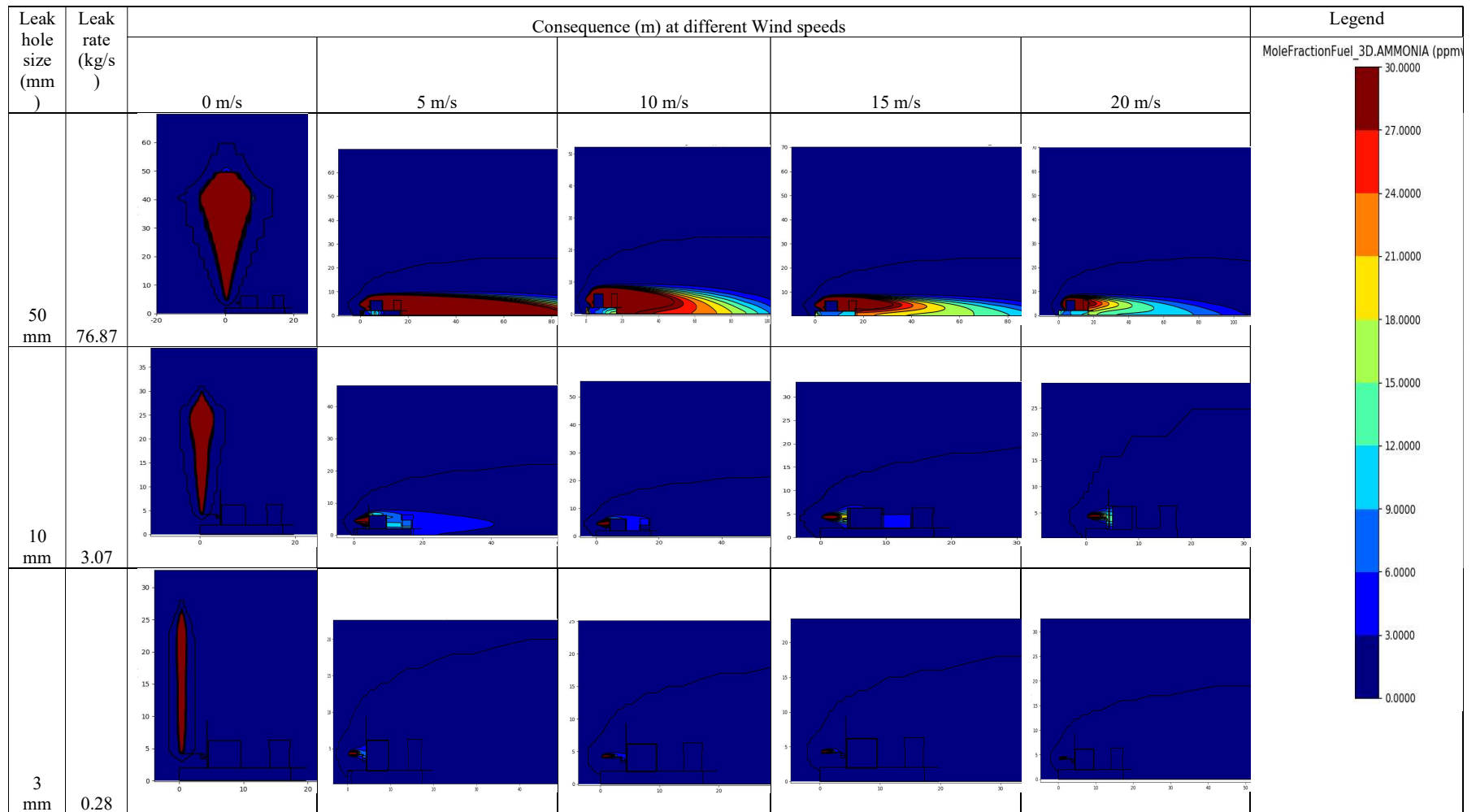


Figure 7.9. Simulation Results (2D XZ plot) for Scenario 1

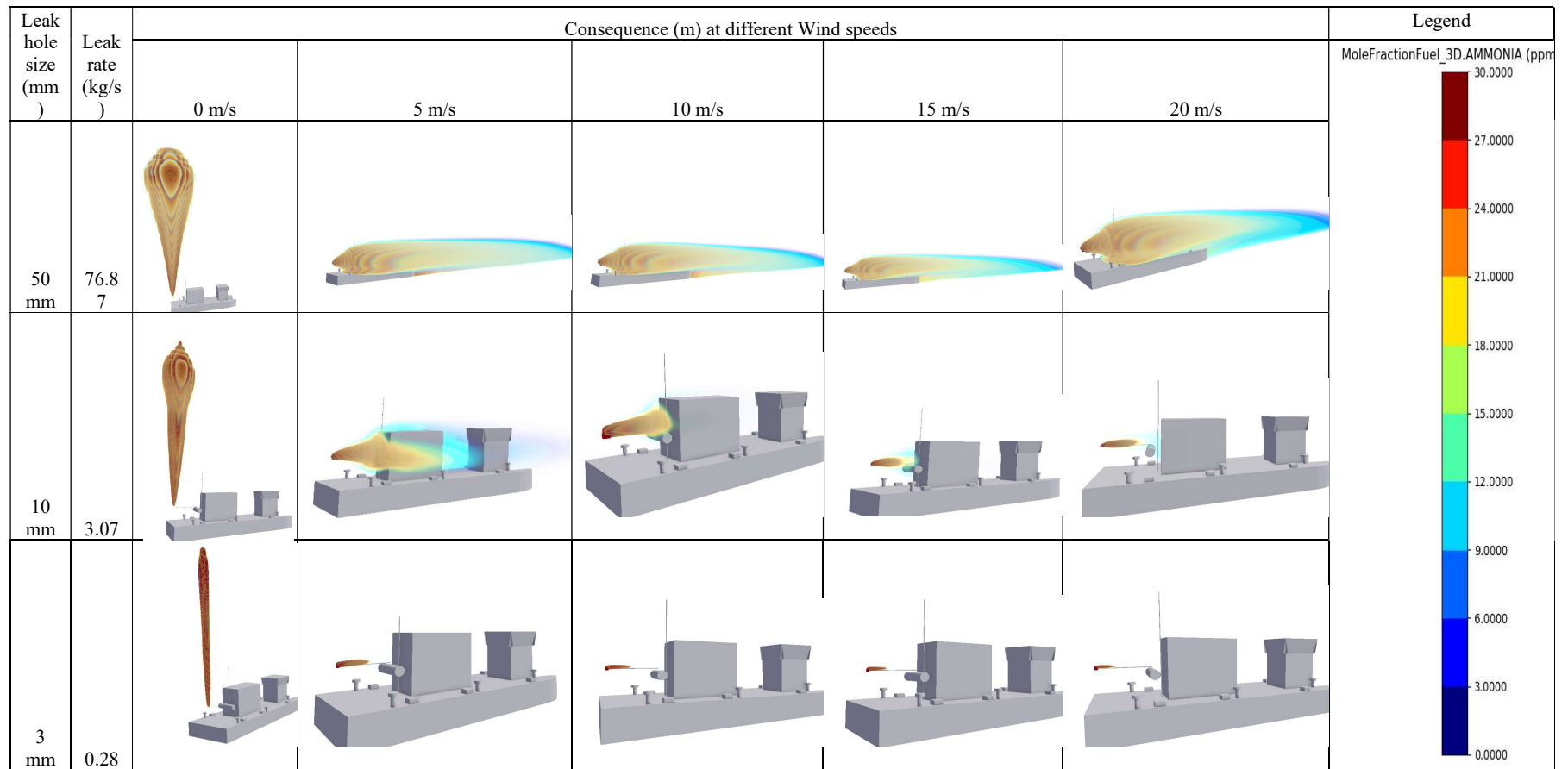


Figure 7.10. Simulation Results (3D plot) for Scenario 1

7.2.3.3.2 Ammonia tank (No. 2)

Table 7.6 presents a quantitative analysis of potential ammonia leakage scenarios from the ammonia tank. Figure 7.11 and Figure 7.12 illustrate the ammonia dispersion patterns in 2D and 3D plots, respectively. The table summarises the leak rates (kg/s), frequencies (per year), and consequence distances (m) where ammonia concentrations exceed 30 ppm under varying wind speeds (0 m/s, 5 m/s, 10 m/s, 15 m/s, and 20 m/s), based on leak hole sizes of 50 mm, 10 mm, and 3 mm.

For the 50 mm hole, the leak rate is significantly high at 76.87 kg/s. In windless conditions, the dispersion distance reaches 7 metres. However, when the wind speed increases to 5 m/s, the dispersion distance extends dramatically to 86 metres. As the wind speed continues to increase, the dispersion distance gradually decreases to 66 metres at 10 m/s, 46 metres at 15 m/s, and 26 metres at 20 m/s. This pattern shows that for large-scale leaks, moderate wind initially enhances the dispersion range, but stronger winds lead to a reduction in the affected area due to rapid dilution.

For the 10 mm hole, the leak rate decreases to 3.07 kg/s. Both under calm conditions and at 5 m/s wind speed, the dispersion distance remains constant at 5 metres. However, with further increases in wind speed, the distance gradually decreases to 4 metres at 10 m/s, 3 metres at 15 m/s, and 1 metre at 20 m/s. This indicates that medium-scale leaks are progressively suppressed by wind, limiting the spread of ammonia.

For the 3 mm hole, the leak rate is the smallest at 0.28 kg/s. Under windless conditions, ammonia disperses up to 3 metres. As the wind speed increases, the dispersion distance rapidly reduces to 1 metre and remains constant at 1 metre for wind speeds of 5 m/s and above. This demonstrates that small leaks are quickly diluted by wind, resulting in a significantly reduced dispersion range.

Table 7.6. Results of ammonia leak scenarios at the ammonia tank

Leak hole size (mm)	Leak rate (kg/s)	Frequency (/year)	Consequence (m) at different Wind speeds				
			0 m/s	5 m/s	10 m/s	15 m/s	20 m/s
50 mm	76.87	4.38E-04	7	86	66	46	26
10 mm	3.07	5.95E-04	5	5	4	3	1
3 mm	0.28	8.88E-04	3	1	1	1	1

Ch.7. Defining hazardous zones for hydrogen-fuelled ships

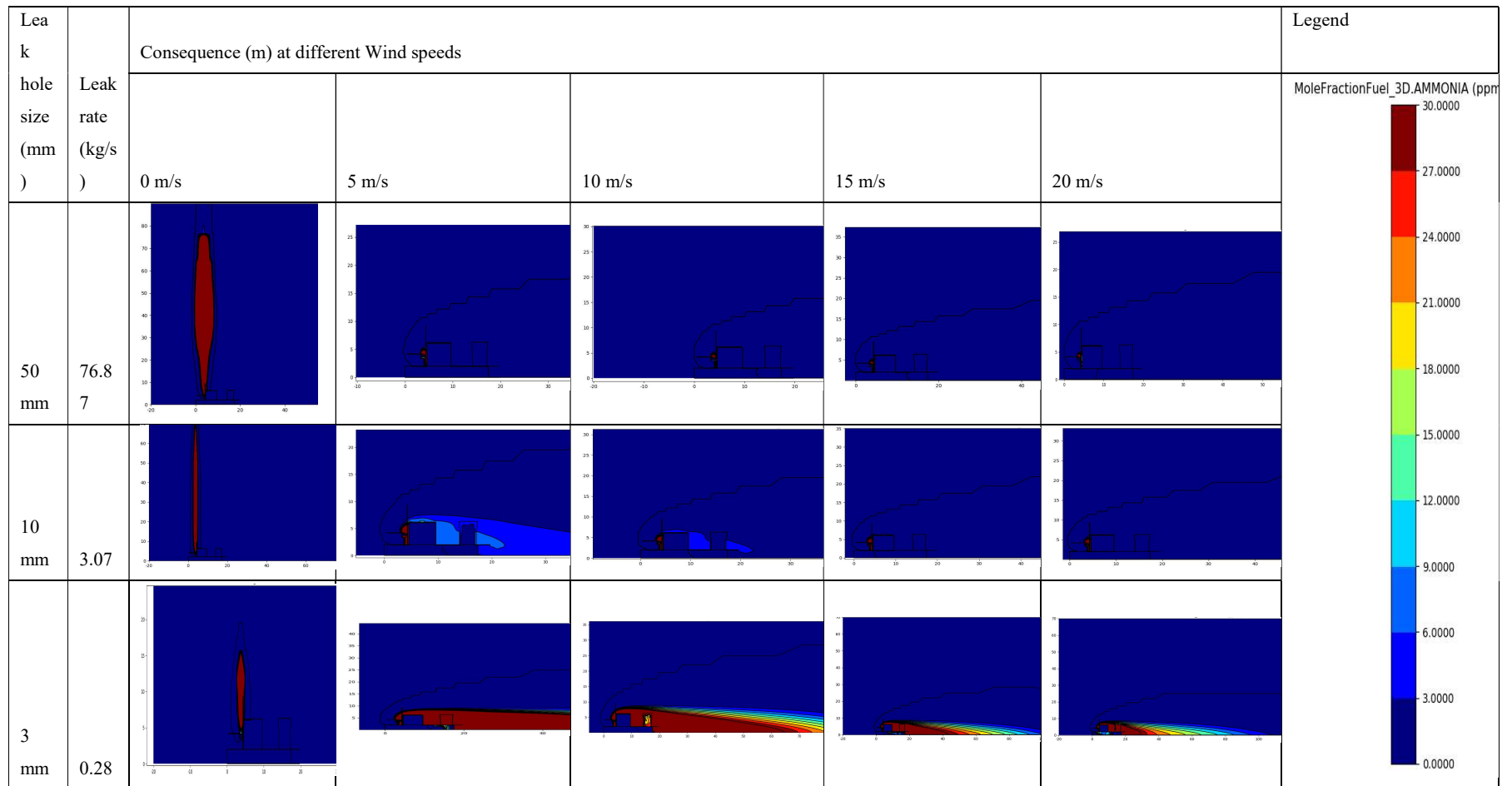


Figure 7.11. Simulation Results (2D XZ plot) for Scenario 2

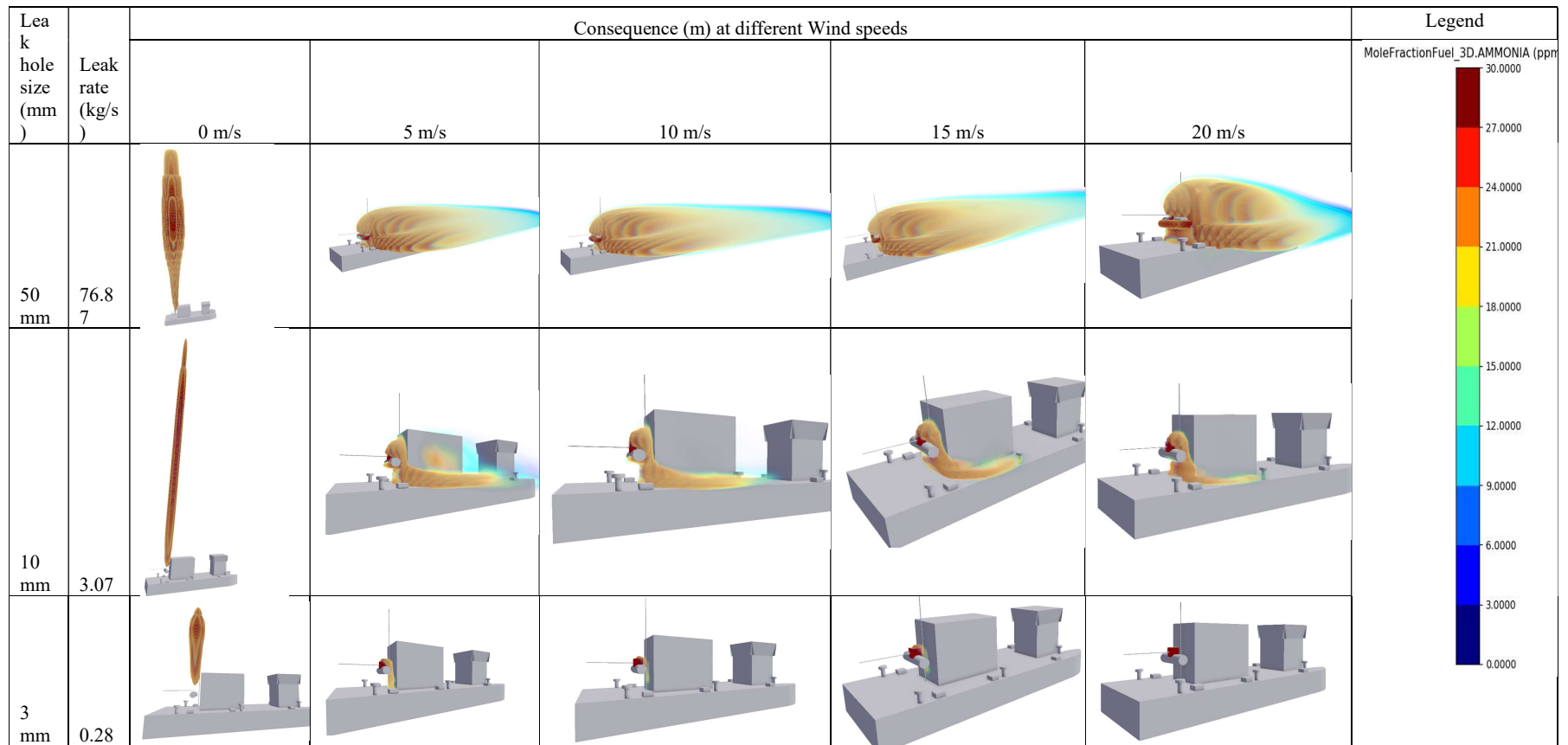


Figure 7.12. Simulation Results (3D plot) for Scenario 2

7.2.3.3.3 Cracking system (No. 3)

Table 7.7 presents a quantitative analysis of potential ammonia leakage scenarios at the cracking system. Figure 7.13 and Figure 7.14 illustrate the ammonia dispersion patterns in 2D and 3D plots, respectively. The ammonia pipeline has a diameter of 1/2 inch (12.7 mm) and operates at a pressure of 20 bar. The table summarises the leak rates (kg/s), frequencies (per year), and consequence distances (m) where ammonia concentrations exceed 30 ppm under varying wind speeds (0 m/s, 5 m/s, 10 m/s, 15 m/s, and 20 m/s), based on leak hole sizes of 12.7 mm, 10 mm, and 3 mm.

For the 12.7 mm hole, the leak rate is the highest at 4.96 kg/s. Under windless conditions, ammonia disperses up to 7 metres. As wind speed increases to 5 m/s, the dispersion distance extends significantly to 18 metres. However, with further wind speed increases, the distance decreases to 13 metres at 10 m/s and drops further to 6 metres at both 15 m/s and 20 m/s. This pattern indicates that moderate wind initially enhances dispersion, but stronger winds reduce the impact area due to rapid dilution.

For the 10 mm hole, the leak rate decreases to 3.07 kg/s. Both under calm conditions and at 5 m/s wind speed, the dispersion distance remains constant at 5 metres. As wind speed increases, the dispersion distance gradually decreases to 4 metres at 10 m/s, 3.5 metres at 15 m/s, and 3 metres at 20 m/s. This demonstrates that medium-scale leaks are progressively suppressed by wind, limiting the spread of ammonia.

For the 3 mm hole, the leak rate is minimal at 0.28 kg/s. Under windless conditions, ammonia disperses up to 3 metres. However, when wind speed reaches 5 m/s or higher, the dispersion distance rapidly decreases to 1 metre and remains constant at 1 metre regardless of further wind increases. This highlights that small leaks are quickly diluted by wind, significantly reducing the dispersion range.

Table 7.7. Results of ammonia leak scenarios at the cracking system

Leak hole size (mm)	Leak rate (kg/s)	Frequency (/year)	Consequence (m) at different Wind speeds				
			0 m/s	5 m/s	10 m/s	15 m/s	20 m/s
12.7 mm	4.96	1.68E-04	7.0	18.0	13.0	6.0	6.0
10.0 mm	3.07	3.34E-04	5.0	5.0	4.0	3.5	3.0
3.0 mm	0.28	9.17E-04	3.0	1.0	1.0	1.0	1.0

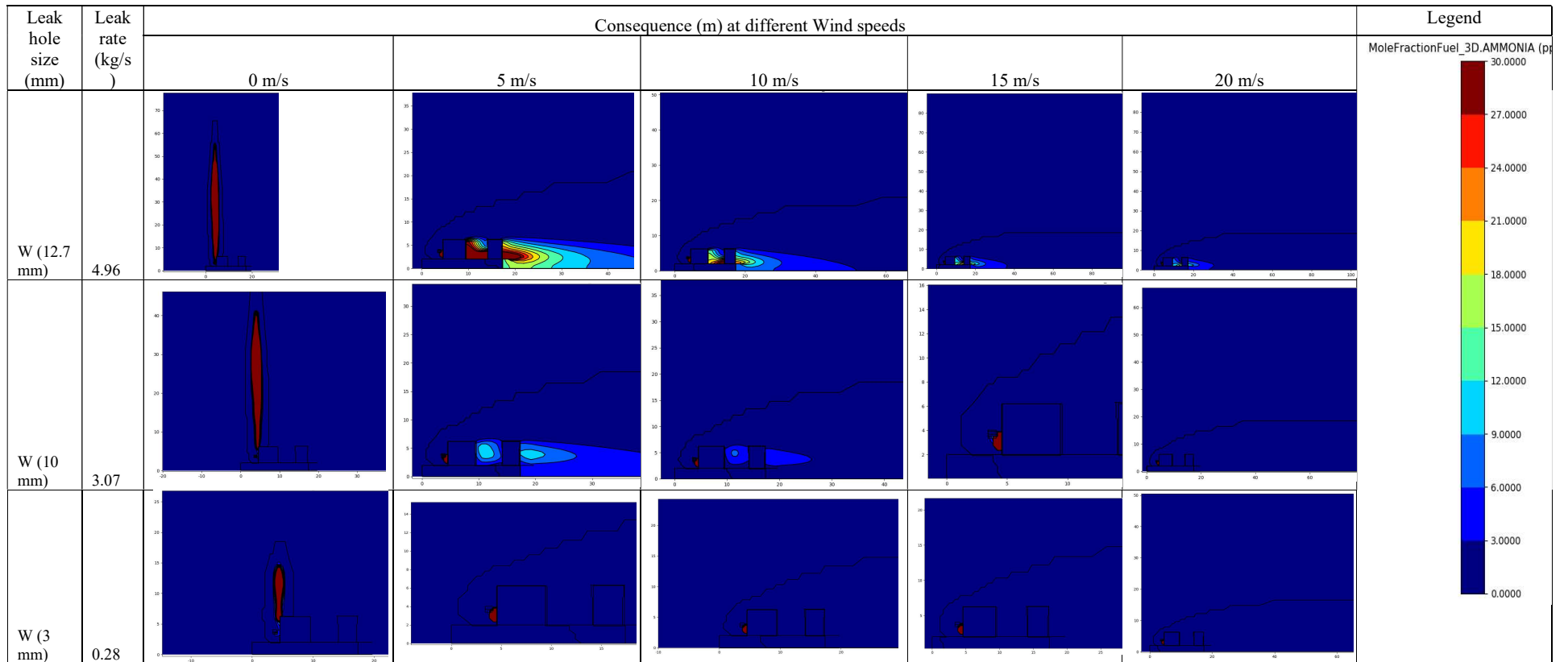


Figure 7.13. Simulation Results (2D XZ plot) for Scenario 3

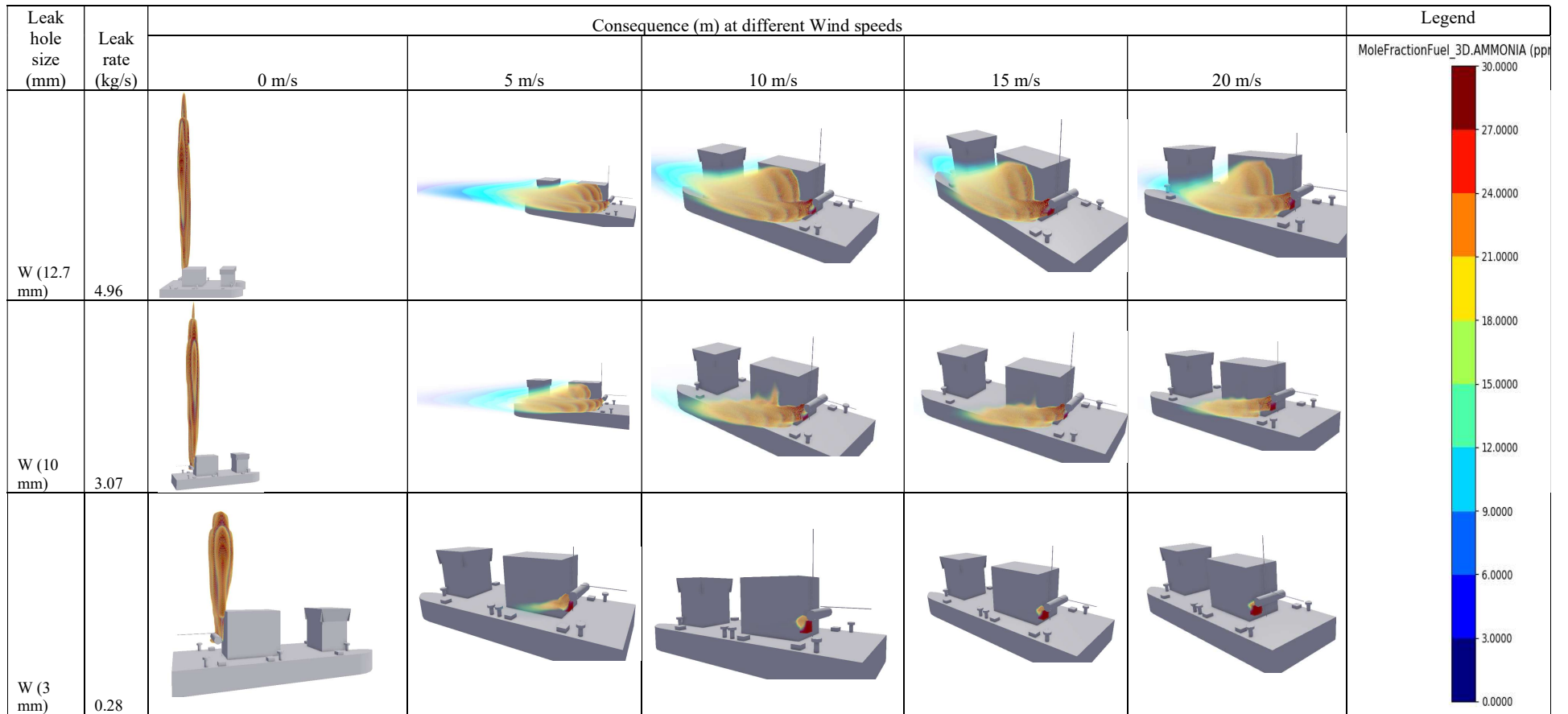
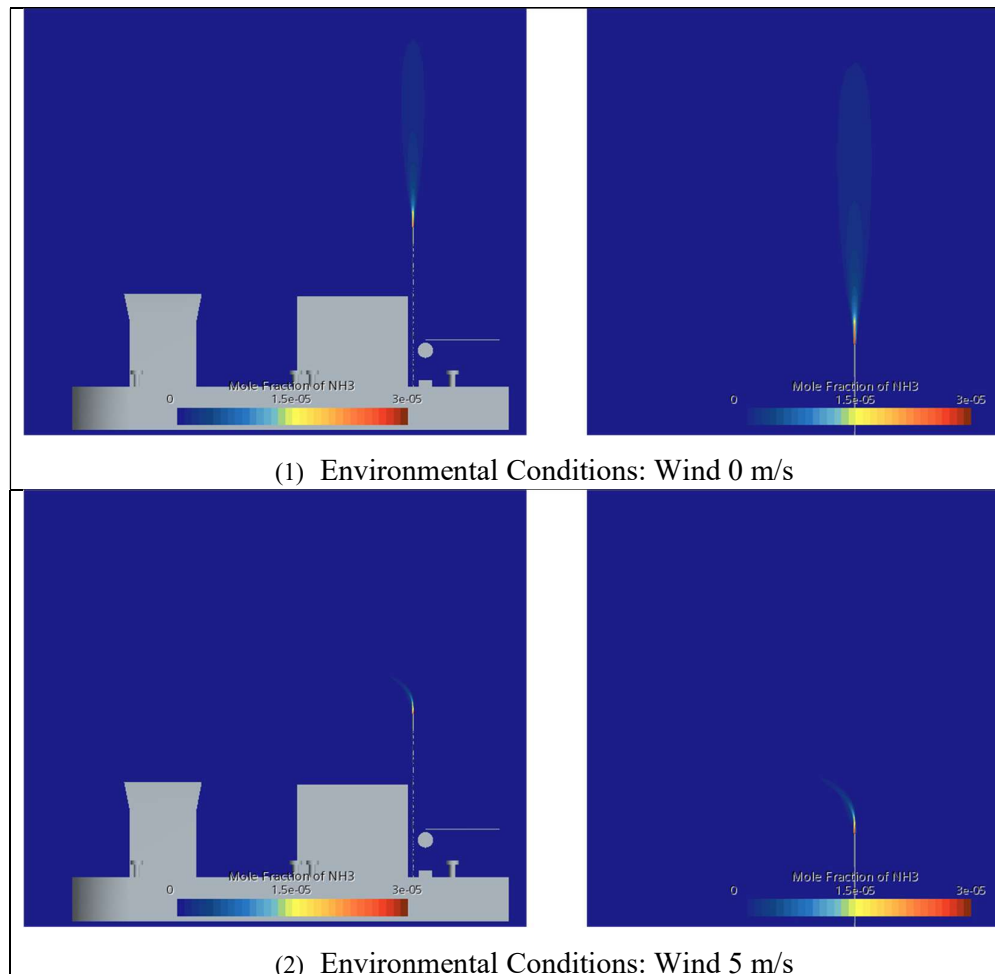
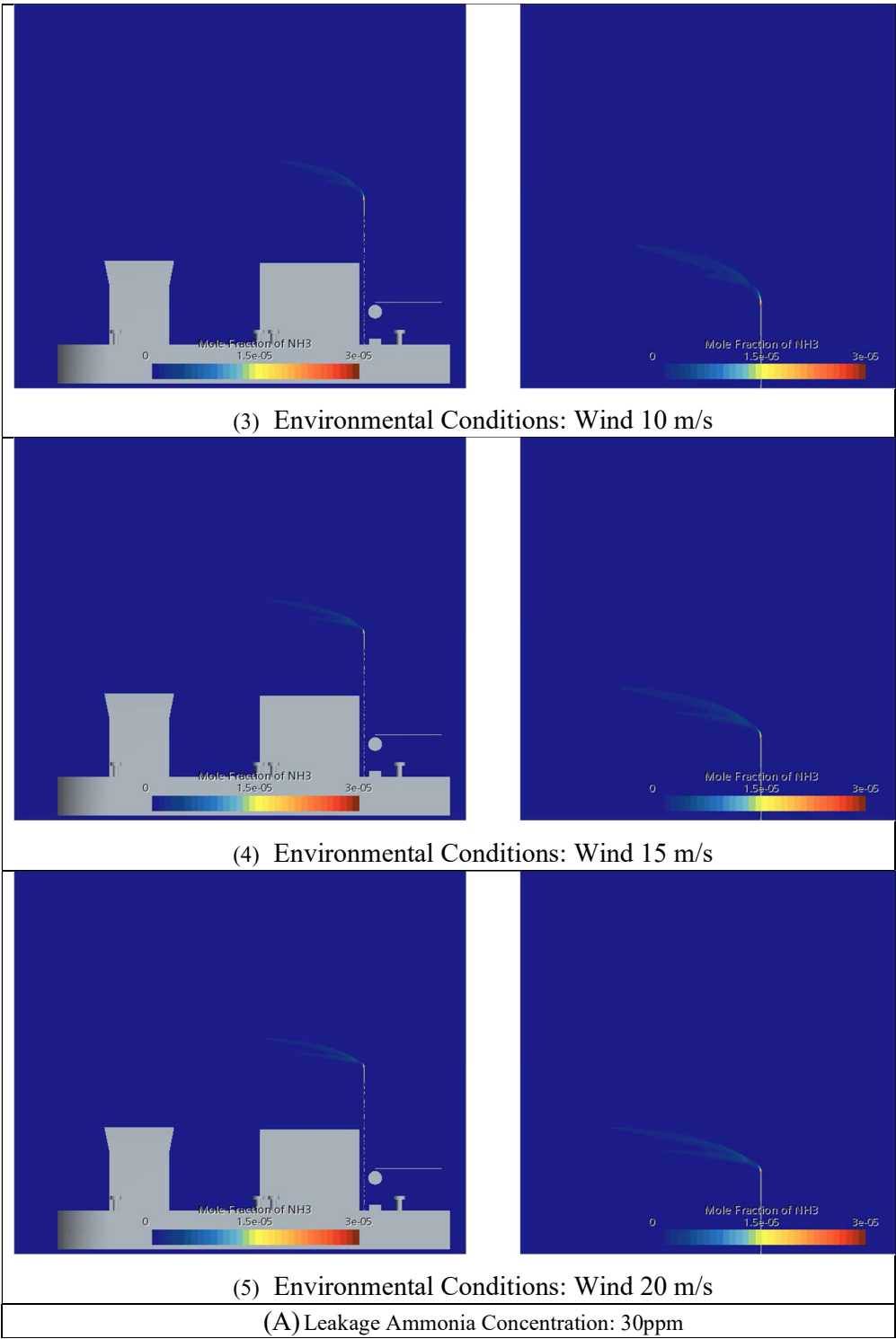


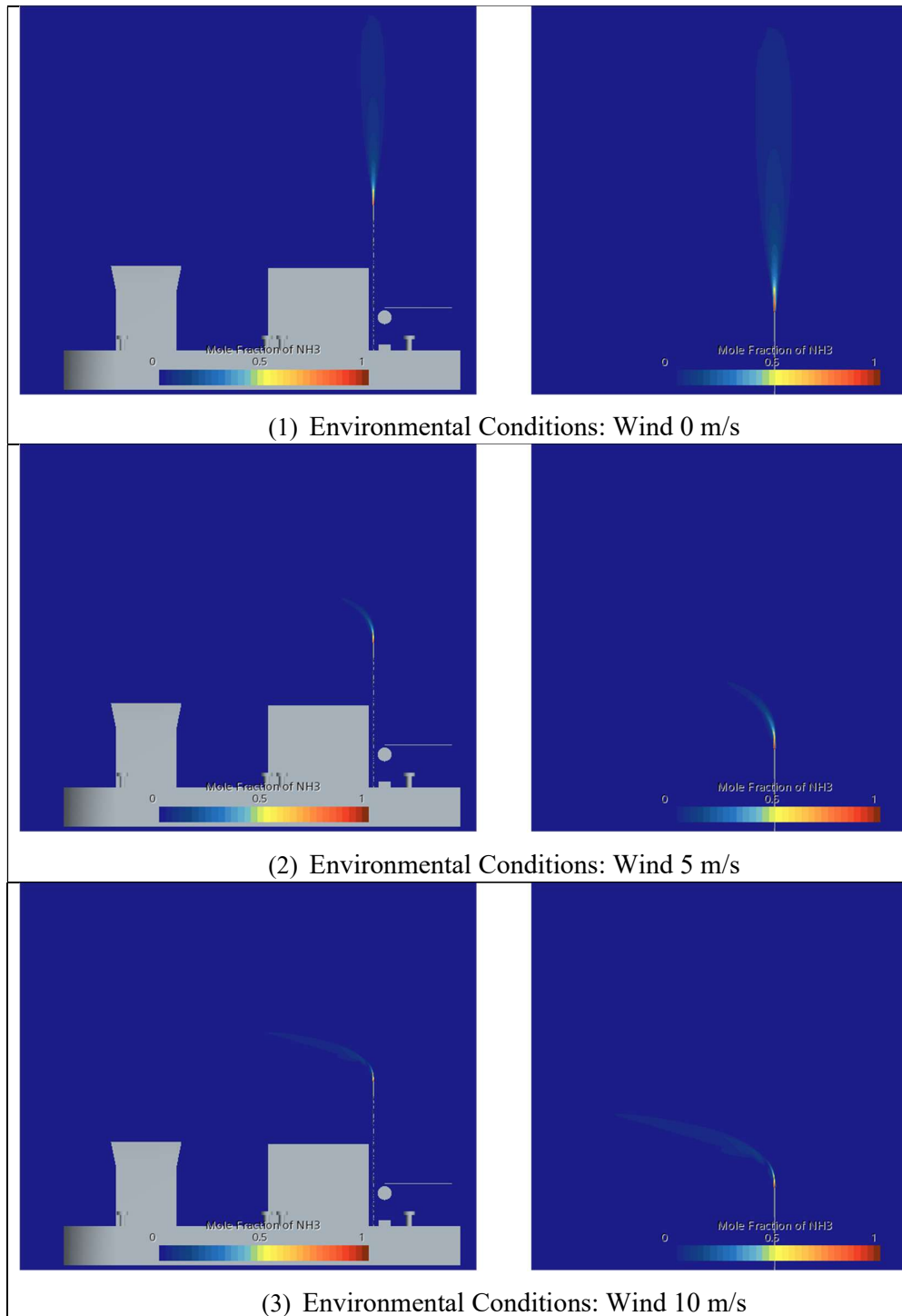
Figure 7.14. Simulation Results (3D plot) for Scenario 3

7.2.3.3.4 Vent master (No. 4)

The simulation results for ammonia dispersion from the No. 4 Vent Master indicate a strong dependence on wind speed and initial concentration (Figure 7.15). At a leak rate of 0.21 kg/s, the dispersion distance, where ammonia concentration reaches 0%, varies significantly between the 30 ppm and 100% ammonia cases. For the 30 ppm concentration, the dispersion remains relatively short, ranging from 0.03 m at 0 m/s to a maximum of 0.07 m at 10–20 m/s. This suggests that at very low concentrations, ammonia dissipates quickly and does not spread significantly, regardless of wind conditions. In contrast, the 100% ammonia case exhibits a much greater dispersion distance, particularly at higher wind speeds. At 0 m/s, the ammonia concentration reaches 0% within 0.7 m, but as wind speed increases, the dispersion distance expands significantly, reaching 5.3 m at 10 m/s, 6 m at 15 m/s, and 8 m at 20 m/s. This trend indicates that stronger winds enhance ammonia dispersion, spreading it over a larger area before it completely dissipates.







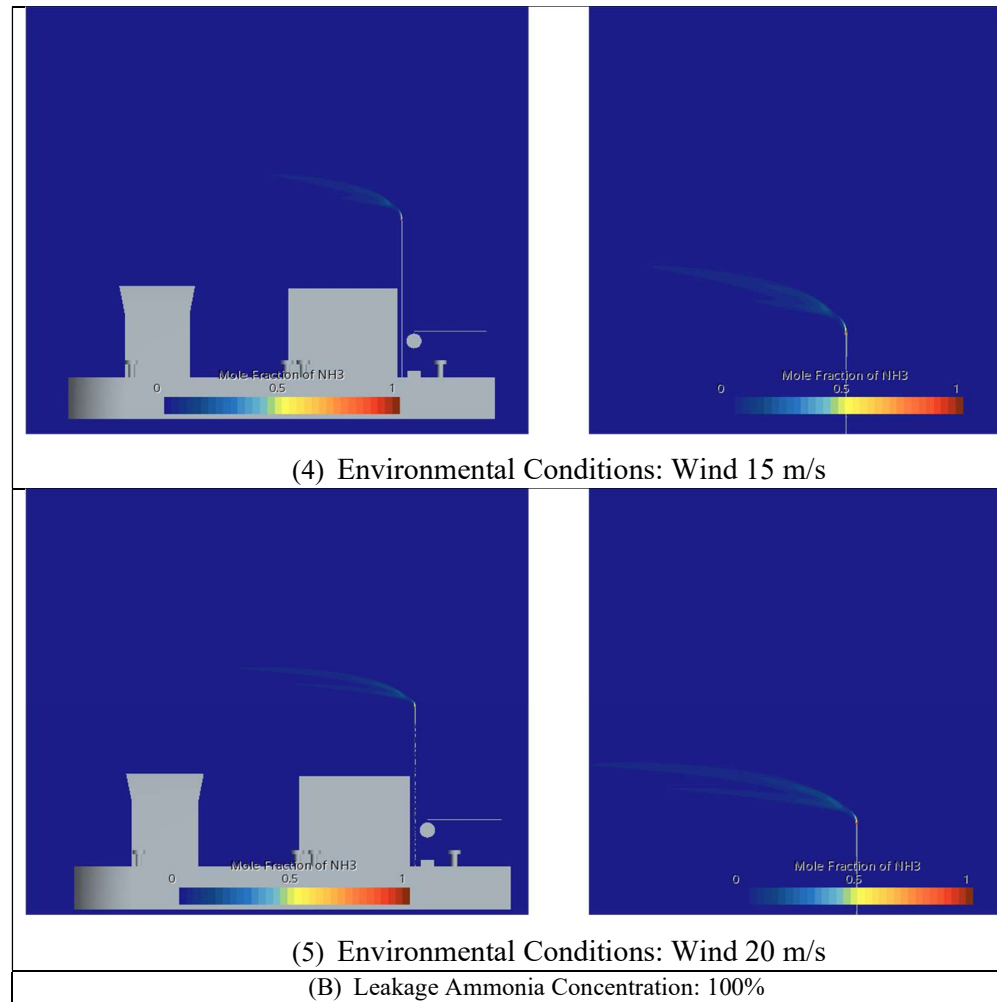
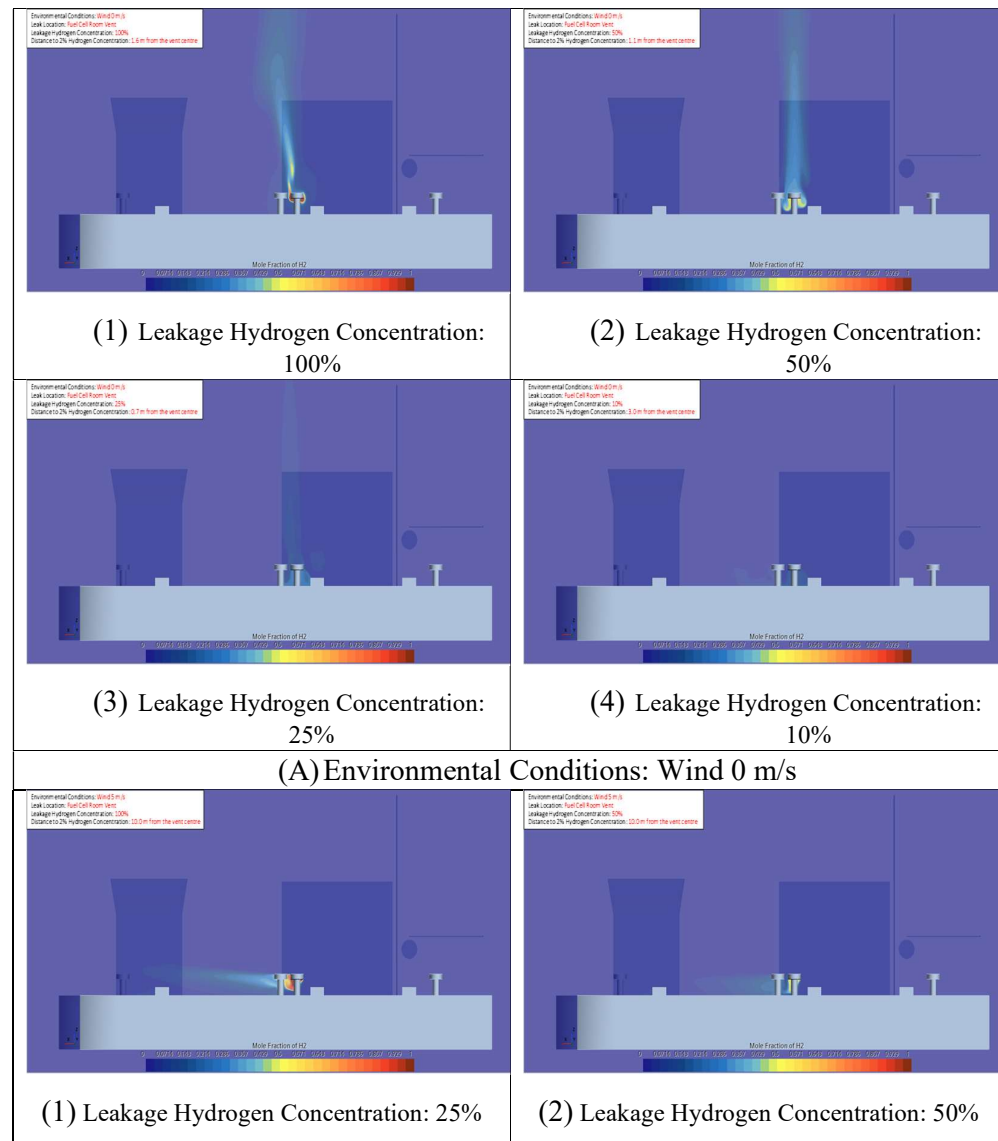


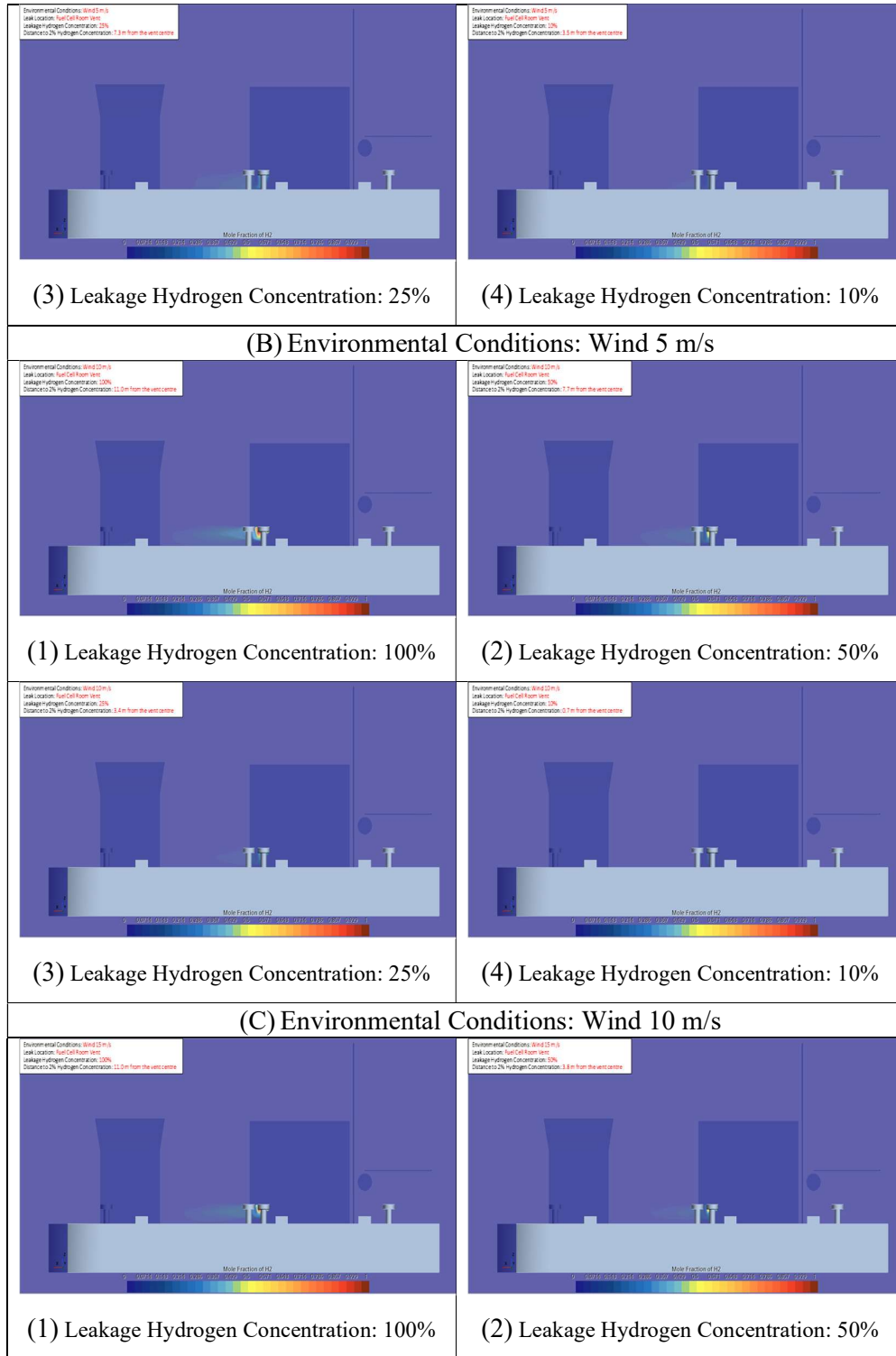
Figure 7.15. Simulation Results for Scenario 4

7.2.3.3.5 Fuel cell room vent (No. 5)

Figure 7.16 illustrates the final state of the simulation analysis for hydrogen leakage at the fuel cell room vent. The simulation results for hydrogen leakage at the fuel cell room vent demonstrate the influence of hydrogen concentration and wind speed on the dispersion distance, particularly the distance at which the hydrogen concentration decreases to 2%. At a 100% hydrogen concentration with a discharge speed of 3 m/s, the dispersion distance varies significantly depending on wind conditions. Under calm conditions (0 m/s), the hydrogen concentration drops to 2% within 1.6 m, whereas at higher wind speeds (10–15 m/s), the dispersion distance increases up to 11 m before decreasing at 20 m/s to 7.3 m. This trend suggests that moderate wind speeds enhance hydrogen dispersion, but excessive wind speeds may promote mixing and reduce the effective dispersion distance. For lower hydrogen concentrations (50%, 25%, and 10%), the dispersion distance generally

decreases. At 50% H₂ concentration, the distance ranges from 1.1 m at 0 m/s to 10 m at 5 m/s, then decreases as wind speed increases. At 25% concentration, the maximum dispersion distance is observed at 5 m/s (7.3 m), with further reductions at higher wind speeds. The 10% hydrogen concentration case exhibits a unique trend, showing a relatively stable dispersion range of around 3–3.5 m at low wind speeds but drastically dropping to 0.7–0.6 m at higher wind speeds. These results indicate that lower hydrogen concentrations lead to shorter dispersion distances, and higher wind speeds accelerate dilution, reducing the potential risk area.





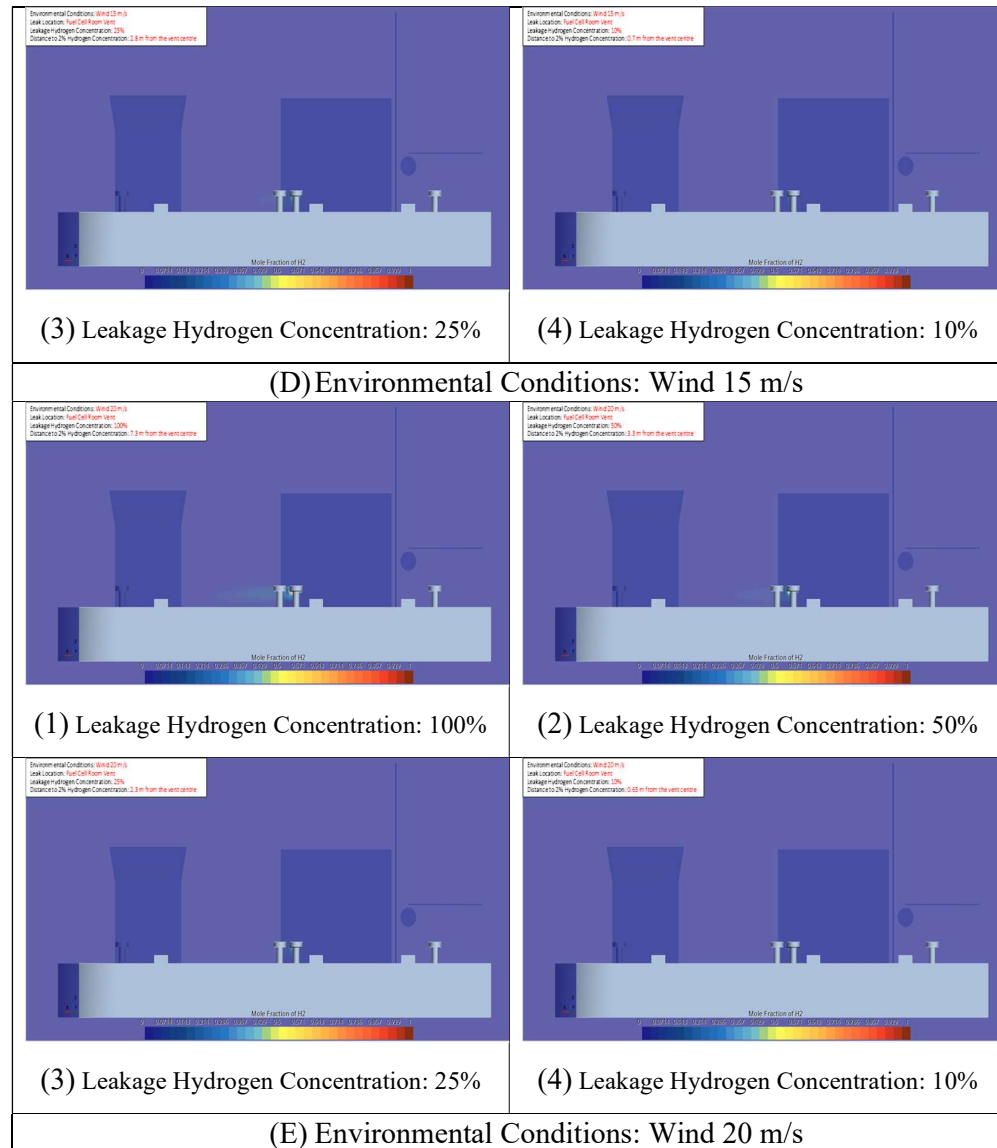


Figure 7.16. Simulation Results for Scenario 5

7.2.4 Phase 4- Risk integration

The purpose of defining toxic/hazardous zones is to restrict access to areas posing a risk to human life and to limit activities within these zones. This, in turn, aims to minimise the potential for casualties resulting from accidents during ship operations. The establishment of safety equipment within the hazardous zone is intended to enhance safety measures, preventing or minimising potential accidents.

7.2.4.1 Risk-informed zone determination

The critical distances for toxic/hazardous zones, determined through consequence analysis, are combined with the results of frequency of occurrence analysis. They are then rearranged from the lowest to the highest risk range. The safety zone for the vessel is set at the highest risk range closest to the acceptable accident frequency (refer to Figure 7.17 **Error! Reference source not found.**). This approach ensures that the safety zones are established based on the closest proximity to the acceptable accident frequency within the analysed scenarios.

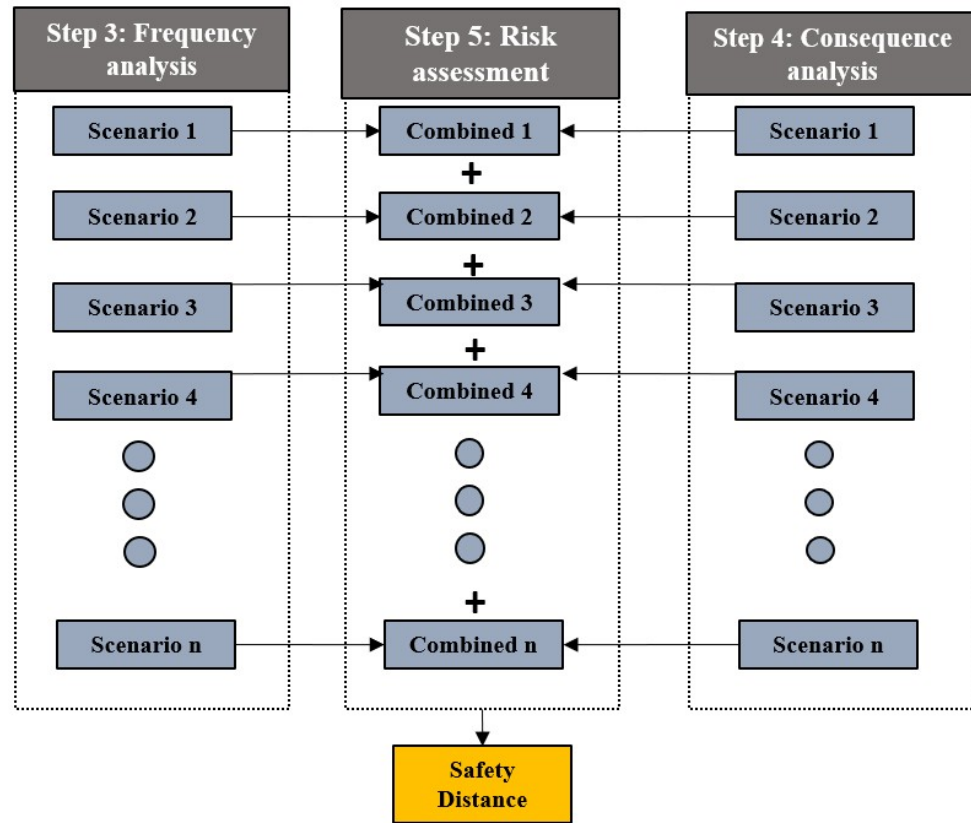


Figure 7.17. Safety zone (toxic/hazardous zone) establishment process through risk assessment

7.2.4.2 Risk acceptance criteria and vulnerability

The criteria for establishing safety zones were determined using a 5×5 risk assessment matrix (similar to HAZOP studies), as shown in Table 7.8 **Error! Reference source not found.** If the occurrence frequency (Frequency Index) falls below 10^{-4} /year, the risk level is considered within the satisfactory range,

irrespective of the Impact Index (Severity Index). Therefore, scenarios with an occurrence frequency of 10^{-4} /year or less were used as the safety criteria for the toxic zones. The final toxic/hazardous zones were then defined by consolidating scenarios with frequencies equal to or greater than this safety criterion.

This frequency criterion serves as the risk acceptance criterion of the integration phase. Unlike Case Study 1, in which the acceptability of the derived zones was additionally verified against population-dependent fatality estimates, the present case study applies the criterion directly to the cumulative frequency of the leak scenarios. This simplification is appropriate because the zones under consideration relate to crew exposure onboard a small vessel rather than to the surrounding population.

Table 7.8. Risk assessment matrix (5×5)

			Likelihood				
			1	2	3	4	5
			Remote	Low	Moderate	High	Very high
			Event physically possible, but the team have never heard of event occurring in shipping	Unlikely to occur (conceivable but would require multiple failures of systems and controls)	Can occur (i.e. easy to postulate a scenario for accident)	More than average (i.e. the team do not have direct knowledge, but suspect that the event may have occurred and represents a credible (have seen it))	Likely to occur (the team have knowledge of an similar event)
Consequence	0	Insignificant	0	0	0	0	0
	1	Minor	1	2	3	4	5
	2	Moderate	2	4	6	8	10
	3	Major	3	6	9	12	15
	4	Critical	4	8	12	16	20

Table 7.9. Frequency Index (occurrence frequency)

FI	Likelihood category	Probability	Description
5	Very high	10^{-1}	Likely to occur frequently
4	High	10^{-2}	May occur several times in the life of an item
3	Moderate	10^{-3}	May occur sometime in the life of an item
2	Low	10^{-4}	Unlikely to occur but possible
1	Remote	10^{-5}	Unlikely to occur at all (Very unlikely)

As depicted in Table 7.9**Error! Reference source not found.**, when the Frequency Index (FI) is 2, the occurrence rate is 10^{-4} /year. This categorisation is defined as "Unlikely to occur but possible," indicating a relatively low probability of occurrence. Table 7.10**Error! Reference source not found.** shows the severity index used for the qualitative risk assessment.

Table 7.10. Severity Index (impact)

SI	Consequence	Health and safety	Environment	Equipment	Business reputation
0	Insignificant	No risk of injury	No significant damage to local environment, can be reversed with some cleanup intervention.	No significant damage to equipment. Equipment still operable.	Insignificant damage to reputation.
1	Minor	Injury requiring first aid or medical treatment, less than 1 day off work.	Localised damage, no medium or long term consequence. May require some cleanup intervention.	Minor damage. Minor overhaul required.	Localised damage to business reputation, no media or regulatory attention.
2	Moderate	Injury requiring evacuation from ship. Medical treatment, absence from work, rehabilitation.	Recoverable damage to an environment requires some cleanup intervention.	Medium damage. Major overhaul required.	Damage to business reputation within the industry, no significant media attention.
3	Major	Permanent injury or extended absence from work, potential fatality.	Extensive damage to an environment involving prolonged recovery period requires significant cleanup intervention.	Major damage to equipment. Extensive overhaul - replacement required.	Damage to business reputation, nationally high profile media exposure, and regulatory attention.
4	Critical	One or multiple fatalities	Permanent and extensive damage to the environment.	Total loss of equipment	Damage to international business reputation, high profile media exposure, and regulatory attention.

7.2.4.3 Safety level verification

This section presents the results of the risk assessment for the five potential leakage points, expressing them as toxic/hazardous zones. The midline of the frequency-distance graph presented for each location (orange colour, Tolerable limit) represents the baseline of 10^{-4} /year. When a point is above this line, it should be

included in the hazardous zone, while if it falls below, it is designated as a safety zone.

Figure 7.18 **Error! Reference source not found.** presents the risk assessment results for the hazardous zone during No. 1 bunkering in the form of a graph (X-axis: critical distance, Y-axis: frequency). It can be seen that the probability of occurrence for all accident scenarios is below 10^{-4} per year. This indicates that the risk of ammonia leakage during bunkering falls within the tolerable range, and therefore, it is judged that there is no need to establish a separate toxic zone.

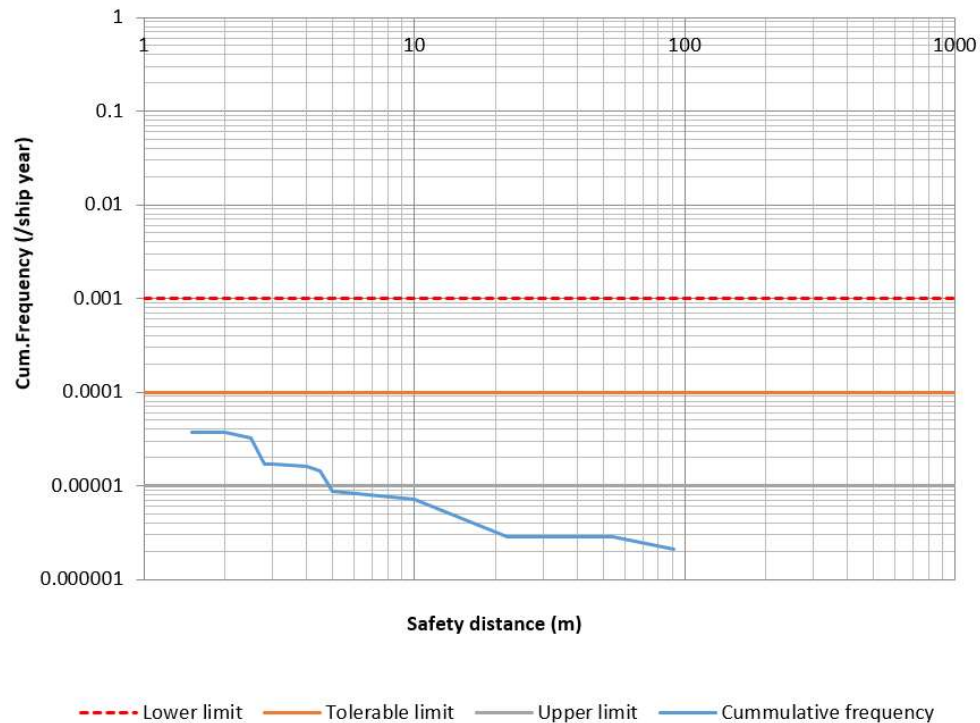


Figure 7.18. Determination of safety distance for potential leaks during ammonia bunkering (No. 1)

Figure 7.19 **Error! Reference source not found.** suggests that it would be advisable to set a toxic range of 7 metres for incidents involving the leakage of liquefied ammonia from the No. 2 ammonia tank connection. This is because the toxic range corresponding to an occurrence probability of 10^{-4} per year is approximately 7 metres for cumulative incidents.

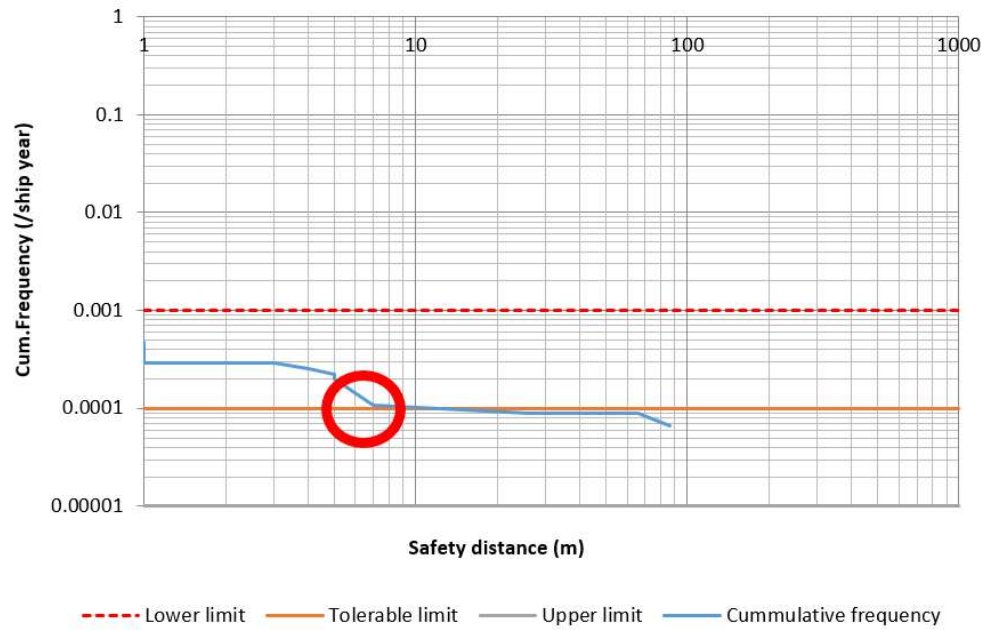


Figure 7.19. Determination of safety distance for potential leaks from the ammonia tank connection (No. 2)

As shown in Figure 7.20 **Error! Reference source not found.**, for potential leakage incidents related to the cracking system, the toxic range corresponding to an occurrence probability of 10^{-4} per year is estimated to be approximately 5 metres.

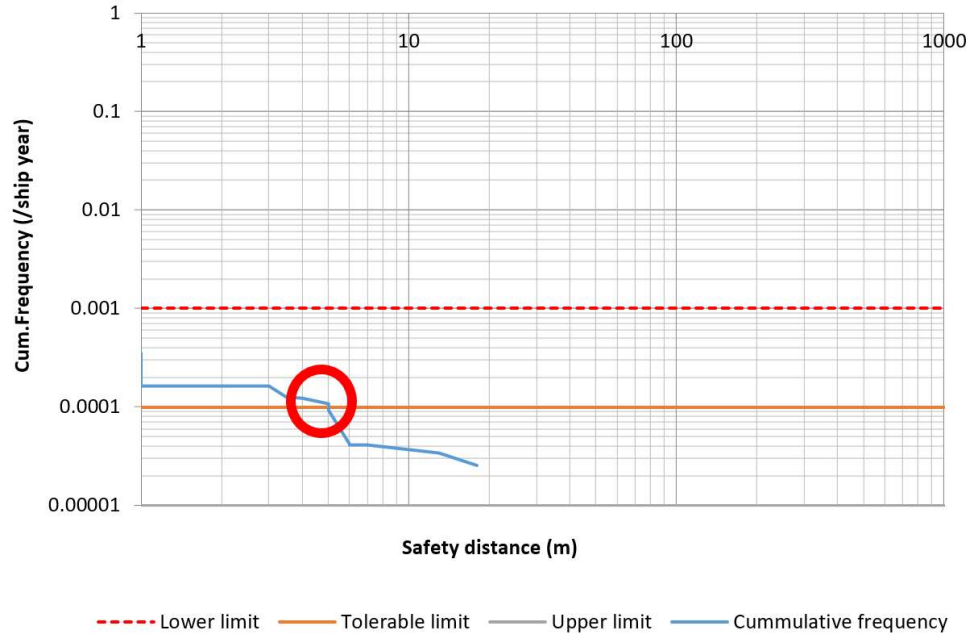


Figure 7.20. Determination of safety distance for potential leaks from the cracking system (No. 3)

For the vent master (No. 4), the dispersion results indicate that, when the release to the atmosphere is limited to a concentration of 30 ppm through the installation of a catching system, the distance over which the concentration remains above the toxic threshold is less than 1 m, and no separate toxic zone is therefore required. In the absence of such a system, a release of 100 % gaseous ammonia would require a toxic zone of up to 8 m radius around the vent outlet.

Based on the risk assessment of hydrogen gas leaks through the hydrogen vent leading to potential fire or explosion, the results are presented in the form of a graph (Figure 7.21) with the X-axis representing critical distance and the Y-axis representing frequency. It can be observed that the probability of occurrence for all accident scenarios is below 10^{-4} per year. This indicates that the risk of hydrogen leakage falls within the tolerable range, and therefore, it is judged that there is no need to establish a separate toxic zone.

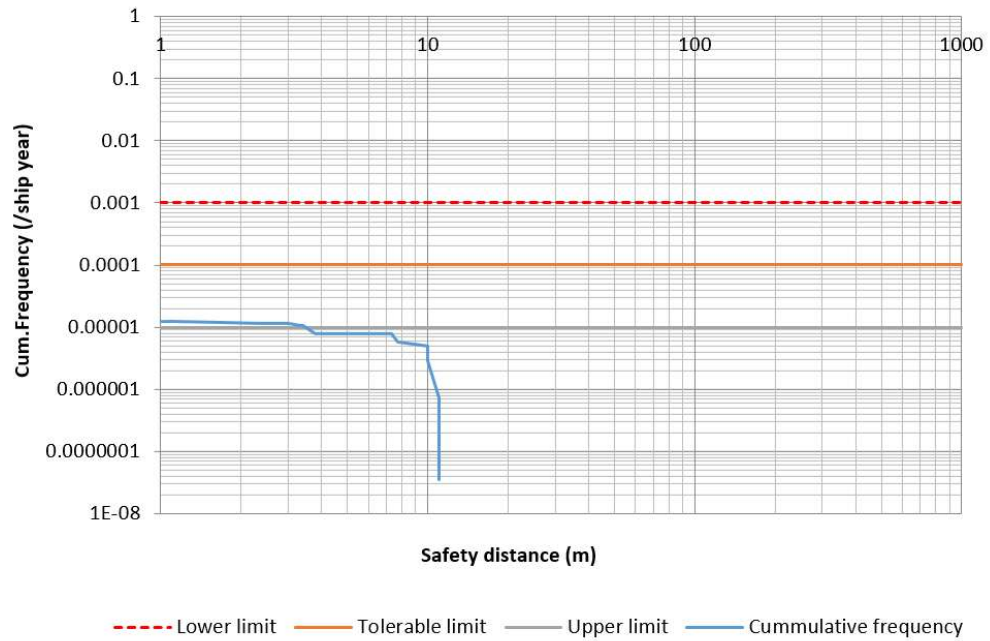


Figure 7.21. Determination of safety distance for potential leaks from the hydrogen vent (No. 5)

The final zone determinations for the five leak locations are illustrated in Figure 7.22.

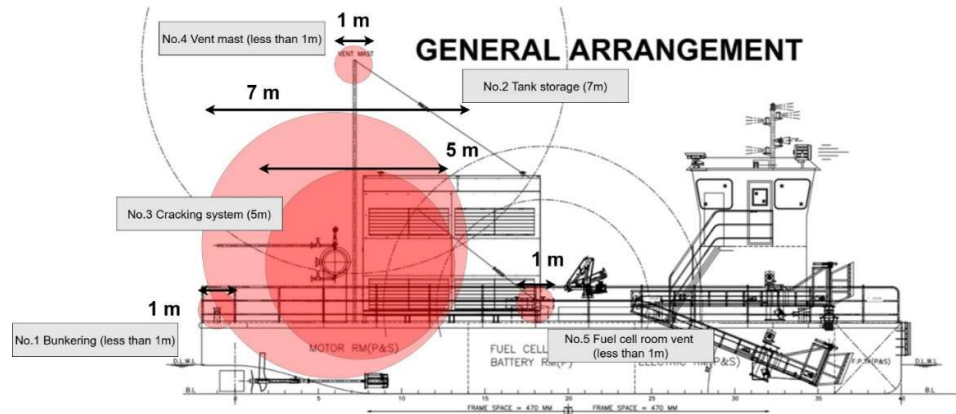


Figure 7.22. Overview of Hazardous Zone

7.2.5 Phase 5- General observations

The final phase consolidates the findings from the preceding analyses to derive observations that extend beyond the specific case vessel configuration. In this case study, Phase 5 evaluates the extent to which the probabilistically derived toxic and hazardous zone dimensions differ from those implied by existing prescriptive regulatory guidance, and identifies systematic patterns across the five leak locations that may inform the development of scale-appropriate safety requirements for small hydrogen and ammonia-fuelled vessels.

A comparison of the zone definitions obtained from this study with those specified in the KR rules for low-flashpoint fuel ships reveals both areas of consistency and significant divergence, reflecting the fundamental difference in scope and intent between risk-based and prescriptive approaches to safety zone determination.

For the ammonia tank connection (Location 2), the probabilistic zone of approximately 7 m is broadly consistent with the generic prescriptive requirement for large-diameter ammonia piping. This consistency confirms that for high-consequence, continuously pressurised connections with large pipe diameters, the prescriptive approach provides a reasonable safety boundary that, in this case, happens to align with the risk-based result. However, for the bunkering connection (Location 1) and the vent master (Location 4), the prescriptive requirements substantially overestimate the risk, with generic zone distances of up to 7.5 m being reduced to less than 1 m by the probabilistic analysis. This overestimation is directly attributable to the prescriptive approach's reliance on worst-case assumptions without accounting for the frequency of the initiating event, the ESD isolation response, or the diluting effect of wind.

This finding is particularly significant in the context of the two design issues identified in the introduction to this chapter. The first issue is that prescribed zone extents are impractical for small vessels, which is directly addressed by the results. The probabilistic analysis demonstrates that, for the majority of leak locations on the case vessel, the risk-justified zone is small enough to be practically implemented without compromising vessel operations. The second issue is that guidelines do not

cover all potential leak points, is addressed by the HAZID study whose outcomes were applied in Phase 2, which identified five specific locations for quantitative assessment and thereby provided a complete coverage of the vessel's ammonia and hydrogen fuel system that is not available from generic prescriptive guidance alone.

7.3 Discussion and novelty

7.3.1 Methodological contributions and key findings

Within the thesis as a whole, the contribution of this chapter is complementary to that of Chapter 6. Case Study 1 provided an overall demonstration of the complete framework, including its parametric PIDA-PDA integration, for a bunkering problem at the ship-shore interface. The present case study instead provides an in-depth application of selected components, taking the consequence modelling of Phase 3 to the level of high-fidelity CFD simulation on two independent platforms and applying it across five distinct release points on a single vessel. This division of roles avoids unnecessary overlap between the two case studies and allows the framework to be examined both in breadth and in depth.

The integrated qualitative–quantitative framework presented in this chapter makes several contributions to the field of safety assessment for hydrogen and ammonia-fuelled ships. First, the study demonstrates the practical effectiveness of combining HAZID-based hazard screening with CFD-based consequence modelling and probabilistic risk integration within a single coherent process. This integration directly addresses the methodological fragmentation identified in Chapter 4, where qualitative and quantitative methods have frequently been applied in isolation without systematic transfer of insights between stages. By ensuring that the scenarios identified during the HAZID workshop are consistently reflected in the CFD simulation setup, including the selection of leak locations, pipe diameters, operating pressures, and boundary conditions, the framework maintains a transparent and traceable link between the qualitative and quantitative stages of the assessment.

Second, the application of two independent CFD tools within a single integrated probabilistic risk assessment represents, to the author's knowledge, the first such dual-CFD approach to onboard toxic zone calibration in the published maritime safety literature. FLACS was employed for open-deck liquid ammonia dispersion, and STAR-CCM+ for enclosed-space and vent master gas release scenarios. This division reflects the fundamentally different physical mechanisms governing liquid and gaseous releases. The use of FLACS in particular, with its explicit capability to model flash evaporation, offers an improvement over studies that apply simplified gas-phase dispersion models to liquid ammonia releases and thereby tend to underestimate the density and extent of the resulting aerosol cloud.

The use of two independent simulation platforms for qualitatively different release scenarios also provides a degree of cross-tool validation that is uncommon in maritime CFD-based safety assessments, where reliance on a single commercial code is the prevailing practice. Each CFD platform embodies different numerical schemes, turbulence modelling assumptions, and dispersion submodels, such that agreement between platforms strengthens confidence in the physical realism of the predicted dispersion fields. The application of this dual-CFD framework to an actual vessel under active construction, rather than a generic ship model, further anchors the results in the practical design context and provides a replicable template for future safety assessments of similarly configured vessels.

Third, the finding that the probabilistically justified toxic zone for four of the five identified locations is less than 1 m has direct implications for regulatory practice. It provides quantitative, evidence-based support for the development of scale-appropriate safety requirements for small hydrogen and ammonia-fuelled vessels. This category of vessel is growing in number, while current guidelines remain poorly adapted to it. The methodology provides a structured and defensible basis for demonstrating to regulatory bodies that reduced zone distances are safety-justified in specific cases, without compromising the overall safety of the vessel. For the case vessel, the zone definitions derived in this study formed part of the basis on which approval was obtained from the Korean Register (KR).

7.3.2 Limitations and future research directions

Several limitations of the present study merit acknowledgement. The frequency estimates used in the risk integration are based on generic component failure data, which may not fully reflect the specific reliability characteristics of ammonia fuel system components under maritime operating conditions. The scarcity of operational failure data for marine hydrogen and ammonia systems remains a significant constraint on the precision of quantitative risk assessments in this field, and the results should be interpreted with this uncertainty in mind.

Furthermore, the CFD simulations conducted in this study were based on a representative set of wind directions and a limited number of wind speed scenarios. In practice, the actual wind conditions experienced during bunkering or normal operation may vary considerably from those simulated, and the sensitivity of the zone definitions to wind direction, which was not systematically investigated, may be important at locations where directional shielding from adjacent structures is present. Future work should therefore examine the sensitivity of the results to a broader range of meteorological conditions.

The case vessel studied here is a small 18-metre harbour ferry, and the specific zone distances derived should not be generalised to larger vessels without independent verification. The methodology itself is readily transferable to other vessel types and scales, and future studies should extend the analysis to larger hydrogen-ammonia ships to establish whether zone requirements scale primarily with pipe diameter and operating pressure, or whether ship geometry and ventilation arrangement play a more significant role. Such studies would provide an important evidence base for the development of size-graded or performance-based zone requirements within future international safety codes.

7.3.3 Concluding remarks

This chapter has presented the application of an integrated qualitative–quantitative risk assessment framework to the determination of practical toxic and hazardous

zones for an 18-metre ammonia-fuelled hydrogen fuel cell ferry. The framework combines qualitative hazard identification through a systematic HAZID study with quantitative CFD-based dispersion simulations using FLACS and STAR-CCM+, enabling the derivation of risk-informed zone definitions that address the limitations of conventional deterministic approaches.

By introducing a probabilistic methodology based on the evaluation of cumulative leak frequencies against an accepted annual frequency criterion of 10^{-4} per year, the study directly addressed the overly conservative and impractical zone estimates produced by prescriptive deterministic assessments, particularly for small vessels where spatial constraints render generic worst-case exclusion zones operationally prohibitive.

Five key potential leak points were identified through the HAZID study and analysed under various leak sizes and wind conditions. These comprise the bunkering connection, tank connection, cracking system, ammonia tank vent master, and fuel cell room ventilation. Based on the integrated frequency and consequence analyses, the toxic zones were defined as approximately 7 metres for the ammonia tank connection, 5 metres for the cracking system, and less than 1 metre for the remaining components.

The findings offer a practical foundation for guiding the development of safety guidelines currently underway by the IMO and classification societies, supporting the safe integration of ammonia and hydrogen as marine fuels. Together with the bunkering safety zone case study presented in Chapter 6, these results demonstrate that the integrated risk assessment framework developed in Chapter **Error! Reference source not found.** is capable of addressing the diverse safety challenges associated with hydrogen and ammonia as marine fuels, from bunkering operations at the ship-shore interface to the complex dual-hazard environment of onboard fuel processing and power generation systems.

8 DISCUSSION

This chapter interprets the findings of the two case studies, positions the integrated risk assessment framework against established risk assessment practice, and reflects on its contribution, limitations, and applicability. The chapter then explains how the findings support the research objectives defined in Chapter 2 and considers the implications for future risk assessment practice and performance-based safety regulation.

8.1 Interpretation of findings

Case Study 1 showed that the extent of a bunkering safety zone is governed by the interaction between fuel properties, release quantity, and ambient conditions rather than by the choice of fuel alone. Under default conditions, the outer zone boundary ranged from approximately 26 m for LH₂ to approximately 601 m for LNH₃. When the leaked fuel quantity was increased to 300% of the default value, the outer zone for LNH₃ extended to approximately 924 m, and when the wind speed was reduced to 10% of the default value, the outer zone for LH₂ increased to approximately 113 m. The governing parameters also differed between fuels. LNH₃ and GH₂ were the most sensitive to increases in bunkering quantity and leaked fuel quantity, wind speed was a critical factor for LNG and LNH₃, and the zones for GH₂ remained relatively unaffected by wind speed, suggesting inherently broad dispersion characteristics. A safety zone derived from a single set of conditions therefore cannot represent the range of hazards associated with each fuel, and risk control measures should be selected on a fuel-specific basis, as recommended in Chapter 6.

The most instructive finding of Case Study 1 is the divergence between the physical extent of a hazard and its societal risk. LNH₃ produced the widest affected area, yet, contrary to the expectation that ammonia would present the highest severity, GH₂ emerged as the most critical fuel in terms of societal risk, falling within the Unacceptable region of the F-N curve even under default conditions, whilst LH₂ did not reach the Unacceptable region in any scenario. A ranking of fuels by zone extent alone would therefore not have identified the fuel of greatest concern for human exposure. This divergence is the empirical justification for the sequential

structure of the PIDA-PDA approach. A safety zone that is adequate as a spatial boundary is not necessarily sufficient to achieve tolerable societal risk, and for GH₂ the results indicate that additional safety barriers are required beyond the zone itself.

Case Study 2 produced a finding of a different kind. The deterministic consequence distances for large releases reached a maximum of 91.5 m on a vessel of approximately 18 m in length, and a zone based on such values could not be implemented onboard. Once the consequence distances were weighted by their estimated frequencies and evaluated against the criterion of 10^{-4} per year, the toxic zones reduced to approximately 7 m for the ammonia tank connection and approximately 5 m for the cracking system, whilst no separate zone was required for the bunkering connection or the fuel cell room vent. For the vent master, a zone of less than 1 m was sufficient when a catching system limited the released concentration to 30 ppm, whereas a release of undiluted ammonia gas would require up to 8 m. The comparison with the KR rules prevents a simple reading of these results as evidence that prescriptive requirements are excessive. For the tank connection, the risk-informed zone of approximately 7 m was broadly consistent with the prescriptive requirement, whereas for the bunkering connection and the vent master, generic distances of up to 7.5 m were reduced to less than 1 m. The prescriptive approach is therefore reasonable for large-diameter, continuously pressurised connections and over-conservative for release points whose initiating frequency is low or whose release is mitigated by design. The value of the risk-informed approach lies in its ability to distinguish between these cases, and the zone definitions derived in Case Study 2 formed part of the basis on which approval of the case vessel was obtained from KR.

Read together, the two case studies show that zone determination for hydrogen-related fuels cannot be reduced to a single governing parameter, a single assumed condition, or a single risk metric. The governing parameters differed between fuels and between release points, lower wind speeds expanded the zones in Case Study 1 whereas the large releases in Case Study 2 dispersed furthest at a moderate wind speed of 5 m/s, and in both studies the extent of a zone and the tolerability of risk proved to be separate questions. These observations support the premise of the framework that zone determination requires a structured link between qualitative

hazard identification, quantitative analysis under varying conditions, and explicit evaluation against acceptance criteria.

8.2 Positioning and contribution

As reviewed in Chapter 4, the principles on which the framework rests are not new. The overall logic of the framework follows the structure of risk assessment formalised in ISO 31000 (ISO, 2018) and in the IMO Formal Safety Assessment guidelines (IMO, 2018), in which hazard identification is followed by risk analysis and risk evaluation, and the results inform risk control decisions. The separation of frequency analysis from consequence analysis, the use of generic failure frequency databases, and the expression of risk through individual risk contours and F-N curves are long-standing features of quantitative risk assessment in the offshore and process industries (Vinnem, 2007). The use of CFD within a probabilistic procedure is established offshore practice, most notably in the explosion risk analysis procedure of NORSOK Z-013 (NORSOK, 2024), and the tolerability framework with an intermediate ALARP region reflects the regulatory philosophy introduced in the United Kingdom after the Piper Alpha disaster (Cullen, 1990, HSE, 2001). The failure frequency data and ignition probabilities applied in Case Study 2 were themselves drawn from datasets developed in the offshore industry. Grounding the framework in these elements is deliberate, since results intended to inform design approval must be interpretable by classification societies and administrations, as the use of the Case Study 2 results in the KR approval illustrates.

Established practice does not, however, provide an operational procedure for the problem addressed in this thesis. The offshore frameworks were developed for large fixed installations handling well-characterised hydrocarbons with long operational histories, and their outputs are used to demonstrate within a safety case that the risk of an installation as a whole has been reduced to ALARP, not to size a spatial boundary around an individual release point. The FSA guidelines operate at the scale of ship categories to support rule-making, ISO 31000 provides principles without an assessment procedure, and LNG bunkering guidance such as ISO/TS 18683 (ISO, 2021) addresses safety zones for a single fuel only. None of these

instruments specifies how hazard identification, frequency and consequence analysis, parametric variation, and risk evaluation should be configured to determine safety and hazardous zones for hydrogen-fuelled ships and bunkering operations, where releases are transient, the exposed population varies with port activity, the physical behaviour of the fuel differs markedly from that of hydrocarbons, and fuel-specific operational data are scarce. Mature industries provide the principles for this task, but not the procedure.

The overarching contribution of this thesis is therefore the integrated qualitative–quantitative framework that converts these established principles into an operational, end-to-end procedure for zone determination. Its originality lies in the structured procedural integration of four elements. First, the release points, operating conditions, and design measures identified in the qualitative stage define the scenario set, modelling boundaries, and parameter ranges of the quantitative stage, a linkage that Chapter 4 showed to be absent from most existing studies. Second, parametric scenario analysis is embedded as a formal sub-phase, so that where historical data are scarce the systematic variation of governing parameters establishes the robustness of the resulting zones. Third, integrated risk results are linked directly to the spatial determination of zones. In the PIDA-PDA approach, individual risk contours define the boundary independently of population, and the F-N curve then verifies whether that boundary remains tolerable for the population actually exposed, whereas in conventional practice an F-N curve judges the tolerability of an activity as a whole and is not connected to the sizing of a boundary. The metrics are the same, but the function they perform is new. Fourth, the framework supports comparative risk profiling across fuel types under standardised conditions, and it was this comparison that revealed the divergence between zone extent and societal risk. The two case studies demonstrate that this procedure can be followed in practice, Case Study 1 in full and Case Study 2 in depth for selected components.

Two further contributions operate within this framework. The first is the use of sensitivity-driven parametric analysis for hydrogen-related fuels, for which empirical incident and failure data remain limited. By systematically varying key input parameters, including total bunkering quantity, leaked fuel quantity, wind

speed, and population density, across representative ranges and tracking their influence on safety zone dimensions, the parametric analysis identifies which parameters most critically govern the risk outcomes. First, it provides a transparent characterisation of the robustness of zone estimates under data-scarce conditions. Second, it provides prioritised guidance on where future data collection should be concentrated. The second is the systematic introduction of probabilistic risk evaluation into the determination of hazardous zones, which moves beyond the worst-case deterministic assumptions embedded in current practice. By weighting consequence distances by their associated frequencies of occurrence rather than treating all scenarios as equally credible, the probabilistic approach produces zones that are proportionate to the assessed risk in both directions, reducing them where the risk is low and confirming them where it is not. In Case Study 2, this evaluation was combined with two independent CFD platforms, FLACS for flashing liquid ammonia releases and STAR-CCM+ for gaseous vent releases, which allowed each release type to be modelled with a solver suited to its governing physics and represents, to the author's knowledge, the first dual-CFD calibration of onboard toxic zone distances using actual vessel data.

8.3 Limitations and future research

The contributions described above must be read alongside the limitations of the present study, each of which indicates a direction for future research.

First, the framework and both case studies address external releases only, for the reasons set out in Chapter 5, and each case study was conducted within a specific operational context. Future research should apply the framework to bunkering operations at ports with different layouts, throughput capacities, and population distributions, and to larger vessels, where hydrogen fuel system configurations are likely to differ substantially in scale, complexity, and exposure, and should extend the analysis to releases within enclosed spaces.

Second, the frequency analysis relied on failure frequency data developed for LNG and hydrocarbon systems, because component failure frequency data specific to hydrogen and ammonia systems are not yet available. Since the zone boundary is

determined at the distance at which the estimated frequency meets the acceptance criterion, the frequency data directly affect the zone dimensions. If reliable data for hydrogen and ammonia components become available and differ substantially from the values adopted, the specific zone dimensions presented in this thesis would need to be recalculated. The procedure of the framework and its methodological contribution would remain unchanged, since updated frequency data can be applied directly within the same phases. As operational experience accumulates from hydrogen and ammonia maritime projects, component-specific failure frequency databases should be developed, together with ignition probability models specific to hydrogen.

Third, the leakage scenario matrix in Case Study 1, while representative of the credible range of bunkering accidents, does not exhaustively enumerate all possible leakage configurations, and the CFD simulations in Case Study 2 examined a limited number of wind speeds without systematically investigating wind direction. In addition, the consequence models used in both case studies were not compared against experimental measurements of hydrogen or ammonia releases in maritime settings. As experimental data from purpose-built test rigs and demonstration vessels become available, the consequence models underpinning the framework should be compared against such data and refined where necessary, and a broader range of meteorological conditions should be examined.

These limitations define the applicability of the outputs. The procedure of the framework is transferable, since its phases are defined independently of fuel, system configuration, and location. The numerical zone dimensions are not. They are specific to the port environment, bunkering configurations, and population data of Case Study 1 and to the pipe diameters, operating pressures, design measures, and geometry of the Case Study 2 vessel, and they can serve as preliminary reference values for early design but not as a substitute for a site-specific or vessel-specific assessment.

8.4 Research objectives

The findings support the four research objectives defined in Chapter 2. The first objective, to identify technical and research gaps through a critical review, was met in Chapters 3 and 4, and the case study findings confirm that the identified gaps have practical consequences, since the deterministic over-conservatism and parametric variability observed in the case studies correspond directly to the gaps identified. The second objective, to develop a structured and integrated framework that adapts established principles to zone determination, was met by the framework presented in Chapter 5, whose inherited and adapted elements have been distinguished above. The third objective, to demonstrate the applicability of the framework through an overall demonstration and an in-depth application, was met by Case Study 1, which executed all five phases across four energy carriers and 76 parametric scenarios, and by Case Study 2, which examined the consequence modelling of Phase 3 through 75 transient CFD simulations on an actual vessel. The fourth objective, to provide recommendations for safe design and risk assessment practice, is addressed by the recommendations of each case study and by the implications set out below.

8.5 Implications for practice and regulation

Two implications for risk assessment practice follow from the findings. First, a safety or hazardous zone should be reported together with the conditions and data on which it depends, since the results showed that zone dimensions can change several-fold with the leaked fuel quantity or wind speed and that the boundary moves directly with the frequency data adopted. Reporting the governing parameters, the parametric range examined, and the frequency basis would allow approving authorities to judge the robustness of a zone. Second, spatial zone determination and the evaluation of risk tolerability should be treated as separate but linked steps. Where population-dependent verification indicates that tolerability is not achieved, as for GH₂ bunkering, additional barriers, operational restrictions, or design changes are required, and the assessment should state this explicitly rather than implying that the zone alone provides adequate protection.

The IGF Code allows alternative designs to be accepted where an equivalent level of safety is demonstrated through engineering analysis (IMO, 2016), and classification societies require qualitative and, increasingly, quantitative risk assessment where prescriptive guidance is absent or insufficient (EMSA, 2025, Jang et al., 2023). However, as discussed in Chapter 1, the prescriptive distances in current codes govern the placement of fuel system components rather than the extent of safety and hazardous zones, and the codes do not specify how the adequacy of a risk-informed zone should be demonstrated. Three implications for performance-based requirements follow. First, the framework provides a structured and traceable route by which a designer can demonstrate the adequacy of a zone, and such requirements could specify the elements that the demonstration must contain, namely the release points identified, the parametric range examined, the frequency basis, and the acceptance criteria applied. Second, the comparison with prescriptive requirements in Case Study 2 supports zone requirements graded according to release characteristics, design measures, and vessel scale rather than a single distance applied irrespective of these factors, which is particularly relevant to small hydrogen-fuelled vessels. Third, the cross-fuel results of Case Study 1 show that the risk criteria established for LNG bunkering cannot be applied to other fuels without adjustment, and, as proposed in Chapter 6, they provide a basis for translating these criteria into equivalent standards for ammonia, liquefied hydrogen, and compressed hydrogen.

Finally, the two case studies applied acceptance criteria suited to their respective problems, namely individual and societal risk criteria for bunkering operations that may affect the surrounding population and a frequency criterion for onboard zones that relate to crew exposure. Because the framework defines the acceptance criteria as an explicit input, it can accommodate whichever criteria regulators specify for each type of application, but the establishment of such criteria remains a regulatory decision that the framework can inform but not replace. The interim guidelines for hydrogen as fuel developed through CCC 11 (DNV, 2025) provide a first international basis for this development, and the framework and results of this thesis offer technical input for its further refinement.

9 CONCLUSIONS

This chapter draws together the principal conclusions of the thesis and closes with remarks on the contribution of the research to the safe adoption of hydrogen as a marine fuel.

9.1 Principal conclusions

Based on the research presented in this thesis, the following conclusions can be drawn. The critical review established that current international regulations, most notably the IGF Code, prescribe distances for the placement of fuel system components but do not define the spatial extent of safety and hazardous zones for hydrogen-fuelled ships, and that the established principles of integrated and probabilistic risk assessment in the offshore industry have not been adapted into a procedure for this purpose. Existing maritime studies have applied qualitative and quantitative methods in isolation, relied on deterministic worst-case assumptions, and treated environmental and operational parameters as fixed inputs.

An integrated qualitative–quantitative risk assessment framework was developed in response, comprising five phases from scenario and system definition to general observations. The framework adapts established principles through an explicit linkage between its qualitative and quantitative stages, a formal parametric scenario analysis sub-phase, a direct link between integrated risk results and the spatial determination of zones, and comparative risk profiling across fuel types. Its contribution lies in this structured procedural integration rather than in the constituent techniques.

The bunkering case study demonstrated the complete framework for LNG, LNH₃, LH₂, and GH₂ at the Port of Hamburg through the PIDA-PDA integrated parametric approach. Ammonia produced the largest safety zones and compressed hydrogen the highest societal risk, and the parameters governing the zones differed between fuels. It was concluded that safety zones must be determined under a range of operating and environmental conditions, that a safety zone alone is insufficient to achieve tolerable risk for compressed hydrogen bunkering at the scale modelled,

and that the risk criteria established for LNG cannot be transferred to other fuels without adjustment.

The onboard case study applied selected components of the framework in depth to an ammonia cracking system on an 18 m hydrogen fuel cell ferry, combining HAZID with CFD simulations on two platforms and a probabilistic evaluation against a frequency criterion of 10^{-4} per year. The resulting toxic zones of approximately 7 m and 5 m for the two governing release points, with no separate zone required elsewhere, replaced deterministic distances of several times the vessel length and were used in obtaining classification society approval for the vessel. It was concluded that risk-informed zones are both more practical and more discriminating than uniform prescriptive distances, confirming the prescriptive requirement where the risk justifies it and reducing it where it does not.

The specific zone dimensions are conditional on the failure frequency data adopted and on the port and vessel configurations examined, and they should be recalculated where fuel-specific data become available. The procedure of the framework is transferable to other hydrogen-fuelled ships, bunkering operations, and fuels for which prescriptive zone requirements are absent or insufficiently defined.

9.2 Concluding remarks

The maritime industry is undergoing a transition towards zero-emission operations. Hydrogen has emerged as one of the most significant candidate fuels, yet its practical deployment remains constrained by unresolved safety challenges and regulations that do not yet define how safety and hazardous zones should be determined. This thesis has responded by developing an integrated risk assessment framework that adapts established risk assessment principles into a structured procedure for this purpose, and by demonstrating its application to bunkering operations and to an onboard fuel system.

By providing ship designers, port authorities, classification societies, and regulatory bodies with a structured and transparent route for determining and demonstrating the adequacy of safety and hazardous zones, this research supports the safe adoption of hydrogen as a marine fuel, contributing to the shipping sector's path towards the

IMO's net-zero emissions target by or around 2050. It is anticipated that the framework developed in this thesis will serve as a foundation for future research and regulatory development in this field, and that the case study results will contribute to the technical evidence base that informs the next generation of safety standards for hydrogen-fuelled ships.

REFERENCES

- (HSE), H. A. S. E. 2025. *Fire Effects* [Online]. Available: <https://www.hse.gov.uk/offshore/strategy/effects.htm> [Accessed].
- ABS 2020. Guidance Note on Risk Assessment Applications for the Marine and Offshore Industries.
- ANEZIRIS, O., KOROMILA, I. A., GERBEC, M., NIVOLIANITOU, Z. & SALZANO, E. 2022. Ship-to-ship Lng bunkering: Risk assessment and safety zones. *Chemical Engineering Transactions*, 91, 535–540.
- ANTHONY COX JR, L. 2008. What's wrong with risk matrices? *Risk Analysis: An International Journal*, 28, 497–512.
- ASTBURY, G. & HAWKSWORTH, S. J. 2007. Spontaneous ignition of hydrogen leaks: a review of postulated mechanisms. *International Journal of Hydrogen Energy*, 32, 2178–2185.
- AVEN, T. 2016. Risk assessment and risk management: Review of recent advances on their foundation. *European journal of operational research*, 253, 1–13.
- CCPS, C. F. C. P. S. 2010. *Guidelines for Chemical Process Quantitative Risk Analysis*.
- CHOI, S. & JEONG, B. 2023. CFD simulation of gas dispersion at hydrogen bunkering station. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, 7, 2261350.
- CORONADO, C. J., CARVALHO JR, J. A., ANDRADE, J. C., CORTEZ, E. V., CARVALHO, F. S., SANTOS, J. C. & MENDIBURU, A. Z. 2012. Flammability limits: a review with emphasis on ethanol for aeronautical applications and description of the experimental procedure. *Journal of hazardous materials*, 241, 32–54.
- CULLEN, W. D. 1990. The Public Inquiry into the Piper Alpha Disaster: Volumes 1 & 2. *United Kingdom: Department of Energy*.
- DAGDOUGUI, H., SACILE, R., BERSANI, C. & OUAMMI, A. 2018. Chapter 4-hydrogen storage and distribution: implementation scenarios. *Hydrogen Infrastructure for Energy Applications*, 4, 37–52.
- DANASA, A., SOESILO, T., MARTONO, D., SODRI, A., HADI, A. & CHANDRASA, G. The ammonia release hazard and risk assessment: A case study of urea fertilizer industry in Indonesia. IOP conference series: Earth and environmental science, 2019. IOP Publishing, 012087.
- DEPARTMENT FOR ENERGY SECURITY AND NET ZERO 2025. UK hydrogen strategy.
- DEPKEN, J., SIMON-SCHULTZ, M., BAETCKE, L. & EHLERS, S. 2024. Comparing the safety of bunkering LH2 and LNG using quantitative risk assessment with a focus on ignition hazards. *International Journal of Hydrogen Energy*, 83, 1243–1250.
- DIAMANTAKIS, N., XYNOPOULOS, N., SHETH, J., ANDRESEN, J. & MAROTO-VALER, M. 2026. Alternative Maritime Fuels for Net-Zero Shipping: A Comprehensive Operational, Techno-Economic and Regulatory Review. *Hydrogen*, 7, 36.
- DNV 2013. Failure Frequency Guidance.

- DNV 2021. Ammonia Bunkering of Passenger Vessel - Concept Quantitative Risk Assessment, Green Coastal Shipping Programme (Grønt Skipfartsprogram).
- DNV 2022. MARITIME FORECAST TO 2050.
- DNV 2025. IMO CCC 11: Interim guidelines for hydrogen as fuel completed.
- DNV 2026. Handbook for Hydrogen-Fuelled Vessels.
- DUONG, P. A., KIM, H. J., RYU, B. R. & KANG, H. 2024a. A quantitative risk analysis during truck-to-ship ammonia bunkering. *Sustainability*, 16, 2204.
- DUONG, P. A., RYU, B. R., JUNG, J. & KANG, H. 2024b. A comprehensive review of the establishment of safety zones and quantitative risk analysis during ship-to-ship LNG bunkering. *Energies*, 17, 512.
- DUONG, P. A., RYU, B. R., SONG, M. K., NGUYEN, H. V., NAM, D. & KANG, H. 2023. Safety assessment of the ammonia bunkering process in the maritime sector: A review. *Energies*, 16, 4019.
- DUTTA, S. 2014. A review on production, storage of hydrogen and its utilization as an energy resource. *Journal of Industrial and Engineering Chemistry*, 20, 1148–1156.
- ELBERRY, A. M., THAKUR, J., SANTASALO-AARNIO, A. & LARMI, M. 2021. Large-scale compressed hydrogen storage as part of renewable electricity storage systems. *International journal of hydrogen energy*, 46, 15671–15690.
- EMSA 2023. Potential of hydrogen as fuel for shipping.
- EMSA 2025. Safety of hydrogen for use in ships.
- ENERGY, D. O. n.d. Hydrogen Safety. *Fact Sheet Series*. U.S. Department of Energy.
- EUROPEAN COMMISSION 2020. A hydrogen strategy for a climate-neutral Europe.
- EUROPEAN COMMISSION 2021. ‘Fit for 55’: Delivering the EU’s 2030 climate target on the way to climate neutrality. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions*.
- EUROPEAN COMMISSION 2023. EU Regulation on the use of renewable and low-carbon fuels in maritime transport (L234/48) in the Official Journal of the European Union.
- FAN, H., ENSHAEI, H. & JAYASINGHE, S. G. 2021. Safety philosophy and risk analysis methodology for LNG bunkering simultaneous operations (SIMOPs): A literature review. *Safety science*, 136, 105150.
- FAN, H., ENSHAEI, H. & JAYASINGHE, S. G. 2023. Dynamic quantitative risk assessment of LNG bunkering SIMOPs based on Bayesian network. *Journal of Ocean Engineering and Science*, 8, 508–526.
- FAN, H., ENSHAEI, H., JAYASINGHE, S. G., TAN, S. H. & ZHANG, C. 2022. Quantitative risk assessment for ammonia ship-to-ship bunkering based on Bayesian network. *Process Safety Progress*, 41, 395–410.
- FAN, H., XU, X., ABDUSSAMIE, N., CHEN, P. S.-L. & HARRIS, A. 2024. Comparative study of LNG, liquid hydrogen, and liquid ammonia post-release evaporation and dispersion during bunkering. *International Journal of Hydrogen Energy*, 65, 526–539.

- FENG, Y., CAO, J., ZHANG, Y. & JIN, D. 2021. Safety analysis and risk control of shore-based bunkering operations for hydrogen powered ships. *World Electric Vehicle Journal*, 12, 162.
- FERDOUS, R., KHAN, F., SADIQ, R., AMYOTTE, P. & VEITCH, B. 2011. Fault and event tree analyses for process systems risk analysis: uncertainty handling formulations. *Risk Analysis: An International Journal*, 31, 86–107.
- FREEMAN, R. A. 1990. CCPS guidelines for chemical process quantitative risk analysis. *Plant/Operations Progress*, 9, 231–235.
- GOERLANDT, F. & MONTEWKA, J. 2015. Maritime transportation risk analysis: Review and analysis in light of some foundational issues. *Reliability Engineering & System Safety*, 138, 115–134.
- HA, S. & LEE, J. 2026. From Flammability to Toxicity: A Comparative Regulatory Analysis of Safety Frameworks for LNG and Ammonia as Marine Fuels. *Processes*, 14, 1387.
- HAMBURG.COM. 2025. *GEOPORTAL HAMBURG* [Online]. Available: <https://geoportal-hamburg.de/#> [Accessed].
- HÄRING, I. 2016. Risk Acceptance Criteria. *Risk Analysis and Management: Engineering Resilience*, 313–342.
- HAUGEN, S. & KRISTIANSEN, S. 2022. *Maritime transportation: safety management and risk analysis*, Routledge.
- HSE, H. A. S. E. 2001. *Reducing risks, protecting people*.
- HU, L., NIU, J., WU, W., ZHAO, Z., DU, M., CHEN, L., ZHENG, Q. & CAO, H. 2024. Quantitative analysis of toxicity risks in the operation of ammonia-fueled tugboats. *Ocean Engineering*, 310, 118759.
- HWANG, I., JEONG, B., JANG, H., KIM, D. & JEE, J. 2025. An integrated qualitative–quantitative risk assessment for defining toxic and hazardous zones on hydrogen-fuelled ships with ammonia cracking systems. *Ocean Engineering*, 341, 122475.
- HWANG, I., JEONG, B., ZHOU, P., WANG, H., MESBAHI, A., JANG, H., MUJEEB-AHMED, M. & YANG, I. 2026. A PIDA-PDA integrated parametric approach for establishing safety zone for hydrogen, ammonia and LNG bunkering operations. *International Journal of Hydrogen Energy*, 206, 153212.
- IANNACCONE, T., LANDUCCI, G., SCARPONI, G. E., BONVICINI, S. & COZZANI, V. 2019. Inherent safety assessment of alternative technologies for LNG ships bunkering. *Ocean Engineering*, 185, 100–114.
- IMO 2002. MSC/Circ.1023 – MEPC/Circ.392, Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-Making Process.
- IMO 2016. *IGF Code: International Code of Safety for Ships Using Gases Or Low Flashpoint Fuels*, International Maritime Organization.
- IMO 2018. MSC-MEPC.2/Circ.12/Rev.2, REVISED GUIDELINES FOR FORMAL SAFETY ASSESSMENT (FSA)
- FOR USE IN THE IMO RULE-MAKING PROCESS.
- IMO 2020a. Fourth IMO Greenhouse Gas Study.
- IMO 2020b. Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel (MSC.1/Circ.1621).
- IMO 2022. Interim Guidelines for Ships Using Fuel Cell Power Installations (MSC.1/Circ.1647).

- IMO 2023a. Interim Guidelines for the Safety of Ships Using LPG Fuels (MSC.1/Circ.1666).
- IMO. 2023b. *Marine Environment Protection Committee (MEPC 80)*, 3-7 July 2023 [Online]. Available: <https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-80.aspx> [Accessed].
- IMO 2024. Maritime Safety Committee - 109th session (MSC 109), 2-6 December 2024.
- ISO 2016. ISO 17776:2016 Petroleum and natural gas industries — Offshore production installations — Major accident hazard management during the design of new installations.
- ISO 2018. ISO 31000:2018 Risk management — Guidelines.
- ISO 2019. IEC 31010:2019 Risk management — Risk assessment techniques.
- ISO 2021. ISO/TS 18683:2021 Guidelines for safety and risk assessment of LNG fuel bunkering operations.
- ISO 2026. ISO/TS 15916:2026 Hydrogen technologies — Basic considerations for the safety of hydrogen systems.
- ITOPF 2025. Oil Tanker Spill Statistics 2024.
- JANG, H., MUJEEB-AHMED, M., WANG, H., PARK, C., HWANG, I., JEONG, B., ZHOU, P. & MICKEVICIENE, R. 2023. Regulatory gap analysis for risk assessment of ammonia-fuelled ships. *Ocean Engineering*, 287, 115751.
- JANG, H., MUJEEB-AHMED, M., WANG, H., PARK, C., HWANG, I., JEONG, B., ZHOU, P., PAPADAKIS, A., GIANNAKIS, A. & SYKARAS, K. 2024. Safety evaluation on ammonia-fueled ship: Gas dispersion analysis through vent mast. *International Journal of Hydrogen Energy*, 83, 1060–1077.
- JEONG, B., LEE, B. S., ZHOU, P. & HA, S.-M. 2018. Quantitative risk assessment of medium-sized floating regasification units using system hierarchical modelling. *Ocean Engineering*, 151, 390–408.
- JEONG, B., PARK, S., HA, S. & LEE, J.-U. 2020. Safety evaluation on LNG bunkering: To enhance practical establishment of safety zone. *Ocean Engineering*, 216, 107804.
- JRC 2026a. Hydrogen Accidents and Incidents Database (HIAD 2.1).
- JRC 2026b. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 267.
- JRC 2026c. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 463.
- JRC 2026d. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 594.
- JRC 2026e. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 702.
- JRC 2026f. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 707.
- JRC 2026g. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 884.
- JRC 2026h. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 911.

- JRC 2026i. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 971.
- JRC 2026j. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 973.
- JRC 2026k. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 976.
- JRC 2026l. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 1044.
- JRC 2026m. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 1089.
- JRC 2026n. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 1091.
- JRC 2026o. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 1102.
- JRC 2026p. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 1103.
- JRC 2026q. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 1138.
- JRC 2026r. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 1152.
- JRC 2026s. Hydrogen Accidents and Incidents Database (HIAD 2.1) / Event ID 1161.
- JRC 2026t. Hydrogen Accidents and Incidents Database (HIAD 2.1) /Event ID 520.
- JRC 2026u. Hydrogen Accidents and Incidents Database (HIAD 2.1) /Event ID 1015.
- JRC 2026v. Hydrogen Accidents and Incidents Database (HIAD 2.1) /Event ID 1020.
- KIM, I.-S., JEONG, B.-U., SONG, M.-K. & NAM, D. 2022. Determination of bunkering safety zones for ammonia-fueled ship. *Journal of Advanced Marine Engineering and Technology (JAMET)*, 46, 261–269.
- KOGBARA, R. B., IYENGAR, S. R., GRASLEY, Z. C., MASAD, E. A. & ZOLLINGER, D. G. 2013. A review of concrete properties at cryogenic temperatures: Towards direct LNG containment. *Construction and Building Materials*, 47, 760–770.
- KOLTHOUM, M., CANTU MEDRANO, V. H., MAHMOOD, S. & JEAN-MARIE, A. Techno-Economic Study of Green Liquid Hydrogen Production for Aircraft Refuelling: A Case Study of Toulouse-Blagnac Airport. Available at SSRN 5227839.
- LEES, F. 2012. *Lees' Loss prevention in the process industries: Hazard identification, assessment and control*, Butterworth-Heinemann.
- LEVESON, N. G. 2016. *Engineering a safer world: Systems thinking applied to safety*, MIT press.
- LI, H., REN, X. & YANG, Z. 2023. Data-driven Bayesian network for risk analysis of global maritime accidents. *Reliability Engineering & System Safety*, 230, 108938.
- LI, K. & LIU, C. Risk Assessment and Application of Port Liquefied Natural Gas Trucks Bunkering Based on Hazard Identification and Computational Fluid Dynamics. E3S Web of Conferences, 2023. EDP Sciences, 01005.

- MARITIME SAFETY COMMITTEE 2016. International code of safety for ships using gases or other low-flashpoint fuels (IGF code). *International Maritime Organization (IMO)*.
- METEOBLUE. 2024. *Weather and Climate Data for Hamburg, Germany* [Online]. Available: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/hamburg_germany_2911298 [Accessed].
- MOLKOV, V. 2012. Fundamentals of hydrogen safety engineering, Part I and Part II. Ventus Publishing ApS, bookboon. com.
- MOON, K.-T., DAVIES, P., WRIGHT, L. & CHOI, S.-J. 2025. DeRiskbeta: Comparative Quantitative Risk Assessment (QRA) of fuel oil, LNG, methanol, and ammonia on a 15,000 TEU containership. *Journal of Advanced Marine Engineering and Technology (JAMET)*, 49, 42–61.
- NG, C. K. L., LIU, M., LAM, J. S. L. & YANG, M. 2023. Accidental release of ammonia during ammonia bunkering: Dispersion behaviour under the influence of operational and weather conditions in Singapore. *Journal of Hazardous Materials*, 452, 131281.
- NORSOK, S. M. 2024. NORSOK Z-013:2024 Risk and emergency preparedness assessment.
- NUBLI, H., FAJRI, A., PRABOWO, A. R. & SOHN, J. M. 2022. CFD implementation to mitigate the LNG leakage consequences: A review of explosion accident calculation on LNG-fueled ships. *Procedia Structural Integrity*, 41, 343–350.
- OGP 2010a. Risk Assessment Data Directory. OGP.
- OGP 2010b. Risk Assessment Data Directory, Ignition probabilities. London, UK.
- PADAPPAYIL, R. P. & BORGER, J. 2023. Ammonia toxicity. *StatPearls [Internet]*. StatPearls Publishing.
- PHOGAT, P., CHAND, B., JHA, R. & SINGH, S. 2025. Hydrogen and methanol fuel cells: A comprehensive analysis of challenges, advances, and future prospects in clean energy. *International Journal of Hydrogen Energy*, 109, 465–485.
- RAJ, P. K. 2008. Field tests on human tolerance to (LNG) fire radiant heat exposure, and attenuation effects of clothing and other objects. *Journal of hazardous materials*, 157, 247–259.
- REUSSER, C. A. & PÉREZ OSSES, J. R. 2021. Challenges for zero-emissions ship. *Journal of Marine Science and Engineering*, 9, 1042.
- SCHAAD, C., MOSLEH, S., YANG, R. & GROTH, K. M. 2025. Quantitative Risk Assessment of hydrogen releases in a hydrogen fueling station with liquid hydrogen storage. *International Journal of Hydrogen Energy*, 112, 111–120.
- SHAO, Y., KANG, H.-K., LEE, Y.-H., KRÓLCZYK, G., GARDONI, P. & LI, Z. 2022. A preliminary risk assessment on development the fuel gas supply system of a small LNG fueled fishing ship. *Ocean Engineering*, 258, 111645.
- SPOUGE, J. 1999. *A guide to quantitative risk assessment for offshore installations*, CMPT Aberdeen.
- STATISTA. 2024. *Population Density in Hamburg, Germany from 1995 to 2019 (in Inhabitants per Square Kilometer)* [Online]. Available:

- <https://www.statista.com/statistics/1107073/population-density-hamburg-germany/> [Accessed].
- TOFALOS, C., JEONG, B. & JANG, H. 2020. Safety comparison analysis between LNG/LH2 for bunkering operation. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, 4, 135–150.
- TOOLBOX, T. E. 2025. *Liquid Ammonia - Thermal Properties at Saturation Pressure* [Online]. Available: https://www.engineeringtoolbox.com/ammonia-liquid-thermal-properties-d_1765.html [Accessed].
- TRANSPORT, D. F. 2019. Clean Maritime Plan.
- UNCTAD 2025. *Review of Maritime Transport 2025: Staying the Course in Turbulent Waters*, Stylus Publishing, LLC.
- UNFCCC 2022. Climate Action Network & Clean Shipping Coalition.
- UNITROVE. 2025. *LNG Density Calculator* [Online]. Available: <https://www.unitrove.com/engineering/tools/gas/liquefied-natural-gas-density> [Accessed].
- VENTIKOS, N., PODIMATAS, V. & KOIMTZOGLOU, A. 2022. LNG bunkering QRA: A case study on the port of Piraeus. *Journal of Risk Analysis and Crisis Response*, 12.
- VERSTEEG, H. K. 2007. *An introduction to computational fluid dynamics the finite volume method, 2/E*, Pearson Education India.
- VESELY, W. E., GOLDBERG, F. F., ROBERTS, N. H. & HAASL, D. F. 1981. Fault tree handbook.
- VÍLCHEZ, J. A., VILLAFANE, D. & CASAL, J. 2013. A dispersion safety factor for LNG vapor clouds. *Journal of hazardous materials*, 246, 181–188.
- VINNEM, J. E. 2007. *Offshore risk assessment: principles, modelling and applications of QRA studies*, Springer.
- WANG, Y., CHA, Z., LIANG, G., ZHANG, X., LI, K. & GUAN, G. 2024. Risk assessment of LNG bunkering vessel operation based on formal safety assessment method. *Process Safety Progress*, 43, 299–312.
- WEST, M., AL-DOURI, A., HARTMANN, K., BUTTNER, W. & GROTH, K. M. 2022. Critical review and analysis of hydrogen safety data collection tools. *International Journal of Hydrogen Energy*, 47, 17845–17858.
- WINDFINDER. 2023. *Wind, Waves & weather forecast* [Online]. Available: <https://www.windfinder.com/forecast/donghae> [Accessed 2023].
- WU, J., BAI, Y., ZHAO, H., HU, X. & COZZANI, V. 2021. A quantitative LNG risk assessment model based on integrated Bayesian-Catastrophe-EPE method. *Safety science*, 137, 105184.
- YANG, M. & LAM, J. S. L. 2024. Risk assessment of ammonia bunkering operations: perspectives on different release scales. *Journal of Hazardous Materials*, 468, 133757.
- ZACHARAKIS-JUTZ, G. E. 2013. *Performance characteristics of ammonia engines using direct injection strategies*. Iowa State University.
- ZHAO, Q., LI, Y., CAO, W. & LI, Y. 2024. Risk analysis of high-pressure hydrogen leakage in confined space with tube skid container for cylinder. *International Journal of Hydrogen Energy*, 60, 581–592.
- ZHENG, J., ZHOU, H., WANG, C.-G., YE, E., XU, J. W., LOH, X. J. & LI, Z. 2021. Current research progress and perspectives on liquid hydrogen rich

- molecules in sustainable hydrogen storage. *Energy Storage Materials*, 35, 695–722.
- ZHENG, Q., TANG, J., WANG, W., DEVECI, M. & MARDANI, A. 2024. Analyzing the risk of the ammonia storage facility using extended FMEA model based on probabilistic linguistic GLDS method with consensus reaching. *International Journal of Hydrogen Energy*, 62, 1231–1244.

A. APPENDIX

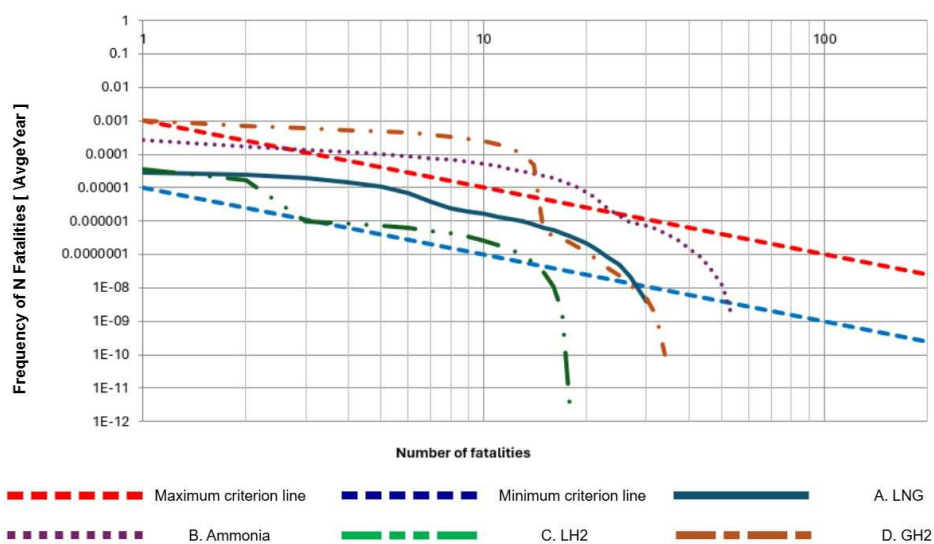


Figure A.1 F-N curve of default scenarios

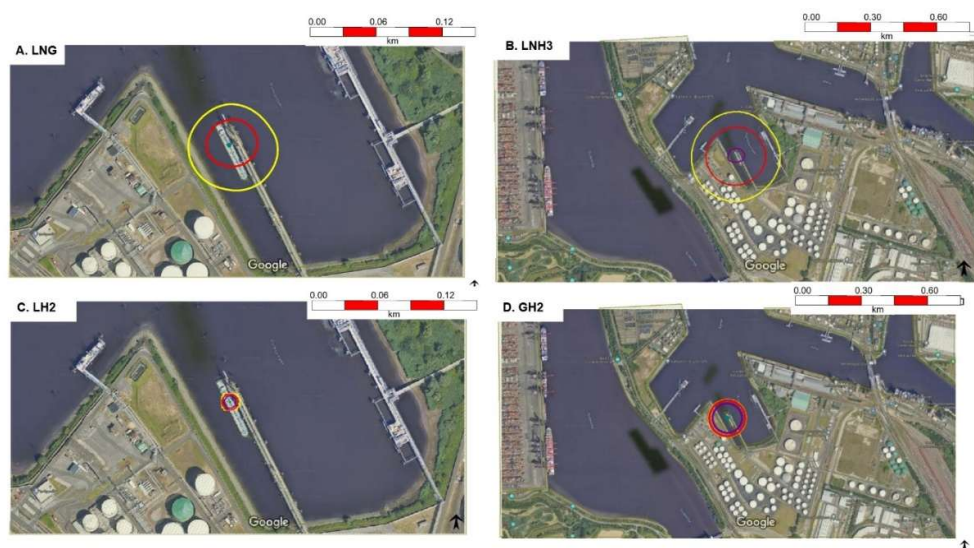


Figure A.2 Default simulation results

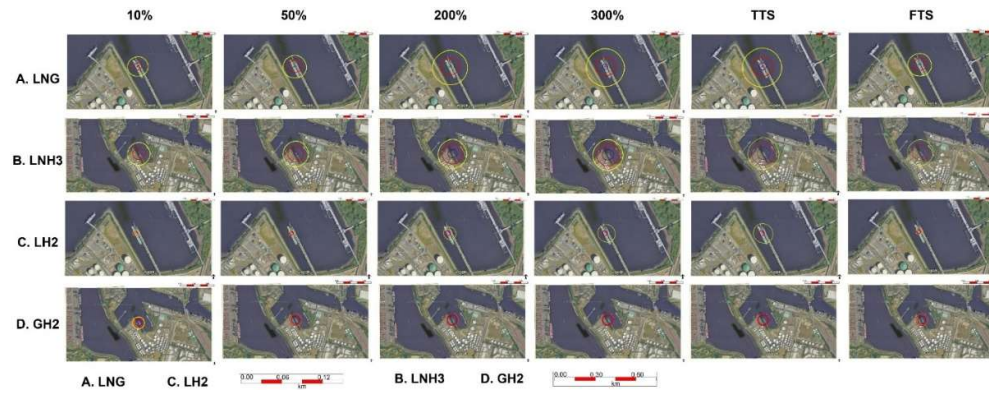


Figure A.3 Results for changing in bunkering time

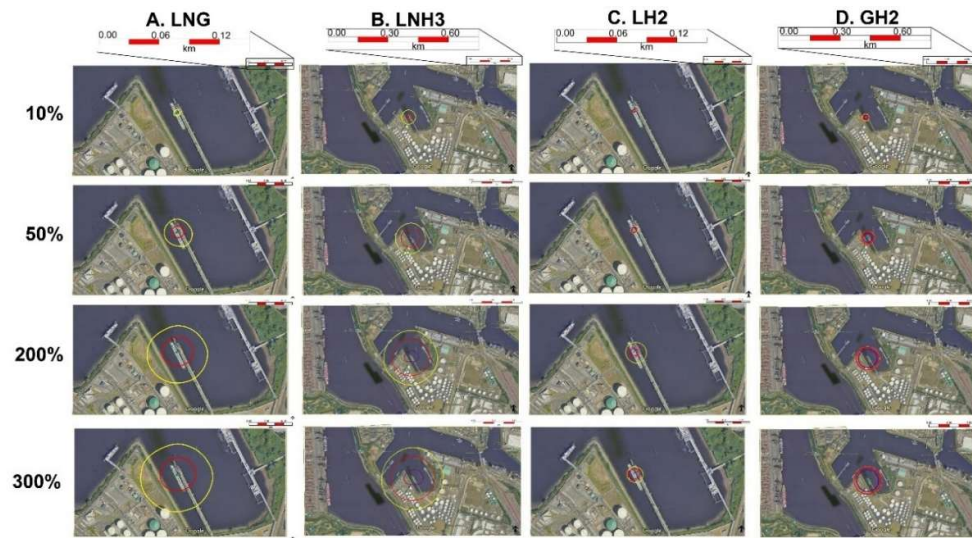


Figure A.4 Results for changing in total leaked fuel quantity

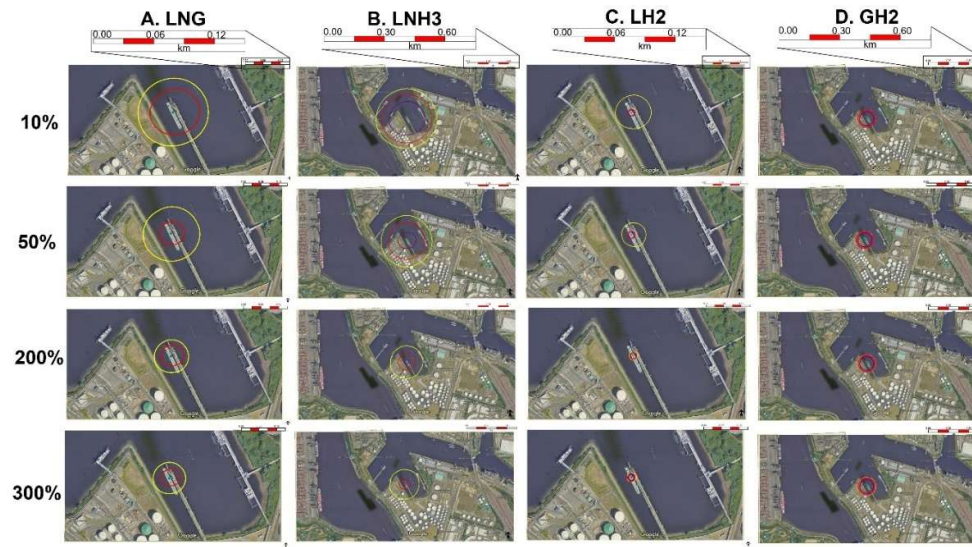


Figure A.5 Results for changing in wind speed

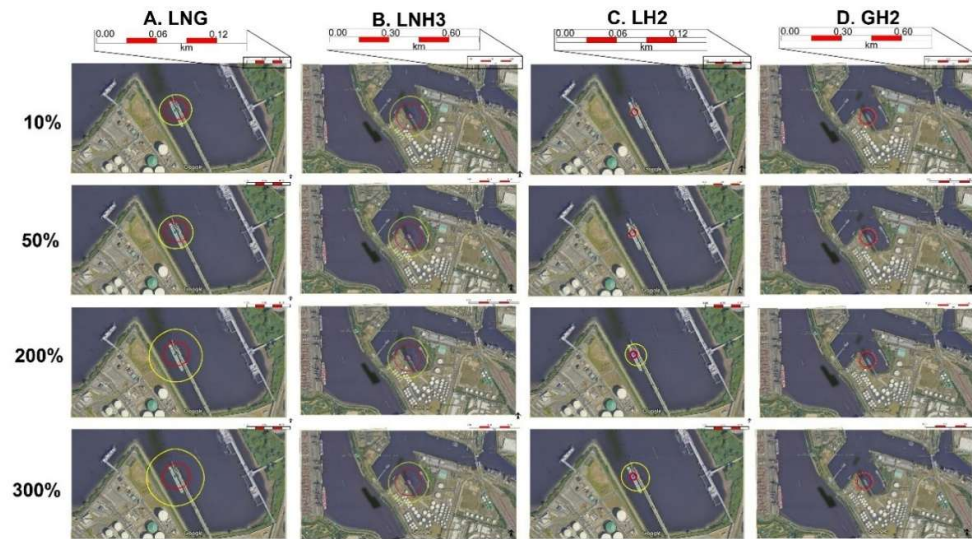


Figure A.6 Results for changing in population

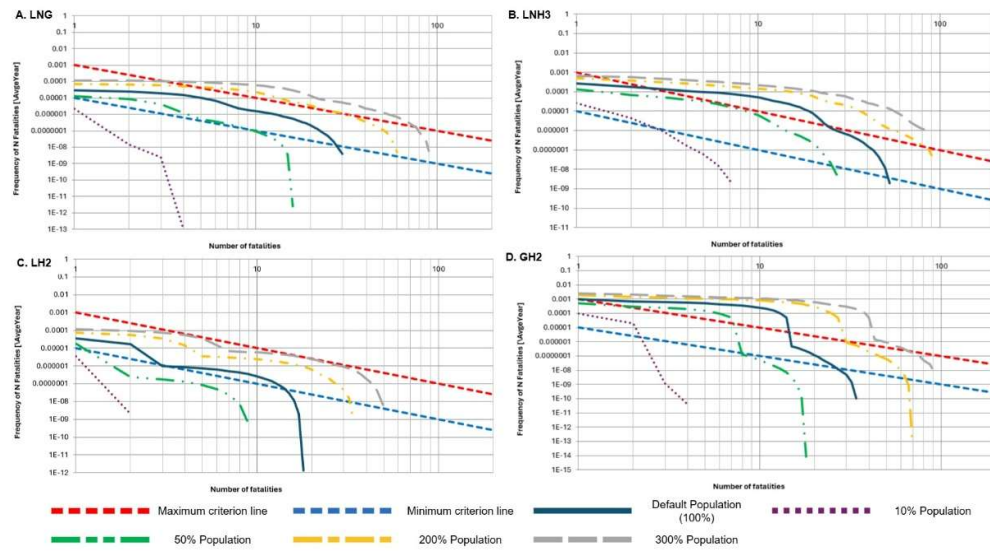


Figure A.7 Results for changing in population (F-N curve)

B. APPENDIX

I. CFD *simulation* for No. 1 bunkering leak, No. 2 ammonia tank leak, and No. 3 cracking system leak

i. Grid generation

For this study, FLACS, a commercial CFD software developed by Gexcon, was utilised to simulate liquid ammonia leakage scenarios. This software's advanced capabilities in modelling complex fluid dynamics, chemical reactions, and dispersion behaviour make it particularly suitable for assessing the safety implications of ammonia leaks in maritime environments.

In the FLACS-CFD simulations, a Cartesian grid system consisting of cubic or rectangular cells was employed, characterised by intersecting vertical and horizontal grid lines. This structured grid configuration ensures precise numerical representation and simulation accuracy. Table B.1 provides an overview of the grid dimensions along the X, Y, and Z axes, the total number of cells, and the smallest cell size used across all planes. Such a structured grid facilitates detailed analysis of fluid dynamics and dispersion phenomena across various leakage scenarios with high computational efficiency.

In the simulation, the grid configuration applied to the ship follows the specifications outlined in Table 8, where grid size parameters are defined. Figure B.1 presents the resulting grid density distribution, illustrating how the mesh is structured across the computational domain.

Table B.1. Grid size and count by scenario

	X,Y,Z Grid size	Number of Grid cells	Smallest Grid cell size (m)
<i>No.1 Bunkering leak</i>	170m × 60m × 70m	24,360	0.6

No.2 Ammonia tank leak	120m × 60m × 50m	86,592	0.6
No.3 Cracking system leak	170m × 60m × 90m	104,386	0.6

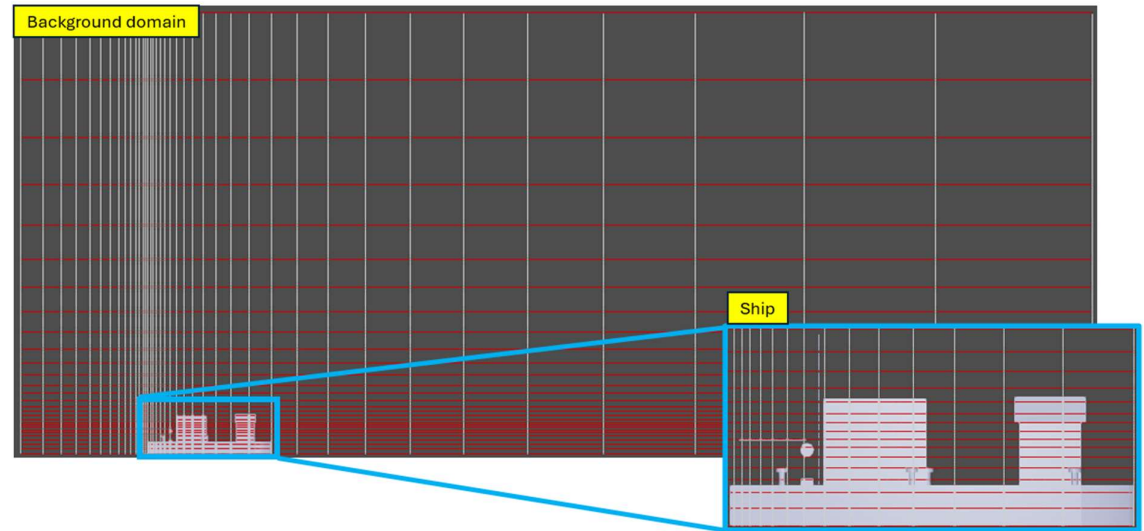


Figure B.1. Gas Leak Simulation Grid Generated in FLACS

In the target vessel's operational context, leakages from bunkering operations, the ammonia storage tank, and the cracking system are anticipated to occur under high-pressure conditions, leading to ammonia being expelled as high-velocity jets. Furthermore, a portion of the leaked liquid undergoes immediate evaporation upon contact with ambient conditions, a phenomenon known as the flashing effect.

The flashing effect is driven by rapid vapor generation due to a pressure drop when a compressed liquid is released into the atmosphere. For ammonia stored under high pressure, this release typically results in a two-phase jet comprising liquid droplets and vapor. Figure B.2 illustrates this phenomenon, with the endpoint of the near-field jet region (denoted as X_f) marking the complete phase change of liquid ammonia. This transition point signifies the onset of air-gas mixture dispersion, critical for understanding the behaviour of the leaked substance.

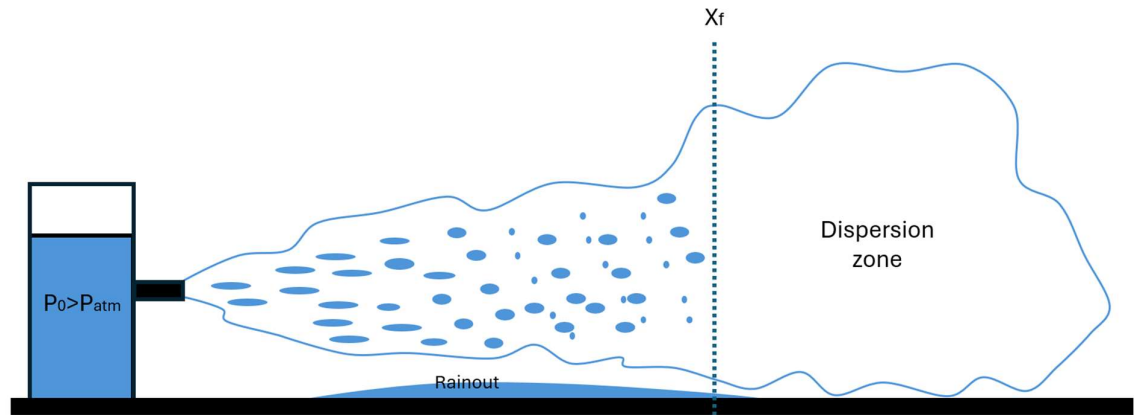


Figure B.2. Flash utility

To accurately account for the flashing effect, FLACS's Flash utility feature was integrated into the simulations, enhancing traditional CFD methodologies. This feature allows for precise representation of phase change phenomena and their impact on gas dispersion dynamics.

The conservation equations for mass, momentum, energy, and species transport were applied to capture the jet dynamics and subsequent dispersion of vapor. The integrated approach ensured that critical aspects of ammonia behaviour, including turbulent mixing, jet breakup, and vapour dispersion, were effectively represented. This methodology forms the foundation for evaluating safety risks and mitigation strategies in maritime ammonia leakage scenarios.

ii. Boundary conditions

The atmospheric dispersion of ammonia was simulated using the Reynolds-Averaged Navier-Stokes (RANS) equations in conjunction with the standard k- ϵ model, incorporating the ideal gas law to characterise ammonia behaviour under atmospheric conditions. To accurately capture the complex dynamics of widely dispersed ammonia, the governing equations were enhanced with Favre averaging, enabling a more refined representation of turbulence. These calculations were performed using the finite volume method, which provides a robust framework for discretising the governing equations.

In this simulation setup, the ship was assumed to be situated in a vast open-water environment, unrestricted by surrounding barriers. Boundary conditions were meticulously defined to reflect realistic flow and environmental interactions. Table B.2 summarises the interpretation of these boundary conditions, as outlined in the FLACS user manual.

Table B.2. Boundary conditions

	Dispersion/ventilation	Explosion: confined	Explosion: unconfined/far-field
EULER/NOZZLE + solid surface	Ground/sea	Ground/sea	Ground/sea
EULER	-	All other	-
NOZZLE	Outflow	-	-
PLANE_WAVE	-	-	All other
WIND	Inflow/parallel boundaries	-	-

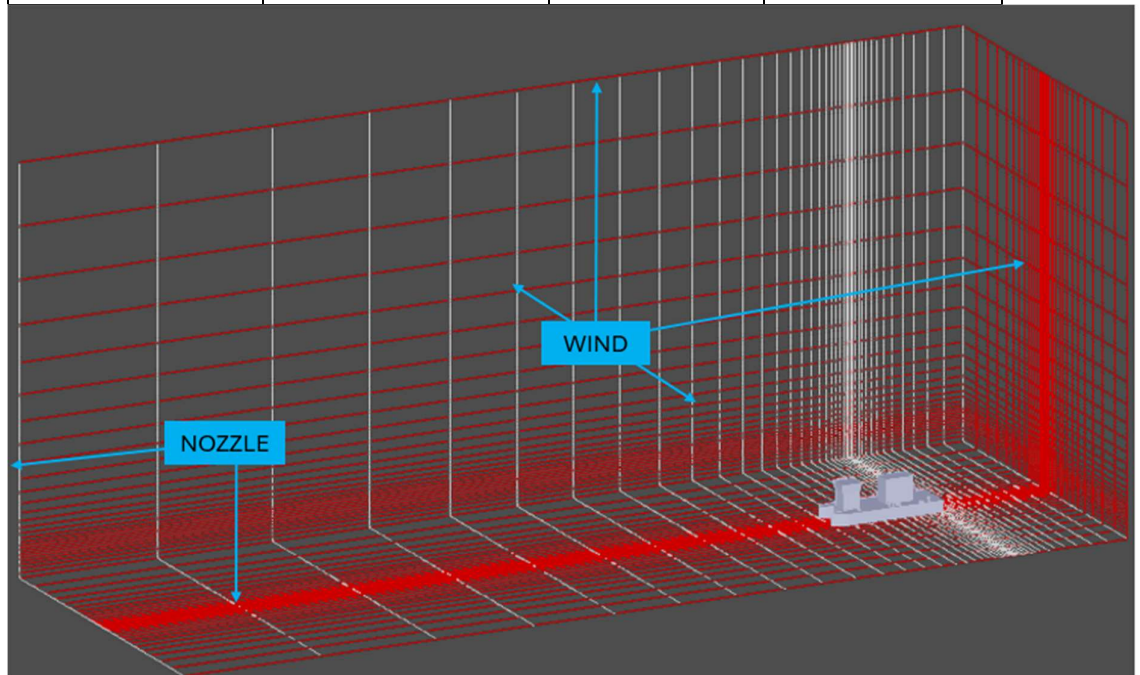


Figure B.3. Boundary conditions applied to the CFD model.

As shown in Figure B.3, the surface areas of the bow, stern, starboard, port side, and the upper part of the ship are designated as boundary conditions called "NOZZLE" to represent land/sea or exhaust conditions. To replicate the desired

environmental conditions, wind direction and speed can be determined at these boundary conditions on the horizontal planes of the bow, stern, starboard, and port side. Therefore, a "WIND" boundary condition was set to simulate wind blowing from the bow to the stern.

For this study, five wind speed scenarios were investigated: 0 m/s, 5 m/s, 10 m/s, 15 m/s, and 20 m/s. Each wind condition was coupled with predefined leakage scenarios to assess the dispersion patterns of ammonia. Leakage scenarios were categorised based on the leakage size, as follows:

- No. 1 Bunkering Leakage: 3 mm, 10 mm, and 50 mm
- No. 2 Ammonia Tank Leakage: 3 mm, 10 mm, and 50 mm
- No. 3 Cracking system Leakage: 3 mm, 10 mm, and 12.7 mm

This extensive setup ensured that the model could capture the critical aspects of ammonia dispersion dynamics under varying environmental and leakage conditions.

iii. Gas detector installation

Ammonia leak simulations were conducted with gas detectors strategically placed at critical locations.

II. CFD simulation for No. 4 vent master and No. 5 vent leak

i. Grid generation

The computational grid for this study was generated using the automatic meshing function of STAR-CCM+, which is well-suited for the Finite Volume Method (FVM). This meshing approach ensures that the numerical solution remains accurate while maintaining computational efficiency. The meshing process involved two key steps: surface meshing and volumetric meshing. To generate a high-quality surface grid that accurately represents the ship geometry, the Surface

Remesher tool was utilised. This tool refines and smoothens surface triangulations, helping to capture complex geometric details while maintaining the integrity of the computational model. Following the surface meshing, the Trimmed Cell Mesher tool was employed to create the volumetric mesh, ensuring a well-structured cell arrangement throughout the computational domain. This method enables efficient grid generation while reducing unnecessary computational overhead. The generated computational mesh primarily consists of hexahedral cells, which are widely preferred in CFD due to their superior numerical stability and computational efficiency compared to unstructured tetrahedral grids. The meshing process was designed to optimise accuracy by implementing local refinement strategies in regions where strong variations in flow variables—such as velocity, pressure, and temperature—are expected. In particular, fine grid resolution was applied in critical areas, including the vent master for ammonia leaks and the vent areas for hydrogen leaks. These regions require finer grids to accurately capture turbulence effects, pressure gradients, and transient flow behaviours. By increasing mesh density in these areas, the simulation can better resolve flow separation, vortex formation, and mixing effects, leading to improved accuracy in predicting gas dispersion patterns. In contrast, coarser grid resolution was adopted in regions with relatively uniform flow characteristics, where significant changes in flow properties are not expected. This selective refinement approach allows for an efficient trade-off between computational cost and solution accuracy. Maintaining a coarse grid in less dynamic regions helps reduce the total number of computational cells without sacrificing the reliability of the overall simulation results.

For Scenarios 4 and 5, approximately 4,500,000 computational cells were generated within STAR-CCM+, striking an optimal balance between numerical accuracy and computational efficiency. This cell count was determined based on a sensitivity analysis, ensuring that the solution remains grid-independent while keeping computational costs manageable. The non-uniform grid structure of the CFD model features adaptive refinement zones, allowing for detailed resolution in key regions while maintaining an efficient computational workload. The overall mesh distribution for Scenarios 4 and is depicted in Figure B.4, illustrating how the grid density varies across different regions of the computational domain. The structured yet adaptive nature of the mesh ensures that the simulation captures essential flow

characteristics, such as jet dispersion, boundary layer effects, and turbulence-induced mixing, with high precision. This meshing strategy, combined with the robust capabilities of STAR-CCM+, enables the accurate prediction of fluid behaviour while maintaining an optimal balance between computational demand and numerical accuracy.

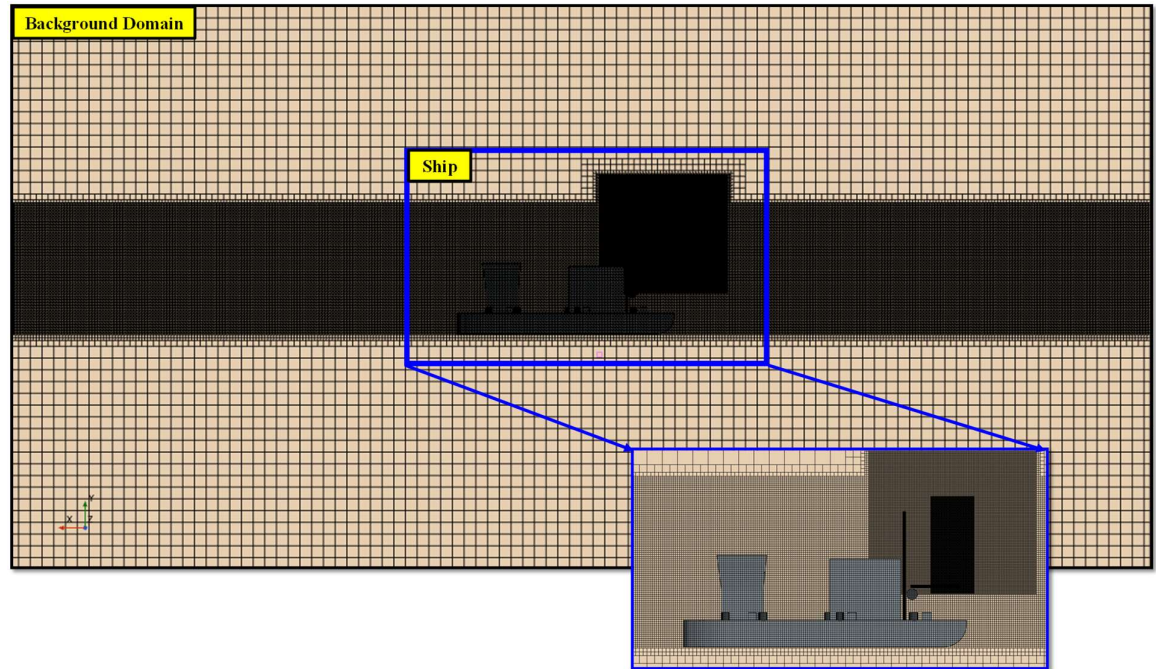


Figure B.4. Gas Leak Simulation Grid Generated in STAR-CCM+ (Scenarios 4 and 5)

ii. Boundary conditions

Applying appropriate initial and boundary conditions is a critical step in ensuring the accuracy and reliability of gas leak simulations performed in STAR-CCM+. The correct specification of these conditions directly influences the numerical stability, convergence behaviour, and physical realism of the simulation results. Since gas dispersion is highly sensitive to factors such as inlet velocity, pressure gradients, temperature distributions, and turbulence effects, defining precise boundary conditions is essential to capturing the complex flow physics involved in

the leakage process. For Scenarios 4 and 5, the detailed boundary conditions applied to the gas leak model are illustrated in Figure B.5. These conditions were carefully chosen to reflect real-world leakage scenarios as accurately as possible. The boundary conditions define how gas enters and interacts with the computational domain, ensuring that key flow characteristics, such as turbulent mixing, jet dispersion, and buoyancy-driven flow patterns, are properly represented.

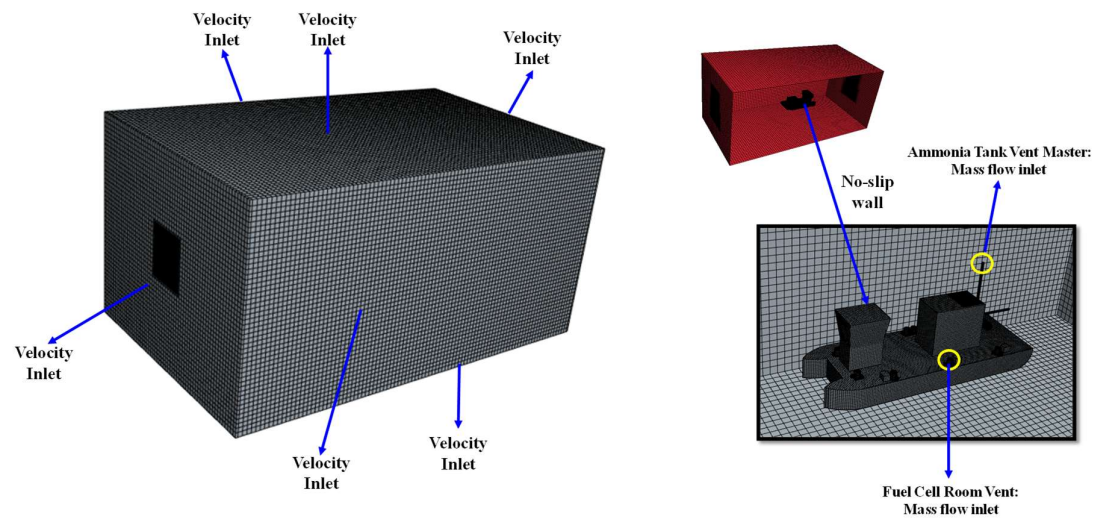


Figure B.5. Boundary conditions applied to the gas leak CFD model.

According to the STAR-CCM+ user manual, each boundary condition plays a distinct role in shaping the flow behaviour within the simulation:

(1) Velocity Inlet: The velocity inlet is applied at an opening located at the boundary of the computational domain where the fluid enters the system with a predefined velocity. This condition is commonly used to model jet flows, forced convection, and controlled fluid injection.

(2) Mass Flow Inlet: The mass flow inlet is another type of inflow condition used to specify the total mass flow rate of the injected gas. Instead of defining the

velocity directly, this boundary condition ensures that a fixed amount of mass enters the system per unit time.

(3) No-Slip Wall: The no-slip wall boundary condition is applied to solid surfaces within the computational domain, such as the vessel walls, ground surfaces, and any structural obstacles. This condition enforces zero velocity at the wall, ensuring that the fluid adheres to the surface due to viscosity.

The computational domain was designed to realistically represent the open-sea environment, where the ship is assumed to be situated in an infinite ocean rather than a confined space. Since external boundaries must be defined to accurately capture the fluid dynamics of wind and gas dispersion, appropriate boundary conditions were assigned to different surfaces within the domain. To effectively simulate wind flow and environmental interactions, the boundary surfaces at the bow, stern, port side, starboard side, top, and bottom of the ship were designated as 'Velocity Inlet' boundaries. This setting allows external airflow to enter the domain, ensuring that the prescribed wind speed and direction are properly introduced into the simulation. The ship's hull was assigned a 'No-slip Wall' boundary condition. This ensures that the velocity of the fluid in direct contact with the vessel's surface remains zero, accurately reflecting real-world viscous effects. This boundary condition is crucial for properly resolving the boundary layer, which significantly affects shear stress, turbulence generation, and overall flow behaviour around the ship's structure.

To accurately model the gas leakage phenomenon, a 'Mass Flow Inlet' boundary condition was applied at the ammonia tank vent master and the fuel cell room vent, where gas leakage occurs. This boundary condition allows for a precisely controlled gas injection rate, ensuring that the simulation correctly represents the rate and dynamics of gas dispersion. For Scenarios 4 and 5, the following parameters were specified for the 'Mass Flow Inlet' boundary:

- Scenario 4 - Leaking Gas: Ammonia (NH_3), Mass Flow Rate: 0.21 kg/s
- Scenario 5 - Leaking Gas: Hydrogen (H_2), Discharge speed: 3 m/s

To ensure an accurate representation of turbulent mixing and dispersion dynamics during the gas leakage event, a widely validated turbulence model was employed in the simulations. The Realizable k- ϵ Two-Layer Model was selected due to its ability to effectively capture:

- Turbulent mixing in high-shear flow regions
- Vortex formation and dissipation due to wind interactions
- Boundary layer effects near the hull and vent master

This turbulence model is particularly well-suited for gas dispersion scenarios, as it improves the accuracy of eddy viscosity predictions and provides enhanced performance in rotating and recirculating flow conditions. For pressure-velocity coupling, the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was used to efficiently solve the Navier-Stokes equations. The SIMPLE scheme is known for its robustness in handling incompressible and weakly compressible flows, making it ideal for leakage-induced dispersion modelling. It ensures numerical stability and convergence while maintaining computational efficiency. Table B.3 summarises the boundary conditions and computational setup applied to the CFD model.

Table B.3 Boundary Conditions and Computational Setup

Component/Region	Boundary Condition/Computational setup	Description
Bow, Stern, Port, Starboard, Top, Bottom boundaries	Velocity Inlet	Allows environmental airflow and wind conditions to be imposed
Hull	No-Slip Wall	Ensures zero velocity at the wall surface, capturing viscous effects and turbulence near the ship
Vent Master (Gas Leak Source)	Mass Flow Inlet	Specifies gas injection rate for realistic dispersion modelling

Scenarios 4 & 5	No.4: Ammonia (NH ₃), Mass Flow Rate: 0.21 kg/s No.5: Hydrogen (H ₂), Discharge speed: 3 m/s	Defines ammonia leak parameters
Turbulence Model	Realizable k-ε Two-Layer Model	Improves accuracy in turbulent dispersion and near-wall effects
Pressure-Velocity Coupling	SIMPLE Algorithm	Ensures stable numerical convergence

iii. Gas detector installation

Leak simulations were conducted with gas detectors strategically placed at critical locations.