Holistic Understanding of Accident-Causing Patterns Using Mixed Methods of Analysis

Iulia Manole

August 2024

Imperial College London

Centre for Transport Engineering and Modelling

Department of Civil and Environmental Engineering

Submitted in part fulfilment of the requirements for the degree of Doctor of Philosophy (PhD) in Civil and Environmental Engineering and the Diploma of Imperial College London (DIC)

Declaration of originality

I hereby declare that the work presented within this thesis is the result of my own research. Where external sources of information and the work of others have been used, these have been cited and referenced appropriately and/or acknowledgement is given. Similarly, the collaborations during my PhD are mentioned in the thesis.

Iulia Manole

5 August 2024

Copyright declaration

‘The copyright of this thesis rests with the author. Unless otherwise indicated, its contents are licensed under a Creative Commons Attribution-Non Commercial 4.0 International Licence (CC BY-NC).

Under this licence, you may copy and redistribute the material in any medium or format. You may also create and distribute modified versions of the work. This is on the condition that: you credit the author and do not use it, or any derivative works, for a commercial purpose.

When reusing or sharing this work, ensure you make the licence terms clear to others by naming the licence and linking to the licence text. Where a work has been adapted, you should indicate that the work has been changed and describe those changes.

Please seek permission from the copyright holder for uses of this work that are not included in this licence or permitted under UK Copyright Law.’

This page is intentionally left blank.

Abstract

The safety of transport systems is vital to everyday life and global commerce. Safety Management Systems (SMS) are essential frameworks for identifying risks and implementing preventative measures. However, current safety assessment methods tend to rely heavily on quantitative data and reactive approaches, often overlooking the complex socio-technical nature of transport systems. This thesis proposes a comprehensive safety analysis framework that integrates mixed methods (quantitative and qualitative) and data sources to address both technical and human-related safety factors. A complementary framework for evaluating safety data quality is also developed.

Adopting a pragmatic and epistemological stance, the research explores real-world safety challenges through four case studies from maritime and aviation sectors. These include safety in UK ports (with a focus on onboard safety and future autonomous vessels), maritime piracy, and the overlooked safety of recreational seaplane pilots in Canada. Each case applies a combination of reactive, proactive and predictive approaches, showcasing the framework's flexibility and depth. Data sources include official databases, investigation reports, tracking systems and voluntary reporting schemes. To complement quantitative gaps, this thesis draws on interviews, focus groups and questionnaires involving 152 participants. Thematic analysis offers insight into human factors, decision-making and socio-technical dynamics not captured in traditional databases.

The framework is designed for broader applicability across diverse transport and safety-critical sectors, particularly in domains with limited regulation, underreporting, or evolving technologies. It supports consistent, system-wide comparisons and informed risk management across modes. The findings advocate for integrating mixed-methods analysis and stakeholder engagement in SMS development and for enhancing policy to promote transparent, high-quality safety reporting. This work advances academic understanding and industry practice by providing a robust tool to improve safety outcomes and strengthen SMS frameworks in both mainstream and niche contexts.

Acknowledgements

Firstly, I would like to thank my supervisors, Prof. Arnab Majumdar and Prof. Washington Y. Ochieng, for giving me the opportunity to conduct my PhD research at Imperial College London. They have shown me great support over the years, offered me guidance and pushed the boundaries of my work beyond initial objectives of my research. I am also extremely grateful for the knowledge they shared with me and for pushing me beyond my comfort zone, to explore qualitative research in great depth.

Secondly, I would like to thank my family for being especially supportive throughout my journey and for helping me keep positive throughout my research. I would like to especially thank my parents, my sister Elena and my grandmother for always being by my side and believing in me. I would also like to thank my partner Daniel and my friends, my fellow colleagues from Imperial College and wardens at Kemp Porter.

This research would not have been possible without the collaboration of experts in transport safety, especially general aviation safety from various organisations in Canada. I am profoundly grateful to Simon Garrett from Transport Canada who was the main collaborator during my PhD, for helping me achieve a qualitative study beyond expectations and reach out to the seaplane community in Canada to take part in my research. I would also like to thank him for making my time in Canada very enjoyable and for introducing me to poutine, as well as for reviewing my research to assure high accuracy of my findings. Special thanks to all the members of the General Aviation Safety Program, especially the Seaplane Working Group, for their help and support in shaping my research.

Last but not least, I am extremely grateful to The Lloyd's Register Foundation for funding this research and allowing me the opportunity to travel to Canada, to meet with my collaborators from Transport Canada and engage with the seaplane community.

Table of Contents

DECLARATION OF ORIGINALITY **2**

COPYRIGHT DECLARATION **3**

ABSTRACT **4**

ACKNOWLEDGEMENTS **6**

TABLE OF CONTENTS **7**

LIST OF FIGURES **11**

LIST OF TABLES **15**

LIST OF ABBREVIATIONS **17**

CONFERENCES AND PUBLICATIONS **22**

1. INTRODUCTION **23**

1.1. BACKGROUND 23
1.2. PROBLEM STATEMENT AND CHALLENGES 25
1.3. AIM AND OBJECTIVES 26
1.4. THESIS OUTLINE 27

2. FUNDAMENTALS OF TRANSPORT SAFETY **30**

2.1. FUNDAMENTALS OF SAFETY MANAGEMENT 30
2.1.1. The concept of Safety *30*
2.1.2. The concepts of hazard and risk *31*
2.1.3. Safety reporting and investigation *33*
2.1.4. Safety culture *33*
2.2. SAFETY MANAGEMENT SYSTEMS (SMS) AND RISK ASSESSMENT 34
2.2.1. Safety Policy *35*
2.2.2. Safety Risk Management *35*
2.2.3. Safety Assurance *38*
2.2.4. Safety Promotion *38*
2.2.5. Conclusions of the SMS review *39*
2.3. REVIEW OF SAFETY APPROACHES 40
2.3.1. Traditional Safety Management *41*
2.3.2. Reactive Safety Approach *41*
2.3.3. Proactive Safety Approach *42*
2.3.4. Predictive Safety Approach *42*
2.3.5. Best Practices for Transport Safety *44*
2.3.6. Conclusions of the review of safety approaches *45*
2.4. REVIEW OF ACCIDENT MODELS 46
2.4.1. Sequential Accident Models *46*
2.4.2. Epidemiological Accident Models *48*
2.4.3. Human Factors Analysis and Classification System (HFACS) *49*
2.4.4. Systems Theoretic Accident Model and Processes (STAMP) *49*
2.4.5. Conclusions of the review of accident models *50*
2.5. THE ROLE OF DATA AND ITS COLLECTION IN TRANSPORT SMS 51
2.5.1. Rationale *51*
2.5.2. Method used *53*
2.5.3. Conclusions of the role of data in transport safety *53*
2.6. SOCIO-TECHNICAL SYSTEMS 54
2.6.1. Definitions for socio-technical systems and socio-technical factors *54*
2.6.2. Complex socio-technical systems *55*
2.6.3. Usability and application of socio-technical systems for the specific maritime and aviation studies in this thesis *56*
2.7. THE HUMAN ASPECT – HUMAN PERFORMANCE 57

2.8. The water environment 60
2.9. Conclusions of Chapter 2 61

3. FUNDAMENTALS OF MARITIME SAFETY 62

3.1. Overview of the maritime industry 62
3.2. Ports 64
3.3. Accident classification and definitions 67
3.3.1. Accidents, incidents, casualties and occurrences 67
3.3.2. Occurrence types 68
3.3.3. Vessel types 69
3.4. Maritime regulations and stakeholders 70
3.4.1. Maritime regulations and stakeholders at an international level 70
3.4.2. Maritime regulations and stakeholders in the United Kingdom 71
3.5. Relevant studies of critical factors affecting the safety of vessels transiting ports 75
3.5.1. Main causes of ship casualties in ports 75
3.5.2. Critical factors for occupational accidents in ports 78
3.5.3. Summary of factors underlying maritime safety 79
3.6. Literature review on the use of data processing methods to study maritime safety 81
3.7. Autonomous vessels 85
3.7.1. Overview of autonomous vessels 85
3.7.2. Available literature on autonomous vessels 86
3.7.3. Literature gaps and conclusions 89
3.8. The use of AIS for analysing port congestion and performance 89
3.9. Conclusions of Chapter 3 91

4. FUNDAMENTALS OF GENERAL AVIATION AND SEAPLANE SAFETY 92

4.1. General Aviation 92
4.1.1. Definition of General Aviation (GA) 92
4.1.2. The General Aviation market around the world 94
4.1.3. The General Aviation market in Canada 95
4.1.4. Licences and permits issued in Canada 96
4.2. Seaplanes 97
4.2.1. Definition of seaplanes 97
4.2.2. Distribution of seaplanes around the world 99
4.2.3. Requirements for seaplane pilots 100
4.2.4. Proposed definition of private, recreational General Aviation seaplane operations in Canada 102
4.3. Accident classification and definitions 103
4.3.1. Phases of flight 103
4.3.2. Accidents, incidents and occurrences 105
4.3.3. Aircraft damage level, fatality and injury 106
4.3.4. Categorisation 107
4.3.5. Reporting requirements 108
4.4. Key stakeholders and safety regulators for GA seaplane operations in Canada 109
4.4.1. General Aviation safety regulations in Canada 109
4.4.2. Stakeholders for General Aviation seaplanes in Canada 111
4.5. Studies on the safety of General Aviation seaplanes 114
4.5.1. Studies on seaplane safety worldwide 114
4.5.2. Studies on seaplane safety in Canada 116
4.5.3. Critical literature gaps in seaplane safety research 118

5. RESEARCH METHODOLOGY AND PHILOSOPHY 122

5.1. Philosophical stance of the researcher 122
5.2. Research approach 127
5.3. Research strategy 129
5.3.1. Choice of maritime safety in UK ports 130
5.3.2. Choice of aviation safety, specific for private, recreational seaplane operations 131

5.3.3. Summary of literature gaps for each case study and justification for the integrated framework to be proposed ... *132*
5.4. PROPOSED RESEARCH METHODOLOGY ... 135
5.5. DATA SOURCES ... 138
5.6. DATA QUALITY ASSESSMENT (DQA) ... 141
5.6.1. Overview ... *141*
5.6.2. Literature review on methods used for assessing data quality ... *142*
5.6.3. Proposed framework for data quality ... *144*
5.6.4. Summary of data quality considerations ... *151*
5.7. CONCLUSIONS OF CHAPTER 5 ... 151

6. ANALYSIS OF MARINE ACCIDENTS AND INCIDENTS ... 153

6.1. SAFETY ANALYSIS OF ACCIDENTS AND INCIDENTS AT PORTS IN THE UNITED KINGDOM ... 153
6.1.1. Aim, objectives and methodology ... *153*
6.1.2. Database description ... *155*
6.1.3. Redefined vessel categories ... *161*
6.1.4. Data quality assessment ... *162*
6.1.5. Trend and contingency analysis ... *164*
6.1.6. Three-way associations ... *174*
6.1.7. Logistic regression ... *179*
6.1.8. The use of other analytical tools, focusing on Bayesian and Complex Networks ... *189*
6.1.9. Interviews with professionals from the maritime industry ... *196*
6.1.10. Conclusions of the first case study ... *199*
6.2. EXPECTED IMPLICATIONS ON MARITIME SAFETY FOLLOWING THE INTRODUCTION OF AUTONOMOUS VESSELS ... 200
6.2.1. Introduction ... *201*
6.2.2. Methodology ... *201*
6.2.3. Database description ... *202*
6.2.4. Data analysis and discussion of the results ... *204*
6.2.5. Improvements of autonomous vessels ... *208*
6.2.6. Qualitative analysis and discussion of the results ... *209*
6.2.7. Conclusions of the second case study ... *215*
6.3. SAFETY ANALYSIS USING IMO DATA (FOR PIRACY-RELATED OCCURRENCES) ... 217
6.3.1. Introduction, aim and objectives ... *217*
6.3.2. Methodology, data and main findings ... *219*
6.3.3. Limitations of the results ... *220*
6.3.4. Conclusions of the third case study ... *222*
6.4. CONCLUSIONS OF CHAPTER 6 ... 222

7. ANALYSIS OF ACCIDENT AND INCIDENT DATA FOR PRIVATE, RECREATIONAL SEAPLANES ... 226

7.1. AIM AND OBJECTIVES OF THE AVIATION CASE STUDY ... 227
7.2. METHODOLOGY OF THE AVIATION CASE STUDY ... 227
7.3. DESCRIPTION OF THE DATABASE OF SEAPLANE OCCURRENCES IN CANADA ... 228
7.3.1. Database description – Seaplane occurrences ... *228*
7.3.2. Data filtering and cleaning – Seaplane occurrences ... *229*
7.3.3. Data quality assessment – Seaplane occurrences ... *231*
7.4. OCCURRENCE CATEGORISATION ... 233
7.5. ANALYSIS OF SEAPLANE OCCURRENCES IN CANADA ... 235
7.5.1. Narrative analysis ... *236*
7.5.2. Trend and contingency analysis ... *237*
7.5.3. Three-way associations ... *246*
7.5.4. Bayesian Networks and Prediction Models ... *249*
7.6. CONCLUSIONS OF CHAPTER 7 ... 250

8. QUALITATIVE ANALYSIS OF PRIVATE, RECREATIONAL SEAPLANE SAFETY - WHAT CAN BE LEARNT THAT COULD NOT BE CAPTURED BY DATA ANALYSIS? ... 253

8.1. AIM AND OBJECTIVES ... 253
8.2. METHODOLOGY ... 254

8.3. Data quality and integrity of the interviews, focus groups and questionnaire 256
8.4. Ethics considerations 258
8.5. Participants 258
8.5.1. General details of the participants 258
8.5.2. Exclusion criteria for the participants 260
8.5.3. Advertisement of this study 260
8.6. Design of the questionnaire, interviews and focus groups 260
8.6.1. Design of the questionnaire 261
8.6.2. Design of the focus groups 262
8.6.3. Design of the interviews 262
8.7. Quantitative data analysis 263
8.8. Qualitative data analysis 267
8.9. Mitigation and safety awareness 279
8.9.1. Mitigation strategies - Training issues and technological reliance 279
8.9.2. Mitigation strategies - Proficiency, currency and safety practices 280
8.9.3. Mitigation strategies – Interactions with boats and jet skis 281
8.9.4. Mitigation strategies – Use of radios 282
8.9.5. Mitigation strategies - Regulatory and infrastructure support for GA seaplane pilots 282
8.9.6. Mitigation strategies – Environmental awareness 282
8.9.7. Mitigation strategies – Mechanical issues and equipment reliability 283
8.9.8. Awareness initiatives 283
8.10. Conclusions of Chapter 8 283

9. DISCUSSION AND IMPLICATIONS 285

9.1. Overview of capabilities of transport safety data 285
9.1.1. Summary of data-related limitations 289
9.1.2. Importance of data quality 293
9.1.3. Limitations of the studied data sources 295
9.1.4. Conclusions 298
9.2. Main findings of data analysis 298
9.2.1. Main findings from quantitative methods of data analysis 298
9.2.2. Main findings from qualitative data analysis 300
9.2.3. Implications of using mixed methods of analysis 302
9.3. Proposed framework for safety data analysis 303
9.3.1. Integration of the proposed framework into SMS 305
9.3.2. Summary of safety recommendations and proposed action plan 307

10. CONCLUSIONS - MAIN CONTRIBUTIONS, IMPACT AND FUTURE WORK 309

10.1. Review of the MET aim and objectives of the thesis 309
10.1.1. Summary of limitations encountered 310
10.2. Main contributions 312
10.3. Research impact 313
10.4. Recommendations and future work 314

REFERENCES 317

APPENDIX 342

List of figures

Figure 1.3. Overview of the thesis structure	*29*
Figure 2.2. Relationship Between Safety Management System and Risk Assessment (Nalty, 2017)	*38*
Figure 2.3. Review of safety approaches, including their main focus, characteristics and limitations.	*45*
Figure 2.4-A. The Domino Theory of accident causation, and interruption of the accident sequence by removing unsafe acts (Heinrich, Petersen & Roos, 1980).	*47*
Figure 2.4-B. Representation of the Swiss Cheese Model (Reason, 1990).	*48*
Figure 3.1. Liner Shipping Connectivity: top 10 countries, 2006-2019 (UNCTAD, 2020)	*63*
Figure 3.3. Occurrence types based on definitions and classification from MAIB (2015b) and EMSA (2017)	*68*
Figure 3.4. Combined operation amongst maritime safety institutions in the United Kingdom (Majumdar, Manole and Garcia Sinobas, 2024).	*73*
Figure 3.7. Impact of automated framework on accident's likelihood (Wróbel, Montewka and Kujala, 2018)	*88*
Figure 4.3. Illustration of the typical phases of flight of a seaplane, excluding Manoeuvring, En Route, Post-Impact and Unknown	*105*
Figure 4.4. Main stakeholders for recreational GA seaplanes in Canada	*113*
Figure 5.2. Methods employed for data analysis and their application	*129*
Figure 5.3-A. The number of fatalities in the USA between 2010 and 2019, for different sectors of the transportation system (Turbli, 2022)	*131*
Figure 5.3-B. The number of fatalities per billion passenger miles and hours in the USA between 2010 and 2019, for different sectors of the transportation system (Turbli, 2022)	*132*
Figure 5.4. Research methodology for safety-related data analysis	*136*
Figure 5.6. Outline of the process of data quality assessment	*145*
Figure 5.7. Research onion of this thesis, based on Saunders et al. (2019)	*152*
Figure 6.1-A. Methodology used for the analysis of factors underlying safety at ports in the United Kingdom	*155*
Figure 6.1-B. AIS data obtained from the UK government for the port of Liverpool (Majumdar, Manole and Sinobas, 2024).	*159*
Figure 6.1-C. Screenshot of the RNLI website showing statistics for 2019-2023 (RNLI, 2024)	*160*
Figure 6.1-D. The studied contributory factors for safety-related maritime occurrences in the United Kingdom	*161*

Figure 6.1-E. Number of ship casualties per year, for different occurrence severities 166

Figure 6.1-F. Number of ship casualties per year, for different accident types 167

Figure 6.1-G. Distribution of accident types 167

Figure 6.1-H. Number of ship casualties per year, for different vessel types 168

Figure 6.1-I. Distribution of vessel types 168

Figure 6.1-J. Distribution of SC for different locations and seasons 169

Figure 6.1-K. Distribution of different environmental conditions. 170

Figure 6.1-L. Variation of different severity levels for occupational accidents between 2013-2022 172

Figure 6.1-M. Three-way associations with 95% confidence level for ship casualties according to their p and phi values 176

Figure 6.1-N. Heatmap of the three-way associations with 99% confidence level, for ship casualties 177

Figure 6.1-O. Traffic densest areas in the UK and all maritime accidents (Manole, Majumdar and Garcia Sinobas) 181

Figure 6.1-P. Vessel Traffic Densities in the 12 UK ports considered (Manole, Majumdar and Garcia Sinobas) 182

Figure 6.1-Q. Accident to Traffic density metrics for the 12 UK ports considered (Manole, Majumdar and Garcia Sinobas) 183

Figure 6.1-R. Vessel Traffic in the 12 UK ports considered (Manole, Majumdar and Garcia Sinobas) 183

Figure 6.1-S. Prior probabilities of the variables considered 192

Figure 6.2-A. Methodology on the case study assessing potential impacts of autonomous vessels 201

Figure 6.2-B. Appointment and level of experience of OOW 207

Figure 6.2-C. Thematic qualitative analysis outline (Erlingsson and Brysiewicz, 2017) 210

Figure 6.2-D. Main steps of qualitative research (Bryman, 2016) 210

Figure 6.2-E. Main themes of the qualitative analysis of maritime professionals regarding expected implications of the introduction of autonomous vessels 212

Figure 6.2-F Main positive and negative aspects of autonomous vessels expected after their introduction in the future 216

Figure 6.3-A. Main results of the analysis of piracy occurrences in West Africa and the Gulf of Guinea, for different levels of severity 219

Figure 6.3-B. Accident characteristics compiled in dataset, using the IMO database and narratives 220

Figure 7.2. Methodology used for the aviation case study of seaplane accidents and incidents in 227

Canada

Figure 7.5-A. Number of seaplane occurrences per year, for all seaplane occurrences vs for only private, recreational operations *238*

Figure 7.5-B. Number of seaplane occurrences per year in the United States of America (Ison, 2024) *239*

Figure 7.5-C. Number of injuries and fatalities per year, for private, recreational seaplane operations in Canada *239*

Figure 7.5-D. Number of occurrences per year for private, recreational seaplane operations using amateur built aircraft, in Canada *240*

Figure 7.5-E. Aircraft damage level per year, for private, recreational seaplane operations in Canada *241*

Figure 7.5-F. Number of destroyed aircraft per year, for private, recreational seaplane operations in Canada *241*

Figure 7.5-G. Number of occurrences during the top 5 phases of flight, for private, recreational seaplane operations in Canada *242*

Figure 7.5-H. Phases of flight for occurrences of recreational GA seaplanes with different landing gear *242*

Figure 7.5-I. Number of occurrences for different categorisation, per different landing gear, for private, recreational seaplane operations in Canada *243*

Figure 7.5-J. Number of occurrences per year, for Take-Off, Climb and Landing, for private, recreational seaplane operations in Canada *244*

Figure 7.5-K. Number of injuries and fatalities per year, for private, recreational seaplane operations in Canada *246*

Figure 7.5-L. Heatmap of the three-way associations for 99% confidence level *248*

Figure 8.7-A. Distribution of the age groups of the participants *263*

Figure 8.7-B. Distribution of the years of experience flying of the participants *264*

Figure 8.7-C. Distribution of the years of experience flying seaplanes of the participants *264*

Figure 8.7-D. Distribution of the number of hours flying a seaplane of the participants *265*

Figure 8.7-E. The types of seaplane training completed by the participants *265*

Figure 8.7-F. The last time a safety course/training related to seaplane operations was completed by the participants *266*

Figure 8.7-G. The best methods of promoting safety and bringing awareness on current seaplane safety issues, according to the participants *267*

Figure 8.8-A. Themes from interviews, focus groups and questionnaire with seaplane industry operators and other professionals *268*

Figure 8.8-B. Training issues 269

Figure 8.8-C. Proficiency and currency 270

Figure 8.8-D. Technological reliance 271

Figure 8.8-E. Hazards of boats and ski jets 271

Figure 8.8-F. Misuse of radios 272

Figure 8.8-G. Improved regulatory and infrastructure support for GA seaplane pilots 273

Figure 8.8-H. Environmental awareness 274

Figure 8.8-I. Mechanical reliability 274

Figure 8.8-J. Safety practices and procedures 275

Figure 8.8-K. Community engagement 276

Figure 8.8-L. Other concerns specific for phases of flight 276

Figure 9.1-A. Main data categories and contributory factors relevant for studying safety occurrences in the transport industry 286

Figure 9.1-B. Main categories of factors relevant for studying safety occurrences in the transport industry 287

Figure 9.1-C: Level of information available in a database (Rao and Marais, 2018). 295

Figure 9.3. Proposed framework for safety data analysis for achieving a holistic understanding of accident causation patterns, while addressing all pillars of the SMS. 304

List of tables

Table 1. Publications during this PhD research	*22*
Table 2.7. Examples of human factors with related publications.	*59*
Table 3. 2. Classification of ports according to different classification methods	*65*
Table 3.3-A. Accident types with descriptions (Manole, 2019) - adapted from (EMSA, 2017)	*69*
Table 3.3-B. Vessel types, according to MAIB definitions (MAIB, 2020b).	*69*
Table 3.4. Description of the stakeholders involved in port activities in the United Kingdom	*71*
Table 3.5. Summary of the literature review on critical factors affecting the safety of vessels transiting ports and the people on board, specific for ship casualties and occupational accidents	*80*
Table 3.6. Publications using different data-driven methods (adapted from Yang et. al., 2024).	*82*
Table 3.9. Summary of the main topics considered in Chapter 3	*91*
Table 4.1. Summary of definitions used for General Aviation	*92*
Table 4.2. Types of seaplanes according to different classification methods.	*97*
Table 4.3. Grouping of CICTT Occurrence Categories (CICTT, 2011).	*107*
Table 4.4. Summarises of the stakeholders for recreational GA seaplane operations in Canada	*111*
Table 5.1. Philosophical debates for: Mixed methods, qualitative and quantitative approach (Mkansi and Acheampong, 2012)	*123*
Table 5.2. The main differences between quantitative and qualitative methods of analysis	*128*
Table 5.5. Description and use of different data sources	*139*
Table 5.6. Data quality dimensions	*146*
Table 6.1-A. The categories and relevant data fields obtained from the Marine Accident Investigation Branch of the United Kingdom	*156*
Table 6.1-B. Redefined vessel categories consistent for both the MAIB and AIS data sources	*162*
Table 6.1-C. Results of the Data Quality Assessment for maritime occurrences in UK ports	*162*
Table 6.1-D. Interpretation of Phi value (Plummer, 2014)	*165*
Table 6.1-E. Parameters used to test for three-way associations, for SC	*175*
Table 6.1-F. AIS and MAIB samples and variables used	*180*
Table 6.1-G. Binary Logit Models performed	*181*
Table 6.1-H. Attributes found after maximum likelihood estimation	*186*

Table 6.1-I. Accuracy of both models *187*

Table 6.1-J. Accident probabilities for Model I *187*

Table 6.1-K. Accident probabilities for Model II *188*

Table 6.1-L. Main results for all variables, highlighting the highest increases in the posterior probability compared to the prior probability (in bold) *193*

Table 6.1-M. Summary of the main findings for each parameter included in the analysis using Bayesian Networks *195*

Table 6.2-A. Data fields extracted from MAIB investigation reports *203*

Table 6.2-B. Data quality assessment results *302*

Table 6.2-C. Human errors, counted for different severity levels *206*

Table 6.2-D. List of interviewed participants *211*

Table 6.2-E. Qualitative analysis discussion using quotes and links to relevant literature, regarding expected implications of the introduction of autonomous vessels *212*

Table 6.2-F. Expected positive and negative impact of autonomous vessels *216*

Table 6.3-A. Main factors driving piracy in West Africa and the Gulf of Guinea *218*

Table 6.4-A. Main findings for the analysis of safety data for marine casualties and incidents in UK ports *223*

Table 6.4-B. Main findings for the analysis of safety data for the expected impact of autonomous vessels on the safety of ports *225*

Table 6.4-C. Main findings for the analysis of safety data for piracy occurrences, using IMO data from investigation reports *225*

Table 7.3-A. Data fields of seaplane occurrences obtained from Transport Canada, compared to the desired information for the analysis (ideal data fields) *228*

Table 7.3-B: Results of the Data Quality Assessment for private, recreational seaplane occurrences in Canada *231*

Table 7.4. Categorisation of private, recreational seaplane occurrences in Canada, from 1990 to 2022 *234*

Table 7.5-A. Description of the accident / incident dataset for private, recreational seaplanes, and types of analysis employed *236*

Table 7.5-B. Parameters used to test for three-way associations *247*

Table 7.6. Main findings for the analysis of accident and incident data for private, recreational seaplanes in Canada *251*

Table 8.5. The number of participants for the interviews, focus groups and online questionnaire *259*

List of abbreviations

ABP	Association of British Ports
ADRM	Aerodrome
AI	Artificial Intelligence
AIS	Automatic Identification System
AMAN	Abrupt Manoeuvre
ANAC	National Civil Aviation Agency
AOPA	Aircraft Owners and Pilots Association
ARC	Abnormal Runway Contact
ARPA	Automatic Radar Plotting Aid
ATAC	Air Transport Association of Canada
AV	Autonomous Vessel
BN	Bayesian Networks
BPA	British Ports Association
CAA	Civil Aviation Authority
CAAC	Civil Aviation Administration of China
CABIN	Cabin Safety Events
CADORS	Civil Aviation Daily Occurrence Reporting System
CARs	Canadian Aviation Regulations
CASA	Civil Aviation Safety Authority
CCTV	Closed-circuit television
CFIT	Controlled Flight Into/Toward Terrain
CGAJSC	Canadian General Aviation Joint Safety Committee
CHIRP	Confidential Human Factors Incident Reporting Programme
CN	Complex Networks
COPA	Canadian Owners and Pilots Association
CPT	Conditional Probability Table

CSTS	Complex socio-technical systems
CTOL	Collision with Obstacle(s) During Take-off and Landing
DQA	Data Quality Assessment
DfT	Department for Transport
ECDIS	Electronic Charts Display and Information Systems
EXTL	External Load Related Occurrences
FBO	Fixed-Base Operators
FUEL	Fuel Related
HSE	Health and Safety Executive
HFACS	Human Factors Analysis and Classification System
EAA	Experimental Aircraft Association
EASA	European Union Aviation Safety Agency
EC	European Commission
ELT	Emergency Locator Transmitter
EMSA	European Maritime Safety Agency
EU	European Union
EVAC	Evacuation
FAA	Federal Aviation Administration
FTU	Flight Training Units
F-NI	Fire/Smoke (Non-Impact)
F-POST	Fire/Smoke (Post-Impact)
GA	General Aviation
GAJSC	General Aviation Joint Safety Committee
GASP	General Aviation Safety Program
GCOL	Ground Collision
GISIS	Global Integrated Shipping Information System
GPS	Global Positioning System

GT	Gross Tonnage
GTOW	Glider Towing Related Events
HSE	Health and Safety Executive
IAOPA	International Council of Aircraft Owner and Pilot Associations
ICAO	International Civil Aviation Organisation
ICE	Icing
IEA	International Ergonomics Association
IMO	International Maritime Organisation
INS	Integrated Navigation Systems
ISM	International Safety Management
LALT	Low Altitude Operations
LOC-G	Loss of Control – Ground
LOC-I	Loss of Control – Inflight
LOLI	Loss of Lifting Conditions En-route
LSCI	Liner Shipping Connectivity Index
MAIB	Marine Accident Investigation Branch
MARPOL	Marine Pollution
MARS	Mariners' Alerting and Reporting Scheme
MCA	Maritime and Coastguard Agency
MMO	Marine Management Organisation
MoUs	Memoranda of Understanding
MSC	Maritime Safety Committee
MUNIN	Maritime Unmanned Navigation Through Intelligence Network
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
OA	Occupational Accidents
OOW	Officer of the Watch

OTHR	Other
PFD	Personal Flotation Device
PMSC	Port Marine Safety Code
PPE	Personal protective equipment
PSC	Port State Control
RAMP	Ground Handling
RE	Runway Excursion
RIFs	Risk Influential Factors
RI-A	Runway Incursion – Animal
RI-VAP	Runway Incursion – Vehicle, Aircraft or Person
RNLI	Royal National Lifeboat Institution
SC	Ship Casualties
SCF-NP	System/Component Failure or Malfunction (Non-Powerplant)
SCF-PP	System/Component Failure or Malfunction (Powerplant)
SEC	Security Related
SM ICG	Safety Management International Collaboration Group
SMS	Safety Management Systems
SOLAS	Safety of Life at Sea
SPA	Seaplane Pilot Association
SPWG	Seaplane Working Group
SRM	Safety Risk Management
SSP	State Safety Programs
STAMP	Systems Theoretic Accident Model and Processes
STCW	Standards of Training, Certification, and Watchkeeping for Seafarers
STPA	Systems Theoretic Process Analysis
STS	Socio-Technical Systems
SWOT	Strengths, Weaknesses, Opportunities, Threats

TC	Transport Canada
TCCA	Transport Canada Civil Aviation
TRB	Transportation Research Board
TSB	Transport Safety Board
TSM	Traditional Safety Management
TURB	Turbulence Encounter
UIMC	Unintended Flight in IMC
UK	United Kingdom
UNK	Unknown or Undetermined
USA	United States of America
USOS	Undershoot/Overshoot
VTS	Vessel traffic services
WSTRW	Wind Shear or Thunderstorm

Conferences and publications

This thesis will reference a series of publications which are either completed or under review. These are presented in Table 1.

Table 1. Publications during this PhD research.

Paper No.	Title	Type	Journal / Conference	Submission status	Chapter / Section
1	Analysis of Port Accidents and Calibration of Heinrich's Pyramid	Conference / Journal	Transportation Research Board Annual Meeting 2021 & Transportation Research Record	Complete, Published	Section 2.5
2	Data quality assessment framework of safety data. An example from aviation, maritime and railways	Journal	Safety Science	Submission	Section 5.6
3	How safe are the United Kingdom's ports? A statistical analysis using accident and AIS data	Journal	Journal of Navigation	Complete	Chapter 3 & Section 6.1
4	Investigation of the risk influential factors of maritime accidents: A novel topology and robustness analytical framework	Journal	Journal of Reliability Engineering & System Safety	Complete	Chapter 3 & Section 6.1
5	Assessing the Impact of Autonomous Vessels on the Navigational Safety of Maritime Transport	Conference / Journal	European Conference On Safety And Reliability, 2023	Complete, Published	Chapter 3 & Section 6.2
6	Analysis of Maritime Piracy in West Africa and the Gulf of Guinea	Conference	Transportation Research Board Annual Meeting 2023	Complete	Chapter 3 & Section 6.3
7	Analysis of factors underlying seaplane occurrences in Canada	Newsletter	Canadian Owners and Pilots Association Newsletters	Submission	Chapters 7 & 8
8	Analysis of factors underlying seaplane occurrences in Canada	Journal		In progress	Chapters 4 & 7
9	Addressing safety concerns of private, recreational seaplane pilots in Canada	Journal		In progress	Chapter 8

1. Introduction

This chapter aims to set the context for the research presented in this PhD thesis by firstly introducing the need to manage and enhance transport safety, focusing on the maritime and aviation sectors. By investigating transport safety, this thesis aims to develop a comprehensive safety management framework that mitigates risks, prevent accidents, and ultimately saves lives, goods, and the environment. Then, this chapter outlines the motivation for this PhD thesis, along with the aim and objectives of this research. This establishes the rationale and steps taken for the development of a new framework for a holistic understanding of accident causation patterns in the transportation field, aiming to enhance transport safety through mixed methods of data analysis. This is followed by a summary of the structure of this thesis.

1.1. Background

A natural or manmade hazard "has the potential to cause harm, injury or damage to individuals, equipment or operations" (DfT, 2016a). Therefore, reducing the likelihood and impact of hazards and mitigating associated risks are primary objectives of transport safety, focusing on protecting people's lives, goods, and the environment. This can be achieved through a systematic hazard and risk analysis. However, it is often the case that only occurrences resulting in a certain level of harm or that occur in specific circumstances are being actively reported, and the majority of these do not lead to a detailed investigation which limits the understanding of contributing factors. Moreover, data of factors that may have contributed to the accident (e.g., environmental, mechanical, information about the people involved, etc.) may not always be publicly available or may need to be obtained from extensive accident reports, which is a time-consuming process and, often, the information extracted is not consistent between the reports. Therefore, even though the statistical analysis of accident data allows for fast processing of large amount of data, which leads to easily identifiable patterns, the quality of used data needs to be assessed and the capabilities and limitations of different data sources must be understood and thoroughly addressed.

Another challenge is the increasing complexity of socio-technical systems, such as transport systems, which render traditional safety theories and accident causation models outdated and inadequate for addressing new hazards (Accou & Carpinelli, 2022). While there are various methods to measure and assess safety, they often only assess a part of the complicated picture of safety. For example, quantitative safety measures often ignore narratives of accidents which can contain much detail on causal factors. Moreover, choosing one method, accident model or safety approach is insufficient for a comprehensive safety analysis. In general, drawing conclusions simply by analysing previous accident reports often provides limited insight into what actually happened and, taking into account

already mentioned limitations of safety data, the results are likely to not fully represent reality. Therefore, comprehensive safety analysis necessitates a mixed-methods approach that incorporates both quantitative and qualitative factors. However, there is no acceptable, robust method employing mixed methods for safety analysis.

It is important to acknowledge the benefits of learning from both what goes well and what goes wrong, and having insights from different countries and even different industries can significantly enhance the understanding of the big picture of safety. This thesis includes case studies from both the maritime and aviation sectors, integrating different data sources to propose a framework that is adaptable to other transport modes and industries. These two sectors, with specific case studies that will be introduced later on in this thesis, have been chosen due to their innovation, lack of studies on the specific sectors, unexpected rising or fluctuating accident rates in recent years, or very little decrease in accident rated despite work already being done to enhance safety. The modelling of the framework using niche case studies proves that it can be used even when data is of lower quantity and quality. This not only adds value to these less researched sectors, but it also proves the versatility of the framework. This holistic approach aids in identifying learning points across different industries regarding data reporting, collection, and analysis. It also has the potential to enhance safety knowledge sharing and awareness within organisations with different perceptions of safety management, risk assessment, and safety culture.

The maritime industry is that it is considered the most complex and dangerous worldwide (Zhang et al., 2021). Additionally, the United Kingdom has extensive maritime history and numerous significant ports, with the second largest maritime industry in Europe. Choosing ports as a focus to study maritime safety is crucial due to their role in providing a protective refuge for vessels, facilitating the transfer of people and goods, promoting trade and economic growth, and serving as significant sources of employment. In particular, ports represent dynamic environments with a complex set of safety challenges.

In complex socio-technical systems, the safety issues of smaller communities within a transport sector can often be overlooked. General safety measures designed for larger communities or sectors may not be effective for smaller ones, so tailored safety strategies are necessary to address their unique challenges. For example, seaplane operations are part of both aviation and maritime sectors and require specific safety measures due to their dual operational environments. Additionally, safety in commercial operations is more thoroughly addressed due to higher scrutiny and regulations needed to protect larger passenger and cargo volumes. In contrast, private operations often fall under less rigorous regulatory frameworks, with fewer mandatory safety measures and oversight, leading to gaps in comprehensive safety standards. Consequently, private pilots may be indirectly affected by

factors less prevalent in commercial aviation, such as less rigorous training and infrequent flying. Given the unique risks associated with recreational seaplane flying, such as varying pilot experience and diverse operating environments, thorough sector-specific analysis is imperative. Analysing subsets of occurrences is crucial to understand and address specific challenges for underrepresented communities in a transport sector. This approach aids in identifying specific safety issues and formulating targeted recommendations to enhance overall safety in complex transport systems.

To address the above limitations, this thesis proposes a framework for achieving a holistic understanding of transport safety not only through data collection and analysis, but also through understanding the importance of minor incidents or near-misses and their reporting, the knowledge and expertise of different stakeholders and industry professionals, and finally assessing how organisational aspects come into play and share safety knowledge. This thesis uses hybrid methods of analysis (quantitative/qualitative and reactive/proactive/predictive) to better understand accident causation factors and limitations of different types and sources of accident data. This thesis is unique because it aims to break the boundaries between different transport sectors and considers mixed methods of analysis. It ultimately achieves a more complete view of accident causation patterns, possible methods of analysis for different types of data and additional considerations aside from accident data analysis.

1.2. Problem statement and challenges

Safety Management Systems (SMS) play a crucial role in managing risks across various transport sectors. However, their implementation is often tailored to mainstream transport operations, such as commercial aviation and large-scale maritime shipping. In these sectors, safety management benefits from extensive regulatory oversight, well-established reporting mechanisms and comprehensive databases. Aviation SMS, for instance, primarily focuses on commercial air transport, where safety procedures are highly structured, standardised and data-rich. Similarly, maritime SMS largely address conventional risks associated with cargo shipping, such as vessel collisions, environmental conditions, and mechanical failures. These mainstream applications ensure that hazards are well-documented and mitigated through established procedures and regulatory frameworks.

This study diverges from traditional SMS research by focusing on niche transport operations, which are often less regulated, have limited oversight, and suffer from data scarcity. Mainstream transport safety refers to well-documented and highly regulated sectors such as commercial airlines and cargo shipping, where accidents and risks are meticulously recorded and analysed. In contrast, niche transport safety pertains to sectors where operations fall outside of these standardised frameworks. Examples include occupational accidents on vessels, the impact of emerging technologies such as

autonomous systems, and private or recreational transport operations that lack stringent regulatory enforcement. These niche cases often fall into regulatory gaps, leading to underreporting of incidents and a lack of structured safety interventions.

One of the major challenges in SMS for niche transport operations is data collection and reporting. Unlike commercial air transport, where occurrences are thoroughly documented due to strict regulatory mandates, smaller-scale operations such as private seaplane flying face significant reporting inconsistencies. In the maritime sector, reports are often only required for serious incidents, leading to substantial underreporting of minor but potentially significant occurrences. This limitation affects the ability to conduct comprehensive risk assessments and develop evidence-based safety interventions. Additionally, the four pillars of SMS (Safety Policy, Risk Management, Safety Assurance and Safety Promotion) are more difficult to implement in niche transport operations. In commercial settings, these pillars are reinforced by continuous oversight from regulatory bodies. In niche sectors, however, operators may lack the resources or incentives to develop robust safety cultures. Private operators, for example, often operate outside of structured safety policies, making it challenging to implement formal risk management frameworks.

A key objective of this study is to explore how SMS can be adapted to niche transport environments by overcoming these challenges. A holistic approach is necessary to bridge the gap between mainstream and niche safety management, ensuring that all transport sectors benefit from structured safety analysis. This study, therefore, investigates how tailored data collection methods, stakeholder engagement, and a combination of reactive, proactive and predictive safety measures can enhance safety in less-regulated domains. By considering underrepresented transport sectors, this research provides a more inclusive view of SMS effectiveness, identifying strategies to improve safety even in environments where traditional regulatory approaches are insufficient.

1.3. Aim and objectives

Given the background presented in the previous section, the decision to focus on transport safety within this PhD research is driven by a profound commitment to enhancing the safety of transport systems, since they lead to numerous deaths, injuries, damage and significant costs worldwide. Additionally, the transport sector's increasing complexity and the limitations of traditional safety models in addressing contemporary hazards underscore the need for innovative safety frameworks.

The research question to be addressed in this thesis has been formulated:

"How can transport safety be enhanced through data analysis to reduce the number of accidents, incidents, and associated lives lost, injuries and property damage?".

Therefore, the aim of this PhD thesis is to develop a robust, versatile framework to improve transport safety management, which can be applied to different transport sectors. To achieve this aim, six research objectives have been formulated.

- Review the role of data and its collection in Safety Management Systems (SMS) in transport.
- Assess the strengths, weaknesses and limitations of current methods of safety data analysis.
- Establish appropriate indicators of data quality using different data quality dimensions, and propose a framework for the quality assessment of accident data.
- Develop and implement a methodology for a holistic understanding of accident causation patterns using data analysis.
- Identify the limitations of current databases and assess additional information requirements.
- Propose a framework which uses multiple sources of safety data and methods of analysis to improve safety in transport operations through SMS, which is generic for different data sources and even transport sectors.

1.4. Thesis outline

This thesis is organised in ten chapters, as detailed below.

Chapter 2 provides essential background information and definitions useful for understanding the complex socio-technical system of transport and its safety. It reviews different aspects of safety, such as hazards, risks, SMS, safety approaches and accident models, which will be used in subsequent chapters. Then, it includes a case study where Heinrich's Pyramid is used as an example of a theory that includes the basis of the SMS to assess the role of data and to check whether such a theory is suitable for transport occurrences. This contributes towards meeting the first objective of this thesis.

Chapters 3 and 4 provide theoretical foundations for the maritime and aviation sectors, respectively, and how they integrate safety. They include systematic reviews of specialised literature to identify risk factors, as well as advantages and limitations of different methods of analysis employed in the two fields. These chapters focus on the management of safety in maritime and aviation, setting the scope of the research objectives within SMS. Data types and sources used in previous safety studies are highlighted and their limitations are emphasised. Additionally, these chapters include specific literature reviews for the maritime and aviation case studies, which are categorised into sub-topics to facilitate a deep dive into low-level qualitative research questions. The topics include port safety and congestion, autonomous vessels, and general aviation seaplane safety focusing on private, recreational operations. Overall, these chapters set the context for the development of a robust methodology in Chapter 5, and for the case studies in Chapters 6-8.

Taking into account the literature review findings, Chapter 5 reviews the research methodology and philosophy used in this thesis towards achieving the answer to the previously defined research question. Two frameworks are proposed, one for data analysis using mixed data sources and methods, and one for data quality assessment (DQA) tailored for accident and incident data.

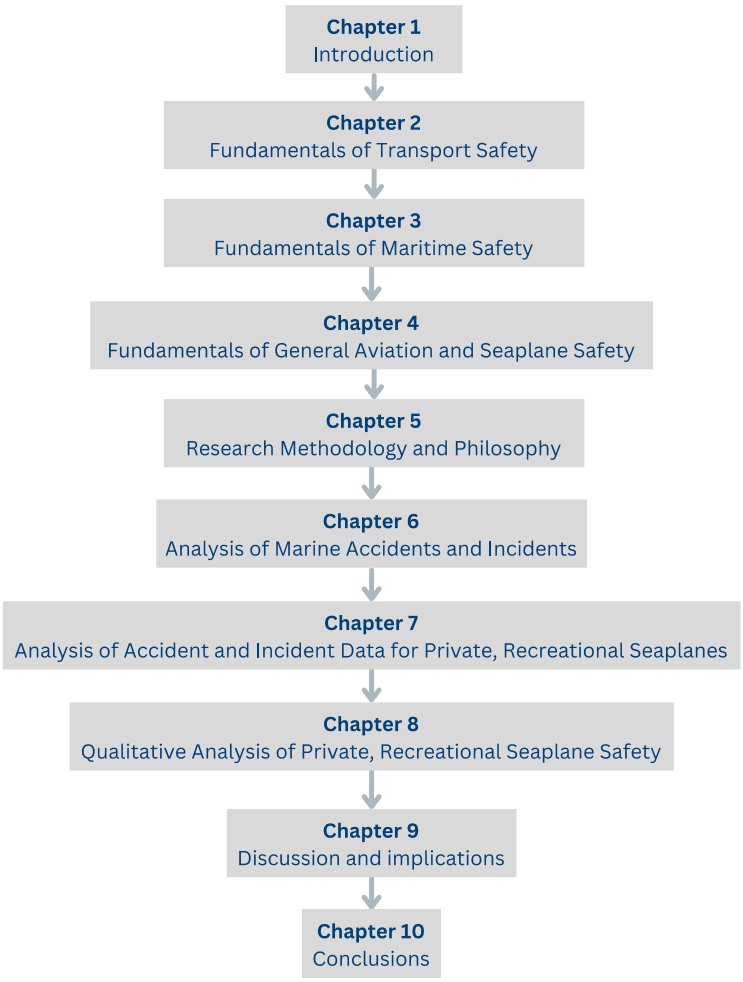
Chapters 6 and 7 demonstrate the application of the proposed frameworks, using different safety approaches. This is accomplished through four case studies that address different safety aspects through the processing, integration and analysis of different data sources, emphasising on their capabilities.

Based on previous research of factors underlying safety in the transport sector, ideal datasets have been developed, tailored for the particularities of each case study to provide a reference for the DQA. Based on the DQA results of different data sources, as well as data limitations mentioned in the literature review where other databases were used, none is determined to be of sufficient quality to be able to address the complexity of transport safety and fully benefit from the proposed framework for data analysis. Therefore, Chapter 8 builds on the previous quantitative-dominant analysis and aims to diminish the data gaps by addressing safety through a different, qualitative-oriented perspective.

Chapter 9 discusses in turn the requirements of the proposed frameworks and their applicability to the transport sector, including the challenges that have been faced. This chapter demonstrates the versatility of these novel frameworks and integrates them into a conceptual framework applicable for the diverse needs of different sectors of the transportation industry and tailored to account for comprehensive safety analyses using available data sources of varying-quality.

This thesis ends with Chapter 10 which reviews the met objectives, providing conclusions achieved throughout this thesis and suggesting areas for future work. and summarised in Figure 1.3. Figure 1.3 outlines the overall structure of this thesis.

Figure 1.3. Overview of the thesis structure.



2. Fundamentals of Transport Safety

This chapter provides essential background information and definitions useful for understanding the complex socio-technical system of transport and its safety. Firstly, the literature on transport safety is comprehensively reviewed across different modes of transport to offer a holistic understanding of safety background and approaches used within the transport sector. Then, after comparing different accident models, the role of data and its collection in Safety Management Systems in transport is assessed. This contributes towards meeting the first objective of this thesis outlined in Chapter 1. Other relevant aspects are introduced in this chapter, such as human performance and the water environment. Detailed classifications and specific definitions related to the maritime and aviation sectors are elaborated in Chapters 3 and 4, respectively.

2.1. Fundamentals of safety management

This section discusses the concepts of safety and risk and reflects on the definitions used in the transport sector. Safety reporting is discussed, along with the requirements for occurrence investigations and how these differ from occurrence data sets. The concept of safety culture is also introduced.

2.1.1. The concept of Safety

Safety is defined as "*a state in which or a place where you are safe and not in danger or at risk*" (Cambridge University Press, 2020). Although the ultimate aim of transport safety is to eliminate accidents and serious incidents, it is acknowledged that the hazards and associated risks cannot be completely eliminated. Since human activities and systems cannot be completely free from operational errors and their consequences, safety must be viewed as a dynamic attribute of the transport systems, requiring continuous risk mitigation. The levels at which risks are considered at an acceptable level is often shaped by both domestic and international standards and culture.

Different transport organisations develop their own definitions for safety, to reflect their operations. Generally, these define safety as the minimisation of risk of injury to individuals or damage to property, within acceptable limits. This is achieved through continuous hazard identification and safety risk management processes. For example, the International Civil Aviation Organisation (ICAO) defines safety as "*the state in which risks associated with aviation activities, related to, or in direct support of the operation of aircraft, are reduced and controlled to an acceptable level*" (ICAO, 2013). In the maritime sector, the International Maritime Organisation (IMO) uses a similar definition for safety. International transport organisations such as the ICAO for aviation and the IMO for maritime

develop regulations and strategies recommended for all member states. These have the aim to standardise definitions and regulations, and promote safety communication beyond borders.

Safety views have evolved over the years, starting with focusing on the investigation and improvement of technical factors and technological errors (1900s to mid 1960s). By the 1950s, technological advancements and regulatory oversight led to a decline in accidents. Then, the second era (early 1970s to mid 1990s) shifted towards understanding the role of human factors and the man-machine interface in accidents, although this initially focused on individual performance without fully considering the operational context. The third era (mid 1990s to present) introduced a systemic perspective, incorporating organisational factors and the concept of "organisational accidents". This era recognises the impact of safety culture and it emphasises a proactive approach to safety management, in addition routine data collection and analysis to monitor and mitigate safety risks (ICAO, 2013).

2.1.2. The concepts of hazard and risk

Identifying hazards is fundamental to the process of managing safety risks. Misunderstanding the differences between hazards and safety risks can lead to confusion. It is crucial to identify and understand hazards and their link to risk management.

Hazards exist at all organisational levels and can be identified through reporting systems, inspections, or audits. A voluntary reporting system is crucial for proactive hazard identification, however these are yet to reach their full potential for less serious incidents and near misses. Reviewing investigation reports can also highlight unaddressed hazards, especially in organisations with less mature safety cultures (ICAO, 2013). Methods to identify hazards include reactive, proactive and predictive approaches, which are discussed in Section 2.3.

A natural or manmade hazard “has the potential to cause harm, injury or damage to individuals, equipment or operations” (DfT, 2016a). Therefore, hazard identification, risk evaluation, consideration of precautions, monitoring, reviewing and recording are vital in the risk management process of all industries, being a precursor to an effective risk assessment. However, only hazards that cause harm in specific situations and circumstances are usually reported. Hazards are unique for every industry and system and, thus, for every port/airport of operations, so the analysis of hazards should be performed locally at a regular basis (DfT, 2016; DfT, 2016a; Kristiansen, 2005).

A categorical list of maritime hazards for UK ports has not been established (Fransas, 2012). Major ports, such as Southampton and London, keep updated databases of hazards that have been identified around their port area, but they may remove certain hazards from their lists if their frequency decreases and they are assumed non-dangerous in the future (Port of London Authority, 2019).

Usually, maritime hazards are identified through statistically analysing past accidents and their underlying causes and factors and through interviews (HSE, 2001).

In the aviation sector, there are numerous types of operations, human operators, tasks, environmental factors etc. that can cause harm. However, there are multiple hazard definitions across stakeholders, but most define a hazard as something with the potential to cause harm. ICAO's SMS manual defines a hazard as being "*generally defined by safety practitioners as a condition or an object with the potential to cause death, injuries to personnel, damage to equipment, loss of material, or reduction of the ability to perform a prescribed function. For the purpose of aviation safety risk management, the term hazard should be focused on those conditions which could cause or contribute to unsafe operation of aircraft or aviation safety-related equipment, product and services*", while an error is "*a normal and unavoidable component of human performance*" (ICAO, 2013).

Having looked at the specifications for the maritime and aviation sectors, in the bigger context of transport safety risk management, hazards can then be defined as conditions that could lead to unsafe vehicle operations or impact people, equipment, products, and services. As previously mentioned, hazards are inherent, but their effects can be mitigated. Furthermore, it is important to distinguish between a hazard and its consequences. For instance, a loss of control of a vehicle is a consequence of the hazard of strong winds or unpredictable weather. Hence, effective hazard identification helps predict and manage possible outcomes.

A risk is a possibility of something bad happening, that can lead to either loss or injury. Hollnagel (2008) defines risk as the statistical relationship between the likelihood of occurrence of an undesired event and its severity or predisposition to cause harm. Risk assessment in transport industries is of great importance due to the complexity of the socio-technical systems involved and the uncertainty in the environmental and surrounding conditions, at every moment in time and space. Hence, the different bodies involved at either international, national or local levels (e.g. ports/airports) must identify, measure and mitigate (if possible) all the risks identified within the system.

For example, ports vary in size and number of movements, which can affect the way they measure risks. A small port can have less to no exposure to certain types of accidents, because of the small number of movements within it. However, this does not mean that there is no risk for those accidents and, thus, they should be accounted for. Therefore, it is important to study risks at a higher level, such as nationally or internationally, as well as learn from other similar environments or different countries, rather than focus on past accidents and incidents at a specific location only.

2.1.3. Safety reporting and investigation

Effective safety management relies on the accurate and prompt reporting of hazards, incidents, and accidents. Data supporting safety analysis come from multiple sources, with direct reporting by frontline personnel being particularly valuable. A culture where staff are trained and encouraged to report errors and observations is essential for robust safety reporting, which is detailed in Section 2.1.4.

Reporting hazards is a vital element of safety management. This data is then analysed alongside other data sources in order to manage the associated risks. Occurrence reporting, ranging from serious accidents to minor incidents, are another method of data collection used for safety management. While mandatory reporting of the more serious events is standard in all transport sectors, a mature safety environment should include the reporting of less serious events and near-misses to monitor potential risks effectively (ICAO, 2013).

Investigations of specific occurrences are triggered by accident severity among other metrics, and are used to identify critical system failures and develop preventive measures. These investigations not only determine root causes but also identify associated hazards and threats, as well as direct causes and systemic or organisational factors (ICAO, 2013). The aim of these investigations is to ensure that future similar occurrences are prevented, but an investigation isn't launched after every occurrence, or even serious accident. Therefore, although these reports are much more detailed than usual occurrence databases, they are not a representative sample of reality. The limitations of analysing such investigation reports are addressed in Chapters 5 and 9.

2.1.4. Safety culture

Safety culture comprises of people's views on how the organisation approaches safety, which makes it an undeniable contributor to maritime safety. It is therefore highly important to establish a positive organisational safety culture, so that an atmosphere of trust can be created throughout all the levels of an organisation, from operational employees to the organisation's management. The constant desire to promote safety culture should be achieved through a non-punitive environment and an atmosphere of trust (Nalty, 2017). For maritime operations, a tool was created to assess human reliability by analysing the way people react to different work environments (Rashed, 2016).

Safety culture has a considerable impact on transport safety, since it determines how safety is perceived by everyone involved in this system. "Safety culture is the attitudes, beliefs, perceptions and values that employees share in relation to safety in the workplace […] Everything to do with shipping has to have an element of safety culture" (Birkett, 2022). The way safety culture is perceived in different transport modes varies. For example, the maritime industry is increasing their focus on

safety culture, and it recognises its importance in all shipping companies, as a collective concern for safety. This is crucial since it is believed that some managers or owners choose to ignore eminent problems in the safety culture and hide the truth from the public reports (Birkett, 2022). For instance, companies may seem to implement strict policies towards the consumption of alcohol, but accidents continue to happen because of that reason.

The IMO and the MAIB continuously encourage a 'just' and effective safety culture, and the effective and non-punitive reporting of lower-severity accidents and marine incidents (IMO, 2008a; UK Government, 2022). In this way, organisations can study all the underlying causes of each occurrence and reflect on how a 'just' culture can help prevent them in the future. This will help them learn from their mistakes and continuously improve. They attempted to encourage this by adopting the International Safety Management (ISM) Code in 2010. This code emphasises the importance of incident reporting and it provides a detailed framework for how organisations might effectively establish or improve their safety culture, using safety-related regulations, and identify and assess risks (Ek et. al., 2014).

2.2. Safety Management Systems (SMS) and Risk Assessment

Safety Management Systems (SMS) are structured frameworks for managing safety risks. They are widely used across various industries to ensure compliance with safety regulations and to enhance overall safety performance. This section provides an overview of SMS, focusing on its definitions, evolution, models, and core components. Additionally, it will delve into the pillars of SMS: Policy, Risk Assessment, Safety Assurance, and Safety Promotion.

ICAO (2014) defines a Safety Management System as "*A systematic approach to managing safety, including the necessary organisational structures, accountability, responsibilities, policies and procedures*". SMS emerged from the integration of risk management and safety defence mechanisms, evolving significantly through the incorporation of management theories, safety risk analysis techniques and safety audit tools (Li & Guldenmund, 2018).

SMS models are generally categorised into two groups: accident-related models and organisational models. Accident-related models focus on understanding and preventing specific types of accidents, while organisational models emphasise the integration of safety practices into the overall organisational structure (Li & Guldenmund, 2018).

The core components of SMS are Safety Policy, Safety Risk Management, Safety Assurance and Safety Promotion. These four pillars are described in the following subsections and offer specifications for UK vessels in ports and seaplane operations in Canada, which are case studies used in this thesis (Chapters 6 and 7, respectively).

2.2.1. Safety Policy

Safety policy forms the foundation of SMS by establishing the organisation's commitment to safety. It defines safety objectives, responsibilities, and the framework for managing safety risks. Effective safety policies are critical for aligning organisational practices with safety goals. Furthermore, this pillar ensures that safety is given the highest priority and integrated into all levels of the organisation (Wallen, 1993).

In the United Kingdom, safety policies for ports are designed to address the complex and dynamic nature of port operations. These policies encompass regulations and guidelines such as the Port Marine Safety Code (PMSC), which provides a national standard for port marine safety. The PMSC outlines responsibilities for port operators to ensure safe navigation, prevent accidents and manage emergencies. Safety policies in UK ports include strict protocols for vessel traffic management, handling hazardous materials and ensuring the structural integrity of port infrastructure. These policies are enforced by the Maritime and Coastguard Agency (MCA) to mitigate risks such as collisions, groundings, and spills (UK Department for Transport, 2016b).

In Canada, safety policies for seaplane operations are governed by Transport Canada's regulations, which focus on the unique challenges of operating aircraft in aquatic environments. The Canadian Aviation Regulations (CARs) set stringent requirements for pilot training, aircraft maintenance and operational procedures. Policies include water survival training for pilots, regular maintenance checks for seaplanes and specific operational guidelines such as for take-offs and landings on water bodies. These policies aim to reduce risks such as water collisions and engine failures, ensuring the safety of seaplane operations in Canada (Transport Canada, 2020e).

2.2.2. Safety Risk Management

Risk management involves the identification, analysis, and mitigation of safety risks. Techniques such as Failure Mode, Effects, and Criticality Analysis and the use of Fault and Event Trees are commonly employed to manage risks systematically (Guillerm & Demmou, 2014).

In UK ports, safety risk management involves comprehensive risk assessments to identify potential hazards associated with port operations. These assessments consider factors such as vessel movements, cargo handling and environmental conditions. Mitigation strategies include implementing advanced vessel traffic services (VTS), conducting regular safety drills and enforcing strict compliance with safety protocols. For instance, risks of collisions and groundings are managed through precise navigation aids and real-time monitoring systems. Regular reviews and updates to risk assessments ensure that emerging threats are promptly addressed (UK P&I Club, 2018).

The 2012 Port Marine Safety Code (PMSC) is an approach to safety standards that provides national guidelines for port safety. These must be considered by all Harbour Authorities and other marine bodies involved in the UK, from major ports to smaller marine terminals (DfT 2016; DfT, 2016b). This code offers flexibility and can be applied to any size or type of harbour, according to local requirements. The PMSC requests members to update and maintain a risk assessment of port hazards as part of their SMS. This can be evaluated using "health checks" that are voluntary or requested by the UK MCA (DfT, 2016). UK ports must assess risk severity, levels of acceptance and imposed costs for minimising those risks. Analysis of past accidents is also recommended to Harbour Authorities, to determine potential hazards specific for their facilities (DfT, 2016). The measures contained in the Code are detailed in Appendix A.

In Canadian seaplane operations, safety risk management focuses on the unique risks posed by aquatic environments. Risk assessments identify hazards such as rough water conditions, submerged objects, and weather-related challenges. Mitigation measures include thorough pre-flight inspections, pilot training in water survival techniques and adherence to strict operational guidelines. Additionally, the use of advanced weather forecasting tools helps pilots make informed decisions about flight safety. Continuous monitoring and updating of risk management practices help maintain high safety standards in seaplane operations (MacDonald et. al., 2021).

The risk assessment guidance for the aviation industry in Canada is presented in Appendix B. It focuses on a comprehensive evaluation of transportation occurrences to determine their potential risks and the necessity for further safety actions. The key aspects of the guidance include:

- Historical Context: Assessing whether similar occurrences have happened before or if the incident is isolated.
- Link to TSB Watchlist: Identifying connections to existing TSB Watchlist issues or outstanding recommendations.
- Scope of Impact: Evaluating how widespread the issues might be across equipment, systems, infrastructure, and personnel.
- Usage Frequency: Considering how often the procedures, practices, and equipment involved are used.
- Systemic Issues: Identifying underlying organisational, management, or regulatory issues posing systemic hazards.
- Severity of Consequences: Assessing the potential severity of the occurrence in terms of lives at risk, property damage, environmental impact, impact on commercial operations and public and media perception.

- Value of Safety Lessons: Determining the potential value of the safety lessons that the investigation could yield, including whether the occurrence sheds new light on existing problems or relates to significant or emerging issues of interest.

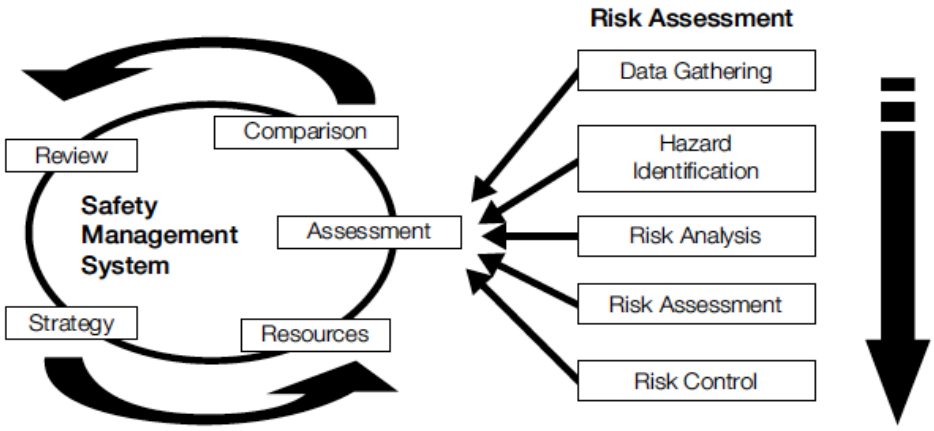
This risk assessment guidance ensures a thorough assessment of risks and impacts and demonstrates a commitment to learning and continuous improvement, but it could be improved by incorporating the following:

1. Prioritisation Framework: While the guidance identifies many factors to consider, it lacks a clear prioritisation framework to help assessors weigh different risks and consequences. Developing a scoring or ranking system could help prioritise investigations more effectively.
2. Targeted guidance: More specific guidance targeting "minorities" in the sectors, such as private operations or specific vessel / aircraft types, adapted to the particular needs of different countries or regions.
3. Stakeholder Engagement: The guidance could be enhanced by including a more explicit focus on engaging stakeholders, such as vehicle operators, in the assessment process, to gather diverse perspectives and increase transparency. This can be particularly useful when certain quantitative data is not available, such as for near-misses, which are not required to be reported in any transport sector, as well as operators' decision making.
4. Feedback Loop: Establishing a feedback loop to review and update the risk assessment criteria based on past experiences and evolving safety landscapes could ensure the guidance remains relevant and effective.
5. Training and Resources: Providing additional training and resources to investigators on how to apply this guidance consistently and effectively could improve the overall quality of risk assessments. Providing additional training resources for vehicle operators with to-dos in certain scenario would also benefit the communities.

In summary, while the risk assessment guidance is thorough and well-structured for different transport sectors, implementing a prioritisation framework, including targeted specifications, enhancing stakeholder engagement, establishing a feedback loop, and offering additional training could further strengthen its effectiveness in advancing transportation safety. These recommendations are explored in subsequent sections (Chapters 6, 7 and 8).

Figure 2.2 shows the different levels of risk assessment and how they fit into SMS.

Figure 2.2. Relationship Between Safety Management System and Risk Assessment (Nalty, 2017).



2.2.3. Safety Assurance

Safety assurance includes processes to ensure that safety risks are managed effectively. This involves monitoring safety performance, conducting safety audits, and ensuring continuous improvement. Performance indicators and worker feedback play crucial roles in this component. Within this pillar, corrective actions based on findings and feedback are implemented (Price & Forrest, 2016).

In UK ports, safety assurance activities include regular audits, inspections, and safety performance reviews, conducted by internal safety teams and external bodies such as the Maritime and Coastguard Agency (MCA). Audits ensure compliance with the Port Marine Safety Code and other relevant regulations. Incident investigations and root cause analyses are carried out to identify systemic issues and implement corrective actions. Safety assurance in UK ports also involves reviewing safety drills and training programs to ensure preparedness for emergencies (MCA, 2016).

In Canada, safety assurance for seaplane operations involves routine inspections and audits conducted by Transport Canada. These inspections cover aircraft maintenance, pilot qualifications and operational procedures. Safety performance is continuously evaluated through incident reporting systems and safety data analysis. Findings from incident investigations are used to refine safety practices and improve training programs. Regular safety audits help ensure that seaplane operators comply with regulatory requirements and maintain high safety standards (Transport Canada, 2020e).

2.2.4. Safety Promotion

Safety promotion aims to enhance the safety culture within the organisation through training, communication, and safety awareness programs. It focuses on promoting safety practices and

ensuring that all employees are engaged in the safety management process. Through this pillar, the reporting of safety issues and methods of continuous improvement are encouraged (Hovden, 1996).

In UK ports, safety promotion involves comprehensive training programs, safety campaigns and regular communication of safety information. Port authorities organise safety workshops and seminars to educate employees about best practices and regulatory requirements. Safety bulletins and newsletters are distributed to keep everyone informed about safety updates and lessons learned from occurrences. Promoting a culture of safety encourages proactive reporting of hazards and fosters a collaborative approach to managing safety (UK Department for Transport, 2016).

For seaplane operations in Canada, safety promotion includes regular training sessions, safety briefings, and dissemination of safety materials. Transport Canada conducts safety workshops and provides resources such as safety manuals and online courses to enhance pilot and crew knowledge. Safety promotion efforts also involve sharing occurrence reports and safety advisories to highlight common risks and preventive measures. Encouraging open communication about safety concerns and fostering a culture of continuous improvement are key aspects of safety promotion in Canadian seaplane operations (MacDonald et. al., 2021).

2.2.5. Conclusions of the SMS review

The available guidance from safety regulations that can improve the organisation's safety management is often overlooked (Valde and Goerlandt, 2018). Risk assessments are used to identify hazards, analyse risks, control risks (aiming to eliminate them or reduce them to a reasonable level) and consider a cost-benefit assessment of risk-reduction measures where appropriate. Accident data is reactive, so it cannot be used alone for developing risk assessments (Niels and Senn, 1995). However, the active reporting of near-misses could give an indication of possible future more serious events. With time, circumstances can change and the safety of the work environment can also also change, so past data becomes outdated (IMO, 2008). Thus, risk assessments should be reviewed periodically and so do the SMS.

After conducting a risk assessment, the SMS must be developed, implemented and maintained. It is used to manage risks and hazards and provides information on emergency preparations, while capturing standard practices to approach different transport operations.

Traditionally, experience and judgement are the basis of risk assessment in ports, which makes them subjective (Rawson and Riding, 2014). Quantifiable analysis is necessary for a rigorous assessment and many policies and other risk mitigation methods were created after disastrous transport accidents worldwide. This is a reactive approach of learning from past accidents in order to reduce the likelihood of reoccurrence. However, these mitigations are developed as a result of a major accident, meaning

that risk assessment and hazard identification have failed. Therefore, mixed quantitative/qualitative or reactive/proactive methods should be preferred, as they can lead to accident prevention before a very serious accident occurs, thus also being cost-effective (Rawson and Riding, 2014). This is also supported by the IMO, which recommends a qualitative and quantitative assessment of risks and hazards, as well as a mathematical and descriptive analysis (IMO, 2007). It should be noted that, at the moment, the proactive approach used in the maritime industry relies on human subjectivity, since decisions for individual ports are made as a result of harbour users' discussion and consultation.

There are limitations associated with expert opinion and people judgement, which are widely discussed in the literature (Rawson and Riding, 2014; Hubbard, 2009; Silver, 2012; Dillon and Tinsley, 2008). These apply to transport industries including the aviation and maritime sectors:

- Risk is generally underestimated, while the accuracy of people's predictions is overestimated. It has been demonstrated that a 95% confidence level corresponds to around 70% in reality (Hubbard, 2009)
- Difficulty in spotting certain patterns and randomness (Silver, 2012)
- Uncertainty can be mistaken with low likelihood
- Near-misses can downgrade the way people perceive risk. It has been proved that people who survived a serious disasters, such as an earthquake, are less likely to evacuate during future events, despite any change in risk (Dillon and Tinsley, 2008)
- Risk is perceived differently by people who work in a safe vs high accident environment.

SMS implementation in both the maritime and aviation sectors is crucial for ensuring safe and efficient operations and to mitigate the unique challenges and risks they face. By prioritising safety through well-structured SMS, both the maritime and aviation industries can safeguard their operations, protect lives and maintain public trust.

In conclusion, the effectiveness of a SMS depends on its proper implementation and continuous improvement to adapt to evolving safety challenges. In this thesis, all four pillars of the SMS are addressed for the specific case studies.

2.3. Review of safety approaches

As discussed in the previous section, safety management is an essential component of any industry, particularly those with high risks such as the aviation and maritime transport sectors. Therefore, effective safety approaches are critical for preventing accidents, protecting lives and minimising economic losses. Over the years, safety management has evolved from reactive to proactive and,

more recently, to predictive approaches. Each of these approaches offers distinct methodologies and benefits, contributing to a comprehensive Safety Management System when used together. This section explores the main aspects of reactive, proactive, and predictive safety approaches, detailing their methodologies, applications and differences. It also discusses best practices for transport safety, focusing on analysing accident and incident data to enhance safety systems.

2.3.1. Traditional Safety Management

Traditional Safety Management focuses on compliance with established regulations and standards. It involves the use of prescriptive measures such as rules, procedures and checklists to ensure safety. The main aspect of this approach is its reliance on routine inspections, audits and enforcement of safety protocols. This method is characterised by its proactive stance on preventing deviations from standard procedures and ensuring consistent application of safety measures. While effective in maintaining compliance, it can be rigid and may not always account for the dynamic nature of complex systems (Reason, 2000).

2.3.2. Reactive Safety Approach

The reactive safety approach focuses on understanding and mitigating the causes of accidents after they occur. Historically, this approach has been the cornerstone of safety management since the first recorded accident investigation in 1908 (Dupuy, 2012). Initially, reactive safety analysis concentrated on forensic examinations of mechanical failures and physical damage to identify the root causes of accidents. Over time, the scope of reactive investigations expanded to include human and organisational factors, providing a more holistic understanding of accidents (Psyllou, 2017).

While Traditional Safety Management and the Reactive Safety Approach share similarities in their goals to prevent accidents and ensure safety, they differ in their methodologies and focus. Traditional safety management is more about compliance and consistent application of safety measures, whereas the reactive approach is about learning from failures and addressing known hazards based on past occurrences. Both approaches are important and can complement each other in a comprehensive SMS.

The reactive approach focuses on the analysis of accidents and incidents to understand what went wrong by identifying the sequence of events and contributing factors, and prevent future occurrences. This approach emphasises learning from failures, by heavily relying on historical data to identify trends and patterns that indicate underlying safety issues. Although effective in mitigating risks that have been previously identified, this approach is often limited by its reactive nature, addressing problems only after they have occurred (Hollnagel, 2014).

For example, the Seaplane Pilots Association's analysis of seaplane accidents from 1983 to 1995 highlighted recurring issues such as rough water conditions, submerged objects, and poor pilot technique (Seaplane Pilots Association, 1996). These findings led to improved safety protocols but also underscored the need for preventative measures to address these recurrent problems proactively.

2.3.3. Proactive Safety Approach

Emerging towards the end of the 20th century, the proactive safety approach marked a significant shift from reactive strategies by focusing on identifying and mitigating risks before they result in accidents. This approach involves analysing incidents, near-misses, and other safety-related events to prevent future occurrences. The proactive approach operates on the premise that addressing these smaller events can prevent larger accidents (Leveson, 2015).

This approach focuses on understanding and promoting what goes right. Its main aspect is the focus on resilience and adaptability within systems. It seeks to understand how everyday operations succeed under varying conditions and how systems can be designed to cope with unexpected challenges. Proactive approaches involve continuous monitoring, feedback loops and fostering safety cultures that encourage reporting and learning from both successes and failures (Hollnagel, 2014).

Hence, implementing a proactive SMS requires robust reporting systems and a strong safety culture that encourages the reporting and analysis of all safety-related occurrences, not just accidents. This approach is characterised by continuous monitoring and assessment of safety performance using tools such as safety audits, hazard identification workshops, and safety performance indicators (Psyllou, 2017). In aviation, for instance, the introduction of SMS has been pivotal in proactive safety management. SMS includes components such as hazard identification, risk assessment and safety performance monitoring, which collectively contribute to reducing the number of accidents (ICAO, 2013). By systematically analysing incidents and near-misses, organisations can identify potential hazards and implement measures to prevent them from escalating into serious accidents.

However, the proactive approach also faces challenges. The assumption that preventing incidents will necessarily prevent accidents is debatable. Some studies suggest that there is not always a direct correlation between incidents and accidents, questioning the efficacy of using incident data as a primary safety measure (Leveson, 2011). Despite this, the proactive approach has significantly improved safety outcomes by fostering a culture of continuous improvement and vigilance.

2.3.4. Predictive Safety Approach

The predictive safety approach represents the latest evolution in safety management, aiming to anticipate and prevent safety issues before they occur. This approach leverages advanced data

analytics, artificial intelligence (AI), machine learning, and predictive modelling to identify patterns and trends that indicate potential safety problems (Sun, Liu, & Zhang, 2017; Gagliardi et al., 2021). The collection and analysis of large operational datasets enable organisations to forecast future hazards and implement targeted preventive measures, significantly enhancing transport safety management (Zhou et al., 2021).

Predictive safety methodologies focus on identifying deviations from normal operations rather than solely investigating past failures. This aligns with Hollnagel's (2014) resilience engineering approach, which emphasises understanding system performance variability to enhance safety. Predictive analytics is now widely applied across various transport sectors, including road traffic management, maritime operations, and aviation safety investigations. For example, Busari (2025) highlights the application of data analytics in predictive traffic law enforcement and accident prevention, demonstrating how real-time predictive modelling can identify high-risk behaviours and optimise safety interventions. Similarly, Fatima (2025) explores AI-driven urban mobility solutions, showcasing the role of predictive AI in smart traffic management and infrastructure optimisation.

In aviation, Ziakkas & Henneberry (2025) discuss how AI-powered analytics can improve aviation incident investigations, allowing safety authorities to analyse historical data and predict potential accident patterns. This aligns with Sun, Liu, & Zhang (2017), who demonstrated the role of predictive maintenance in aviation, using big data to anticipate aircraft component failures and minimise unscheduled maintenance. Additionally, Bolbot et al. (2025) employ Bayesian trend analysis and association rule mining to predict accident causes in maritime safety, demonstrating the value of predictive safety models beyond traditional aviation applications.

Recent research has also explored predictive analytics in maritime risk assessment. Xu et al. (2025) applied radar image analysis to predict ship collision risks, enhancing real-time navigation safety. Gagliardi et al. (2021) further developed AI-based predictive safety models for vessel traffic risk management, reinforcing the importance of integrating predictive approaches in maritime transport. In autonomous transport systems, Zhou et al. (2021) proposed predictive machine learning models for proactive risk assessment in intelligent transportation systems, highlighting the role of AI in optimising safety strategies.

Despite its potential, the predictive approach faces significant implementation challenges. Advanced predictive models require large datasets, high computational resources, and rigorous validation methods to ensure reliability. Cao et al. (2022) discuss the complexities of predictive safety implementation, emphasising the need for robust model validation and real-world applicability testing. Additionally, the lack of standardised predictive safety frameworks across transport sectors

hinders large-scale adoption (Zhou et al., 2021). Nonetheless, predictive analytics continues to evolve, offering a forward-looking approach to transport safety management that enhances both proactive and reactive safety measures.

2.3.5. Best Practices for Transport Safety

Each safety approach (reactive, proactive and predictive) has unique strengths and is most effective when integrated into a comprehensive SMS. The reactive approach provides valuable insights from actual incidents, enabling organisations to learn from past mistakes and implement corrective actions. The proactive approach focuses on preventing these incidents from occurring in the first place by identifying and mitigating potential risks. The predictive approach offers a forward-looking perspective, allowing organisations to anticipate and address safety issues before they manifest.

In the context of transport safety, integrating reactive, proactive, and predictive measures can create a robust SMS. For example, in the aviation industry, reactive measures provide critical lessons from past accidents, proactive measures ensure continuous monitoring and improvement, and predictive measures enable foresight into potential safety issues (ICAO, 2013; Sun, Liu, & Zhang, 2017). Appendix C links the reactive, proactive and predictive safety theories to SMS pillars.

For effective transport safety, particularly in analysing accident and incident data, the proactive approach is highly effective. Proactive SMS that include comprehensive reporting, continuous monitoring, and robust safety cultures can significantly reduce the likelihood of accidents. However, incorporating predictive analytics can further enhance safety by providing advanced warning of potential issues and enabling timely interventions.

Cao et al. (2022) emphasise the role of AI-powered prediction models in maritime and aviation safety, demonstrating how machine learning algorithms can detect patterns in accident trends and optimise risk mitigation strategies. Similarly, Zhou et al. (2021) propose predictive models for intelligent transport systems, highlighting the cross-sector applicability of predictive safety frameworks.

Best practices in predictive safety include:

- Integrating real-time monitoring systems for continuous safety assessment (Xu et al., 2025).
- Leveraging AI-driven risk prediction models to enhance decision-making (Gagliardi et al., 2021).
- Standardising predictive safety methodologies across transport sectors for consistency (Zhou et al., 2021).
- Encouraging open data-sharing between stakeholders to improve predictive model accuracy (Cao et al., 2022).

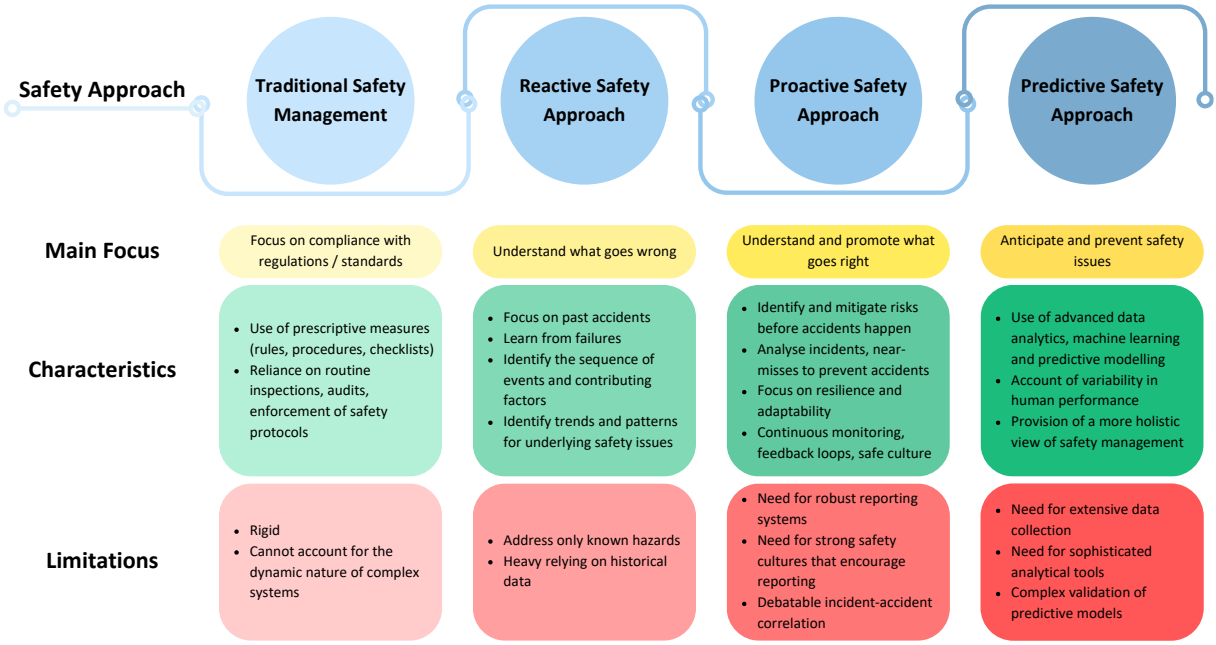
- Implementing training programs for safety professionals to use predictive analytics effectively (Fatima, 2025).

A strong safety culture is fundamental to the success of predictive safety methodologies. Encouraging transparent reporting of incidents and near-misses, providing ongoing education and training, and leveraging advanced analytical tools for risk prediction can help organisations maintain high safety standards and enhance safety performance across all transport modes. By integrating reactive, proactive and predictive safety measures, transport organisations can develop a robust and future-oriented SMS, ensuring a higher standard of safety and risk management.

2.3.6. Conclusions of the review of safety approaches

Figure 2.3 summarises the key elements of the safety approaches presented in this section.

Figure 2.3. Review of safety approaches, including their main focus, characteristics and limitations.



Firstly, while the reactive approach is foundational and provides crucial insights, it is inherently limited by its retrospective nature. Organisations must not solely rely on reactive measures, as they are essentially a response to failures that have already occurred. Instead, the proactive and predictive approaches should be given more emphasis, as they aim to prevent incidents and accidents before happening.

Secondly, the proactive approach, although effective, hinges heavily on the quality and comprehensiveness of reporting systems and the organisational safety culture. Ensuring that all incidents and near-misses are reported and analysed requires significant organisational commitment and continuous effort to maintain and improve safety cultures. Moreover, the assumption that all

incidents are precursors to accidents may not always hold true, as highlighted by Leveson (2015). Therefore, while proactive measures are generally useful, they should be complemented by predictive analytics to provide a more rounded safety management strategy.

Thirdly, the predictive approach represents the future of safety management. By leveraging advanced data analytics and machine learning, organisations can anticipate and mitigate potential risks more effectively. However, the implementation of predictive safety measures requires substantial investment in data collection infrastructure, analytical tools, and skilled personnel. Additionally, the accuracy and reliability of predictive models need constant validation to ensure their effectiveness.

In the realm of transport safety, an integrated approach that combines reactive, proactive, and predictive measures is paramount. The aviation industry can benefit greatly from predictive maintenance and real-time data analytics, which can pre-emptively address potential safety issues. However, this should not diminish the importance of a robust safety culture and comprehensive incident reporting systems that underpin proactive safety management.

In conclusion, the integration of reactive, proactive, and predictive safety approaches, supported by a strong safety culture and continuous improvement, offers the most effective strategy for managing safety in high-risk industries. By leveraging the strengths of each approach, organisations can create a resilient SMS that not only responds to past incidents, but also anticipates and prevents future risks. In this thesis, all three safety approaches (reactive, proactive and predictive) are considered, commenting on their suitability for each case study.

2.4. Review of accident models

Accident models play a crucial role in understanding, analysing, and preventing accidents across various high-risk industries, including the transport industry. These frameworks enable safety professionals to identify causal factors and implement measures to mitigate risks effectively. Over the years, several accident models have emerged, each providing distinct perspectives and methodologies for accident analysis. This section delves into key accident models, including the sequential model, the epidemiological model, the Human Factors Analysis and Classification System (HFACS) and the Systems Theoretic Accident Model and Processes (STAMP). Additionally, it explores the Domino Theory and the Swiss Cheese model, highlighting their main aspects, applications and differences, focusing on examples from the maritime and aviation sectors.

2.4.1. Sequential Accident Models

Sequential accident models, such as the Domino Theory, suggest that accidents result from a linear progression of events, with each event triggering the next, ultimately leading to an accident. The core

idea is that intervening at any stage in this sequence can prevent the subsequent events and, thus, the future accidents.

The Domino Theory (Figure 2.4.1), introduced by Heinrich in the 1930s, is one of the earliest and most influential accident models. It identifies five dominos or layers that are placed in a sequence: ancestry and social environment, fault of the person, unsafe act or mechanical/physical hazard, accident, and injury (Heinrich, Petersen & Roos, 1980). This theory emphasises human error and unsafe acts as primary causes of accidents. The methodology involves identifying and eliminating unsafe acts in order to prevent accidents (Heinrich, Petersen & Roos, 1980). Despite its historical significance, the Domino Theory is often criticised for its oversimplified, linear view that does not account for complex interactions and multiple causative factors.

Over time, the Domino Theory has been adapted to address its limitations, considering the interactions between human, technical, and environmental factors. For instance, Bird and Germain (1985) introduced an updated domino model that incorporates management's role in accident prevention, providing a more comprehensive understanding of accident causation.

Figure 2.4-A. The Domino Theory of accident causation, and interruption of the accident sequence by removing unsafe acts (Heinrich, Petersen & Roos, 1980).

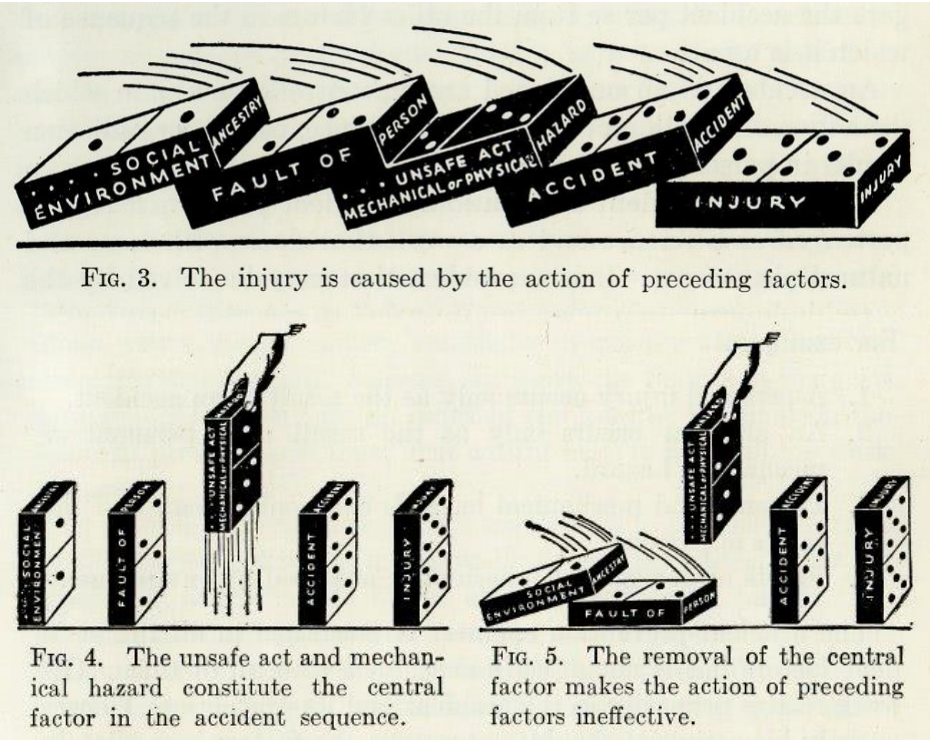


FIG. 3. The injury is caused by the action of preceding factors.

FIG. 4. The unsafe act and mechanical hazard constitute the central factor in the accident sequence.

FIG. 5. The removal of the central factor makes the action of preceding factors ineffective.

In the maritime sector, the Domino Theory has been adapted to train crew members on the importance of safe practices to prevent the initial events that could lead to accidents. For instance, Zhang et. al. (2013) utilised the Domino Theory to analyse accidents in Chinese shipping, identifying

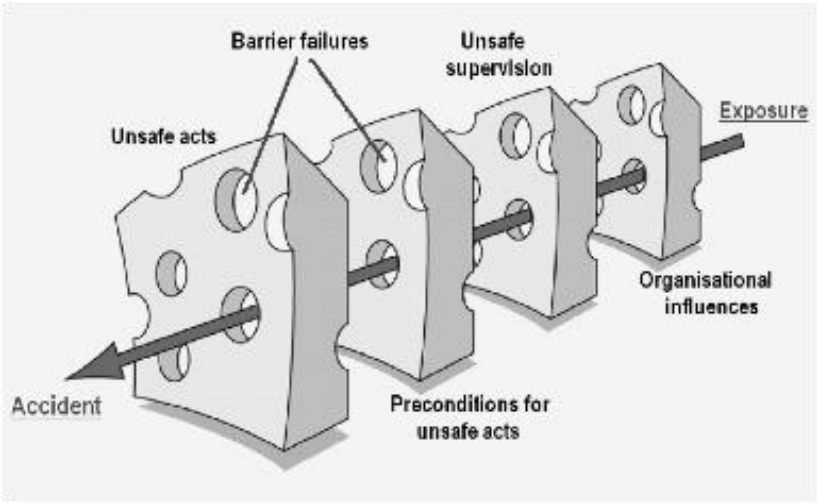
common unsafe acts and proposing measures to improve safety training. Similarly, in aviation, the Domino Theory's principles underpin many safety training programs. Early aviation safety training manuals incorporated the Domino Theory to explain accident causation and prevention (Heinrich, Petersen, & Roos, 1980), emphasising the need to prevent unsafe acts to avoid accidents.

2.4.2. Epidemiological Accident Models

Epidemiological accident models, such as the Swiss Cheese Model, compare the occurrence of accidents to how diseases are spread, suggesting that accidents result from a combination of latent conditions and active failures. Therefore, these models emphasise the interplay of various factors that contribute to accidents.

The Swiss Cheese Model, developed by James Reason in the 1990s, visualises an organisation's defences against failure as slices of Swiss cheese, with holes representing weaknesses in each defence layer. As represented in Figure 2.4-B, accidents occur when the holes in multiple layers align, allowing hazards to pass through all defences (Reason, 1997). The methodology involves identifying and reinforcing these defence layers to prevent accidents. Therefore, the model's strength lies in its ability to illustrate how multiple small failures can align to cause a significant accident.

Figure 2.4-B. Representation of the Swiss Cheese Model (Reason, 1990).



Widely adopted in industries like aviation, healthcare, and nuclear power, the Swiss Cheese Model has evolved to incorporate more sophisticated understandings of organisational behaviour and human factors. Reason's later works integrate concepts of "latent conditions" and "active failures", emphasising the importance of organisational culture and decision-making processes in accident prevention (Reason, 2000). In the maritime sector, the Swiss Cheese Model is used in safety audits and occurrence investigations to understand how multiple failures align to cause an accident. Hetherington, Flin, and Mearns (2006) discussed the application of the Swiss Cheese Model in

analysing maritime accidents, highlighting its effectiveness in identifying organisational weaknesses. In aviation, the Swiss Cheese Model is extensively used to analyse accidents and incidents, focusing on the alignment of failures across multiple layers of defence. For example, Reason's (1990) application of the Swiss Cheese Model in aviation is well-documented, demonstrating its effectiveness in understanding complex accident causation.

2.4.3. Human Factors Analysis and Classification System (HFACS)

The Human Factors Analysis and Classification System (HFACS) builds on Reason's Swiss Cheese Model by specifically focusing on human factors involved in accidents. According to Shappell & Wiegmann (2000), HFACS divides human error into four categories: unsafe acts (errors and violations committed by operators), preconditions for unsafe acts (factors such as environmental conditions and individual states), unsafe supervision (failures in oversight and management) and organisational influences (broader factors within the organisation, including policies and safety culture). Therefore, the HFACS methodology conducts an in-depth examination of human errors at various levels, offering a thorough framework to identify the root causes of accidents.

Over the years, HFACS has been adapted and fine-tuned for various industries. It is widely used in aviation, military, and healthcare sectors to systematically analyse human errors and identify their underlying causes. The structured approach of the model aids organisations in implementing targeted safety interventions. However, the model's effectiveness hinges on the thoroughness of its application and the users' expertise, as the classification can be intricate and detailed.

In the maritime sector, HFACS has been modified to provide a structured method for examining human and organisational factors in accidents. Chauvin et. al. (2013) applied HFACS to analyse maritime accidents in the fishing industry, identifying critical human errors and suggesting corrective actions. In aviation, HFACS is also used to systematically analyse human errors and organisational factors contributing to accidents. Wiegmann and Shappell (2003) presented a comprehensive application of HFACS in aviation, demonstrating how the model aids in understanding human factors in accidents and enhancing safety measures.

2.4.4. Systems Theoretic Accident Model and Processes (STAMP)

The Systems Theoretic Accident Model and Processes (STAMP), introduced by Leveson (2004), marks a significant departure from traditional linear accident models. STAMP perceives accidents as arising

from complex interactions within socio-technical systems, emphasising the role of system constraints and control structures (Leveson, 2004).

STAMP's approach involves a comprehensive analysis of the entire system, incorporating organisational, technical and human components to understand how these elements interact and influence safety or lead to accidents. It prioritises the enforcement of safety constraints and maintaining control over system operations to prevent accidents. Unlike the previously mentioned conventional models that focus on sequences of events or individual errors, STAMP considers the broader system context, including organisational and regulatory influences.

This model has been used in various high-risk industries such as aerospace, nuclear power, and software engineering to examine system-level failures. STAMP has evolved to include tools like the Systems Theoretic Process Analysis (STPA), which aids in identifying potential hazards in system designs and operations. While STAMP offers a comprehensive framework for understanding accidents, its complexity and the need for a detailed understanding of systems theory can pose implementation challenges. Nevertheless, its holistic approach provides valuable insights into the dynamic interactions within socio-technical systems.

In the maritime industry, STAMP is used in risk assessments and system design to ensure safety constraints are upheld. Östrom and Wilhelmsen (2012) showcased the application of STAMP in analysing maritime accidents, highlighting the model's capability to address systemic issues. In aviation, STAMP's holistic approach is being employed to address the complexities of modern aviation systems. Leveson's (2011) work on STAMP includes numerous aviation case studies, illustrating the model's effectiveness in understanding and preventing systemic failures.

2.4.5. Conclusions of the review of accident models

Each accident model provides distinctive insights and tools for the analysis and prevention of accidents. Sequential models, such as the Domino Theory, offer a clear framework but are restricted by their linear approach. Epidemiological models, like the Swiss Cheese Model, introduce the concept of multiple defence layers, providing a stronger framework for understanding failures. HFACS enhances this by classifying human errors into multiple levels, making it especially valuable for human factors analysis. STAMP, with its systems-theoretic approach, offers the most comprehensive framework, capable of addressing the complexities of contemporary socio-technical systems. Overall, by integrating these models, safety professionals can achieve a more holistic understanding of accidents and implement more effective safety measures.

Specifically for transport safety, integrating multiple accident models can provide a comprehensive understanding of accidents and enhance safety measures. The Swiss Cheese Model and HFACS are

particularly useful for analysing human and organisational factors, while STAMP's system-based approach can address the complexities of modern transport systems. Combining these models can allow safety professionals to leverage the strengths of each, developing more effective strategies to prevent accidents. Additionally, proactive safety management systems that include comprehensive reporting, continuous monitoring and robust safety cultures can significantly reduce the likelihood of accidents. Incorporating predictive analytics can further enhance safety by providing advanced warning of potential issues and enabling timely interventions.

On one hand, traditional models such as the Domino Theory and Swiss Cheese Model offer valuable frameworks, but they are constrained by their linear perspectives. On the other hand, the complexity of modern transport systems demands more advanced approaches like STAMP, which accounts for the dynamic interactions within socio-technical systems. However, implementing such sophisticated models requires significant expertise and resources and it is not widely used in practice by the national bodies designated with the analysis of accident and incident data. Nevertheless, HFACS is particularly useful for its focus on human factors, providing a structured method for identifying and mitigating human errors. Yet, its effectiveness relies on thorough application and the users' expertise, along with detailed data on human factors, which is not available for transport databases as only a few occurrences lead to an investigation resulting in a detailed report.

In conclusion, adopting a multi-model approach that integrates elements from sequential, epidemiological, and systems-theoretic models is advisable for transport safety. This combined strategy utilises the strengths of each model, offering a comprehensive framework for analysing and preventing accidents. Promoting open reporting of incidents and near-misses, continuous education and training, and the use of advanced analytical tools can help organisations improve their databases' quality, therefore maintaining high safety standards.

2.5. The role of data and its collection in transport SMS

Sections 2.1 and 2.2 provided research on reportable occurrences, the SMS and how it relies on understanding near misses. Data collection methods and requirements specific for the maritime and aviation industries are detailed in Chapters 6 and 7. In this section, Heinrich's Pyramid has been used as an example of a theory that includes the basis of the SMS, to assess the role of data and to check whether such a theory that is part of a reactive approach is suitable for marine casualties and incidents.

2.5.1. Rationale

Heinrich's Pyramid, also known as Heinrich's Triangle or Heinrich's Law, is a theory in occupational safety that suggests a relationship between the number of minor incidents, serious accidents, and

fatal accidents in a workplace. According to the theory, for every major accident or fatality, there are 29 less serious injuries and 300 near-misses. This implies that addressing and mitigating minor incidents and unsafe acts can significantly reduce the occurrence of more severe accidents. Therefore, even though this theory uses data of past accidents and incidents, it emphasises on the importance of proactive safety measures and hazard management to prevent serious accidents (Heinrich, 1931). The reasons why this theory has been chosen are detailed below.

Firstly, Heinrich's Pyramid Theory complements the Domino Theory, which was presented in Section 2.4.1. While the Domino Theory focuses on the linear sequence of events leading to an accident, the Pyramid Theory emphasises the frequency and relationship between different types of incidents. Both theories collectively highlight the importance of preventing unsafe acts to break the sequence of events that could lead to an accident. Secondly, in the context of the Swiss Cheese Model (Section 2.4.2), Heinrich's Pyramid Theory can be used to identify and address the "holes" or weaknesses in each layer of defence. Thus, by focusing on minor incidents and near-misses, organisations can reinforce their defence layers, reducing the alignment of failures that lead to major accidents.

Thirdly, Heinrich's Pyramid Theory also aligns with HFACS (Section 2.4.3) by highlighting the importance of addressing lower-level errors and unsafe conditions. By analysing and mitigating these factors, HFACS helps organisations prevent the escalation of incidents as suggested by Heinrich's Pyramid. Additionally, STAMP's system-theoretic approach (Section 2.4.4) considers complex interactions within socio-technical systems, which the Heinrich Pyramid Theory supports by emphasising the need to monitor and control minor incidents and unsafe behaviours within the system.

Lastly, Heinrich's Pyramid Theory fits into SMS (Section 2.2) by providing a foundation for understanding and managing safety risks at different levels. Heinrich's Pyramid Theory underscores the importance of a strong safety policy that addresses all levels of incidents, not just major accidents. In the risk management component of SMS, Heinrich's Pyramid Theory guides the identification and mitigation of risks associated with minor incidents and near-misses. This proactive approach helps prevent the escalation of risks into major accidents. Heinrich's Pyramid Theory also supports the safety assurance pillar of the SMS by highlighting the need to track and analyse all levels of incidents. Organisations can use this data to identify trends and implement corrective actions before minor issues escalate. Moreover, Heinrich's Pyramid Theory reinforces the importance of safety promotion by encouraging the reporting and analysis of minor incidents and unsafe behaviours, which is usually not mandatory in transport. This helps create an environment where safety is prioritised at all levels.

2.5.2. Method used

A paper on this has been presented at the Transportation Research Board annual meeting in 2020 and then published in Transportation Research Record: Journal of the Transportation Research Board (Majumdar, Manole & Nalty, 2022). This paper reviews the available literature, specifically on the use of Heinrich's Pyramid and previous calibration in the maritime sector and other transportation sectors. Then, a methodology is established for the calibration of the Pyramid for marine accident and incident data in UK ports. This calibration is achieved by using K-Means Clustering Analysis. Finally, the results are discussed in comparison to other results from the literature review, considering their likelihood and data limitations.

To accomplish the pyramid ratio calibration, K-Means Clustering Analysis has been employed using five years (2013-2017) of port accident data involving vessels travelling around or berthed within a UK port area, which was obtained from the MAIB. Three clustering methods have been used:

1. Sub-sets of 330 accidents, to match Heinrich's pyramid (1+29+300)
2. Make clusters such that each cluster has exactly one "Very Serious" accident
3. Test the optimal number of clusters.

2.5.3. Conclusions of the role of data in transport safety

The clustering analysis results confirm that the analysed data does not match Heinrich's original severity ratios and pyramid shape. One of the biggest differences was that the Very Serious to Serious accident ratio was 4:1 for occupational accidents and 1:5 for the other casualties with a ship (involving the ship, its equipment or its cargo), in contrast with Heinrich's 1:29. However, these results may not fully represent reality due to accident reporting requirements under UK law which can cause the underreporting, as well as a lack of an agreed taxonomy of risk and hazard definitions which have been discussed in this section. If less serious accidents were to be excluded for casualties with a ship, the data would indeed be pyramid shaped using all three clustering methods.

UK maritime experts have confirmed the theory behind the assumption that there is most likely a higher rate of less serious incidents and near-misses compared to more severe ones. Even if incident reporting was accurate, merging this information from different datasets would be of high difficulty because a unique hazard/reporting taxonomy does not exist among different levels of accident reporting (individual ports, accident investigation bodies, insurance companies, etc.). Similar incidents could be allocated different severity levels and/or the details of contributory factors could be reported inconsistently.

It can also be difficult to determine when a near-miss occurred, since the involved parties can miss the signs as there are no guidelines for that (Bhattacharya, 2009; Lloyds List, 2016). This is supported by Capt. Rose from CHIRP, who claims that there is no culture built by industry to encourage the active reporting of near-misses (Kyriakidis, Pak, and Majumdar, 2015). For example, Seafarers prefer to rely on their skills and instinct rather than following a checklist, but this can result in an unconscious bias against how/when potentially unsafe acts are acknowledged. The fact that the reporting of less severe incidents is not mandatory, along with the safety/reporting culture potentially focusing more on blame, are additional factors causing an incentive not to report.

2.6. Socio-technical systems

The term “socio-technical system” has been used in this thesis as it is a suitable representation of the transport system worldwide. This section provides all necessary information to understand this term and why it is used in this context.

2.6.1. Definitions for socio-technical systems and socio-technical factors

Socio-technical systems (STS) study the combined changes of two aspects: social (communication, interactions, and relationships between people, as well as individual values and motivation, or organisational culture) and technical (procedures, knowledge, skills, and other tools that people use for an activity) (Trist, 1981). The complexity of socio-technical systems continues to increase with rapid advancements in automation, artificial intelligence (AI), and data-driven decision-making, making traditional accident causation models less effective in assessing new types of hazards (Leveson, 2004; Underwood and Waterson, 2013). Additionally, the integration of emerging technologies into transport systems introduces new layers of complexity, requiring more adaptive safety models (Preutenborbeck et al., 2025). Regulatory policies and public perceptions also evolve alongside technological advancements, necessitating the continuous development of updated models to address these challenges (Wu and Huang, 2019).

These changes can be observed in all transport sectors, which involve an intricate relationship between technological components and social elements within the transportation networks. Therefore, it can be directly implied that the STS concept is the right approach for the transportation sector, as it emphasises that social and technical aspects must operate harmoniously. It provides a thorough perspective, strengthens safety management, boosts organisational efficiency, and is adaptable to various changes (Baxter & Sommerville, 2011; Clegg, 2000; Waterson et. al., 2015). Hence, specific for the transport industry, it can be implied that STS include integrating technology, such as vehicles, traffic management systems, and infrastructure, with human elements like drivers, operators, passengers and regulatory bodies. The primary objective is to enhance the overall

performance, safety, and user satisfaction of the transport system by ensuring a seamless integration of its social and technical components.

For example, automated and autonomous transport systems are reshaping traditional STS structures, shifting responsibility from human operators to AI-driven decision-making models (Thylén, 2025). Therefore, the STS concept remains a suitable framework for transportation safety, as it emphasises the interdependence of human and technical components. Recent studies highlight the importance of STS in ensuring human-technology integration, particularly in aviation, maritime and road transport safety (Kalliola et al., 2025; Swaine & Crossley, 2025). For instance, structural causal modelling has been applied to hydrogen-powered rail systems, highlighting how socio-technical interactions influence risk perception and safety performance (Compare et al., 2025).

STS in the transport industry involves integrating advanced technologies such as automated traffic management systems, AI-driven predictive safety models, and real-time risk monitoring with human decision-making processes (Hassan, 2024). This integration aims to enhance safety, efficiency, and user experience by ensuring seamless cooperation between infrastructure, vehicles, operators, passengers and regulatory authorities. The shift towards autonomous transport and teleoperated mobility further underscores the need to refine socio-technical frameworks to accommodate human oversight and technological advancements (Grabbe et al., 2024).

Socio-technical factors in the transport sector refer to the specific elements within a transportation system that impact its functioning. These factors can be social, such as driver behaviour, passenger interactions, and organisational culture, or technical, such as vehicle design, traffic control systems, and maintenance procedures. The focus is on understanding and managing these individual components to enhance the performance and safety of the transport system. The goal is to identify and address these factors to improve the overall efficiency and integration of the socio-technical transport system. Recent studies emphasise that disruptions in socio-technical balance, such as poor human-machine interaction in automated driving or inefficient data-sharing between stakeholders, can compromise safety (Guo et al., 2024). Addressing these challenges requires a multi-layered approach that combines human-centred safety management with adaptive technological solutions.

To summarise, while socio-technical systems encompass the entire transportation network, including all interactions between social and technical elements, socio-technical factors focus on specific components within the broader system. With the growing reliance on automation, AI, and intelligent transport solutions, future safety frameworks must account for the evolving dynamics of socio-technical systems to optimize transport safety, efficiency, and user adaptability.

2.6.2. Complex socio-technical systems

Complex socio-technical systems (CSTS) build on the STS concept by focusing on intricate interactions and dependencies among various social and technical components in dynamic environments. These systems are characterised by high interconnectivity, emergent behaviours and the continuous evolution of risks (Weyer, 2024). They are particularly relevant in transport, where human operators, advanced automation, artificial intelligence and organisational processes must integrate seamlessly to ensure efficiency, adaptability and safety (Mirkovic et al., 2024).

In conclusion, CSTS are particularly suitable for transport safety analysis because they:

- Consider non-linear interactions: CSTS take into account the unpredictable and emergent behaviours that arise from interactions within the system (Hollnagel, 2012; Weyer, 2024).
- Address Systemic Risks: By understanding how different parts of the system contribute to overall risk, CSTS provide a comprehensive approach to risk identification, assessment and mitigation (Leveson, 2004; Saurin et al., 2025).
- Support Resilience Engineering: Analysing how systems can adapt to and recover from unexpected disturbances helps build more resilient and flexible transport operations (Hollnagel, Woods, & Leveson, 2006; Grabbe et al., 2024).

2.6.3. Usability and application of socio-technical systems for the specific maritime and aviation studies in this thesis

Ports, on one hand, represent complex socio-technical environments where vessels, human operators, and various technologies interact. Accidents and incidents in ports can result from multiple factors, including human error, technical failures and environmental conditions (Correa-Jullian et al., 2024). For example, collisions between ships and port infrastructure often involve complex interactions between navigational technologies, ship control systems, and pilot decision-making, making safety management highly dependent on system-wide coordination (Psaraftis & Kontovas, 2009; Goerlandt & Montewka, 2015). The socio-technical approach can help identify these interdependencies and improve safety by optimising both the social and technical components of port operations (Goerlandt & Montewka, 2015). The socio-technical approach enables a more adaptive and proactive safety culture, addressing both human and technological elements. Below are some examples of how CSTS can contribute to port safety, from literature publications:

- *Human errors* remain one of the most significant contributors to port accidents. A socio-technical analysis can reveal gaps in decision-making, training, and situational awareness, enabling more effective safety interventions (Kim & Gausdal, 2020; Wamugi et al., 2024).
- *Integration of advanced technologies*, such as automated docking systems and AI-driven navigation aids, must be carefully designed to align with human workflows. A socio-technical

perspective ensures that automation supports rather than replaces human decision-making, reducing over-reliance on technology and enhancing operational safety (Saurin et al., 2025).

Seaplane operations, on the other hand, face unique challenges due to their dual nature of operating both in the air and on water. Unlike other aircraft, seaplanes interact with maritime vessels, requiring the simultaneous application of aviation and maritime safety principles (Mirkovic et al., 2024). Accidents and incidents can occur during any phase of flight or water operations, influenced by pilot error, mechanical failures, and environmental hazards (Xiao, Luo, & Li, 2020). Applying a socio-technical perspective to seaplane operations can enhance safety by addressing the interplay between human, technical, and environmental factors (Swaine & Crossley, 2025). Key ways in which CSTS can contribute to seaplane safety include:

- Pilot training, experience, and cognitive workload are crucial for safe seaplane operations. A socio-technical analysis can identify deficiencies in training programs, automation reliance, and risk perception, leading to better-prepared pilots for challenging operational environments (MacDonald, Brooks, & McGowan, 2021; Swaine & Crossley, 2025).
- Safety equipment and emergency procedures must be designed with end-user usability in mind. The effectiveness of life jackets, emergency exits, and water survival tools depends on how well they integrate into operational workflows. A socio-technical approach ensures safety equipment is regularly tested, intuitive, and aligned with human cognitive abilities (Xiao, Luo, & Li, 2020; Correa-Jullian et al., 2024).

As maritime and aviation sectors increasingly adopt automation, digitalization and AI-based risk assessments, socio-technical systems will play an essential role in guiding safety strategies. Ensuring human-technology alignment and enhancing resilience within these sectors will be crucial for the future of transport safety (Grabbe et al., 2024; Hassan, 2024).

2.7. The human aspect – human performance

The human element in transport safety is one of the most unpredictable factors, influenced by cognitive workload, fatigue, external pressures, and even automation biases (Chen et al., 2025). Sanders and McCormick (1993) define human error as an inappropriate or unacceptable action that reduces system performance and efficiency. However, recent literature suggests that human error should be reframed as "systemic human contributions to risk," recognising that errors are often symptoms of deeper systemic issues rather than isolated operator failures (Nanyonga et al., 2025).

Human behaviour has three levels, as described by Rasmussen (1982): skill-based, rule-based, and knowledge-based performance. Reason (1990) expanded on this by defining "unsafe acts" as errors caused by human performance failures, which can be categorized into errors (e.g., failures of

attention, misjudged distance) and violations (e.g., distractions, policy violations). He further introduced a four-tier model of failures: unsafe acts, preconditions for unsafe acts, unsafe supervision and organisational influences. These layers form the Swiss Cheese Model, a widely accepted safety framework applied across aviation, maritime, and road transport sectors (Haque, 2025).

Analysing past accidents and incidents to determine root causes and contributing factors remains one of the primary methods for identifying human errors. Advanced AI-driven safety analysis is increasingly being used alongside traditional accident investigation tools, such as the Human Factor Analysis and Classification System (HFACS), originally developed by the US military (Galieriková, 2019). HFACS helps identify patterns of human error and organisational weaknesses, but concerns remain over the accuracy of classification due to inconsistencies in accident coding and reporting methods (Celik & Cebi, 2009). Recent studies suggest integrating machine learning into HFACS to improve the reliability of human error classification in transport safety assessments (Nanyonga et al., 2025).

The shipping industry, for example, has historically focused on increasing efficiency, vessel design and system reliability to reduce occurrences. However, technological advancements alone have not significantly reduced human-related maritime accidents, suggesting that improving ship structures and automation is only part of the solution. Cognitive workload, situational awareness and automation complacency remain major challenges in maritime safety (Haque, 2025).

ICAO (2013) defines human performance as the “human capabilities and limitations which have an impact on the safety, security and efficiency of aeronautical operations”. However, even though the usual methods of data analysis to study human-related factors can uncover the most common and repetitive errors, the transport systems are complex socio-technical systems (Section 2.6), and most reporting requirements do not cover the less severe occurrences and human-related factors (Chen et al., 2025). Integrating human performance analytics with predictive safety modelling can enhance safety management and provide real-time insights into human factors risks (Wandenkolk et al., 2025). Therefore, mixed methods of analysis would benefit the system’s safety and enhance the understanding of human factors. The reporting requirements specific for the case studies included in this thesis are addressed in future sections (Sections 3.4 and 4.3.5).

Human error remains the dominant cause of accidents across transport sectors. Berg (2013) estimated that 80% of maritime accidents result from organisational and human factors. More recently, Allianz Global Corporate & Specialty (2017) reported that 75% to 96% of shipping accidents are linked to human error, leading to significant economic, environmental, and human costs. Cognitive biases, stress levels and automation reliance play crucial roles in transport safety, requiring a shift toward human-centred safety designs (Chen et al., 2025).

While past studies, such as McLachlan (2017), primarily analysed human behaviour in seagoing ships, recent research emphasises the need for a more comprehensive approach, including safety culture assessments at ports, air traffic control and multimodal transport hubs (Esmaeeli et al., 2025). Veiga (2002) demonstrated that implementing a complete safety culture can significantly reduce maritime incidents, yet shipping companies still struggle with integrating human-centred safety frameworks.

In transport safety studies, human factors refer to the various aspects of human performance and behaviour that impact the safety and efficiency of operations. Table 2.7 includes examples of human factors according to relevant publications, which are essential in designing, operating and managing transport systems to ensure safety and efficiency.

Table 2.7. Examples of human factors with related publications.

Human factor	**Description**	**Publications**
Fatigue	Physical and mental tiredness can significantly impair an operator's performance, leading to slower reaction times and decreased vigilance, thus increasing the risk of accidents. Effective fatigue management programs are crucial in sectors like aviation and maritime transport to ensure operators receive adequate rest.	Dinges, 1995; Caldwell et. al., 2009; Cevik, Elfvengren & Dahanayake, 2022; Yu et. A., 2022.
Training and experience	The level of training and experience of operators affects their ability to handle routine operations and respond to emergencies. Operators with better training and more experience are more capable of managing complex and unexpected situations.	Berrones-Sanz, 2021; Salas & Cannon-Bowers, 2001; Shiwen et. al., 2019.
Stress	High stress levels can negatively impact decision-making and performance. Stressors may include time pressure, heavy workload, and adverse working conditions. Effective stress management and a supportive work environment are essential for maintaining safety.	Böcker et. al., 2022; Cohen, 1980; Hockey, 1997; Mamcarz et. al., 2019.
Situational awareness	The ability to perceive, understand, and anticipate the status of the surrounding environment is crucial for safe transport operations. A loss of situational awareness can lead to errors such as navigation mistakes or collisions.	Endsley, 1995; Narri et. al., 2021; Nourbakhshrezaei, Jadidi & Sohn, 2023)
Communication	Clear and effective communication among operators, crew members, and ground support is vital for coordinated and safe operations. Miscommunication can result in misunderstandings and mistakes.	Jiménez, 2022; Kanki et al., 2010; Yang et. al., 2023.
Decision making	The capacity to make sound decisions, especially under pressure, is critical for transport safety. Poor decision-making processes can result in critical errors, such as misjudging weather conditions or selecting inappropriate routes.	Klein, 2008; ORR, 2023.
Human-machine interaction	The design of interfaces and controls that operators use affects their ability to perform tasks accurately and efficiently. Poorly designed systems can lead to operator errors and accidents.	Li, Li, & Loianno, 2022; Norman, 1990)
Ergonomics	The physical design of workspaces, including the arrangement of controls and displays, impacts operator comfort and performance. Ergonomic design can reduce physical strain, enhancing ease of use.	Kroemer & Grandjean, 1997; Vorozhbiian et. al., 2023.
Teamwork and collaboration	The ability of operators to work effectively as a team influences safety outcomes. Good teamwork involves coordination, mutual support and shared situational awareness.	Nadtochiy et. al., 2022; Salas et al., 2005; Whyte and Narvey, 2017.

Cognitive load	The mental demand placed on operators can affect their performance. Excessive cognitive load can overwhelm operators, leading to mistakes, while insufficient load can lead to complacency.	Ma, Liu & Yang, 2023; Sweller, 1988; Wang et. al., 2023.

Fatigue is one of the human factors most considered in transport literature which, for seafarers, can result from their living, sleeping and working environment. Between 2011 and 2016, it caused 75% of the marine casualties in the UK during the night (Russ, 2018). Various factors can lead to fatigue at sea, including: long and late working hours, extreme levels of noise, fluctuations in temperature, light and humidity (Seafarers, 2019). The crews on board of vessels are usually pressured by their voyage schedules, which may result in having to solve tasks with fewer people than ideally required (Project Martha, 2016). Fatigue can lead to stress, reduced vigilance, slower reaction time, or even long-term effects which can potentially lead to physical and mental disorders. Thus, it affects people's wellbeing and behaviour. A method that measures fatigue levels has been developed and it is currently used as the industry standard (Russ, 2018). Project Martha and Project Horizon contributed greatly in understanding fatigue, by showing that the performance of seafarers is directly related to their work patterns (Project Martha, 2016; Project Horizon, 2012).

2.8. The water environment

The water environment is a dynamic domain that plays a critical role in global transportation and commerce. Ports act as vibrant centres of maritime activity, where ships of diverse sizes and types conduct the loading, unloading, and transfer of goods or people, making them essential to international trade. Simultaneously, seaplanes operate in these environments, using the water surface for take-offs and landings, often in the proximity of maritime traffic. Examining the safety of both ships in ports and seaplanes is vital due to the distinct challenges and risks this shared space presents. These challenges include potential collisions, navigational hazards and environmental factors such as weather conditions and water-specific parameters. Ensuring the safety of operations for both vessels and seaplanes is crucial not only for protecting lives and property, but also for maintaining the efficiency and sustainability of the maritime and aviation industries. By understanding and mitigating the specific risks associated with these operations, safety protocols can be enhanced and more robust safety management systems developed, which address the complexities of the water environment and the particularities of both sectors.

Research on the safety of the water environment for ships and seaplanes together is scarce, but there are a few studies that mention both. These have revealed several key areas of concern and methodological approaches. Gao (2014) conducted an extensive risk analysis of seaplane operations in Sanya Port in China, comparing the maritime traffic environment of seaplanes to that of other vessels and emphasising unique safety challenges. Similarly, Vidan, Slišković & Očašić (2016) explored

the operational and environmental safety of seaplane traffic in Croatia, noting differences in waste management between seaplanes and traditional vessels. These studies emphasise the need for customised safety protocols that consider the specific dynamics of seaplanes on water.

In conclusion, the water environment is a complex and dynamic place where two transport sectors intersect. Even though the literature including both seaplanes and vessels is very limited, it is nevertheless important to study these sectors separately and mitigate their specific risks. Both the maritime and aviation sectors benefit from tailored SMSs that incorporate human factors and risk assessment methodologies. Therefore, this thesis will primarily focus on analysing maritime and aviation safety separately, through different case studies, while also detailing potential areas of concern between the two.

2.9. Conclusions of Chapter 2

This chapter provided critical safety-related background for this thesis. This included the concepts of Safety Management Systems (SMS) and risk assessment. Safety approaches have been described and their suitability for analysing accident and incident data has been discussed. These include traditional safety management, and the reactive, proactive and predictive safety approaches. Afterwards, the following accident models have been discussed, also focusing on their suitability for analysing occurrence data in the maritime and aviation fields: sequential and epidemiological models, Human Factors Analysis and Classification System (HFACS) and Systems Theoretic Accident Model and Processes (STAMP). Then, Section 2.5 assessed the role of data and its collection, and applied Heinrich's Theory for maritime data. This concluded that, while the theory seemed inappropriate, that could be because of underreporting. This issue will be further discussed in this thesis.

In this chapter, socio-technical systems have been defined to understand why this term is applicable for transport systems. The last sections provided essential background on human performance and the water environment, which are critical in understanding the methodology of this thesis presented in Chapter 5. Before that, the following two chapters provide critical background and literature reviews of different aspects of the maritime and aviation industries, necessary for understanding the subsequent case studies, which build on the safety information presented in this chapter.

3. Fundamentals of Maritime Safety

Having reviewed fundamentals of transport safety in the previous chapter, this chapter focuses on the safety of the maritime sector only, with emphasis on ports in the United Kingdom (UK). It provides useful definitions and classifications, as well as a comprehensive literature review, needed to understand the context of maritime safety, which is also useful for the subsequent analysis in Chapter 6.

As mentioned in the previous chapter, the maritime industry is a complex socio-technical system, and various hazards are part of its operations. Therefore, it is crucial to study the interdependencies between different risk factors, including vessel design, human performance, automation and environmental conditions, to develop effective risk mitigation strategies (Ismail, 2023; Hendriks & Gooyert, 2023). Recent studies emphasise the role of cybersecurity, automation failures and climate-related disruptions as emerging risks affecting port and vessel safety (Putra, Octavian, & Susilo, 2024; Punt, Monstadt, & Witte, 2023).

This chapter is structure into nine sections. The first four set the context of the maritime sector, including an overview of the industry, the role of ports, specific accident classification and other definitions, and details of the regulations and stakeholders involved in port operations and safety. The following four sections provide detailed reviews of the literature relevant for the subsequent case studies, including publications which address port safety, port congestion, methods of data analysis, autonomous vessels. Finally, the last section provides a summary of the achievements of this chapters.

3.1. Overview of the maritime industry

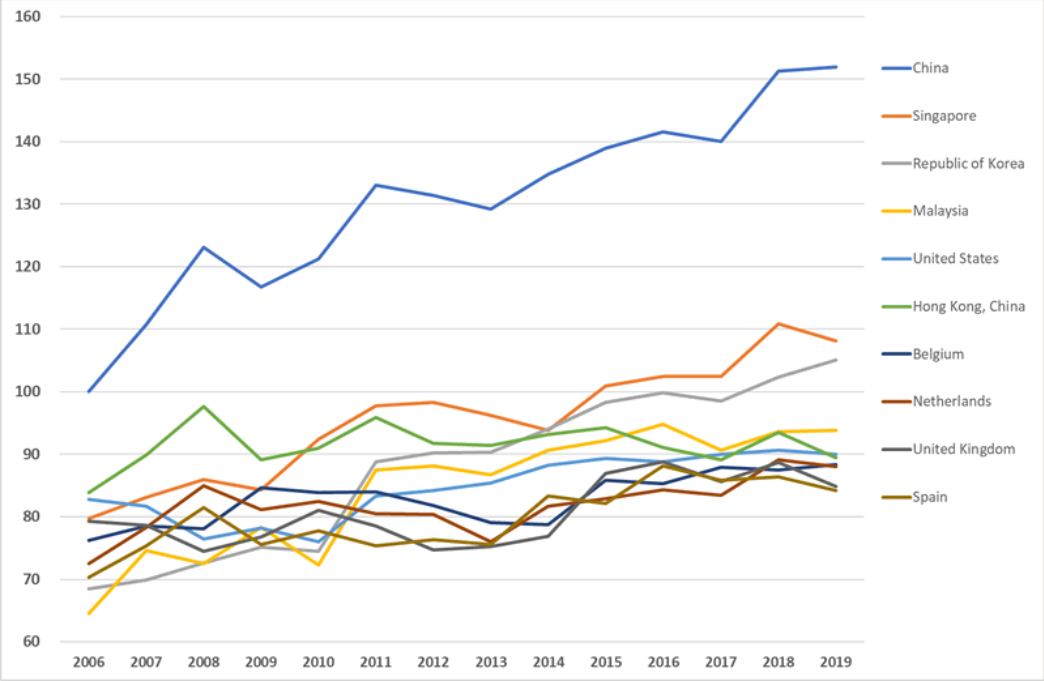
This section provides an introduction to the maritime industry and how this sector in the United Kingdom fits into the global one.

The maritime industry is a vital component of global trade, enabling the movement of goods and resources across international waters. This industry encompasses various activities, including shipping (e.g., commercial shipping, passenger transportation), port operations (e.g., port management, handling of goods in terminals) and maritime services (e.g., vessel maintenance, insurance providers, laws, regulations). This section provides an overview of the global maritime industry, discussing its economic significance, key trends, safety concerns, and the regulatory framework governing it.

The maritime industry is fundamental to global trade, as it facilitates the transportation of around 80% of international goods (UNCTAD, 2021). This sector is a significant contributor to the global economy, as it connects producers and consumers across continents, supporting millions of jobs around the world and generating substantial income. The countries with the largest maritime trade

networks in the world are presented in Figure 3.1.1. This figure displays the Liner Shipping Connectivity Index (LSCI) which reflects a country's level of integration into global liner shipping networks, and the higher the values, the better the connectivity. This is important because a nation's access to international markets is heavily influenced by its transport connectivity, particularly in the maritime industry for importing and exporting manufactured goods. This figure is based on UNCTAD's port LSCI for over 900 ports, along with new statistics on port calls and the time vessels spend in ports (UNCTAD, 2019). Data for January 2006 to June 2024 has been obtained from UNCTAD (2024) about the quarterly rankings using this index. It could be seen that, according to the most current ranking as of June 2024, the top 5 countries were the same as in Figure 3.1, however the places of Singapore and Republic of Korea, as well as of Malaysia and the United States of America (USA) were reversed. The UK maintained the same position in the ranking, while Spain raised from 10th to 6th place.

Figure 3.1. Liner Shipping Connectivity: top 10 countries, 2006-2019 (UNCTAD, 2020).



Given the geographical position of the United Kingdom, the maritime industry is crucial to the UK's economy. Around 95% of all its national imports and exports are transported by sea, through ports, which are worth more than £500 billion each year (Maritime UK, 2024). This is significant especially because, at a global level, shipping accounts for only 80% of the global trade volume (Bueger, 2015; Li et. al., 2023). Furthermore, in the UK, the maritime industry supports over one million jobs across the country and, every year, it adds over £46 billion to the country's economy (Maritime UK, 2024).

Nonetheless, in recent years, significant changes have been observed in the global maritime industry, which are especially related to technological advancements and environmental concerns. Innovations

such as digitalisation, automation and the use of big data are transforming maritime operations. As such, technologies as autonomous vessels and advanced navigation systems are considered to enhance efficiency and safety (IMO, 2019b). This aspect is detailed in Section 3.7 of this chapter, while Section 6.2 presents a case study about the expected impact of autonomous vessels, and whether this intended positive outcome on maritime safety is true. At the same time, the industry faces increasing pressure to reduce its environmental footprint. For example, the International Maritime Organisation (IMO) has implemented regulations to limit sulphur emissions from ships, aiming to reduce air pollution and protect marine ecosystems (IMO, 2020x). The adoption of greener technologies, such as liquefied natural gas as fuel, is becoming more common. However, studying implications of pollution from the shipping industry is outside the scope of this thesis.

3.2. Ports

This section provides an insight into the importance of ports as part of the bigger picture of the maritime industry which has been addressed in the previous section, with an emphasis on the ports within the United Kingdom. Then, a detailed classification of ports according to different factors is presented.

Ports are essential parts of the maritime sector. They represent harbours or other areas that aim to provide a protective refuge for various types of boats and vessels which transfer people or cargo. Not only do ports facilitate the loading and unloading of vessels, but they also serve as hubs for social activities, therefore simulating the social and economic growth of a region. Ports promote trade and commercial welfare, and they are a significant source of employment, but they can also serve other purposes such as military-related. Maritime trade is typically calculated as the product between the transported tonnage and the distance travelled, in tons/mile, and its cost compared to the final price of the product is significantly less than for other transport modes. This is why maritime trade is the most popular transportation choice worldwide.

In the United Kingdom, the port industry is the second largest in Europe. The national economy highly benefits from the port operations since, as previously mentioned, approximately 95% of the UK trade passes through its ports (ABP, 2019; BPA, 2022). In the UK, the port industry supports various maritime sectors including fishing, freight, leisure and offshore facilities (ICS, 2019). Additionally, the revenue from this industry almost doubled in 2022 compared to 2000 (Statista, 2023b).

There are around 120 commercial ports around the UK, including all-purpose ports, ferry ports, specialised container ports, ports catering for specialised bulk traffic and smaller ports for local traffic, fishing or other particular sectors (Statista, 2023a). Additionally, there are more than 400 non-cargo

handling ports and harbours in the country (Maritime UK, 2024). Their main aim is to facilitate smaller communities for fishing and provide links to remote areas in the UK.

Depending on their ownership, UK ports are divided into private, trust and local authority owned. Private ownership ports have no ownership interest from the Government, and they are owned by private companies or international groups. Trust ports are usually smaller ports that cannot be owned by other stakeholders, being financially and strategically independent bodies. However, some major ports are part of this category, such as the Port of London. Local authority owned ports, such as Portsmouth, function on a commercial and competitive basis. All UK ports are categorised as major or minor, whether they deal with more or less than 1 million tonnes of cargo every year (Maritime UK, 2022).

Having described the most common types of ports in the UK, Table 3.2 summarises all types of ports according to their use, geographical location, purpose, size, technology, ownership, and so on. This is relevant since, in this thesis, the focus is on civil ports of different purpose and size.

Table 3.2. Classification of ports according to different classification methods.

No.	Port type	Description
I	**According to their use:**	
1.	Civil port	Ports used for the loading and discharging of passengers and cargo, without any military use.
2.	Military port	Also called naval base or navy base. It is an establishment for warships and naval ships, where they are docked for restock, repairs or other activities such as training when they are not involved in a mission at sea.
II	**According to their geographical location, depth, ship sizes, purpose:**	
1.	Inland / interior port	Port on an inland waterway which may or may not be connected to the sea. It facilitates vessels movement between an ocean inland and a port, for cargo loading or unloading.
1.1.	On a navigable lake	
1.2.	On a river (fluvial port)	
1.3.	On a canal with access to a sea or ocean	
2.	Seaport	Town/harbour that facilitates docking of seagoing ships, as well as taking on / discharging cargo.
2.1.	Cruise port / port of load	
a.	Cruise home port	Port where passengers embark / disembark the cruise ships. This is also where the supplies for these ships are loaded (e.g., fresh water, food, fuel).
b.	Port of call	Intermediate stop for vessels along their sailing route. Here, cargo ships may stop for loading / unloading of cargo, fuel or supplies. Cruise ships may stop for embarking / disembarking of passengers.
2.2.	Cargo port	Port that handles numerous types of cargo, which are loaded / unloaded from vessels using mechanical means. Cargo ports comprise

		of separate operating terminals for each cargo type, which are operated by different companies (stevedores / terminal operators).
a.	Bulk port	Cargo port that handles only one type of cargo (e.g., wood, grains, liquid fuels, automobiles).
b.	Break bulk port	Cargo port that handles various types of cargo.
c.	Container port	Cargo port that deals with containerised cargo
3.	Fishing port	Used for the landing and distribution of fish. It is the only type of port that is dependent on ocean products.
3.1.	Recreational	Fishing port used for recreational purposes.
3.2.	Commercial	More common. Fishing port of commercial use.
4.	Hot / warm water port	Port in frozen places (e.g., Russia), where the water does not freeze during the winter.
5.	Dry port	Inland extension of a seaport. Interior intermodal terminal connected via highways or railway lines to a seaport. It is used to facilitate the shipment of goods or containers from seaports to interior ports. Dry ports may accommodate the storage/consolidation of goods, or even the maintenance of cargo carriers by road/rail. These facilities of a dry port represent competition for the ones offered by the seaport itself.
III	**According to their geographical location, purpose and technology:**	
1.	Smart port	Port of greater automation that uses new technologies such as Artificial Intelligence (AI) or Internet of Things (IoT), which increase their efficiency in handling goods.
IV	**According to size**	
1.	Major port	Port with at least two berths, which has facilities and equipment that can facilitate the discharge of 100,000 cargo tons / month.
2.	Minor port	Port that can facilitate cargo discharge only from coasters or lighters.
V	**According to their ownership (in the UK)**	
1.	Trust port	Term used in the UK for a port that is administered as a trust. This is done by an Act of Parliament that sets an independent statutory body which is governed independently by its own statutes and rules. Several trust ports have been privatised.
2.	Private port	Privately-owned port.
3.	Municipal port	Port owned by the local municipal authority.
VI	**Other**	
1.	Outport	Small port used to support a larger port with its commercial operations
2.	Port of entry	Port at the border of a country, used to lawfully enter / exit the country. Seaports can be ports of entry, under certain constraints set by the civil authority controlling the port. In the United States, however, the definition of ports of entry is different: the small so-called ports of entry that are not required to have a Port Director are called “stations” within a bigger port of entry.
3.	Home port	Port where a vessel is based, which may or may not be its port of registry. Cruise industry: this term is also used for the port where most of the passengers of a cruise ship embark / disembark, while the ship takes on fuel and other necessary supplies. For naval ships, their home port is the one that is best to offer maintenance and

		weaponry restock. After a tour of duty, the vessel usually returns to its home port, making it easier for sailors' family to visit them on leave.
4.	Transit port / Through port	Port where most cargoes are not coming from or going to the local market.
5.	Port of registry	Port where a vessel is registered.
6.	Landlord port	Port where the port authority builds the wharves which are later rented or leased to a terminal operator that invests in cargo-handling equipment, hires laborers and negotiates contracts with ocean carriers for loading/unloading of cargoes.
7.	Operating port	Similar to a landlord port, but the port authority also owns the cranes and cargo-handling equipment, so they also hire laborers. that pick cargo up pre-delivered to the docks and bring it to the storage facility.

3.3. Accident classification and definitions

Having reviewed the maritime industry and the importance of ports in the previous sections, this section provides various definitions and methods of classification related to port operations, including accidents, incidents, types of occurrences and types of vessels. These are useful for understanding the subsequent analysis of port safety in Chapter 6.

3.3.1. Accidents, incidents, casualties and occurrences

DfT (2017a) defines a marine accident as any Marine Incident or casualty. However, for the consistency of this thesis between the maritime and aviation terminologies, while also respecting specific taxonomies of the sectors, the word "occurrence" is introduced for the maritime sector, with the same meaning as for aviation (Section 4.3.2). Therefore, for the maritime safety, the word "occurrence" will be used as a synonym for "accident", with the subcategories "marine casualty" and "marine incident".

A marine casualty is described as an event resulting in the death or serious injury of humans, the loss of vessels or of people from them, considerable material damage to vessels or other marine infrastructure, collisions or pollution of the environment (MAIB, 2017). According to their severity, marine casualties can be grouped into:

- Very Serious (event resulting in severe pollution, loss of life or total loss of ship).
- Serious (event resulting in less severe pollution, partial loss of ship or when shore assistance is sought).
- Less Serious (any other casualties) accidents.

A Marine Incident, however, represents near-misses associated with the operation of a vessel, which have the potential to affect the safety of vessels, humans or the surrounding environment (MAIB, 2017). The IMO combines Less Serious accidents and Marine Incident, while the MAIB separates them when recording marine occurrences (IMO, 2014; MAIB, 2016), which is in line with EMSA practice (EMSA, 2015).

However, the MAIB requires reporting of Serious and Very Serious accident levels only, leading to a large potential for underreporting of less severe occurrences (MAIB, 2018b). Anderson (2003) has undergone a large-scale survey of the shipping industry to assess the way near-misses and accidents of different severity levels are reported, and proved that less severe occurrences are routinely underreported largely because seafarers are reluctant to report them.

3.3.2. Occurrence types

The maritime industry focuses on preventing not only life loss, but also vessel damage and environmental pollution. Therefore, accidents in the UK maritime industry can also be classified as Ship Casualties (SC) or Occupational Accidents (OA), according to regulations from the International Maritime Organisation (IMO) and the European Union (EU) (MAIB, 2015a, EMSA, 2016). An occurrence is referred to as CS when it affects a ship, its equipment or its cargo, while OA refers to humans being harmed on-board of a vessel. Figure 3.3 shows the accident types for SC and OA, while Table 3.3-A adds descriptions to each accident type. Both the figure and the table are in accordance with official classifications for accident types in the EU and UK, from MAIB (2015b) and EMSA (2017).

Figure 3.3. Occurrence types based on definitions and classification from MAIB (2015b) and EMSA (2017).

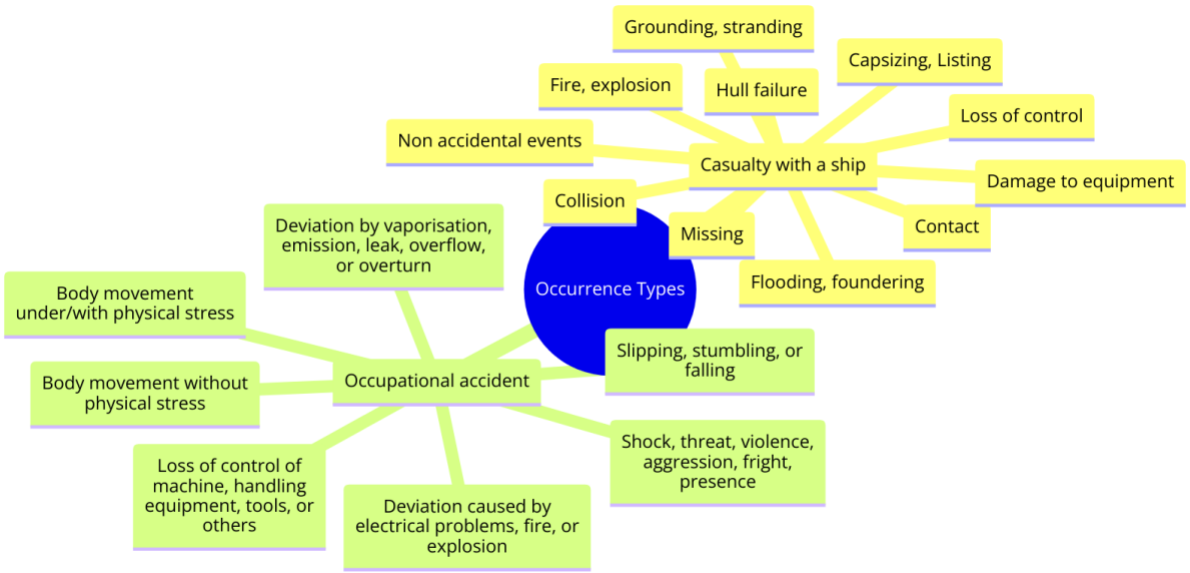


Table 3.3-A. Accident types with descriptions (Manole, 2019) - adapted from (EMSA, 2017).

Accident type	Description
Casualty with a ship	
Capsizing/Listing	The ship no longer floats in the right-side-up mode
Collision	The ship strikes or is struck by another ship
Contact	The ship strikes or is struck by an external object
Damage to equipment	Equipment is damaged or the ship is not covered by another casualty type
Grounding/stranding	The ship strikes the sea bottom/shore/underwater wrecks
Fire/explosion	The uncontrolled ignition of flammable substances on board of a ship
Flooding/foundering	The ship takes water on board
Hull failure	The ship structural strength is affected by a failure
Loss of control	The total/temporary loss of the ability to manoeuvre the ship, electric power failure
Missing	The fate of a ship is undetermined and there is no information on the loss after a certain period of time.
Non-accidental events	Intentional events, illegal or hostile acts
Occupational accident	
Shock, threat, violence, aggression, fright, presence	
Deviation by vaporisation, emission, leak, overflow or overturn	
Slipping, stumbling or falling	
Loss of control of machine, handling equipment, tools or others	
Body movement without physical stress	
Body movement under / with physical stress	
Deviation caused by electrical problems, fire or explosion	

3.3.3. Vessel types

The vessel types used in the UK by the MAIB coincide with those used internationally by the European Maritime Safety Agency (EMSA) and the IMO. However, the MAIB includes six vessel types outside the scope of EU Directive 2009/18/EC: fishing vessels of less than 15 metres, primitive wooden ships, ships unpropelled by mechanical means, inland waterway vessels, commercial recreational craft with less than 13 people on board and government-owned vessels (MAIB, 2016). The vessel categories used by the MAIB are summarised in Table 3.3-B, while the main causes of injury in ports are detailed in Section 3.5.

Table 3.3-B. Vessel types, according to MAIB definitions (MAIB, 2020b).

Vessel Type	Description
Merchant vessels over 100gt	Vessels over 100gt used for trading or non-reading, excluding fishing vessels
Merchant vessels under 100gt	Commercial vessels under 100gt, excluding fishing vessels
Commercial recreational	Subset of the merchant vessels described above. Examples: tall ship, luxury yacht, chartered yacht, rented dinghy

Vessel Type	Description
UK fishing vessels	Any commercial fishing vessel registered in the UK
Passenger	Seagoing passenger vessels and inland waterway vessels
Service ship	Offshore industry vessels, tugs, dredgers, SAR craft
Recreational craft	Commercial or non-commercial
Non-UK vessels in UK waters	Any vessel that is not believed to be a UK vessel, but the events took place within 12 miles of UK territorial waters

3.4. Maritime regulations and stakeholders

The maritime industry is heavily regulated to ensure safety, security, and environmental protection. This section provides an overview of the main stakeholders and regulations relating to maritime safety internationally and in the United Kingdom.

3.4.1. Maritime regulations and stakeholders at an international level

Key regulatory bodies include the International Maritime Organisation (IMO), national maritime authorities and port state control (PSC) regimes. The IMO is the primary international regulatory body for the maritime industry, responsible for developing and maintaining a comprehensive framework of international maritime regulations. One of the first tasks of the IMO was to adopt a modern version of the International Convention for the Safety of Life at Sea (SOLAS). They have not only established international standards and regulations for seafarers, but also developed international conventions and codes of practice. Other conventions include MARPOL (Marine Pollution) and STCW (Standards of Training, Certification, and Watchkeeping for Seafarers) (IMO, 2021). Additionally, PSC regimes, such as the Paris and Tokyo Memoranda of Understanding (MoUs), play a critical role in enforcing international regulations by inspecting foreign ships in national ports. These inspections help ensure compliance with safety, security, and environmental standards (Paris MoU, 2020).

IMO's senior technical body on safety-related matters is called the Maritime Safety Committee (MSC). It comprises of a number of Sub-Committees which aid it in its work, from which the most relevant are: Implementation of IMO Instruments, Human Element, Training and Watchkeeping and Ship Systems and Equipment (IMO, 2021).

The occupational safety on vessels is a constant matter of concern, for national and international maritime organisations. As such, regulations are adopted and adapted to improve the safety conditions of maritime operations. The best approach to improve safety is thought to be the development of international regulations that must be accepted and adopted by all shipping nations (IMO, 2019a). For example, the research of Zhang et. al. (2018) on port governance includes 77 international studies. It determined the main constituting elements of port governance to be the port

and governmental organisations, although other specific governance systems exist in different countries.

3.4.2. Maritime regulations and stakeholders in the United Kingdom

Because of the already established international nature of maritime shipping and to ensure that safety and environmental concerns are appropriately addressed, the authorities that develop the regulations and frameworks for the maritime safety within the UK can be divided into four categories: international, European, national and local. From a regulatory perspective, UK's safety standards are largely dependent on its national legislations and local regulations.

UK legislation requires all marine casualties to be reported, with few exceptions, and these are subsequently investigated by the MAIB which is an independent unit within the Department for Transport. The MAIB investigates both marine accidents involving UK vessels worldwide and international vessels in UK territorial waters. The MAIB is not required to report occurrences to the European Union anymore, and it operates independently of EMSA as, following Brexit, it introduced a new case management system. Consequently, the MAIB undertakes safety investigations on behalf of the Category 1 Red Ensign Group of British Shipping Registers that includes the United Kingdom, UK Overseas Territories and Crown Dependencies. Vessels registered in any of these countries fly the Red Ensign flag (MAIB, 2020b, REG, 2022).

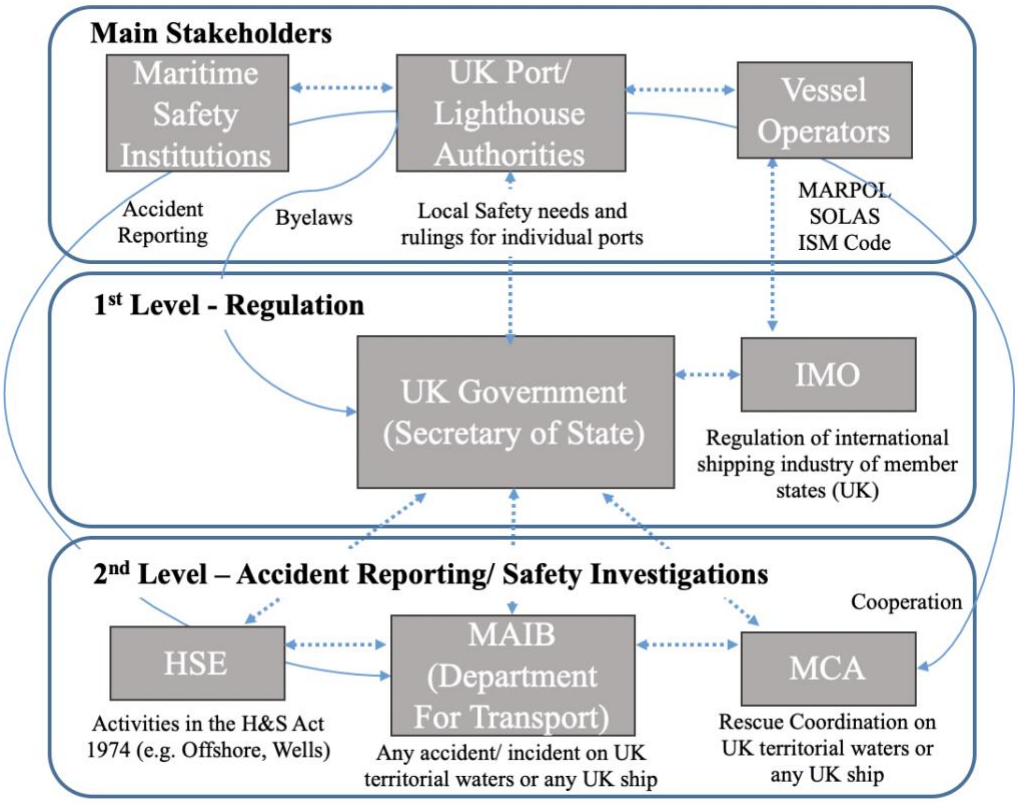
Table 3.4 provides a description of the stakeholders involved in UK port activities, of which some have been included in Figure 3.4. Figure 3.4 presents the organisational and regulatory framework of maritime safety institutions within the UK, which have been separated in three categories according to their main responsibilities: main stakeholders, regulations, and accident reporting / safety investigations. The figure focuses on the roles, responsibilities, and the cooperative nature of maritime safety governance in the UK, referring to UK territorial waters, covering up to 12 nautical miles from the UK shore, where these organisations exercise their safety responsibilities.

Table 3.4. Description of the stakeholders involved in port activities in the United Kingdom.

Name	Description
International level	
IMO	It is the UN agency responsible for establishing maritime shipping regulations at a global level. IMO seeks to enhance the safety of maritime operations, considering the protection of the marine environment, the health and life. The conventions that are developed by this organisation are later adopted into codes of practice and into law (*IMO, 2019a*). Consequently, the Formal Safety Assessment has been used since 2002 to determine the potential risks of different shipping activities.
IEA	It is the international federation that comprises the human factors and ergonomics societies worldwide. It seeks to develop the practice of ergonomics and to improve people's lives, by expanding its contribution to the society. According to IEA (*IEA, 2019*), the main goals of the

	association are to expand the practice of ergonomics internationally and to establish more effective means of communication with other federations and societies.
European level	
EC & EMSA	Until the end of 2020, as a current member of the EU, the UK enacted maritime safety laws from the European Commission, with input from the European Maritime Safety Agency. EMSA is an association in the EU in charge of offering technical assistance regarding Directive 2009/18/EC, which contains the main principles that underly the accident investigation related to maritime transport. This agency is responsible for controlling and embellishing the European Marine Casualty Information Platform, which is a means of storing and evaluating investigation reports and data about casualties at a EU level (*EMSA, 2021*). The safety laws delivered by the EC consider the examination of past maritime accidents in the EU, and they also conform to the codes from the IMO.
National level	
DfT & MCA	The national Government Departments and Agencies that enforce the UK Maritime Safety Regulations are: the Department for Transport, which is tasked with administrating the maritime policy and for providing reports on Maritime Statistics, and the Maritime Coastguard Agency, which is responsible for implementing policies and regulations for maritime safety (*MCA, 2019*).
MAIB	The agency responsible for accident analysis in the UK is the Maritime Accident Investigation Branch. Its objective is to improve maritime safety by professionally analysing past accidents in the UK, in compliance with EMSA protocols (*MAIB, 2018b*). Recommendations based on lessons learnt from past accidents represent a key part of MAIB investigations. Their aim is to promulgate the safety message, in order to avoid future accidents. After an accident investigation, the MAIB typically makes achievable recommendations to relevant stakeholders at a local level that are best to implement them, in order to prevent re-occurrences. They can accept or deny a recommendation.
ABP	The Associated British Ports is the biggest port operator in the UK, comprising of a 21 ports network across England, Wales and Scotland, including the nation's busiest port of Immingham and UK's second largest port of Southampton (*ABP, 2019*). Being so experienced in managing these ports, ABP is a leader for the development of the 2016 Port Marine Safety Code, which specifies all the responsibilities of Harbour Authorities. This port operator aims to promote safety and efficiency for their ports by implemented a transparent work policy, and by studying in detail and solving any areas of concern.
BPA	The British Ports Association (BPA) represents 350 ports and facilities around the UK and it takes the environmental responsibilities very seriously. Its chairman at the time of writing, Alec Don, declared that, due to Brexit, BPA can develop a sustainable development plan that helps preserve UK's environment. He also claims that the role of the association is to manage the seas in a careful, sustainable way, making sure that the ports are secure, safe and independent of the Government (*BPA, 2022*).
Local level	
Vessel owners and operators	
Port and harbour authorities	
Industry and regulatory bodies	

Figure 3.4. Combined operation amongst maritime safety institutions in the United Kingdom (Majumdar, Manole and Garcia Sinobas, 2024).



At an international level, as mentioned in the previous section, the UK follows maritime safety laws and regulations from the IMO. Furthermore, the International Ergonomics Association is the international federation comprising of the human factors and ergonomics societies worldwide, with the aim to improve people's lives (IEA, 2019). All the marine occurrences reported to the IMO are part of the Global Integrated Shipping Information System (GISIS). The methods for accident reporting to the IMO are based on periodically updated rules which are published on their website (IMO, 2022).

Since the maritime industry is very diverse and multicultural, it makes its specific vocabulary or taxonomy for hazard identification a challenge (Stoyanov, 2009; Badawi and Halawa, 2003). To address this issue, language standardisation procedures such as the IMO's Standard Marine Common Phrases exist. EMSA has its own accident taxonomy for their casualty information platform (EMCIP), but it is used only when the accident investigation agencies of Member States upload their formal incident reports to EMSA. However, as previously mentioned, the MAIB is not required to do so anymore.

At a national level, the United Kingdom enacts internal protocols for the safety of both UK vessels worldwide and non-UK vessels that operate in UK territorial waters (within a 12 nautical miles radius). These regulations comply with the IMO and European Commission (EC) guidance. The national Government Department that enforces maritime safety regulations in the United Kingdom is the

Department for Transport (DfT), which administers maritime policy and shares reports with updated maritime statistics (MCA, 2019).

As previously outlined in Figure 3.4, the role of the DfT in the maritime safety involving UK territorial waters is fulfilled by three institutions, which are tasked with accident reporting and safety investigations in the UK. These are:

- the MAIB - focused primarily on investigating marine accidents and incidents,
- the Maritime and Coastguard Agency (MCA) - concerned with shipboard and coastal activities, particularly from an occupational health and safety perspective, and
- the Health and Safety Executive (HSE) - conducts investigations related to the Health and Safety Act of 1974, largely focusing on occupational accidents involving offshore structures.

These institutions operate within a framework that encourages collaboration with maritime industry stakeholders such as port and coast authorities, vessel operators, and non-governmental organisations like the Royal National Lifeboat Institution (RNLI). This collaborative approach enhances local maritime navigational safety regulations and practices. Additionally, these institutions share the roles for promoting, co-ordinating, implementing and enforcing the safety of the maritime sector in the UK (DfT, 2022). The MCA, as well as harbour and inland waterway authorities, must report all accidents to the MAIB.

The MAIB is the agency responsible for accident analysis in the UK. The main maritime data used in this thesis is obtained from MAIB databases. This agency aims to improve maritime safety by professionally analysing past accident and incident occurrences in the UK, while complying with EMSA protocols (MAIB, 2018b). Recommendations are provided, based on the lessons learnt from the investigation of past accidents. Their objective is to promote safety, so that future accidents can be avoided.

One of the maritime SMS requirements in the PMSC (introduced in Section 2.2.2) is that ports operate local accident reporting schemes, while establishing their own procedures for safety evaluation and enforcement. These reports can be sent to the MAIB or kept for internal records. Regarding internal reporting, UK ports use the same classification schemes as the ones proposed by the MAIB for “Serious” and “Very Serious” marine casualties (Port of London Authority, 2023; Forth Ports, 2016). Nalty (2017) stated that the taxonomy for the lower-severity accidents and marine incidents differs across ports, terminals and individual shipping companies. Additionally, Harbour Authorities set enforcement policy that conform to formal risk assessments (DfT, 2016). However, as mentioned previously in Section 3.3.1, the fact that less serious accidents and marine incidents are not mandatory to report at a national or international level lowers the quality of the research using such databases.

In addition to this, taxonomy for risks and hazards may also vary at a local level, since small ports are privately operated and they develop their own hazard identification schemes. This is also the case for larger ports, as their terminal operators are private. The Port of London Authority, for example, addressed this by implementing routine port-wide Hazard Identification meetings. However, the terminal operators may have other methods of hazard identification (Port of London Authority, 2023).

To address the issue of underreporting and fear of punishment, there are two main methods of voluntary reporting in the UK's maritime sector: the Confidential Human Factors Incident Reporting Programme (CHIRP) and the International Mariners' Alerting and Reporting Scheme (MARS). These are programmes that implement a confidential voluntary reporting system for mariners, while emphasising on the importance of learning from near-misses and less severe accidents. They help identify unsafe operations and hazards. Since the reporting is confidential, they do not forward information beyond final reporting to the MAIB. On average, CHIRP receives around 100 reports annually, from which some are published in their magazines and annual reports. They believe that mitigating minor accidents and near misses can lead to a reduction in the more severe accidents (Lloyds List, 2016). Similar to CHIRP, the people reporting are required to submit a narrative description of the incident only to MARS databases. These are then anonymously included in their monthly newsletter.

Having reviewed relevant stakeholders and maritime regulations, the following section provides an overview of the literature on factors affecting the safety of vessels transiting ports.

3.5. Relevant studies of critical factors affecting the safety of vessels transiting ports

There are different views throughout the literature on the best ways to address maritime safety. For example, Hänninen (2015) stated that this industry can be analogised to as a tightly coupled system, while Perrow (1984) defined the interactions of this industry as linear, implying that these interactions are familiar and expected.

This section addresses the differences in literature reviews and findings through two sub-sections which examine factors influencing safe vessel transits through ports, separately for SC and OA. This is because, as previously mentioned in Section 3.3.2, these categories include distinct accident types, so their contributory factors are expected to differ.

3.5.1. Main causes of ship casualties in ports

As previously mentioned, marine casualties and incidents can be divided in two categories: ship casualties (SC) and occupational accidents (OA). This section analyses critical factors for ship casualties

only, which are underlined for easy spotting, and focuses on the research of the following categories of factors: port characteristics, vessel characteristics, environmental conditions and technology.

Previous studies used accident data, incident data, surveys and interviews to study factors contributing to SC. The factors described a wide spectrum of aspects including port and vessel characteristics, weather and sea state, traffic conditions, human factors for the key actors during embarking and disembarking (i.e. pilot, ship master, tug master and vessel traffic service (VTS) operator), technologies (e.g. navigation and communication technologies) and traffic management systems (e.g. VTS). These factors are discussed below.

Pak et. al. (2015) studied the impact of port characteristics on port safety by distributing a survey across 27 captains, who were operating in the Korean ports. Using fuzzy analytical hierarchy process, Pak et. al. (2015) found that high traffic volumes reduced port safety. They identified that the depth and width of the channel connecting to the port were critical factors. Fog and strong wind also contribute to port safety at the similar level as the depth of the channel condition. In a study of accident risks in ports of Japan, Hashimoto and Okushima (1990) revealed that speed regulation and traffic control can reduce accident risks. However, there was no convincing evidence to suggest that such restrictions reduce accidents in a recent study of the efficacy of reduced-speed zones (Chang & Park, 2016). However, Chang & Park (2016) revealed that, to save money, an increase in fuel price can result in reduced cruise speed, possibly reducing accident risk.

Li, Yin and Fan (2014) developed a maritime safety index to compare the safety level of the vessels. The index considered vessel age, size, flag state and type, the location of the accidents and the season they occurred. They used records of 130,000 commercial vessels to calibrate binary regression analysis models. The analysis indicated that cargo and passenger vessels were the most hazardous vessel types. Therefore, it can be expected that large vessels, cargo and passenger vessels will be the most frequent type of vessels reported in the maritime safety databases. The environmental conditions that vessels are exposed to (i.e., weather, natural light, wind speed, sea state and visibility) have been studied by Balmat et. al. (2009) and by Pak et. al. (2015). However, the relationships between the environmental conditions and vessel characteristics have not been taken into account in the accident prediction models in the literature.

Navigation technologies used in the bridge (featured in the bridge system) are the Electronic Charts Display and Information Systems (ECDIS), Integrated Navigation Systems (INS) and the radar, with digital technologies replacing paper and analogue systems. According to a survey of the use of navigation technologies by seafarers (Vu, Lützhöft & Emad, 2019), the use of the displays by seafarers depended on the situation the seafarers were into and it was influenced by a wide array of factors

including the sailing area, traffic conditions, weather conditions and presentation of information. For example, in areas that there was little sea room to manoeuvre, the seafarers engaged with the emerging technologies to monitor the ship position. In high traffic density areas, they also engaged with the collision avoidance systems and other devices to plan alternative route (Vu, Lützhöft & Emad, 2019). In cases of unfavourable weather and sea conditions, the seafarers looked at weather data and forecast more intensively than favourable weather conditions. When working with radar/chart overlay and Alert Management, seafarers faced information overload potentially degrading their performance (Vu, Lützhöft & Emad, 2019). For example, some seafarers confirmed radar echoes using radar/chart overlay whereas other seafarers faced difficulties to locate such information.

The manoeuvring near ports is a collaborating activity involving the VTS operator at the shore, the pilot, the ship master and the tug masters onshore. According to Mansson, Lutzhoft & Brooks (2017), the way all these four operators communicated differed as follows: the ship master and pilot interacted face-to-face, and the tug masters used the Very High Frequency (VHF) radio to talk to the pilot and VTS operator. Due to the poor sound quality, they sometimes assumed what was said on the radio based on their perceived traffic and weather conditions leading to miscommunication. To overcome the limitation of poor sound quality, the pilot and VTS operators often talked via a mobile phone (Mansson, Lutzhoft & Brooks, 2017). However, the use of multiple communication mediums has a limitation: the pilot needs to pass the information to the other bridge crew, and this sometimes does not happen leading to reduced situation awareness of the other bridge crew.

According to Mansson, Lutzhoft & Brooks (2017), team coordination was typically facilitated by the pilot leading and directing the embarking and disembarking of the vessel. Pilots sometimes preferred to perform autonomous actions rather than joint actions due to the poor communication in the bridge, lack of language proficiency and different expectations of the role and responsibilities of the members the tug masters and VTS operators. Thus, it was perceived that the pilot was the team leader who made the navigation decisions causing a conflict between the ship master and the pilot. Therefore, both miscommunication and miscoordination at the bridge and between the shore and the bridge can cause safety problems.

In addition to the previously mentioned factors, the living, sleeping and working environment of seafarers can lead to fatigue causing major safety problems as crew performance can degrade affecting both seagoing and approaching a port (Russ, 2019). Fatigue at sea can be caused by numerous factors, such as long working hours, excessive noise, temperature variations, light, humidity (Seafarers, 2023). Moreover, ships' crews are constantly under pressure from their voyage schedules and they sometimes deliver tasks with fewer people than required (Project Martha, 2016). Fatigue

can result in stress, slower reaction time, reduced vigilance, or long-term effects that may cause mental and physical disorders, affecting people's behaviour and wellbeing.

VTS operators also play a critical role in safety as they manage the traffic at port. According to Abdulla (2011), using surveys and interviews, the following degraded the VTS operator's performance: lack of experience of the local shipping traffic density, a busy radio frequency, lack of sea experience by the VTS operator, lack of regulatory functions for such a vessel traffic service and the variations of the VTS among ports. Some participants also identified English language abilities as an underlying factor of safety. These findings highlight the importance of onshore systems to the port's safety. Furthermore, Chauvin et. al. (Chauvin, 2013) concluded that accidents were attributed primarily to decisions made by the crew. They also identified that poor visibility, the misuse of the technologies, e.g., radar, and miscommunication between the crew also contribute to the accidents. Whilst it is not clearly specified, it is assumed that they used long detailed accident reports.

3.5.2. Critical factors for occupational accidents in ports

In contrast with the previous section, this section analyses critical factors for Occupational Accidents (OA) only, focusing on the research of human-related factors and consequences. This section includes OA factors at an international level and in the United Kingdom, which are underlined for easy spotting.

There are substantially fewer studies focusing on occupational accidents, possibly because these are more difficult to study since, as previously mentioned, relevant details related to humans are not present in databases. For example, it is generally impossible to determine from databases why people stumbled.

According to the International Maritime Organisation (IMO, 2014), slips, trips and falls constitute the main causes of maritime accidents, representing 20% of the personal injuries in ports internationally. Many of these accidents are reported on container ships (Lecue and Darbra, 2019). Another study highlighted that wet and slippery surfaces can become hazardous, increasing the risk of slipping, as 38% of reported slips were found to have occurred on wet surfaces (Zhou et. al., 2017). Poor lighting can also contribute to trips and falls by obscuring hazards, especially in areas such as engine rooms and lower decks (Smith et. al., 2015). For example, Brown et. al. (2016) concluded that poor lightning and fatigue contribute to numerous accidents on cargo ships. Other contributors to slips and falls are fatigue and distraction of crew members working long hours or under high-stress conditions who may be less attentive to their surroundings (Hansen et. al., 2016) or wearing inappropriate footwear that lacks proper grip or is inappropriate for the work environment (Dawson et. al., 2017, Taylor et. al., 2018).

Additionally, port employees can also suffer from health issues because of dust or noise (Pak et. al., 2015). Furthermore, the number of accidents related to cranes and other mobile equipment that can be found in ports has been increasing, resulting in fatalities and serious injuries (Lecue and Darbra, 2019). One explanation can be the increased awareness on reporting such accidents. It is also possible that integration of advanced technologies at ports and vessels might have created new hazards that have not been well articulated in the safety management and thus their risk was not mitigated.

The introduction of automated systems can lead to accidents if the systems fail or are not properly understood by the crew. For example, the automation of navigation systems can cause over-reliance on technology, leading to reduced vigilance (Fisher, 2020), or navigation automation failing, leading to collisions and groundings (Grech, Horberry & Koester, 2008). Cybersecurity has also been discussed in the literature, such as hackers compromising navigation and communication systems (Tam and Jones, 2019).

In the United Kingdom, according to ABP (2019), the main causes of ill health and injury at ports are the following: workplace transport, slips, trips, falls from height, lifting operations, confined spaces and freight containers. Workplace transport can lead to people being crushed by vehicles, noting that the people who drive in ports can work for different employers, being unfamiliar with the port environment (ABP, 2019). Fall from height, although less often than the already mentioned types of accidents, is one of the biggest causes of major injuries and fatalities in a work-related environment at the British ports (ABP, 2019). This risk is present in many port activities and can also lead to risk of drowning. ABP (2019) claims that slips and trips cause over a quarter of the reported accidents and can result in major health effects, especially when leading to falls from heights or in the water. However, actions such as reporting any untidy workspace, could perhaps mitigate this risk (Ljung et. al., 2014). A vast range of lifting equipment is used at ports for loading and unloading, such as cranes and trucks. Poor planning of lifting operations can result in major risks for the people around. Furthermore, the equipment that is properly maintained and well-functioning will enhance safety. Another accident factor leading to serious injuries and fatalities is confined spaces. The people affected are not only those working in such a space, but also the ones with inadequate equipment or training who try to rescue the victims.

3.5.3. Summary of factors underlying maritime safety

Table 3.5 outlines a summary of this section about critical factors affecting the safety of vessels transiting ports and the people on board, including the factors considered in the literature review of ship casualties and occupational accidents, and studies that considered them. Understanding these factors is crucial as they could influence safety performance, which is evident from the literature.

Table 3.5. Summary of the literature review on critical factors affecting the safety of vessels transiting ports and the people on board, specific for ship casualties and occupational accidents.

Factor	Source	Assumption in this study
Ship Casualties		
Port characteristics including sea room	(Pak et. al., 2015), Ismail (2023)	Small volume of space (including width and depth of waters) increases the effort to manoeuvre the vessel.
High traffic volumes	(Pak et. al., 2015), Hendriks & Gooyert (2023)	High traffic volumes increase the effort to manoeuvre the vessel and maintain a safe distance from vessels and objects.
Environmental conditions (e.g., Visibility, Wind, Sea state)	(Pak et. al., 2015), (Balmat et. al., 2009), Hendriks & Gooyert (2023)	Reduced visibility degrades situation awareness of both the pilot and the VTS operator. Strong wind challenges the control of the vessel. Ship design relates to the impact of the wind and sea state on the ability to navigate the vessel.
Speed	(Hashimoto and Okushima, 1990)	Low speed improves the control of the navigation and manoeuvre, decreasing the accident risk.
Communication, Cognitive, Technological	(Vu, Lützhöft & Emad, 2019), (Mansson, Lutzhoft & Brooks, 2017), (Chauvin et. al., 2013), (Mansoor, 2011)	Miscommunication between bridge crew increases the accident risk. So does the miscommunication between the bridge, the tug masters and the VTS. Poor sound quality of the VHF radio can lead to communication errors leading to reduced awareness and poor decision making. Busy radio frequency and language barriers also increase the accident risk.
Coordination between shore and bridge	(Mansson, Lutzhoft & Brooks, 2017), Hendriks & Gooyert (2023)	Varied perception of the role and responsibilities of the key actors, i.e., pilot, ship master, tug master and VTS, degrades the performance of all actors increasing the accident risk.
Vessel Traffic Services (VTS)	(Abdulla, 2011), Putra et al. (2024)	The following can degrade VTS operator's performance increasing accident risk: VTS's lack of experience of the local shipping traffic density, lack of sea experience by the VTS operator, a busy radio frequency making it difficult to isolate information, lack of regulatory functions for such a vessel traffic service and the variations of the VTS among ports.
Cybersecurity and Automation Risks	Punt et al. (2023), Putra et al. (2024)	
Fatigue	(Seafarers, 2023), (Project Martha, 2016)	Fatigue can degrade crew's performance due to among others long working hours, excessive noise, temperature variations, light, humidity.
Occupational Accidents		
Wet or Slippery surfaces, Poor lightning	(Zhou et. al., 2017), (Lecue and Darbra, 2019), (Smith et. al., 2015), (Brown et. al., 2016), (Dawson et. al., 2017)	Wet and slippery surfaces are the primary causes of slips. Poor lightning can also lead to slips and falls. Weather conditions (e.g., rain, sea spray) or operational activities (e.g., washing the deck) can increase the hazard of slippery surfaces.
Untidy workspace	(ABP, 2019)	Trips can result in injuries. For example, poor housekeeping practices, such as leaving tools, equipment or cargo unsecured, can create tripping hazards.
Dust, Noise	(Pak et. al., 2015)	Dust and noise can contribute to health issues, usually short-term.
Mobile equipment, Lifting operations	(Lecue and Darbra, 2019), Hendriks & Gooyert (2023)	The number of accidents related to cranes and other mobile equipment found in ports has been increasing. An example is lifting equipment, such as cranes and trucks. These can result in fatalities and serious injuries.

Advanced technologies, Cybersecurity	(ABP, 2019), (Fisher, 2020), (Grech, Horberry & Koester, 2008), (Tam and Jones, 2019), Punt et al. (2023)	The integration of advanced technologies at ports and vessels might have created new hazards, including failure of automated systems and cybersecurity.
Workplace transport	(ABP, 2019), Ismail (2023)	Workplace transport can lead to people being crushed by vehicles. This can relate to unfamiliarity with the port environment or unawareness.
Fall from height	(Smith et. al., 2015), (Hansen et. al., 2016), (ABP, 2019)	Fall from height is one of the biggest causes of major injuries and fatalities, as it leads to physical injuries or drowning. This can also occur because of lack or improper use of safety equipment, such as harnesses and guardrails.
Poor planning	(Haddon-Cave, 2009), (Ljung et. al., 2014), (ABP, 2019)	Poor planning of operations, inadequate risk assessments and lack of coordination can result in major risks for the people around.
Confined spaces unfamiliarity	(Brown et. al., 2016), (Dawson et al., 2017), (ABP, 2019)	Confined spaces can have low oxygen levels or toxic fumes. The people affected can be workers or even rescuers without adequate equipment or training.
Inadequate training	(Williams & Geller, 2013), (Taylor et. al., 2018), (ABP, 2019)	Inadequate training can lead to lack of emergency preparedness or some of the already mentioned factors, such as poor planning, improper use of mobile equipment or new technologies.

3.6. Literature review on the use of data processing methods to study maritime safety

As observed by reviewing previous research on the analysis of marine casualties and incidents in the previous section, the majority employ techniques such as descriptive statistics and trend analysis, which are seen as “basic” in some of the more recent published studies. This section focuses on publications which adopt more advanced strategies aimed at performing comprehensive risk analyses with the ability to address the complex interactions between different factors affecting safety. Table 3.6 presents an overview of literature using different methods of analysis, accounting for the advantages and disadvantages of these methods.

Table 3.6. Publications using different data-driven methods (adapted from Yang et. al., 2024).

References	**Methods**	**Application**	**Advantage**	**Disadvantage**
Wang et. al. (2021)	Ordered logistic regression	Generate the RIFs related to maritime accident severity.	Applicable to ordered categorical dependent variables (e.g., severity). The model is highly interpretable and does not need to satisfy the linearity assumption.	Multiple covariance issues between RIFs and a high requirement of the data quality.
Liu et al. (2016)	Simulation trials	Model and analyse complex systems under variable conditions to assess potential outcomes and identify optimal strategies.	Can simulate previous occurrences to obtain factors that are missing in the database or report.	Large amount of data required for a satisfactory calibration required for the simulation experiments. Inaccurate results are likely.
Arend (2020)	Fuzzy evaluation	Address ambiguity in decision making.	Address uncertainty and imprecision in data by assigning degrees of belonging to different criteria. Promotes a flexible decision-making process. Able to provide accurate results.	Complex calculation and highly subjective method. Fuzziness can worsen, provide poor results and even impair judgement.
Louhichi (2014)	Grey clustering	New method developed and tested on artificial dataset.	Effective, simple and efficient method. Can find arbitrarily shaped clusters in noisy datasets.	Sensitive to infrequent or extreme values. Can be unstable in handling distributed sets of large databases.
Wang et. al. (2024)	HFACS & Bayesian network (BN)	Hybrid methodology to investigate the human and organisational factors of collision accidents between two types of ship.	Ability to incorporate the hierarchical framework with the quantitative analysis.	Model validation and sensitive to missing data.
Fu et. al. (2023)	Object-oriented BN	Quantitative risk assessment of navigational accidents in the Arctic.	Ability to reflect relationships between RIFs and quantify their impact.	Additional decision-making methods are needed to evaluate the effectiveness.

References	Methods	Application	Advantage	Disadvantage
Ma et. al. (2022)	Text mining	An algorithm capable of extracting keywords from accident reports.	Ability to extract information from unstructured data.	Computationally complex, data quality issues and explicability.
Weng and Li (2019); Cakir, Fiskin & Sevgili (2021)	ARM	A comparative analysis between two ARM algorithms.	Suitable for large-scale data and the ability to discover implicit relationships.	Hard to explain the results well if just reliant on the model parameters.
Lan et. al. (2023)	ARM	An algorithm to mine the critical factors of ship total loss accident.	Ideal for initial exploration of an area and the ability to discover implicit relationships.	Complexity is positively correlated with the amount and latitude of data.
Li (2014); Hänninen (2014)	BN	A data-driven BN model to analyse the RIFs of accident severity.	Strong predictability and explain ability. The Stable classification efficiency.	Computationally complex for a large network. Error rate in classification decision.
Fan and Yang (2024)	Least Absolute Shrinkage and Selection Operator & BN	A data-driven combined method to investigate the human fatigue.	Strong explain ability and easy to handle multiple data types.	Limited data and sensitive to missing data.
Sui et. al. (2021); Lan et. al. (2023)	Complex network	A comprehensive framework to investigate the key factors in collision accidents.	Ability to model and visualise complex relationships.	Lack of systematic topological analysis and dynamic evaluation.

Various data processing methods used for safety analysis have been presented in Table 3.6, including Bayesian networks (BN) and Complex Networks (CN). These emphasise the importance of thorough quantitative risk assessment and safety management to improve a system's safety. Hence, it is essential to make well-informed assumptions during the analysis stage to effectively prioritise the implementation of risk management strategies. For example, the BN method is highly regarded for its ability to support causal inference, and has been used often in recent years to study accident causation patterns. This is because it excels in identifying critical accident indicators, including the relationships among them.

Due to the previously mentioned advantages of this method of analysis, such as its ability to model complex, probabilistic relationships among risk factors, Bayesian Networks have already been employed in the analysis of maritime safety. BN are particularly advantageous in this field because they can facilitate the integration of data sources and expert judgments to predict the likelihood of different types of accidents and their potential severities. Therefore, their application in maritime safety has been extensive and varied.

For example, Wang et. al. (2023) used BNs to understand and mitigate risks associated with maritime operations, more specifically collisions of vessels carrying liquified natural gas. Hänninen (2014) applied BN to model the causative factors of maritime accidents, using data from historical accident reports and expert elicitation to construct the network. The study highlighted the ability of the networks to incorporate both empirical data and expert knowledge, providing a comprehensive risk assessment framework. However, Li, Ren & Yang (2023) mention the data limitations of BN, stating that 16 previous publications that addressed maritime safety using this method needed to overlook some essential pre-identified factors because of data limitations.

Similarly, Fan et. al. (2020) used a similar method of analysis, also to study risk factors influencing maritime transport accidents, demonstrating the capability of BN to predict the probability of different accident types under varying conditions. They integrated six years of data from the Marine Accident Investigation Branch of the UK and the Transport Safety Board of Canada. Although providing insightful results, this study also faces several limitations. Similar to the majority of research using BN, data limitations impact the significance and robustness of the results, especially for human factors. Moreover, expert judgment has not been incorporated into the definition of the BN, despite the data scarcity.

Other studies focused on specific aspects of maritime safety. More specifically for port safety, BN have been used to assess and manage risks associated with port operations. For example, Yang, Wang & Li

(2013) evaluated the safety of port operations focusing on human error, equipment failure and adverse weather conditions. They provided a detailed risk assessment model that could assist port authorities in prioritising safety interventions.

In summary, Bayesian Networks can be a flexible, powerful tool for maritime safety analysis, providing insights into the probabilistic relationships between pre-defined factors underlying the safety of this sector. While significant progress has been made in applying BN to different aspects of maritime safety globally, many countries including the United Kingdom lack comprehensive studies using this method. Additionally, specific limitations especially related to incomplete databases and overall data quality must be addressed (Ramoni and Sebastiani, 2000; Hänninen, 2014).

3.7. Autonomous vessels

One of the risk influencing factors discussed in Section 3.5 is the introduction of new technology. All other factors are recurrent, so that lessons can be learned from studying marine casualties and incidents from the past, thereby using a reactive approach as described in Section 2.3.2. However, when introducing new technologies such as Autonomous Vessels (AVs), new hazards and risks need to be forecasted using a predictive approach as historical data is not available.

This section starts with an overview of AVs. Since AVs represent novelty in the field and there is no related safety data, there is also a lack of literature for AVs in comparison with the other factors discussed in previous sections. Hence, this section will then provide a review and critique of available literature, and finally identify gaps to be later addressed in Section 6.2 through a case study. This section is based on a conference paper presented at the European Safety And Reliability conference in 2023 and later published in the same year (Manole and Majumdar, 2023).

3.7.1. Overview of autonomous vessels

The concept of Autonomous Vessels (AVs) dates to 1973, when Schonknecht discussed the possibility that captains steer ships from the shore, with on-board computers (Schonknecht, 1983). Then, it had been sought to advance automation but not fully, due to shipping companies hiring low-cost crews and high operational and maintenance costs of automation. Then, European research groups began project MUNIN to develop an autonomous cargo vessel. Therefore, remotely controlled unmanned vessels may soon navigate around the seas and completely change the safety of ports (Crawford, 2018).

The International Maritime Organisation started to work with the Maritime Safety Committee on a plan to consider the safety and environmental protection conditions that AV operations

could have. The IMO defines autonomous vessels as Maritime Autonomous Surface Ships that navigate without human interaction. To facilitate the process of regulating such vessels, the IMO has determined four degrees of automation, but vessels can use more than one in a single journey (International Maritime Organisation, 2023):

- Degree 1: Vessel with automated processes and choice help. Crew is on board to operate and make decisions;
- Degree 2: Remotely controlled vessel, crew on board;
- Degree 3: A vessel that can only be controlled remotely and has no crew on board;
- Degree 4: Fully AV. The vessel's working framework can make decisions and actions without human response.

Generally, AVs are expected to increase safety around seas and ports, since up to 96% of maritime accidents can be attributed to human errors (Allianz, 2023). This is also supported by the literature review of port safety in the previous section. However, questions arise due to the uncertainty of the sector about their ability to maintain safe navigation, detect hazards and compete with human capacity. The available literature on AVs is presented in the following section, after which the gaps are highlighted.

3.7.2. Available literature on autonomous vessels

There are only around 1,000 maritime autonomous surface ships in the world, but they are not in complete use and there is little literature on their impact on safety. A review of 47 documents published during the past decade indicates that the focus is on the technical aspect of autonomous operations and vessel design (Wróbel, Gil & Montewka, 2020). For example, studies exist on the application of the automatic identification system (AIS) data on path guidance of autonomous catamaran ferry (Xu, Rong & Guedes, 2019), the potential of remote pilotage operations (Lahtinen et. al., 2020) and the assessment of collision risk for autonomous surface ships (Huang and van Gelder, 2020). However, the changes in legal, organisational and social factors must also be considered, as they affect the safe and efficient development of autonomous shipping systems.

Research on the safety of autonomous systems is limited to hazard identification and analysis. Fan et. al. (2020) proposed a framework to identify factors influencing navigational risks by categorising an AV's voyage into operational phases. Risk influencing factors (RIFs) were determined through a literature review and subsequently grouped using an expert panel of subject matter experts. Fan et. al. (2020) determined that human related factors were the most prevalent, assuming that the AVs were controlled from shore. Thus, even with the removal of crews operating onboard a vessel, human

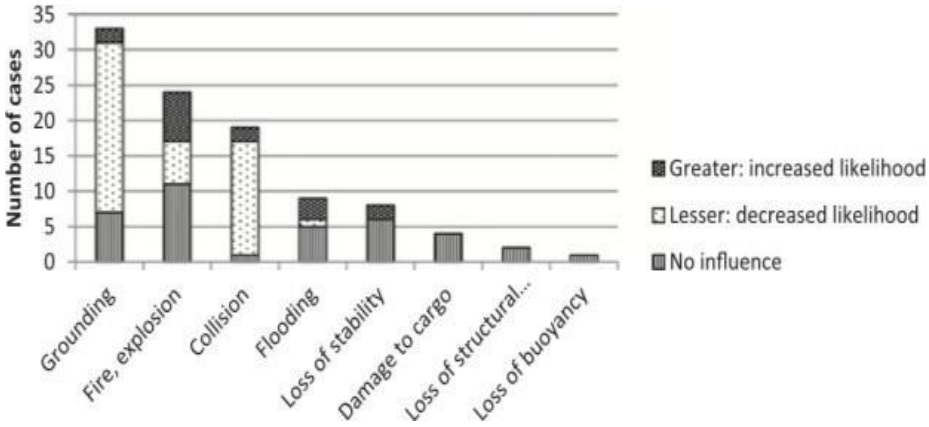
errors will still exist albeit in another realm. RIFs were most frequent in open sea navigation, while the manoeuvring and pilotage phases were determined to generally be more navigationally complex in nature (Fan et. al., 2020). However, there is no mention if the duration of the phases was considered.

Two papers have sought to evaluate the safety impact of deploying AVs by analysing existing safety reports. The first one of Wróbel, Montewka and Kujala (2017) proposed a safety assessment of unmanned vessels through a "what-if" analysis of existing maritime accident reports, based on the Human Factors Analysis and Classification System for Marine Accidents, originating from Reason's Swiss Cheese theory. This has been explained in Section 2.4. Wróbel, Montewka and Kujala (2017) studied 100 maritime accidents, assuming that unmanned ships operate autonomously only during ocean passage, while coastal navigation, pilotage and berthing are conducted by a shore operator. Of the 100, 52 were navigational accidents (grounding and collision). The remaining accidents were due to fire, flooding or structural failure of the vessels, which can also occur on a poorly designed and maintained AV. Thus, greater emphasis should be placed on analysing navigation-related accidents. Another important finding is that unmanned vessels were determined better in reducing the likelihood of accidents rather than reducing their severity, while the accidents were attributed to the lack of situational awareness of the bridge team and the inadequate maintenance or supervision of mechanisms (Wróbel, Montewka and Kujala, 2017).

Similarly, the second paper assessing the safety impact of deploying AVs by analysing existing safety reports (de Vos, Hekkenberg and Valdez Banda, 2021) studied the potential decrease in human casualties and lost ships with the introduction of autonomy. De Vos, Hekkenberg and Valdez Banda (2021) quantified the reduction of number of lives lost through the removal of crew from ships, then assessed the reduction in navigation-related accidents through the implementation of autonomous systems.

However, as AVs seek to eliminate certain risks, new ones could appear and need to be studied using a predictive approach. Figure 3.7 shows the frequency of various types of accidents in relation to the type of ship. For grounding and collision, the number of accidents decreases considerably when changing the type of ship. The exception in this case comes with accidents caused by fire or explosions, in which it is fairly even. However, the increase in this type of accidents after introducing AVs might be due to the complexity of electrical installations and putting out fires in areas that are not prepared for it (Wróbel, Montewka and Kujala, 2018).

Figure 3.7. Impact of automated framework on accident's likelihood (Wróbel, Montewka and Kujala, 2018).



To sum up the literature considered so far, even though the number of accidents can be expected to decrease significantly on AVs, once they occur, their consequences could be significantly greater than at present because the absence of a crew will lead to a delay in any response. However, by eliminating the crews of the ships and reducing the staff members at the dock, the death toll will be reduced significantly since 95% of maritime deaths are caused by human errors (Wróbel, Montewka and Kujala, 2018).

In addition to the previously mentioned literature, various projects on autonomous shipping exist or are under development, such as the Maritime Unmanned Navigation Through Intelligence Network (MUNIN) and YARA Birkeland, which are discussed below.

MUNIN was created by the European Commission in 2012 and ended in 2015, with the aim to analyse the technical, legal and economic viability of the AV concept. It concluded that the introduction of AVs will reduce ship operations costs and gas emissions, having a positive environmental impact and bringing innovation. Most vessel losses are caused by collision and sinking, which may decrease by 10% due to smarter operational systems for avoiding collisions in ports during docking or undocking. Additionally, the main cause of maritime accidents is the human errors, which will gradually be reduced through automation, using smart consoles and no crew on board. The major concern in developing MUNIN was cyber-security, a new risk that appears with autonomation. Overall, the European Commission concluded that AVs could generate savings of about 7 million US dollars over 25 years compared to conventional bulk carrier (European Commission, 2023).

Project Yara Birkeland arose from MUNIN and is the world's first emission-free and autonomous container ship (Yara, 2023). It has been operational since 2022 and is expected to gradually become fully autonomous in 2024. This will allow a reduction of 40,000 truck road trips from Yara fertiliser plant to Brevik and Larvik ports in Norway, with the implied emissions reduction. This project aims to

reduce NO_2 and CO_2 emissions by reducing road transport, and to improve air quality and safety. Initial tests were successful, demonstrating both the concept and the technology (Yara, 2023).

3.7.3. Literature gaps and conclusions

The studies and projects discussed in the previous section can be expanded by assessing the impact of the implementation through the analysis of the proportion of navigation accidents that can be eliminated, since not all accidents of such nature are directly influenced by human errors. For example, collisions between ships can occur due to mechanical malfunction, e.g., the total loss of steerage control. Hence, such failure modes may also occur on AVs. The common point of previous publications is that the studied accidents happened in a system operated by humans, which will be automated, therefore safer. Section 6.2 of this thesis aims to determine how the implementation of the autonomous system could reduce the frequency of these accidents and detect new challenges. The next section, however, addresses a new topic, that of the use of real-time location tracking to model port congestion and performance.

3.8. The use of AIS for analysing port congestion and performance

The Automatic Identification System (AIS) tracks the real-time locations of vessels using satellite signals and transceivers, which can help determine vessel routes and identify ships in real time (MMO, 2014). In addition to the previously studied factors contributing to SC and OA in ports, this section reviews the use of the AIS system to analyse port congestion and performance through the available literature. Data from the AIS will be used in this thesis in addition to accident and incident data, in the first case study presented in Section 6.1.

The AIS is an automatic electronic tracking system based on transceivers used by vessels to broadcast their position and identification messages. Originating in Sweden in the early 1990s for navigation safety and collision avoidance, AIS was adopted by the IMO in 1998. Coastal stations and ships can receive messages from ships worldwide. As Fujino and Claramont (2023) stated, AIS data are the dominant contributor to maritime big data and offer useful resources for discovering maritime trends and patterns.

The phenomenon of congestion can happen in different places within a port, such as the berth, load discharge points, which cause queuing and therefore increase vessel waiting time (Pruyn et al. 2020). Peng et al (2022) studied port congestion using AIS data for 3,957 container ship movements, and then proposed a model that predicts congestion in ports, based on different factors including congestion propagation effects. There are various studies on port congestion, however, as concluded by (Peng et al, 2022), these mainly use port authority databases (at a regional level), making their

findings inconsistent and inapplicable for other ports, or for national or even international statistics. Pruyn et al. (2020) studied port congestion with more accurate methods, using AIS data along with vessel characteristics from Lloyd's list, then implement a congestion prediction model for short- and long-term.

Port performance has been widely measured using big data, with different aims: to measure port congestion and performance for determining the impact of a port congestion index on the economics of the shipping market (Bai et al. 2021), and to analyse various port performance aspects. These aspects include how ship location is related to port connectivity (Jia et al., 2017), as well as spatial-temporal dynamics of the volume of traffic in a port (Zhang et al. 2019). Aside from these, Chen et al. (2016) studied port performance indicators for container ports, by using both AIS and maritime open data. One such indicator is traffic volume, which will also be considered in this thesis.

There have been several reviews that provide either a general overview of the use of AIS data or focused on specific topics in maritime research, e.g., Rawson and Brito (2022) and Yang, Yang, Li and Zhang (2024). These reviews highlight the potential for the use of AIS and also certain limitations. For example, the analysis of Rawson and Brito (2022) highlights that AIS data has been used for the following purposes:

i. to predict the risk of vessel transits and particularly collision situations (e.g., Liu, Wang, Cai, Liu, and Liu (2020)).

ii. to predict vessel speed and heading in a port approach channel (Tsou, 2018).

iii. to model how non-accident events such as marine incidents might be used instead of historical accidents (Du, Goerlandt, & Kujala, 2020).

In conclusion, the AIS plays a crucial role in enhancing maritime safety and efficiency by providing real-time tracking of vessels, as well as aiding in navigation, collision avoidance, and congestion analysis. The review of studies in this section supports the fact that AIS data is instrumental in understanding and predicting port congestion, vessel movements and maritime traffic patterns. In addition, AIS contributes significantly to maritime big data, offering valuable insights for both short-term and long-term planning. Therefore, its integration with other data sources in this thesis will further enhance the accuracy and applicability of maritime safety and operational strategies.

3.9. Conclusions of Chapter 3

This chapter provided fundamentals of maritime safety and detailed literature reviews of specific topics. It provided a background for the subsequent analysis through three maritime-related case studies in Chapter 6. Table 3.9 summarises the main topics considered in this chapter, and provides a brief summary of main findings.

Table 3.9. Summary of the main topics considered in Chapter 3.

Section	Main Topics Covered	Description / main findings
3.1	The maritime industry	Vital component of global trade.
3.2	Ports	Ways ports integrate into the bigger picture of the maritime industry. Provided a detailed classification of ports.
3.3	Accident types	Accident vs incident vs casualty vs occurrence. Ship casualty (SC) vs occupational accident (OA).
3.4	Regulations	IMO, SOLAS, MARPOL, STCW, PSC regimes.
	Stakeholders	IMO, IEA, EC, EMSA, DfT, MCA, MAIB, ABP, BPA.
3.5	Risk influencing factors	Port characteristics, traffic volumes, environmental conditions, speed, communication, technology, fatigue, poor lightning, untidy workspace, dust, noise, cybersecurity, workplace transport, training,
3.6	Data analysis methods	Review of different methods, focus on BN and its limitations.
3.7	Autonomous vessels	How to address new risks of unmanned vessels.
3.8	AIS	Modelling of port congestion and performance.

While this chapter established the foundational knowledge of maritime safety necessary for the initial case studies related to this transport sector, the final case study in Chapters 7 and 8 shifts focus to the aviation sector. Thus, similar to the type of information presented in this chapter, the next chapter will include useful definitions and literature that provide the background for aviation safety. Both these chapters contribute to the development of a robust methodology for this thesis in Chapter 5.

4. Fundamentals of General Aviation and Seaplane Safety

In this section, the General Aviation (GA) and seaplane sectors are defined and explored. A new definition is proposed for the purpose of this study, for private, recreational GA seaplane operations in Canada. Additional definitions are provided to help understand the subsequent analysis of seaplane occurrences in Chapter 7. Finally, the literature is reviewed and critiqued for publications about seaplane safety, with the focus on GA.

4.1. General Aviation

This section provides an overview of the General Aviation (GA) sector, including its definition, global market, national market in Canada and the types of licenses and permits issued for this purpose in Canada. This is helpful in understanding GA and its practices.

4.1.1. Definition of General Aviation (GA)

The International Civil Aviation Organisation defines General Aviation (GA) as “all civil aviation operations other than scheduled air services and non-scheduled air transport operations for remuneration or hire” (ICAO, n.d.). There are inconsistencies in how GA is defined, and are usually described as everything but commercial, military or state flights. For example, GA includes private jets, air ambulances, air taxis, pilot training flights, flights used for air sports such as parachuting, agricultural aviation, business aviation, and aerial firefighting. This sector plays a crucial role in providing air services to communities not served by commercial airlines, contributing significantly to local economies and the overall aviation industry (Federal Aviation Administration, 2018; European Union Aviation Safety Agency, 2020). Most GA accidents and serious incidents involve pleasure flights or flight training, so studying these is of paramount importance for improving the safety of GA operations (EASA, 2021). Moreover, GA pilots are not part of an organisation that manages safety and so the only information they offer is data of accidents or incidents. Table 4.1. summarises the definitions used for GA around the world.

Table 4.1. Summary of definitions used for General Aviation.

International Civil Aviation Organisation (ICAO)	General Aviation (GA) refers to "all civil aviation operations other than scheduled air services and non-scheduled air transport operations for remuneration or hire." This broad definition includes a variety of activities such as recreational flying, aerial work, and corporate aviation (ICAO, n.d.).
International Council of Aircraft Owner and Pilot Associations (IAOPA)	IAOPA’s definition of GA includes: • “Corporate aviation: company own-use flight operations • Fractional ownership operations: aircraft operated by a specialised company on behalf of two or more co-owners

	• Business aviation (or travel): self-flown for business purposes • Personal/private travel: travel for personal reasons/personal transport • Air tourism: self-flown incoming/outgoing tourism • Recreational flying: powered/powerless leisure flying activities • Air sports: aerobatics, air races, competitions, rallies, etc." (IAOPA, 2024)
United States of America - Federal Aviation Administration (FAA):	The FAA defines General Aviation as encompassing "all flights that are not conducted by scheduled airlines or the military." This includes activities ranging from private flying and flight training to agricultural aviation and medical transport (FAA, 2020).
European Union - European Union Aviation Safety Agency (EASA):	The EASA (the EU regulator) defines General Aviation as "non-commercial aviation operations, including light aircraft flights, gliders, helicopters, and private jets." This definition emphasises safety and regulatory compliance across diverse activities, which encompass a wide range of aircraft and operational purposes (EASA, 2020).
Canada - Transport Canada	Transport Canada defines GA as "all civil aviation operations other than scheduled air services" covering private flying, flight training, air ambulance services, and agricultural aviation. The regulations focus on safety and operational standards for non-commercial aircraft (Transport Canada, 2020).
United Kingdom - Civil Aviation Authority (CAA)	The CAA defines General Aviation as "all civil aviation operations excluding commercial air transport." This includes activities such as private flying, gliding, ballooning, and business aviation, with an emphasis on regulatory compliance and safety (CAA, 2018).
Australia - Civil Aviation Safety Authority (CASA)	CASA defines General Aviation as "non-scheduled operations," which include private flying, flight training, and agricultural aviation. This definition is tailored to the unique needs of Australia, emphasising the role of GA in connecting remote areas and providing essential services (CASA, 2019).
China - Civil Aviation Administration of China (CAAC)	The CAAC defines General Aviation as "all civil aviation activities excluding scheduled airline services." This includes private flying, aerial work, flight training, and emergency medical services, with a focus on expanding GA infrastructure to support economic development and connectivity in rural areas (CAAC, 2018).
Brazil - National Civil Aviation Agency (ANAC)	In Brazil, General Aviation is defined as "all civil aviation activities that are not part of commercial air transport services." This broad definition covers private flights, agricultural aviation, air taxi services, and flight training, highlighting GA's vital role in reaching remote areas and supporting agricultural productivity (ANAC, 2020).

While the core concept of General Aviation as encompassing non-commercial aviation activities remains consistent, the emphasis and specifics can vary:

- Scope of Activities: Some regions, like the U.S. and EU, have broad definitions that include various types of non-scheduled commercial operations. Others, like Canada and Australia, emphasise GA's role in connecting remote areas and providing essential services.
- Regulatory Focus: European and North American definitions often stress regulatory compliance and safety standards, reflecting their mature aviation markets. In contrast, countries like China and Brazil focus on expanding GA infrastructure to support economic development.

- Economic and Geographic Considerations: In countries with vast and remote areas (e.g., Canada, Australia, Brazil), GA is crucial for connectivity and economic activities like agriculture and resource extraction.

4.1.2. The General Aviation market around the world

According to the Federal Aviation Administration (FAA), the United States of America (USA) have the largest GA market in the world, with 287,771 registered GA aircraft under 5,700 kg of which 256,279 active, as of 2023, and 5,193 airports for public use, as of 2022 (FAA, 2023; Statista, 2022; Bellamy, 2023). It is believed that the USA had 1,197,530 active GA pilots in 2022, 80 of which are recreational pilots, 119,680 commercial, 122,880 flight instructors and 6,843 sport pilots (Bellamy, 2023). Their GA sector is very divers, and it is used for various activities such as recreational flying, flight training or emergency medical services.

The FAA develops safety programs and regulatory frameworks to improve GA safety around the country (FAA, 2020). The General Aviation Joint Safety Committee (GAJSC) is a government-industry partnership that aims to improve GA safety in the USA since 1997, by reducing risk through data analysis and industry engagement (GAJSC, 2024). The GAJSC includes members from the FAA, the Aircraft Owners and Pilots Association (AOPA), the Experimental Aircraft Association (EAA), government agencies and various GA associations in the USA, and it has observers even from outside the USA such as the Canadian Owners and Pilots Association (COPA), European Union Aviation Safety Agency (EASA), Flight School Association of North America, the National Transportation Safety Board (NTSB), Soaring Society of America, and Transport Canada Civil Aviation (GAJSC, 2023).

In the European Union (EU), the European Union Aviation Safety Agency (EASA) focuses on facilitating regulations that accommodate all member states, with the aim to provide high safety standards and ensure cross-border operations. The EU has many airports used for GA, with the highest activity in the UK, Germany and France. As of 2022, the EU reported around 140,000 registered GA aircraft, but the number of airports used for GA activities could not be estimated (GAMA, 2022; EASA, 2020). Specific numbers vary by country. The EU GA market is also diverse, with its main purpose being flying clubs and private operators. EASA has a GA Safety Team, which aims to promote GA safety in the EU while bringing awareness on safety concerns and aiming to change pilot behaviours to diminish the number of human-related accidents (EASA, 2024).

In the United Kingdom, GA includes activities such as private flying, flight training, and business aviation, with around 21,000 registered GA aircraft and 373 airports for GA activities (CAA, 2018). The

UK has a good network of airports and flying clubs, and GA safety is assured by the Civil Aviation Authority (CAA) (CAA, 2018).

In Australia, the Civil Aviation Safety Authority (CASA) focuses on safety regulations and supports the growth of the GA operations in Australia, in a way that reflects the unique needs of the Australian landscape. Similar to Canada, GA plays a critical role in connecting remote areas. GA is also used for private flying, flight training, medical evacuations, aerial firefighting and agricultural aviation. Australia has around 15,000 registered GA aircraft and 2,000 aerodromes and airstrips, most of which support GA activities (CASA, 2019). According to Bellamy (2023), Australia does not track GA pilot licencing, but they have 14,889 registered GA aircraft under 5,700 kg. In New Zealand, CAA New Zealand (2020) reported 5,680 private and recreational pilot licences with an active medical certificate, with around 65,000 hours flown, in 2019.

In Brazil, General Aviation is also used for reaching remote areas, particularly in the Amazon region. Aside from this, GA in Brazil includes private flights, agricultural aviation, air taxi services, and flight training. The National Civil Aviation Agency (ANAC) ensures the GA in Brazil adheres to the highest safety standards and is available to successfully supports critical activities such as agriculture and healthcare (ANAC, 2020). Brazil is one of the countries with most airports, having around 12,000 registered GA aircraft and 2,500 airports, most of which support GA activities (ANAC, 2020).

China's General Aviation sector is rapidly developing, driven by government initiatives to support economic growth and expand infrastructure. According to the Civil Aviation Administration of China (CAAC), their GA purposes include private flying, aerial work, flight training and emergency medical services. The CAAC has been promoting the development of GA to enhance connectivity in rural and remote areas and to support various economic activities (CAAC, 2018). China reported around 3,000 registered GA aircraft and 500 airports used for GA activities (CAAC, 2018).

General Aviation is a diverse sector within the global aviation industry, and it is essential in providing services that complement scheduled airline operations. While the core concept of GA is consistent throughout the world, regional differences are reflected by their regulatory focuses, economic priorities, and geographic considerations. The ongoing development and support of GA are crucial for enhancing connectivity, supporting economic activities, and ensuring safety across all aviation operations, especially since flight training is included in this category.

4.1.3. The General Aviation market in Canada

Canada’s vast and unique geography makes GA an essential part of the transportation network, providing services that are not feasible for scheduled airlines. Canada's GA, in contrast to other

countries, has a crucial role of connecting remote and rural areas where other means of transportation are not available or hardly accessible. Other purposes of GA in Canada include private flying, flight training, air ambulance services, and aerial work for agricultural purposes (Transport Canada, 2020).

Canada has the second largest GA market in the world, after the USA, with 36,780 registered GA aircraft in 2021, around 30,000 GA pilots in 2019 and 5,193 airports for public use as of 2022. (Statista, 2022; Bellamy, 2023).

4.1.4. Licences and permits issued in Canada

The Canadian Aviation Regulations (CAR) provide detailed requirements for pilots to fly. In summary, these are: a valid permit or licence, a valid medical certificate and a valid aviation document booklet. Additionally, TC gives directions that pilots must follow to stay current, and recommendations on ways to be proficient (TC, 2020d). All licences and permits discussed in this section are in compliance with legislation, regulations and standards provided by the Aeronautics Act and the CAR.

According to Transport Canada (2019 and 2019b), there are two types of permits: Student Pilot Permit and Pilot Permit. A pilot Permit can be for Ultralight Aeroplane, Gyroplane or Recreational Aeroplane. A Student Pilot Permit is the first permit pilots need to fly. After the medical certificate is obtained, it may then be brought to a Flight Training Unit, where the Student Pilot Permit can be issued by an authorised person. Then Transport Canada provides the formal licence. This is under the condition that the following proofs are checked: age, citizenship, medical fitness and meeting the experience and skill necessary to fly alone.

After getting a Student Pilot Permit, the majority of people go for a Private Pilot Licence first, but there are a number that do the Recreational Pilot Permit first. On one hand, people that do not have as much money typically do the Recreational Pilot Permit as a stepping stone, then obtain their Private Pilot Licence at a later date. On the other hand, people who have more money would go straight to a Private Pilot Licence. A Private Pilot Licence is required before getting the Commercial Pilot Licence, which is required before obtaining an Airline Transport Pilot Licence.[1]

Different Aeroplane Class Ratings include Seaplane Rating, Landplane Rating, Multi-engine Class Rating and Multi-engine Centre Line Thrust Class Rating. Aircraft Type Ratings include Blanket and Individual Type Ratings. Other ratings include Night Rating, VFR Over-the-Top Rating, Instrument Ratings, Second Officer Rating, Passenger-carrying ratings and Flight Instructor Ratings.

[1] Information obtained from a field expert in General Aviation, Seaplanes and aviation safety.

4.2. Seaplanes

Having reviewed GA, this section focuses on the seaplane industry around the world and in Canada. In particular, the definition of seaplanes is reviewed, and a definition for private, recreational GA seaplane operations is proposed for the purpose of this thesis.

4.2.1. Definition of seaplanes

Seaplanes are generally defined as aircraft that can take off and land on water. The ICAO defines a seaplane as "An aeroplane on floats (amphibious or non-amphibious) or a flying boat (water-only or amphibious)" (ICAO, 2015). The two main categories of seaplanes used in Canada are floatplanes and amphibious. Floatplanes have floats but no wheels, and amphibious planes have floats and retractable wheels, so they have the capability to land and take-off from both the land and the water. In addition, according to the 1972 International Regulations for Preventing Collisions at Sea (COLREGs), a seaplane is regarded as a vessel when it is on the water, whether it is landing, anchored, or being launched from a water slide. However, when the seaplane is out of the water, it is treated as an aircraft (IMO, 1972).

Seaplanes can be classified in several ways, based on their design, land capabilities, usage, size, etc. The main types and subtypes of seaplanes are summarised in Table 4.2.

Table 4.2. Types of seaplanes according to different classification methods.

No.	Seaplane type	Description
I	**According to their design and technological characteristics:**	
1.	Floatplanes	
1.1.	Single-Float Floatplanes	Floatplanes with one large float for buoyancy and smaller stabilising floats on the wingtips.
1.2.	Twin-Float Floatplanes	Floatplanes with two main floats mounted beneath the fuselage, providing stability.
2.	Flying Boats	Generally larger than floatplanes and can carry more weight.
2.1.	Single-Hull Flying Boats	Flying Boats designed with a boat-like hull, to land directly on water.
2.2.	Double-Hull Flying Boats (Catamaran)	Flying Boats designed with two hulls. These have greater stability on water.
II	**According to their landing gear configuration:**	
1.	(Pure) Seaplanes	Seaplanes that can only land on water. This includes traditional floatplanes and flying boats.
2.	Amphibious Seaplanes	Seaplanes that have retractable landing gear, enabling them to land on both water and solid ground.
III	**According to their purpose or usage**	
1.	Civilian Seaplanes	Seaplanes used for recreational flying, transportation, and tourism.
2.	Military Seaplanes	Seaplanes utilised for reconnaissance, patrol, search and rescue, and other military operations.
IV	**According to their size and capacity:**	

No.	Seaplane type	Description
1.	Light Seaplanes	Smaller seaplanes used for personal and recreational purposes.
2.	Medium Seaplanes	Seaplanes suitable for regional transport and logistics.
3.	Heavy Seaplanes	Larger aircraft capable of carrying more passengers or cargo, used for commercial or military purposes.
V	**According to their number of engines**	
1.	Single-Engine Seaplanes	Seaplanes powered by a single engine.
2.	Multi-Engine Seaplanes	Seaplanes equipped with two or more engines, providing increased power and redundancy.
VI	**According to their operational range**	
1.	Short-Range Seaplanes	Seaplanes designed for short distances, often used in local or regional flights.
2.	Long-Range Seaplanes	Seaplanes capable of extended flights, suitable for longer routes and transoceanic operations.
VII	**According to their wing configuration**	
1.	High-Wing Seaplanes	Seaplanes with their wings mounted above the fuselage, providing better visibility and stability on water.
2.	Low-Wing Seaplanes	Seaplanes with their wings mounted below the fuselage, which may provide better aerodynamics and ease of boarding for passengers.
VIII	**According to their hull design**	
1.	Step Hull	Seaplanes with a hull design with a step to reduce water resistance during take-off.
2.	Planing Hull	Seaplanes where their hull allows them to glide on the water surface, improving speed and efficiency during take-off and landing.
IX	**According to their specific use**	
1.	Firefighting Seaplanes	Seaplanes equipped with tanks and systems to scoop and drop water on fires.
2.	Search and Rescue Seaplanes	Seaplanes designed with advanced navigation and communication equipment for rescue missions over water.
3.	Cargo Seaplanes	Built to carry cargo over water, often with larger storage capacities.
4.	Passenger Seaplanes	Used to transport passengers, often in areas with limited runway infrastructure.
X	**Hybrid seaplanes**	
1.	Flying Boat/Amphibious Hybrids	Seaplanes combining features of both flying boats and amphibious planes, allowing for versatile operations on both water and land.
2.	Amphibious Floatplanes	Floatplanes with retractable gear for both water and land operations.
XI	**Tilt-Rotor seaplanes**	
1.	VTOL (Vertical Take-Off and Landing) Seaplanes	Seaplanes that have tilting rotors or engines that allow for vertical take-off and landing, which can be useful in confined water spaces.
2.	Tilt-Wing Seaplanes	Seaplanes for which the wings tilt to enable vertical take-off and transition to horizontal flight.
XII	**Ultralight seaplanes**	
1.	Basic Ultralight	Small, lightweight seaplanes that are fixed wing, power driven, with no design standard requirements. Designed for one or two people.

No.	Seaplane type	Description
2.	Advanced Ultralight	Ultra-light seaplanes that are declared to be in compliance with specific design standards.
XIII	**Amateur-built seaplanes**	
1.	Kit-Built Seaplanes	Seaplanes that are mostly assembled by an aviation enthusiast (builder), using a kit.
2.	Plans-Built Seaplanes	Seaplanes that are mostly assembled by a builder, using raw materials and providing more opportunity for customisation.
XIV	Owner-maintained seaplanes	
1.	Certified Owner-Maintained Seaplanes	Seaplanes whose elementary work can be performed by their owner, under specific regulations.
2.	Experimental Owner-Maintained Seaplanes	Seaplanes that can be maintained by their owners without standard certification constraints.
XV	**Other**	
1.	Convertible Seaplanes	
1.1.	Land/Water Convertible Aircraft	Aircraft designed to be quickly converted between landplane and seaplane configurations, allowing greater flexibility.
1.2.	Interchangeable Floatplanes	Aircraft that can be converted between landplane and floatplane by attaching or detaching floats.
2.	Solar-Powered Seaplanes	Solar-powered aircraft that could potentially be adapted for seaplanes.
3.	Electric Seaplanes	
3.1.	Battery-Powered Seaplanes	Seaplane powered by electric motors, reducing emissions and operational costs, suitable for short-range flights.
3.2.	Hydrogen Fuel Cell Seaplanes	A concept for a hydrogen fuel cell-powered seaplane, offering longer ranges and quick refuelling.
4.	Drone Seaplanes	
4.1.	Unmanned Seaplanes	Remotely piloted or autonomous seaplanes used for surveillance, reconnaissance, and other applications.
4.2.	Autonomous Cargo Drones	An autonomous cargo drone with potential adaptations for water operations, designed to carry significant payloads over long distances.
5.	Experimental / Concept / Prototype Seaplanes	Other aircraft in the development phase, testing new technologies or design principles for future seaplane models.

4.2.2. Distribution of seaplanes around the world

Exact numbers for seaplane fleets around the world are hard to find, as these are not reported separately from other types of aircraft. Any statistics for GA seaplanes are not available for public use, and even harder to find. Below is a list of any information that could be found from an extensive research of trusted sources regarding either the number of registered seaplanes or pilot populations, total or for GA:

- GAMA (2019) provides only one statistic which includes the number of seaplanes in the UK (only 3 in 2019) while, for other countries, they do not separate seaplanes from other types of aircraft.

- GAMA (2016) provides only one statistic which includes the number of seaplanes in Cyprus (only 1 in 2015 and 0 in 2016).
- Seaplane Pilots Association (2001) created a figure to show the seaplane pilot population per US state in 2001. However, the figure is of poor quality and illegible for most states. Moreover, the numbers are just estimates of active, certified seaplane pilots across different states. This has been derived from FAA airman certificate data, which was adjusted to account for the inactivity of approximately five out of six certified seaplane pilots, as well as regional activity rates.
- ICAO (2019) addresses requirements of water aerodromes, and reports that around 500,000 passengers travel yearly on scheduled seaplanes flights in Canada. These are made possible by over 150 commercial float plane operators using 450 registered seaplanes. Additionally, there are 326 registered aerodromes in Canada and over 2,000 unregistered. However, these numbers consider only the commercial side of seaplane operations.
- Air Charter Service (2018) estimated around 35,000 seaplane pilots in 2018 in the USA with a valid medical certificate.

It has been attempted several times in 2023-2024 to find data on the number of registered seaplanes and pilot populations around the world, and all findings have been presented above. Using the last resort, AI, more precisely ChatGPT-4o advanced AI language model developed by OpenAI, on 5 July 2024, it was obtained, without accurate references, that Canada ranks second globally with around 7,000 registered seaplanes, following the USA with around 11,000, and above Finland with around 3,000 registered seaplanes. This substantial fleet size reflects the country's strong engagement in seaplane operations. Canada also occupies the second position in seaplane flight hours annually, recording 1.5 million hours. This figure, although half of the USA's 3 million hours, is significantly higher than any other country's recorded hours. SKYbrary (2024) was given as a reference, however, the link provided by ChatGPT-4o was not working and this data could not be found anywhere on that website. This highlights the inaccuracies of AI and importance of conducting research using trusted sources. However, the numbers produced using AI were compared to the values which could be found using reliable sources, and they were very similar, so the results using ChatGPT-4o were kept for the data that could not be found through other sources.

4.2.3. Requirements for seaplane pilots

To be able to fly seaplanes, pilots must obtain a Seaplane Rating. Previous requirements include holding a Private Pilot Licence (minimum requirement), or a Commercial Pilot Licence for commercial

operations. Pilots can also obtain their Seaplane Rating after holding a Recreational Pilot Permit. Additionally, Ultralight Permit holders, even though they do not have a rating, can fly on floats.[2]

Air Charter Service (2018) estimates that 3% of the number of pilots hold a Seaplane Rating. According to Canadian regulations (TC, 2019a), the requirements for a Seaplane Rating are:

- 7 hours of seaplane training, which include
    - at least 5 hours dual instructions.
    - 5 solo take-offs and landings.
    - Training exercises for taxiing sailing, docking, take-offs and landings.
    - Optional training exercises for glassy and rough water, as well as crosswind, where conditions permit this.
- 1 successful qualifying flight supervised by a TC inspector or another qualified person, within one year before applying for a seaplane rating.

Some differences exist for personnel of the Canadian Forces, active or retired, and for foreign applicants (TC, 2019b). There are ratings that can be added to the Seaplane Rating, such as Night Rating, Instrument Rating or Multi-Engine Rating. These provide additional capabilities, but are not mandatory for basic seaplane operations.

The Instructor Guide for Seaplane Rating provides detail guidelines on suggested organisations of activities included in training, planning and preparations before flights, and how to handle the seaplane in different situations, and during different phases of flight TC (1996). It also provides information on more advanced exercises such as operations in confined areas, rough water and step turns.

Other than optional training for rough water, glassy water and crosswind conditions, there are no other requirements for emergency procedures, underwater egress or possible accident scenarios. The training for Commercial Pilot Licences address safety aspects and regulations are stricter. However, for GA, any safety-oriented training, such as underwater egress, flying under different environmental and geographic conditions, or scenario training, remains under the judgement of the pilot. Most GA seaplane pilots do not complete any further trainings because of money constraints, or just because it is not required.

[2] Information obtained from a field expert in General Aviation, Seaplanes and aviation safety.

4.2.4. Proposed definition of private, recreational General Aviation seaplane operations in Canada

There are inconsistencies in how GA is defined, and are usually described as everything but commercial, military or state flights. Because GA includes diverse activities, including private jets, air ambulances, air taxis, pilot training flights, flights used for air sports such as parachuting, etc., the specific needs of each subsector of GA need to be addressed separately.

In Canada, because of the unique geography with many lakes and remote areas, private, recreational seaplane flights are very common, especially for private, recreational use. Because of this, for seaplanes, the term GA is commonly used to describe private, recreational, operations only, and a definition for this subset only of GA does not exist.

Because of the diverse nature of GA, a single definition cannot easily encapsulate all the activities. Creating numerous sub-groups can make research overly detailed and a complicated definition, but oversimplification of the definition is not the solution. For this thesis, a new definition is developed for private, recreational seaplane operations. This definition will expand on Transport Canada's definition for GA ("all civil aviation operations other than scheduled air services"), accounting for the scope of TCCA's General Aviation Safety Program (GASP) and any particularities for seaplanes.

The scope of TCCA's GASP is "all recreational aircraft including aeroplanes, balloons, gliders, gyroplanes, helicopters, ultra-light aeroplanes that are: 1) not operated under CAR Part 7 (Commercial Air Services), 2) not a large aeroplane, a turbo-jet-powered aeroplane, or a turbine-powered pressurised aeroplane certificated for more than six passenger seats (CAR 604 - Private Operators)". This scope also includes flights in the flight training units (Bellamy, 2023).

Proposed definition for private, recreational GA seaplane operations, to reflect the subpart of GA seaplane operations used in this study:

Private, recreational GA seaplanes are defined as all fixed wing aeroplanes that has the capability to take-off and land on water, including ultralight, advanced ultralight, amateur built and any aircraft used for flight training purposes, that are privately registered, do not operate under CAR Part 7 (Commercial Air Services), and weight under 2,250kg.

This definition excludes balloons, unmanned aircraft, gliders and helicopters and large seaplanes over 2,250kg. It also excludes non-private aircraft registration types, such as commercial, corporate, manufacturer, state or other.

4.3. Accident classification and definitions

After having reviewed seaplanes in the previous section, this section provides various definitions and methods of classification related to seaplane operations, including phases of flight, accidents and incidents, aircraft damage and occurrence categorisation. These are useful for understanding the subsequent analysis of seaplane occurrences in Chapter 7.

4.3.1. Phases of flight

It is important to correctly categorise the phase of flight when an accident or incident occurred. For this purpose, Goblet, Fala and Marais (2015) provide a comprehensive list of possible safety events during each phase of flight, and develop an algorithm to detect the phase of flight. However, the phases of flight proposed by Goblet, Fala and Marais (2015) are for commercial operations and there are some changes made below to reflect the phases of flight for GA operations. It should be noted that, for seaplanes, a runway can also be on a body of water.

For this study, the phases of flight where an occurrence can happen for GA seaplane operations in Canada have been separated into 14 categories which are presented below. These categories have been created and redefined by adapting CICTT (2013) definitions of phases of flight to reflect the phase categories used by Transport Canada occurrence reports, which were then adapted for GA[3]:

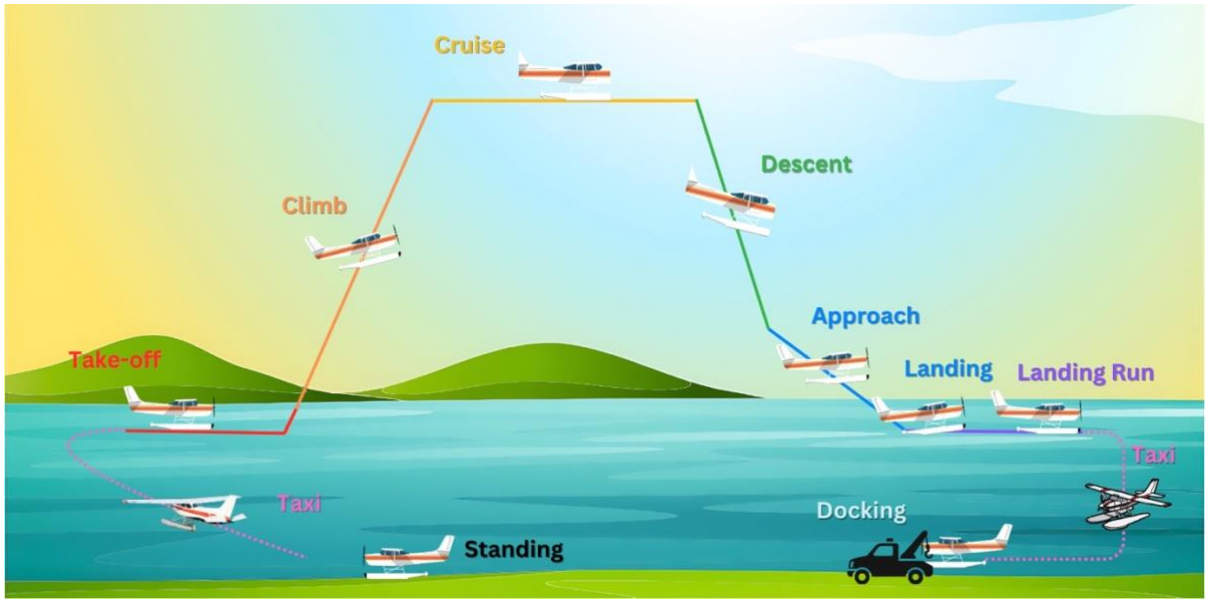
- **Standing**: Stationary aircraft at dock before taxi.
- **Taxi**: Aircraft unassisted in moving before take-off or after landing.
- **Take-off**: Starts when take-off power is applied, until either being airborne above 35 feet from the runway/water elevation, or when the gear is up. This includes rejected take-offs.
- **Climb**:
  - **Initial Climb**: After take-off, until the aircraft either reduces prescribed power for the first time or reaches 1,000 feet above the runway/water elevation.
  - **Cruise Climb**: Subcategory added to account for the period after the initial climb and prior to level off at cruise altitude.
- **Cruise**: Level flight segment between end of climb and beginning of descent for landing.
- **Manoeuvring**: Intentional altitude changes during low altitude (not associated with take-off and landing).
- **Descent**: Descent between level flight and 1,000-2,000 feet above the runway/water elevation. It includes emergency and uncontrolled descent.

[3] Information validated by a field expert in General Aviation, Seaplanes and aviation safety.

- **Approach**: Constant altitude decrease in preparation for landing, from 1,000-2,000 feet above the runway/water elevation until the beginning of the landing flare. It includes Missed Approaches and Go-Arounds for up to 200 feet above the runway/water elevation.
- **Landing**: The phase that immediately follows the approach, where the aircraft transitions to the landing attitude enabling the aeroplane to touch down on the landing surface at the slowest speed possible commensurate with safety. This transition is known as the flare. The flare is normally executed at 50 feet or less above the runway/water elevation. For touch-and-go's, this phase ends the moment power is applied for take-off. Landing includes flare, touchdown, and aborted landings after touchdown.
- **Landing Run**: The phase that immediately follows the water landing, when the aircraft slows down to taxi speed (normally with the engine at idle), until reaching the end of the landing runway or coming to a stop on the runway.
- **Docking**: The transition from idle taxi to the safe securing of the seaplane to a permanent structure fixed to the shore. Docking is normally executed with the engine stopped.
- Other
    - **En Route**: After initial climb, through cruise and controlled descent, until the initial approach. Often used when it is not clear in which of the airborne phases of flight the occurrence took place.
    - **Post-Impact**: Considers the segment of flight after impacting terrain, obstacles, people or objects.
    - **Unknown**: For accident and incident data, when the phase of flight of the occurrence could not be determined.

Figure 4.3 has been created to account for 10 out of the 14 phases of flight. It does not include Manoeuvring, En Route, Post-Impact and Unknown.

Figure 4.3. Illustration of the typical phases of flight of a seaplane, excluding Manoeuvring, En Route, Post-Impact and Unknown.



4.3.2. Accidents, incidents and occurrences

ICAO Annexes 13 and 19 to the Convention on International Civil Aviation are used to define accidents and incidents (ICAO, 2014; ICAO, 2016). ICAO provides international standards, and their definitions are adopted by all countries. The word "occurrence" is used in this thesis to account for both accidents and incidents, and its chosen definition is provided by Regulation (EU) 376/2014, in line with CAST/ ICAO Common Taxonomy Team, which is listed below (EU, 2014). For the purpose of this thesis, the definitions presented below are for manned aircraft (i.e., the pilot is present on board and mans the aircraft), and the sections on unmanned aircraft are excluded.

It should be noted that this terminology is different from the one used for the maritime sector in the previous section. There, an "accident" is synonym to an "occurrence", while here an accident is what is called "casualty" in the maritime sector. Definitions and examples are given for each sector to help understand the differences.

Accident

"An occurrence associated with the operation of an aircraft which, in the case of a manned aircraft, takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, […] in which:

a) a person is fatally or seriously injured as a result of:

— being in the aircraft, or

- *— direct contact with any part of the aircraft, including parts which have become detached from the aircraft, or*
- *— direct exposure to jet blast, except when the injuries are from natural causes, self-inflicted or inflicted by other persons, or when the injuries are to stowaways hiding outside the areas normally available to the passengers and crew; or*

b) the aircraft sustains damage or structural failure which:

- *— adversely affects the structural strength, performance or flight characteristics of the aircraft, and*
- *— would normally require major repair or replacement of the affected component, except for engine failure or damage, when the damage is limited to a single engine, (including its cowlings or accessories), to propellers, wing tips, antennas, probes, vanes, tires, brakes, wheels, fairings, panels, landing gear doors, windscreens, the aircraft skin (such as small dents or puncture holes), or for minor damages to main rotor blades, tail rotor blades, landing gear, and those resulting from hail or bird strike (including holes in the radome); or*

c) the aircraft is missing or is completely inaccessible."

Incident

"An occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety of operation."

ICAO Annex 13, Attachment C includes a list of typical examples of serious incidents, which can be used for safety-related research, to understand the difference between accidents and serious incidents (ICAO, 2016).

Occurrence

"An accident or incident or other undesired safety-related event, which endangers or — if not corrected or addressed — could endanger an aircraft, its occupants or any other person."

4.3.3. Aircraft damage level, fatality and injury

ICAO's Annex 13, Attachment E, offers guidance with examples for whether different types of damage are categorised as accidents (ICAO, 2016). The aircraft damage level categories used in this study are based on the ICAO definitions and the dataset of occurrences in Canada: "No Damage", "Minor", "Substantial", "Destroyed" and "Missing Aircraft". Aircraft are considered missing if they have not been located by the end of the official search.

The words fatality and injury are self-explanatory. However, it should be noted that injuries can be of different severities (minor injury or serious injury). Serious injuries are defined by ICAO (2014) in Annex 13, Chapter 1, with clear examples. Anything else with a lower severity is considered a minor injury. In addition, if an injury results in death within 30 days from the date of occurrence, it is classified, as a fatal injury (ICAO, 2014).

4.3.4. Categorisation

Hazards which can lead to an occurrence are categorised using the Hazards Common taxonomy (CICTT, 2014), according to the type of hazard. These are: Human, Technical, Environmental and Organisational. For this study, the human and organisational categories are explored in more detail, while technical and environmental hazards are included in the quantitative analysis as possible contributory factors to an occurrence, and explored only in the qualitative analysis.

Aviation occurrences are categorised using the Aviation Occurrence Categories from the Commercial Aviation Safety Team and the International Civil Aviation Organisation (ICAO), as of May 2021 (CICTT, 2011), according to their contributory factor(s). These categories are grouped into the following: Take-off and landing, Airborne, Ground operations, Aircraft, Non-aircraft-related, Weather and Miscellaneous. The CICTT categories are shown in Table 4.3, and their detailed definitions are presented in the document compiled by CICTT (2011). The categorisation is not part of the recorded data fields of a reported accidents or incidents, and it is determined separately only for the few occurrences that require deeper investigation and have a published TSB report.

Table 4.3. Grouping of CICTT Occurrence Categories (CICTT, 2011).

Code	**Category**
Airborne	
AMAN	Abrupt Maneuver
MAC	Airprox/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions
CFIT	Controlled Flight Into/Toward Terrain
FUEL	Fuel Related
GTOW	Glider Towing Related Events
LOC-I	Loss of Control – Inflight
LOLI	Loss of Lifting Conditions En-route
LALT	Low Altitude Operations
UIMC	Unintended Flight in IMC
Aircraft	
F-NI	Fire/Smoke (Non-Impact)
SCF-NP	System/Component Failure or Malfunction (Non-Powerplant)
SCF-PP	System/Component Failure or Malfunction (Powerplant)
Ground Operations	
EVAC	Evacuation
F-POST	Fire/Smoke (Post-Impact)
GCOL	Ground Collision
RAMP	Ground Handling
LOC-G	Loss of Control – Ground
RE	Runway Excursion

RI-A	Runway Incursion – Animal
RI-VAP	Runway Incursion – Vehicle, Aircraft or Person
Miscellaneous	
BIRD	Bird
CABIN	Cabin Safety Events
EXTL	External Load Related Occurrences
OTHR	Other
SEC	Security Related
UNK	Unknown or Undetermined
Non-aircraft-related	
ADRM	Aerodrome
ATM	ATM/CNS
Take-off and Landing	
ARC	Abnormal Runway Contact
CTOL	Collision with Obstacle(s) During Take-off and Landing
USOS	Undershoot/Overshoot
Weather	
ICE	Icing
TURB	Turbulence Encounter
WSTRW	Wind Shear or Thunderstorm

4.3.5. Reporting requirements

This section focuses on the reporting requirements that apply for General Aviation. In Canada, according to Transport Canada (2023), all serious aviation occurrences must be reported to the Transport Safety Board (TSB) as soon as possible, by either pilots, crew members or air traffic controllers. Serious occurrences are those involving injury of any degree, death, major damage to the aircraft, missing aircraft or collision.

These “incident reports” are then sent to Transport Canada and included in their Civil Aviation Daily Occurrence Reporting System (CADORS). In addition, all air operators with a Safety Management System must internally report any incidents, so that they can implement appropriate corrective actions, while TC oversees these SMSs regularly (TC, 2023). A full list of reportable occurrences is attached in Appendix D.

4.4. Key stakeholders and safety regulators for GA seaplane operations in Canada

This section provides an overview of GA seaplane stakeholders in Canada relevant for this thesis.

4.4.1. General Aviation safety regulations in Canada

Safety Management Systems (SMS) are essential in aviation, as they help organisations identify and mitigate safety risks through structured processes. These systems are particularly crucial for GA, including private and recreational operations such as seaplanes. SMS in these sectors focuses on continuous improvement by identifying hazards, reporting occurrences, managing risks, and measuring performance to ensure safety standards are met and maintained. Implementing SMS helps in making informed decisions, improving safety, and achieving operational efficiencies, which are beneficial for attracting clients and ensuring successful business operations. Moreover, SMS enable companies to detect potential safety hazards before they escalate into major issues. According to Transport Canada regulations, the aviation industry must implement these systems as an additional protective measure to enhance safety and preserve lives. Safety Management Systems are the international standard, and Canada has these systems already established. This is largely due to the TC inspectors who have continuously insisted on significance of safety management systems (TC, 2020b).

Transport Canada acts as the regulator, overseeing aviation operations to ensure they adhere to safety standards and regulations are enforced when these standards are not met. Additionally, TC evaluates the effectiveness of industry SMS, extending their role beyond mere inspection. This dynamic approach allows industry groups to adapt their SMSs within regulatory frameworks, to meet specific operational requirements, with the expectation that they will also assess the system's efficacy. Some industry groups have already reported that implementing SMSs is beneficial not only for enhancing safety, but also from a business perspective (TC, 2020b). A safer operation attracts more clients, leading to business success. These positive outcomes are encouraging other companies to adopt systems that comply with the new regulations.

The International Civil Aviation Organisation (ICAO) aims to prevent the reoccurrence of accidents by recommending specific prevention measures through the findings of accident analysis. In Canada, the Transport Safety Board (TSB) is an independent agency that helps enhance transport safety by investigating all transport sectors, including aviation and maritime occurrences. The TSB produces accident/incident investigation reports, except for military occurrences. For aviation, GA accidents are usually investigated by one or two investigators, and the details on specific definitions used by the TSB in Canada for aviation accidents vs incidents can be found in Section 4.3.2. The results of TSB

investigations lead to the identification of safety deficiencies, for which recommendations are made. Their findings are used to improve regulations and practices across the aviation sector.

Transport Canada Civil Aviation (TCCA) is one of the three founders of the Safety Management International Collaboration Group (SM ICG), which was formed to promote the understanding and use of SMS internationally. This group aims to standardise safety management practices worldwide, and enhance aviation safety through shared principles, collaborative efforts, and harmonised practices. Members of the SM ICG work together on shared topics of interest related to SMS and State Safety Programs (SSP). They exchange lessons learned, promote the harmonisation of SMS/SSP, and disseminate related products within the aviation community. Additionally, they collaborate with international organisations such as ICAO and Civil Aviation Authorities (CAA) that have implemented or are in the process of implementing SMS and SSP (SM ICG, 2022).

NAV Canada is a private, non-profit organisation responsible for managing Canada's civil air navigation system. Its role in GA safety includes providing air traffic control, flight information, weather services and airport advisories. NAV Canada works closely with Transport Canada to maintain compliance with aviation safety standards and regulations (NAV Canada, n.d.).

The Air Transport Association of Canada (ATAC) collaborates with regulatory agencies like Transport Canada and Nav Canada to develop and enforce safety standards. ATAC's activities include policy development, conducting safety audits, and sharing best practices among members. They facilitate communication and cooperation among various stakeholders, including commercial operators, flight schools and maintenance organisations, to promote a strong safety culture. By participating in regulatory consultations and providing industry feedback, ATAC helps ensure that safety regulations are practical and effective.

The Canadian Owners and Pilots Association (COPA) is another non-profit organisation that represents the GA interests in Canada. It provides information, support and advocacy for its 12,000 members, making it the largest aviation association of its kind in the country (COPA, 2024). The organisation works to ensure that regulations and policies support the freedom to fly, provide resources and education to enhance safety, and promote the benefits of GA to both the public and policy makers (COPA, 2024). COPA is also a member of the International Council of Aircraft Owner and Pilots Association (IAOPA), working internationally to support GA.

Transport Canada developed the General Aviation Safety Program (GASP), which has the aim to keep the GA community informed about safety and reduce the number of safety occurrences, by engaging with the industry (TC, 2020c). Since the GASP analyses various aspects of GA safety, this program has

been structured into working groups created to tackle specific areas, which are overseen by the CGAJSC. Such a working group is the Seaplane Working Group (SPWG). Similar to the FAA GAJSC in the USA (presented in Section 4.1.2), Canada has a similar committee designated to improve GA safety. The Canadian General Aviation Joint Safety Committee (CGAJSC) was formed by the GASP for guidance and support, and it is co-chaired by two representatives from TC and the industry. It was designed after the one in the USA and it is an informal partnership between TC and COPA as an effective way to raise, discuss, and mitigate safety issues and concerns, in the best interest of the GA community. TC attends the GAJSC meetings and the FAA attends the CGAJSC meetings, as observers, to exchange results and safety knowledge, and enhance safety in both countries. Overall, the GA regulatory model in Canada can be seen as a combination of self-regulation and government regulation.

4.4.2. Stakeholders for General Aviation seaplanes in Canada

Seaplane operations in Canada include both commercial and GA. It is evident from previous sections that there is more focus on commercial operations, so this section puts together the stakeholders for GA seaplanes in Canada. In the previous section (Section 4.4.1), stakeholders such as COPA, ATAC, TSB, TC and Nav Canada have been presented, in relation to their contribution to GA safety in Canada. In addition, Seaplane Pilot Associations (SPAs) around Canada, Flight Training Units (FTU) providing seaplane training and/or rental, seaplane pilots and owners, and airports / seaplane bases have been added to reflect specific stakeholders for seaplane operations.

Other stakeholders for GA seaplane operations in Canada include Provincial and Local Governments, Maintenance Organisations, Fixed-Base Operators (FBO), Environmental Agencies (e.g., Fisheries and Oceans Canada, Canadian Wildlife Service), Waterway Management Authorities (e.g., local harbour authorities, lake associations), and Aviation Insurance Providers.

Table 4.4 summarises the stakeholders for GA seaplane operations in Canada and their interactions with other stakeholders. Appendix E shows the relationships between these stakeholders, and Figure 4.4 is the simplified version which includes only the main stakeholders relevant for this thesis.[4]

Table 4.4. Summarises of the stakeholders for recreational GA seaplane operations in Canada.

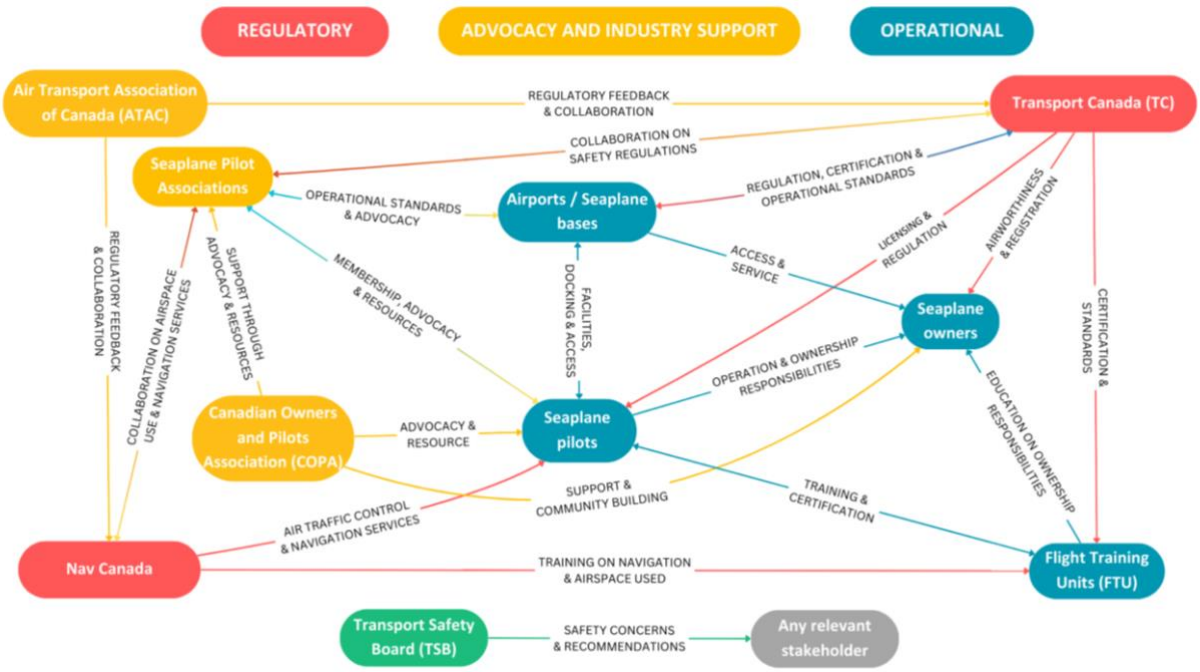
Stakeholder	Description	Interactions	Detailed Interactions
Regulatory			
Transport Canada (TC)	Federal authority responsible for transportation	Pilots, FTUs, FBOs, SPAs, TSB, Maintenance Organisations, Aircraft Owners,	Licenses and regulates pilots, certifies FTUs, enforces regulatory compliance for FBOs, ensures maintenance organisations adhere to safety regulations, handles airworthiness and registration for aircraft owners, certifies airports / seaplane bases, collaborates with seaplane pilot

[4] Information validated by a field expert in General Aviation, Seaplanes and aviation safety.

	policies and programs.	Airports / Seaplane Bases	associations on safety regulations, receives safety recommendations from TSB.
Nav Canada	Manages civil air navigation services.	Pilots, FTUs, FBOs, SPAs, TSB	Provides air traffic control and navigation services to pilots, offers training on navigation and airspace use to FTUs, coordinates air navigation services with FBOs, works with SPAs on airspace use, receives TSB safety recommendations.
Advocacy and Industry Support			
Canadian Owners and Pilots Association (COPA)	Advocates for the rights and interests of pilots and aircraft owners.	Pilots, Aircraft Owners, TSB	Provides advocacy and resources for pilots, supports and builds community for aircraft owners, shares safety information and findings from TSB.
Air Transport Association of Canada (ATAC)	Represents Canada's air transport industry.	TC, Nav Canada, TSB	Collaborates with TC and Nav Canada on regulatory feedback, receives safety recommendations from TSB. ATAC is mostly focused on commercial operations, but includes FTUs.
Seaplane Pilot Associations	Represents the interests of seaplane pilots and promotes safety.	Pilots, TC, Nav Canada, Airports / Seaplane Bases, TSB	Provides advocacy and resources for pilots, collaborates with TC on safety regulations, works with Nav Canada on airspace use, collaborates with airports / seaplane bases on operational standards, receives safety recommendations from TSB.
Operational			
Pilots	Individuals licensed to operate seaplanes.	Aircraft Owners, FTUs, Maintenance Organisations, FBOs, Airports / Seaplane Bases, SPAs, TC, Nav Canada, TSB	Operate aircraft owned by themselves or others, receive training from FTUs, ensure aircraft maintenance with maintenance organisations, utilise services and support from FBOs, access operational facilities at airports / seaplane bases, provide charter services, join SPAs for advocacy, receive licenses and regulations from TC, receive air traffic control and navigation services from Nav Canada, receive safety findings and recommendations from TSB.
Seaplane Owners	Individuals or entities that own seaplanes.	Pilots, Maintenance Organisations, FBOs, Airports / Seaplane Bases, COPA, SPAs, TC, TSB	Own and manage seaplanes operated by pilots, ensure maintenance with maintenance organisations, use hangar space and maintenance services from FBOs, access and use airports / seaplane bases, receive support and community building from COPA, join SPAs for advocacy, ensure airworthiness and registration with TC, receive safety findings and recommendations from TSB.
Flight Training Units (FTUs)	Institutions that provide pilot training.	Pilots, Future Aircraft Owners, TC, Nav Canada, TSB	Train pilots and educate future aircraft owners, receive certification and standards from TC, train on navigation and airspace use in collaboration with Nav Canada, receive safety recommendations from TSB.
Airports / Seaplane Bases	Facilities that support seaplane operations.	Pilots, Aircraft Owners, TC, Environmental Agencies, Provincial and Local Governments, SPAs, FBOs, TSB	Provide operational facilities and docking for pilots, offer access and services for aircraft owners, comply with regulation and certification from TC, adhere to environmental regulations from environmental agencies, obtain permits and land-use planning from provincial and local governments, collaborate with SPAs on operational standards, receive services from FBOs, receive safety recommendations from TSB.
Other			

Transportation Safety Board of Canada (TSB)	Provide independent occurrence investigations.	Any stakeholder	When necessary, shares safety concerns and recommendations with any stakeholder able to address them.
Maintenance Organisations	Provide aircraft maintenance services.	Aircraft Owners, Pilots, TC, TSB	Ensure maintenance and safety compliance for aircraft owners, ensure airworthiness of aircraft for pilots, follow regulations and safety standards set by TC, receive safety recommendations from TSB.
Insurance Providers	Offer insurance services.	Aircraft Owners, Pilots	Provide insurance coverage for aircraft owners, offer liability and personal insurance for pilots.
Fixed Base Operators (FBOs)	Provide ground services to aviation operators.	Pilots, Aircraft Owners, Airports / Seaplane Bases, Nav Canada, TC, TSB	Provide fuelling, parking, and other services to pilots, offer hangar space and maintenance to aircraft owners, provide service facilities for airports / seaplane bases, coordinate with Nav Canada for air navigation services, comply with regulatory standards from TC, receive TSB safety recommendations.
Environmental Agencies	Enforce environmental protection regulations.	Airports / Seaplane Bases, Pilots, TSB	Regulate environmental impact and compliance for airports / seaplane bases, enforce environmental protection rules for pilots, interact with TSB on environmental factors in investigations.
Provincial and Local Governments	Manage local and regional regulations.	Airports / Seaplane Bases, Pilots, TSB	Issue permits and enforce local regulations for airports / seaplane bases, ensure compliance with provincial laws for pilots, receive safety recommendations from TSB.
Waterway Management Authorities	Manage the use and safety of waterways.	Airports / Seaplane Bases, Pilots	Manage waterway use and safety for airports / seaplane bases, enforce navigation rules and waterway access for pilots.

Figure 4.4. Main stakeholders for recreational GA seaplanes in Canada.



Recreational GA seaplane pilots are not required to be part of an organisation that manages safety, and they often improve their safety knowledge by checking accident data or reports on general statistics and trends. The regulators and operational stakeholders are those who can benefit most from the outcomes of this thesis. The findings can also be helpful the industry support stakeholders.

4.5. Studies on the safety of General Aviation seaplanes

Literature about seaplanes safety is scarce, with no research focusing specifically on GA seaplane safety (private, recreational operations). The literature review was conducted searching for combinations of keywords related to the topic. For example, searching for "seaplane accident analysis" on Google Scholar provided 5,540 publications. Further filtering has been done by sorting the results by relevance (and considering the first 50 publications), then by recency (this filtering method provided irrelevant studies). A similar approach was also conducted on Research Gate, where an extra filtering method was available - by citation count. Google search has also been used, especially for information on official websites such as TC and COPA.

Although, historically limited research has been conducted for seaplane safety, the available studies and their methodologies are described in Sections 4.5.1 and 4.5.2, focusing on those that analysed accident and/or incident data. The literature gaps are addressed in Section 4.5.3.

4.5.1. Studies on seaplane safety worldwide

The last comprehensive analysis on seaplane safety was conducted by the Seaplane Pilots Association, in 1996 (SPA, 1996). It included 195 seaplane accidents from 1983 to 1995, in the USA. The Seaplane Pilots Association (1996) determined the most common contributing factors to the seaplane accidents to be: rough or glassy water, striking submerged objects, wheel-down landings, poor weather (including wind), and improper pilot technique or procedures followed, which was the case in 72% of the accidents. This research has certain data deficiencies, as non-commercial seaplane activity is not consistently tracked or recorded, hence the results for GA may differ from reality.

The research of the Seaplane Pilots Association (1996) was expanded by Ison (2024), who conducted a comprehensive and robust literature review of reports and other research on seaplane safety, along with a statistical analysis of accident reports between 1982-2021. The analysis was also conducted for the USA, with data sourced from the NTSB. Ison (2024) attempted to use further data from insurers, however the data provided was incomplete. This paper addresses the challenges in finding relevant data for seaplane operations, especially for GA. Ison (2024) employed various statistical methods to analyse trends and risk factors in seaplane operations, comparing the results between seaplane and non-seaplane groups. The use of pilot demographics and detailed event sequence analysis adds depth

to the understanding of accident causes. However, this study focused only on historic data analysis, for which data gaps were stated. It did not find alternative sources to fill these data gaps, and their qualitative analysis was limited to the information in the accident narratives which is scarce especially regarding human decision-making process and possible errors in judgement.

Xiao, Luo and Li (2020) assessed and predicted risks associated with seaplane operations, using Bayesian Network (BN). Both quantitative and qualitative data have been used in this study, as it identifies risk factors through mixed methods of analysis: literature review, historical accident data, surveys and interviews. The interviews were conducted with five experts in the aviation and maritime sectors, only one being a GA seaplane pilot, in China. The key findings indicate that the most critical risk factors for seaplane operations are mental barriers, mechanical failures, visibility issues, and improper emergency disposal.

Out of 110 National Transportation Safety Board (NTSB) seaplane accidents between 2010 and 2016 that have been analysed, 87 of these were used for parameter learning and 23 for model validation. It is unclear why this data sample has been chosen and the type of data it contains. Overall, Xiao, Luo and Li (2020) provide a good literature review of risk factors affecting the safety of seaplane operations and present their data analysis and BN model well. However, the paper lacks information, in particular for the surveys and interviews. For example, it is unclear what the interviews and two surveys consisted of, how and why they were conducted. Moreover, using data and participants from different countries can affect the results, and the paper does not discuss the reason for choosing that specific sample of participants for interviews and surveys.

Another publication about seaplane accident analysis is de Voogt, Campos and Lu (2023), which aims to investigate the safety issues associated with amphibious seaplanes in the USA through statistical analysis. Utilising accident data from the NTSB between 2005 and 2020, the study examines 183 accidents involving amphibious airplanes, with a particular focus on identifying contributing factors and patterns. The research covers accidents that occurred across various states in the United States, notably highlighting the states of Florida and Alaska due to their higher incidence rates. The methodology includes logistic regression to analyse the relationships between accident parameters.

The qualitative research of Andrade, Kalakou and Lopes da Costa (2022) aims to investigate the potential challenges of seaplane operations in Greece. The study employs a mixed-methods approach, combining a survey of stakeholders involved in seaplane operations and a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis to identify key factors influencing the success of seaplane services. The survey collected data from various stakeholders, including operators,

regulators, and passengers, to gather comprehensive insights into the operational landscape. The SWOT analysis further contextualised these findings by assessing internal and external factors affecting seaplane operations. The study does not focus on specific accidents but rather on operational and strategic aspects.

Ganesan et. al. (2017) analyse the factors affecting seaplane landings. The study uses empirical accident data from 2010 to 2016 and expert analysis to assess how these factors influence landing performance. The data includes 150 seaplane landings from accident reports in North America, as well as expert interviews, to provide insights into environmental and mechanical influences on seaplane landings. The findings highlight the significant impact of weather conditions, water surface characteristics and aircraft design on the safety and efficiency of seaplane landings. Another relevant publication is the qualitative study of Guo, Xu & Wu (2016), which provides a comprehensive summary of safety management practices in seaplane operations on water, and it includes a detailed risk index system for seaplane take-offs and landings.

Weng and Zhou (2013) identify and analyse the risk factors associated with collisions between seaplanes and vessels in China, proposing targeted safety countermeasures. The study employs a qualitative approach, utilising expert interviews and literature reviews to gather data on past accidents and risk factors. The location focus is likely to be areas with significant seaplane and vessel traffic.

4.5.2. Studies on seaplane safety in Canada

There are two main studies focusing on seaplane safety in Canada, one from 2021 (MacDonald, Brooks & McGowan, 2021), on survival rates for seaplane accidents, and one from 2023 (MacDonald, Brooks & McGowan, 2023), focusing on ultralight safety. In addition to these, the Transport Safety Board of Canada has two publications. One of these is from 1993 and addresses seaplane pilot knowledge and skills (TSB, 1993), and the second one is from 1994 and focuses on survivability for seaplane accidents (TSB, 1994). The latter is expanded on by MacDonald, Brooks & McGowan (2021).

Both studies from the TSB examine 1,432 seaplane accidents between 1976 and 1990, in Canada (TSB, 1993; TSB, 1994). They determined that seaplanes are involved in 18% of the number of aircraft accidents in Canada, and they represent around 19% of the fleet. However, because seaplane fly only seasonally (around half of the year), this statistic makes seaplanes operations more unsafe than other aircraft types. During 1976-1990, seaplane occurrences were most often during approach/landing and take-off/climb, accounting for 34% and 35% of accidents, respectively. For these phases of flight, the most recurring accident types (adjusted to be consistent with the categorisation detailed in Section

4.3.4) were loss of control (LOC-I and LOC-G), engine failure (SCF-PP), collision (such as CTOL and GCOL) and abnormal runway contact (ARC). For these, the contributory factors were studied, and these include: unfavourable environment for take-off or landing, incomplete preparation before flights, unfavourable wind conditions, issues with: maintaining air speed, landing flare, glassy water, obstructions, or following different procedures.

The first TSB study (TSB, 1993) tested for associations between the phase of flight, the most recurring accident types and the contributory factors. They determined that LOC-G during take-off is more likely to be caused by wind, while LOC-I during climb were generally attributed to the pilot's lack of experience or skill. Other relevant results of TSB (1993) include the fact that 54% of the pilots involved were GA pilots, and that most accidents and incidents occurred for less experienced pilots, with under 100 hours flown on floats. Another issue explored and attributed to the high number of human-related occurrences is that "[…] by their nature, seaplane operations require a high degree of independence of problem-solving", and that many pilots rely on knowledge shared by other pilots in their area, news or friends, which might not always be accurate (TSB, 1993). This emphasises the importance of making the trusted sources for safety awareness easily available for seaplane pilots, and that more ways to share safety knowledge and bring awareness to current risks should be implemented. Nowadays, ways to stay current and proficient are now easily accessible on the TSB website. The biggest limitation of the TSB (1993) report is that the data requirements for reporting accidents or incidents are minimal, which does not allow for a deep dive into certain issues such as pilot decision making, fatigue, environmental conditions, checks before flight etc. Improving the quality of reported data would significantly improve safety, as more specific factors could be addressed, in greater detail.

The second TSB report (TSB, 1994) focuses on factors contributing to the survivability of seaplane accidents, considering a subset of the data to account only for accidents with fatalities. The results reveal concerns about people unable to exit the aircraft after impact, especially when it is on a body of water, which leads to drowning. However, from the people who were able to exit the aircraft, but the occurrence was on water, 86% died from drowning (TSB, 1994). These outcomes were attributed to improper briefing of passengers on emergency procedures, lack of use of seatbelts and floatation devices, and incorrect bracing of belongings and other objects on-board, which could restrict the ability to escape the aircraft.

MacDonald, Brooks & McGowan (2021) expanded on the 1994 TSB report, analysing data from 1995 to 2019 and developing a classification system for human errors. Less serious occurrences which are unlikely to cause injuries or fatalities were excluded from this research, as the focus was on survivability in serious accidents. For example, long or short landings, runway excursions and incidents

after which the pilot was able to safely taxi the aircraft to the dock were excluded (MacDonald, Brooks & McGowan, 2021). This resulted in a dataset of 487 accidents in Canada, with a survival rate of 87%. This study determined that the top cause of accidents is LOC-G (with 8% fatality rate on take-off and 9% on landing), however, unknown cause, LOC-I and stalls on approach are the deadliest, with 89%, 82% and 48% fatality rates, respectively. Interesting to note is that the survival rate increased from 39% in 1976-1990 to 87% in 1995-2019 (TSB, 1994; MacDonald, Brooks & McGowan, 2021), however, the TSB report analysed only accidents with fatalities. Another difference is that, while the proportion of accidents during take-off decreased from 41% to 26%, those during landing increased considerably from 37% in the TSB report to 49% in the more recent study. Nonetheless, these two publications have common findings about the fact that most deaths while on board are attributed to drowning, and about the non-use or incorrect use of harness and floatation devices.

The second paper from MacDonald, Brooks & McGowan (2023) focuses on accidents of ultralight seaplanes, which were excluded by MacDonald, Brooks & McGowan (2021). The study reviewed 1,021 ultralight accidents between 1990-2020 reported to the TSB of Canada, of which 114 ended in water (MacDonald, Brooks & McGowan, 2021). The majority of accidents occurred during landing (52%) and, with less than 15 seconds of warning before the accident in 78% of these. Common causes included loss of control and adverse environmental conditions. The study highlighted the need for better preparation before flights, underwater egress training, and use of safety equipment like life jackets and restraint harnesses to enhance survival chances in ultralight water accidents.

4.5.3. Critical literature gaps in seaplane safety research

Despite the extensive search and analysis, significant gaps remain in the literature on seaplane safety, particularly regarding GA seaplane operations. The current body of research is limited in several key areas, which are critical for developing a comprehensive understanding of seaplane safety and for informing effective safety measures.

Most studies, including the comprehensive analysis by the Seaplane Pilots Association (1996) and the subsequent work by Ison (2024), primarily focus on commercial seaplane operations or combine data for all seaplane activities, which can obscure the unique safety challenges faced by GA seaplane pilots and operators. It is assumed that GA seaplane activity is not consistently tracked or recorded, such as the number of hours flown on seaplanes, leading to potential discrepancies in understanding the safety landscape for GA seaplanes. This gap highlights the need for more targeted research on private and recreational seaplane operations, to address unique risks and safety concerns in this sector and develop tailored safety recommendations and interventions.

Another gap is the limited research on the effectiveness of current training requirements and programs, particularly in areas addressing safety, such as emergency procedures or underwater egress. Future studies should focus on evaluating and improving training methodologies to better prepare pilots for the unique challenges of seaplane operations, especially in the private/recreational sector. In addition, there are different training requirements for private/recreational pilots compared to commercial pilots, and these differences can influence the likelihood of an occurrence or of survivability in case of an occurrence. This further enhances the importance to study private, recreational operations separate from commercial.

Many studies, including those conducted by the Seaplane Pilots Association and the Transport Safety Board of Canada, highlight deficiencies in data quality and consistency. There is a lack of detailed reporting on factors such as pilot decision-making processes, environmental conditions, and pilot experience and demographics. Many studies rely on historical accident reports obtained from regulators such as local Government branches, which often have incomplete or inconsistent data. There is abundant literature analysing occurrence reports from Government branches, and not data sets as it is common for these to not be publicly available. However, only occurrences that can lead to regulatory changes or other lessons learned are investigated in greater detail and such a report is provided, so the reports together may not represent reality. In addition to this, Ison (2024) highlighted the challenges in obtaining complete data from other sources such as insurers. Improved data collection standards and practices, including more detailed reporting requirements for accidents and incidents, would significantly enhance the quality of safety research and allow for more nuanced analysis of contributing factors.

Studies such as those by Xiao, Luo, and Li (2020) and the TSB reports (1993, 1994) have identified critical risk factors and contributing elements to seaplane accidents by using accident and incident data. Given the data limitations already mentioned, there is a notable lack of in-depth qualitative analysis, particularly regarding human factors such as seaplane pilot decision-making in critical situations. There is also a lack of engagement with the seaplane industry, especially with the GA pilots, who have more freedom and less strict requirements for training and safety than the commercial pilots. Furthermore, in the GA case or whenever the data does not provide enough information on certain parameters, alternative methods and sources should be pursued, until researchers are confident that the results reflect reality. Mixed methods of analysis should be used to maximise the meeting of research objectives when one type of analysis, such as accident data analysis, proves to not be enough.

While several studies provide valuable insights into seaplane safety in specific regions like the USA and Greece, there is limited research that compares seaplane operations across different geographical and operational contexts. Researchers often work with datasets they see as most complete and better than others; in this case, NTSB data for seaplane occurrences in the USA is widely used. The differences in environmental conditions, regulatory frameworks, operational practices and simply pilot attitudes and behaviours can significantly impact safety outcomes. Comparative studies that encompass diverse regions and operational settings are needed to develop globally applicable safety recommendations.

Historical accident and incident data analysis provides valuable insights into past accident trends and causes. However, there is a need for longitudinal studies that track the impact of implemented safety measures over time. This gap can be filled by providing research on the evaluation of the effectiveness of regulatory changes, technological advancements and training enhancements in reducing accident rates and improving survival outcomes. This would also help refine and optimise safety strategies.

Lastly, the fact that, at a global level, the seaplane market is small compared to other transport modes or even other types of aircraft, makes it unlikely to receive investment for safety development ahead of the bigger markets. Non-commercial seaplanes are an even smaller market, making it challenging to obtain the necessary resources for comprehensive safety assessments. Addressing these literature gaps is essential for developing a more robust understanding of seaplane safety, particularly for GA operations.

In Canada, the two TSB studies on seaplane safety (TSB, 1993 and TSB, 1994) are comprehensive but outdated, the last year of data considered being 1990. The other two studies (MacDonald, Brooks & McGowan, 2021 and MacDonald, Brooks & McGowan, 2023), while more recent, have limited focus on either survivability or ultralights. When it comes to seaplane operations, as previously discussed in Section 4.2.2, Canada ranks second in the world in terms of the number of seaplane pilots and registered seaplanes. Additionally, Canada's unique nature and vast remote areas increase the dependency on certain populations on seaplanes, for various remote activities, especially for private and recreational purposes. Thus, addressing this subgroup of seaplane operations separately, by considering specific accident and incident analysis, along with addressing the concerns of private seaplane pilots and improving the engagement with the community is imperative. Implementing a comprehensive Safety Management System (SMS) tailored to GA seaplane operations, akin to those mandated for other aviation sectors in Canada, could ensure a more consistent safety culture and improve safety reporting and behaviour.

By addressing these gaps in existing research, this thesis aims to provide GA-specific insights that could lead to improved safety measures and training programs specifically tailored for private, recreational seaplane operations. There are currently no comprehensive studies that concentrate on the safety of private, recreational seaplanes. This oversight is significant because the sector includes flight training units, which play a vital role in shaping the skills and safety practices of new pilots.

Having identified literature gaps for the seaplane industry in this chapter, and for different aspects of the maritime industry in the previous chapter, the following chapter provides the research methodology and philosophy adopted in this thesis to fill these gaps.

5. Research Methodology and Philosophy

This chapter outlines the research philosophy and the underlying methodology used in this thesis to answer to the main research question "How can transport safety be enhanced through data analysis to reduce the number of accidents, incidents, and associated lives lost, injuries and property damage?". The rationale underlying the process of framing the research question, philosophy and methodology follows that of Savin-Baden and Howell Major (2013).

This chapter starts by determining the appropriate research philosophy and approaches in Sections 5.1 and 5.2. The reasons for choosing specific case studies from different transport sectors for subsequent analysis are subsequently discussed in Section 5.3. Having reviewed the relevant literature and identifying the gaps in the previous chapters, Section 5.4 describes the rationale in this thesis towards the development of a robust methodology for achieving a holistic understanding of accident causation patterns using mixed methods of analysis. The data sources utilised throughout the process of framing the research question, philosophy and methodology are then described in Section 5.5. Finally, the framework for assessing the suitability and quality of this data is proposed in Section 5.6.

5.1. Philosophical stance of the researcher

This section summarises the selection of the appropriate research philosophy, while the relevant approaches are discussed in the subsequent section. Both the research philosophy and approach have been selected on the basis of their suitability with the research question (Section 1.2), objectives of the study (Section 1.2) and the type of data that is used (Section 5.5).

The research philosophy outlines the beliefs that underpin the research of this thesis, to ultimately enable the production of valuable and actionable insights that meet the research goals. Mkansi and Acheampong (2012) analyse the debates in the literature about different philosophies and state that understanding the different philosophies is challenging because there are no universal definitions. In addition, further debates consider how qualitative, quantitative and mixed methods of analysis are related to research philosophies (Johnson and Duberley, 2000; Bryman, 1984; Morgan and Smircich, 1980; Caelli et al., 2003). Table 5.1 provides an overview of these debates related to the three methods of analysis.

Table 5.1. Philosophical debates for: Mixed methods, qualitative and quantitative approach (Mkansi and Acheampong, 2012).

Philosophical debates for: Mixed methods, Qualitative and Quantitative approach	
Research approaches	**Philosophical debates for the approaches**
Mixed Methods	Mixed method is believed to be rooted in pragmatism (Denscombe, 2007; Johnson and Onwuegbuzie, 2004); but Barrett (2010) asserts the opposite and considers critical realism to be the theoretical foundation of mixed method research.
Qualitative approach	Guba and Lincoln (1994) identified four paradigms that compete in qualitative research, namely; positivism, post-positivism, critical theory and constructivism. However, other scholars (McNabb, 2008; Denzin and Lincoln, 2005) assert that interpretive and critical paradigms are central to qualitative approach. A detailed analysis of these debates is fully discussed amongst other scholars (Guba and Lincoln, 1994; Denzin and Lincoln, 2005).
Quantitative aapproach	Scholars (Polit and Beck, 2008; Steen and Roberts, 2011) assert that positivist and naturalist are philosophies for quantitative approach. Furthermore, Alvesson and Skoldberg (2009) add post-postivism, social constructionism, and critical realism as other philosophical stances.
Qualitative vs. Quantitative approach	The debates stretch further from which different philosophies is best for a single research approach (i.e. pragmatism against critical realism for mixed methods); to whether a particular philosophy is for qualitative or quantitative approach (i.e. positivism for qualitative vis-à-vis quantitative). This is best demonstrated in research findings by amongst other scholars (Bryman, 1984; Becker, 1996).

However, Johnson and Onwuegbuzie (2004) argue that differences in epistemological beliefs and logic for justifications in the literature should not dictate the specific data collection and analytical methods used. They contend that these differences should not hinder the utilisation of any methods, an assertion also supported by Guba and Lincoln (1994), who emphasise that the grounding of approaches is secondary to the paradigm and does not restrict the use of either qualitative or quantitative methods within any research paradigm. Becker (1996) also discusses the often-trivial nature of philosophical differences in relation to research approaches.

Therefore, the subsequent sub-sections will include differences in the philosophies and determine those most appropriate for this thesis.

5.1.1. Ontology vs epistemology

A research philosophy can take the form of an approach that is either ontological or epistemological, both of which are key concepts in research philosophy that influence how researchers approach their studies (Denzin and Lincoln, 2018). Understanding these concepts is essential for aligning research methods with the theoretical framework and ensure coherence of this thesis. Throughout the literature, there are different categorisations of the ontological and epistemological perspectives, as

illustrated by Ritchie and Lewis (2003) compared to Saunders et al. (2019), however these concepts have similar definitions.

On one hand, **ontology** deals with the nature of reality and what exists, addressing questions about the essence of being, existence, and the structure of reality. Ontological positions can range from realism, i.e., there is an objective reality independent of human perception, to relativism which argues that reality is constructed through social processes and is therefore subjective and varies between individuals and contexts (Denzin and Lincoln, 2018). Realism asserts that reality exists independently of perceptions and can be objectively known. This perspective is often associated with quantitative research, where the goal is to discover generalisable truths about the world (Bhaskar, 1975). On the other hand, relativism suggests that reality is socially constructed and differs based on individual experiences and contexts. This view aligns more closely with qualitative research, focusing on understanding the meanings and experiences of people (Denzin & Lincoln, 2011).

Epistemology is concerned with the nature of knowledge and the process of how people know things. It explores questions about the nature, sources and limits of knowledge, and influences the choice of research methods and the interpretation of findings (Creswell, 2014). Epistemological positions can vary widely, influencing how research is conducted and interpreted. Empiricism, a key epistemological stance, asserts that knowledge is derived from both a sensory experience and empirical evidence (Creswell, 2014). This view supports quantitative methods such as experiments and surveys, which rely on measurable data. In contrast, constructivism states that knowledge is constructed through human interactions and experiences. This perspective supports qualitative methods, such as interviews and ethnography, which explore subjective meanings and social contexts (Patton, 2002). The last epistemological stance is pragmatism, which emphasises the practical application of research findings, integrating both quantitative and qualitative methods to address research questions effectively (Creswell & Plano Clark, 2014). Pragmatists prioritise the usefulness and applicability of knowledge over adherence to any single philosophical framework. This approach is particularly suitable for research that seeks to address real-world problems through practical solutions (Creswell & Plano Clark, 2014).

5.1.2. Critical realism

Critical realism is a philosophy that combines ontology and epistemology (Bhaskar, 1975). Critical realism is suitable for this thesis because it allows for the investigation of both observable events, such as accidents and incidents, and the underlying mechanisms that cause these events, such as organisational practices and human factors (Maxwell & Mittapalli, 2010).

As previously mentioned, constructivism considers knowledge through the perspective of human interactions and experiences. This supports the results to be obtained through the qualitative methods considered in this thesis, such as interviews and focus groups. Guba and Lincolm (1989) states that constructivism is linked to critical realism, so it will not be considered separately as critical realism has a broader applicability.

The epistemology of critical realism, known as transcendental realism, seeks to understand both empirical data and the deeper structures that generate these data. This aligns with using a mixed-methods approach, integrating both quantitative data, such as accident statistics, with qualitative insights from interviews and surveys (Creswell, 2014). By integrating diverse data sources, this philosophy provides a comprehensive understanding of transport safety, allowing for the development of actionable safety interventions based on a holistic view of the factors at play (Maxwell & Mittapalli, 2010).

5.1.3. Pragmatism

Another example in the realm of philosophy is pragmatism, which is believed to have evolved from realism (Thayer, 1981), as both share a common set of assumptions, positioning them within a broader philosophical context. While they possess critical shared assumptions, they emphasise different implications of these assumptions. For example, although each philosophy focuses on explaining methodological differences in research, they utilise different categorisations and classifications (Mkansi and Acheampong, 2012).

As mentioned previously, pragmatism allows for flexibility in choosing methods that best address the research questions. This approach integrates both quantitative and qualitative methods, emphasising actionable outcomes and practical solutions, which are critical for enhancing transport safety (Tashakkori & Teddlie, 2010).

Pragmatism also combines ontology and epistemology. It is characterised by a pragmatic ontology, which is flexible and focused on practical outcomes. Pragmatists are hence less concerned with abstract notions of reality and more with what works in practice to solve problems and achieve goals (Patton, 2002). Furthermore, pragmatists adopt a pragmatic epistemology, emphasising the utility of knowledge and its application in practical contexts. They prioritise methods and approaches that are effective in addressing specific research questions and achieving practical results (Creswell, 2014).

5.1.4. Phenomenology

In addition to the already-mentioned philosophies, phenomenology is a significant research philosophy that has implications for both ontology and epistemology. Phenomenology primarily focuses on human experiences and the meanings individuals ascribe to those experiences. In research, it provides a framework for exploring the nature of experiences (ontology) and the ways in which these experiences are understood and interpreted (epistemology) (Husserl, 1970; Heidegger, 1962).

Therefore, phenomenology is deeply concerned with the nature of reality as experienced by individuals, exploring how things appear to consciousness and emphasising the lived experiences and the essence of phenomena. This focus places phenomenology within the realm of ontology (Denzin & Lincoln, 2011). However, phenomenology also has a strong epistemological dimension, as it is concerned with how knowledge of these experiences is obtained and understood. It emphasises the subjective nature of knowledge and the importance of personal perception and interpretation. Phenomenology examines how individuals come to know and make sense of their experiences, thus addressing key epistemological questions (Patton, 2002). By exploring how experiences are perceived and interpreted, phenomenology contributes to understanding the processes through which knowledge is constructed and validated.

This dual focus makes phenomenology a versatile approach in qualitative research, where understanding the depth and complexity of human experiences is essential (Creswell & Plano Clark, 2011). In this thesis, phenomenological methods such as focus groups and questionnaires can uncover the rich, detailed experiences of operators, passengers and safety personnel. In this case, this ontological exploration helps reveal the essence of safety experiences, while the interpretation of these experiences and the meanings ascribed to them by participants contribute to the epistemological understanding of safety perceptions and practices.

5.1.5. Conclusions of philosophical stance of the researcher

This thesis addresses real safety issues of the transport sector, involving both the quantitative analysis of accident and incident data, as well as qualitative analysis involving human knowledge and perceptions. Therefore, overall, the main philosophical approach pursued in this thesis is epistemology, through a pragmatic philosophy given the focus on real-world problems through practical solutions and the desire to prioritise the usefulness and applicability of knowledge over adherence to one single philosophical framework.

Additionally, the epistemological approach is particularly suited for this thesis as it allows for the examination of decision-making, safety protocols and risk perception that are crucial to how safety

measures are implemented and followed (Creswell, 2014; Denzin & Lincoln, 2011). Furthermore, since transport safety research involves multiple stakeholders, their differing perspectives must all be considered to fully understand what contributes to safe and unsafe practices. Epistemology is also suitable for this, as it allows for interdisciplinary collaboration, which is essential for a comprehensive understanding of transport safety by enhancing both the richness and applicability of findings (Nowotny et al., 2001).

Even though critical realism is used to understand underlying mechanisms that cause accidents, such as organisational practices and human factors, which seems suitable for this thesis, pragmatism has been used instead. This is because, as previously mentioned, pragmatism is regarded as an evolution of realism and it allows for more flexibility in choosing a methodology that suits the research questions best.

In addition, in one of the case studies, aspects of phenomenology are used. Phenomenology complements pragmatism in Chapter 8, offering a robust framework that addresses both the nature of reality and the processes through which knowledge is acquired, to deeply explore and understand human experiences. These will be used in the design of a questionnaire and interviews. Since the critical realism and phenomenology philosophies are used only for part of one of the case studies, Section 8.2 in Chapter 8 will offer more details on the methodology employed for that particular case study. In conclusion, these philosophies will provide a holistic understanding of research phenomena and offer practical solutions, for each case study.

5.2. Research approach

A **deductive reasoning** approach is used in this thesis, which is in line the pragmatic research philosophy adopted. Deductive reasoning involves drawing specific conclusions from general premises (Glaser and Strauss, 1967) and, in this thesis, these premises are based on the literature review from Chapters 3 and 4, for the maritime and aviation industries, specifically. Consequently, a deductive approach is necessary to establish how existing theories and gaps revealed through the literature review are addressed through the methodology of this thesis.

As previously argued in Sections 2.2, 2.6 and 2.7, the transport system is a complex socio-technical system where choosing one method, accident model or safety approach is insufficient for a comprehensive safety analysis. Therefore, to effectively use deductive approaches, a **mixed methods** approach will be employed in this thesis to enhance the study and fulfil the research objectives presented in Section 1.2 . In particular, the definition and guidance of Creswell and Plano Clark (2018) have been followed in the decision to use this approach and how it was implemented.

The mixed methods of data analysis leverages the strengths of both quantitative and qualitative methods of analysis (Hussein, 2009; Almajali and Dahalin, 2011; Fielding, 2012). According to Creswell and Plano Clark (2018), there are three types of basic designs for mixed methods:

- Sequential Explanatory Design - Quantitative data is collected and analysed first before the qualitative data, which is later used to explain the quantitative results.
- Sequential Exploratory Design - Qualitative data is collected and analysed before quantitative data, which is later used to test or generalise the initial findings.
- Convergent or Concurrent Triangulation Design - Both qualitative and quantitative data are collected simultaneously but analysed separately to compare and contrast the results.

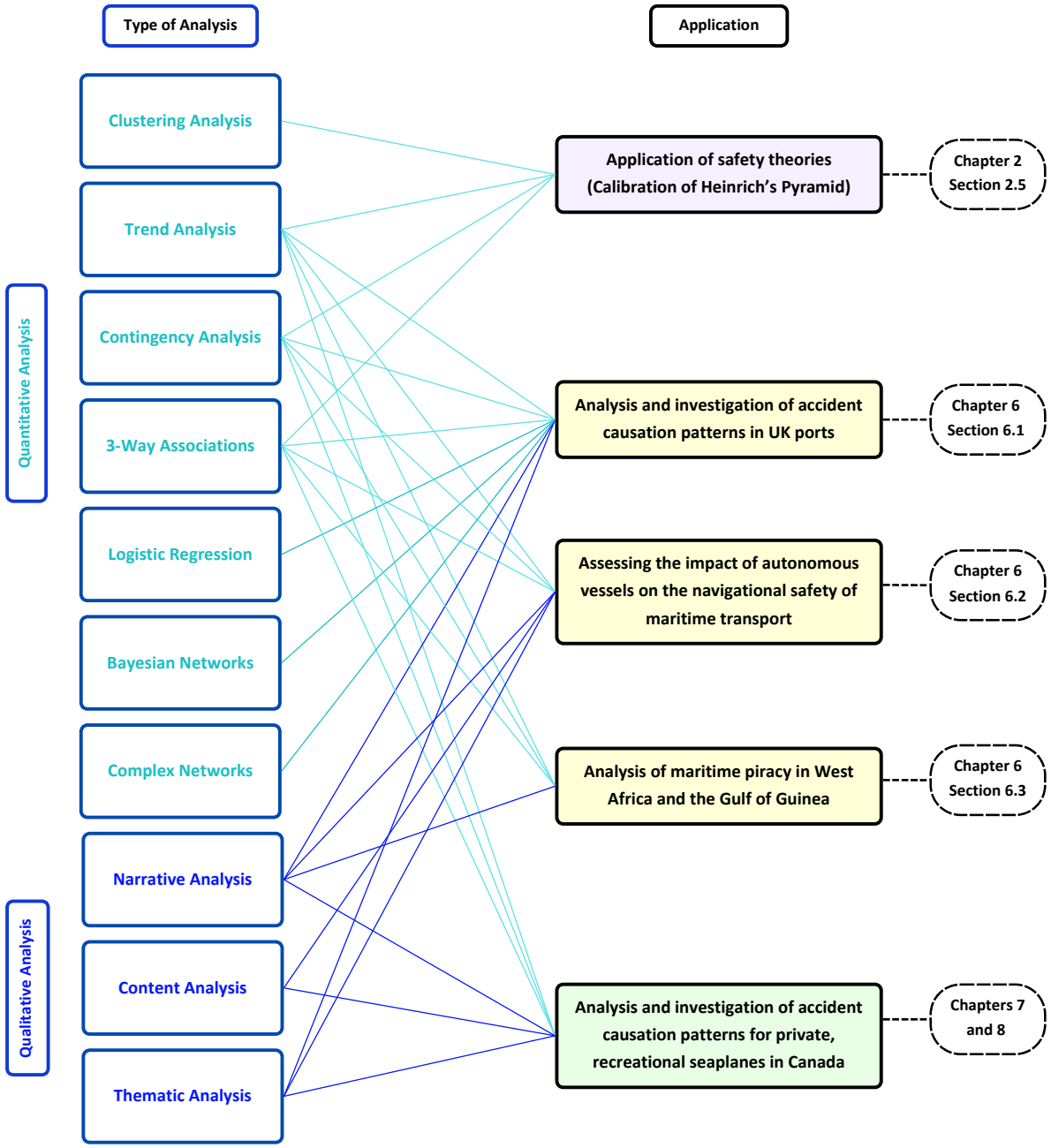
In this thesis, the Sequential Explanatory Design is used since the qualitative data collection is based on the results of the quantitative analysis. The main differences between quantitative and qualitative methods are summarised in Table 5.2.

Table 5.2. The main differences between quantitative and qualitative methods of analysis.

Differentiation category	**Quantitative methods**	**Qualitative methods**
Research questions	Often answer "how many" or "how much" questions	Often answer "why" or "how" questions regarding behaviours and experiences
Nature of data	Deal with numerical data and aim for precision, objectivity, and generalisability	Deal with non-numerical data and aim for depth of understanding, context, and detailed exploration of the subject matter
Analysis techniques	Use statistical, mathematical, or computational techniques	Use interpretive, thematic, and narrative techniques
Outcomes	Aim to produce generalisable results through statistical analysis	Aim to provide a deep, contextual understanding of a phenomenon through detailed analysis

The quantitative and qualitative methods of analysis used are summarised in Figure 5.2, along with their application in this thesis. In viewing Figure 5.2, the following legend should be noted: the lighter blue and darker blue fonts of the methods employed correspond to the category of analysis (quantitative and qualitative, respectively), and match the text colours used in Section 5.4, in Figure 5.4 about the research methodology. The methodologies and reasons for choosing these types of analyses are explained in the relevant chapters where they are employed, as seen in Figure 5.2.

Figure 5.2. Methods employed for data analysis and their application.



The following section provides a summary of the chosen case studies, for which this methodology will be applied in the subsequent chapters.

5.3. Research strategy

This section presents the research strategy, which is in the form of case studies. Two different environments will be considered in this thesis, maritime and aviation, through four case studies. An additional fifth case study has been included which does not follow the same methodology. This case study aims to calibrate Heinrich's Pyramid for the study of transport safety, and it has already been

presented in Section 2.5. Its aim was to assess the application of a widely used safety theories to transport safety.

The maritime environment includes three scenarios (represented in the yellow boxes in Figure 5.5 of the previous section), while the aviation environment includes one (represented in the green box in Figure 5.5 of the previous section). These four scenarios, outlined below, assess past accidents and incidents using different databases, following the methodology which will be described in the following section (Figure 5.2). Details about the methods of analysis employed and data sources used are presented in the following sections (Sections 5.4 and 5.5, respectively).

- Case studies for the Maritime transport sector:
    - Analysis and investigation of accident causation patterns in UK ports.
    - Analysis of the impact of autonomous vessels on the navigational safety of maritime transport.
    - Analysis of maritime piracy in West Africa and the Gulf of Guinea.
- Case study for the Aviation transport sector:
    - Analysis and investigation of accident causation patterns for private, recreational seaplanes in Canada.
- Case study for the application of safety theories:
    - Application of safety theories through the calibration of Heinrich's Pyramid for the study of transport safety, in particular the safety in UK ports.

5.3.1. Choice of maritime safety in UK ports

The primary reason for choosing the maritime industry as the first case study is that it is considered the most complex and dangerous worldwide (Celik and Selcuk, 2009; Hetherington, Flin and Mearns, 2006). Additionally, the United Kingdom has extensive maritime history and numerous significant ports, and the second largest maritime industry in Europe, providing an ideal context for this investigation. Furthermore, choosing ports as a focus for the study of maritime safety is crucial due to their role in providing a protective refuge for vessels, facilitating the transfer of people and goods, promoting trade and economic growth, and serving as significant sources of employment. In particular, ports represent dynamic environments where the interplay between vessels, cargo operations and human activities creates a complex set of safety challenges.

Hence, the first two case studies in Chapter 6 (Sections 6.1 and 6.2) will apply the methodology of this thesis to the study of factors underlying safety in UK ports. The first one will consider the safety of people on-board ships in UK ports, while the second one will look at expected improvements and

challenges once autonomous vessels are introduced in the future. In these case studies, the three main safety approaches previously described in Section 2.3 (reactive, proactive and predictive) will be employed.

5.3.2. Choice of aviation safety, specific for private, recreational seaplane operations

Figure 5.3-A. shows the number of fatalities in the USA between 2010 and 2019, for different sectors of the transportation system, which do not include the majority of the maritime sector. It emphasises that most death occur on the roads. Because the road traffic accidents lead to considerably more deaths and injuries than other transportation sectors (National Safety Council, 2023), this transport mode receives substantially more funding for improving its safety than other sectors such as maritime and aviation. Additionally, this sector is the only one that focuses its attention on the private side rather than commercial. It should be noted that Figure 5.3-A is not to scale.

Figure 5.3-A. The number of fatalities in the USA between 2010 and 2019, for different sectors of the transportation system (Turbli, 2022).

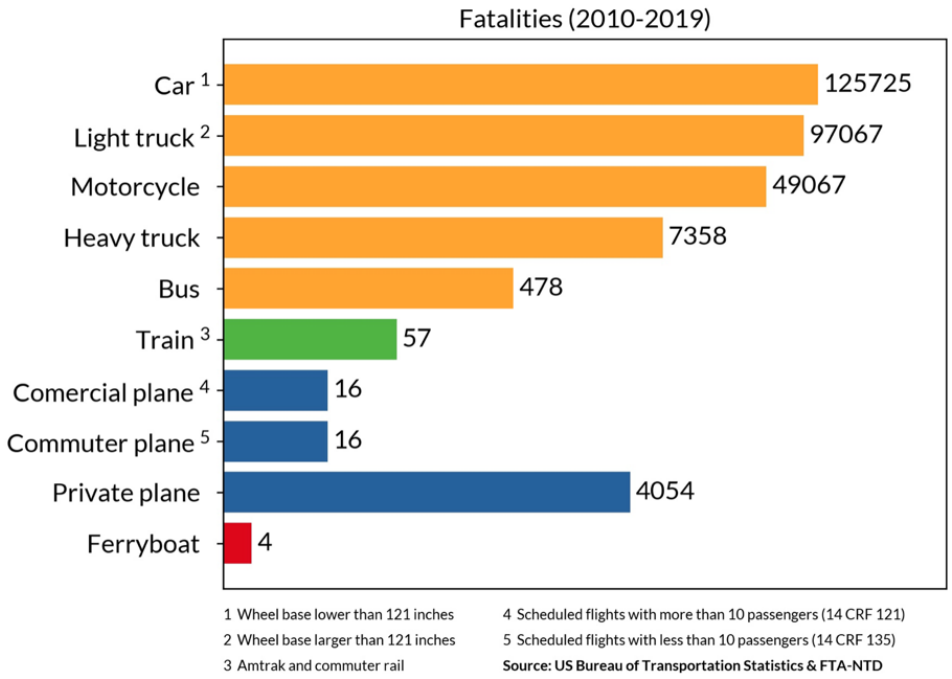
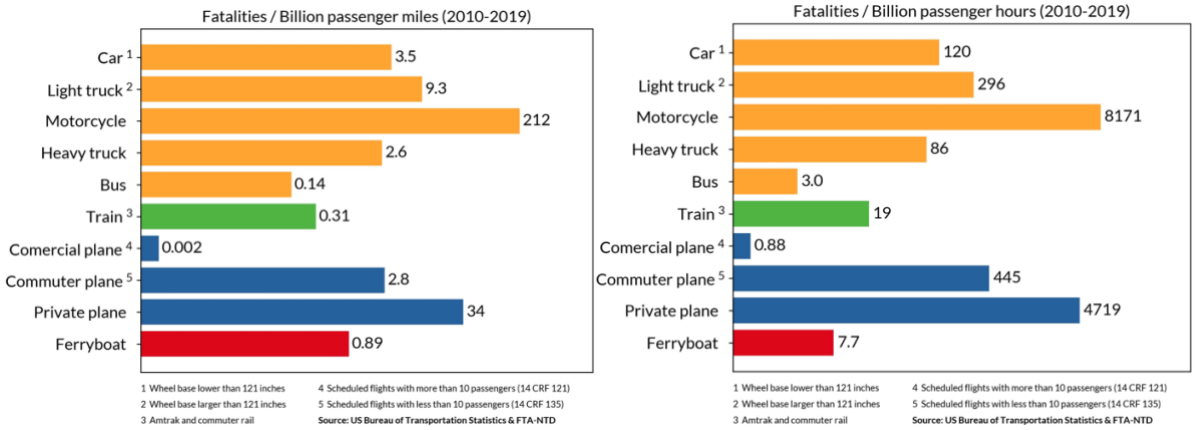


Figure 5.3-B. shows the death rates, per billion passenger miles and hours, and it has been included here as a comparison to the previous figure, to emphasise the concerning rate of fatalities for private planes. It should be noted that the charts in Figure 5.3-B are not to scale. In contrast with this finding, (Turbli, 2022) assess that the commercial airline transportation is the safest, showing a big discrepancy in the results for airline, small commercial and private aircraft safety.

Figure 5.3-B. The number of fatalities per billion passenger miles and hours in the USA between 2010 and 2019, for different sectors of the transportation system (Turbli, 2022).



In addition to this, as previously concluded in Chapter 4, seaplane safety in particular, with its unique operational challenges, faces significant literature gaps, particularly regarding General Aviation seaplane operations. Seaplanes are uniquely suited for a variety of operations but carry additional risks due to the environments in which they operate. However, the focus is on commercial operations or combined data for all seaplane activities, which can obscure the unique safety challenges faced by GA seaplane pilots and operators, as previously argued in Chapter 4. Geographically, Canada's unique nature and vast remote areas increase the dependency of certain populations on seaplanes, for various remote activities, especially for private and recreational purposes. The Canadian context offers a rich landscape for examining the interplay between seaplane operations and safety protocols. Thus, addressing this subgroup of seaplane operations separately, by considering specific accident and incident analysis, along with addressing the concerns of private seaplane pilots and improving the engagement with the community is imperative. These are the main reasons why the fourth case study targets research on private and recreational seaplane operations, to address the unique risks and safety concerns in this sector that are overlooked, and then develop tailored safety recommendations and interventions. This oversight is significant because the sector includes flight training units, which play a vital role in shaping the skills and safety practices of new pilots.

5.3.3. Summary of literature gaps for each case study and justification for the integrated framework to be proposed

<u>Case Study 1: Use of Heinrich's Pyramid in transport safety</u>

Identified literature gaps:

- Heinrich's Pyramid has been widely applied but lacks validation in modern transport safety contexts.

- Limited research on adapting safety theories to sector-specific accident patterns.
- The need for empirical testing of Heinrich's principles in contemporary safety applications.

Relevance to the proposed methodological framework of the thesis:

- The study evaluates Heinrich's Pyramid, a widely used safety theory, in the context of modern transport safety challenges.
- The research aims to enhance the pyramid's applicability by integrating contemporary safety data analysis techniques.

Case Study 2: Safety in UK Ports

Identified literature gaps:

- Limited research on accident causation patterns in UK ports despite their complex and high-risk operational environments (Celik & Selcuk, 2009; Hetherington, Flin & Mearns, 2006).
- Lack of comprehensive analysis integrating accident reports, Automatic Identification System (AIS) data and other sources to assess trends and risks.

Relevance to the proposed methodological framework of the thesis:

- The study employs mixed methods of analysis to identify key safety concerns.
- Integrating AIS data with accident data from databases and reports, proves that the proposed framework improves SMS, particularly focusing on risk assessment.
- The study's findings contribute to enhancing safety measures and policies tailored for UK ports.

Case Study 3: Impact of autonomous vessels on maritime navigational safety

Identified literature gaps:

- Existing studies focus on the technical aspects of autonomous vessels rather than their safety implications and human-machine interactions (Wróbel, Gil & Montewka, 2020).
- Lack of systematic studies analysing how autonomous systems impact traditional maritime safety structures.
- Limited research on crew adaptation, emergency response and regulatory readiness.

Relevance to the proposed methodological framework of the thesis:

- The study compares accident trends and human factors before and after automation implementation.

- A mixed-methods approach, integrating different methods of data analysis with qualitative expert analysis, provides an understanding of future safety risks.
- The framework offers regulatory recommendations for adapting safety protocols to autonomous operations.

Case Study 4: Maritime piracy in West Africa and the Gulf of Guinea

Identified literature gaps:

- Fragmented research on piracy incidents and their impact on maritime safety and economic security (IMO, 2023).
- Limited data-driven analysis linking piracy patterns to vessel characteristics and operational contexts.
- Insufficient studies on the effectiveness of countermeasures and international policies.

Relevance to the proposed methodological framework of the thesis:

- The study integrates data from the IMO's GISIS database with statistical trend and thematic analysis to identify piracy risk factors, underlying the capabilities of a widely used maritime data source.
- Findings contribute to developing proactive piracy mitigation strategies tailored for high-risk regions.
- The proposed framework enhances maritime security policies and vessel operational guidelines.

Case Study 5: Accident causation patterns for private, recreational seaplanes in Canada

Identified literature gaps:

- Lack of research specific to General Aviation (GA) seaplane operations, with most studies focused on commercial aviation (Transport Canada, 2022).
- Insufficient data on human factors affecting private seaplane safety, including pilot training and decision-making.
- Need for an improved classification system distinguishing private recreational seaplane accidents from other GA occurrences.

Relevance to the proposed methodological framework of the thesis:

- The study employs statistical data analysis to identify key accident causes, based on which further insights into specific causes is sought through qualitative analysis of interviews, focus

groups and questionnaires with industry professionals. This represents a mix of data sources and methods of analysis used, while incorporating expert knowledge, validation and comparison measures, to overcome the identified data and analysis-related limitations.

- The proposed framework includes insights into all SMS pillars and proves the applicability of the proposed framework in a real-life scenario.

Overall literature gap justification and the need for an integrated framework:

Across all case studies, common literature gaps include:

- Lack of comprehensive, cross-sectoral safety analysis methodologies.
- Insufficient research on ways to assess and integrate factors not available through traditional accident and incident data analysis.
- Inconsistent data quality and reporting standards across transport sectors.
- Lack of research on how to explore sources of data of low quality and quantity.

The proposed integrated framework addresses these gaps by:

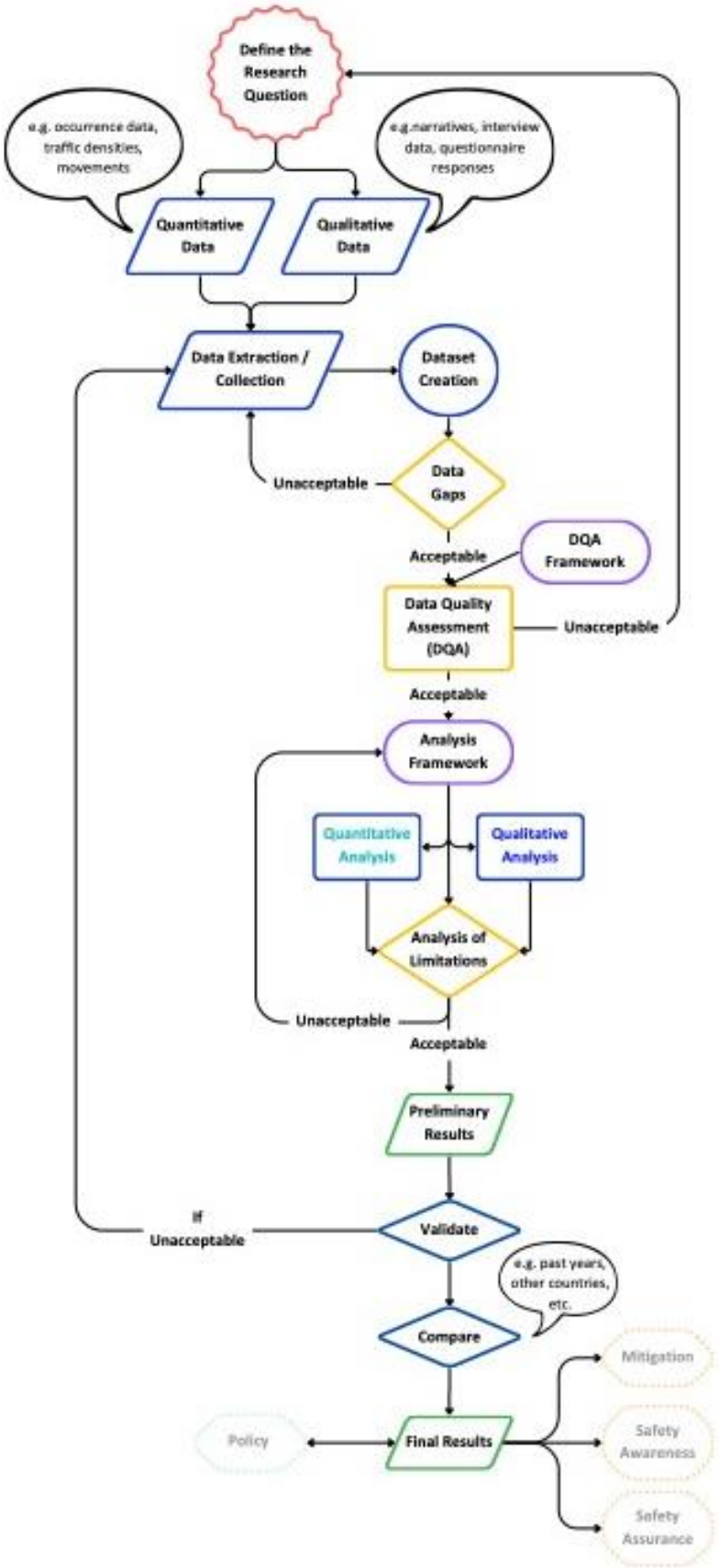
- Employing mixed-methods analysis: combining quantitative accident/incident data analysis with qualitative research into areas underrepresented by the available data sources, ensuring a holistic understanding of transport safety.
- Developing a standardised data quality assessment framework: ensuring consistency and reliability in safety data collection and analysis.
- Incorporating expert opinion and stakeholder engagement to validate the results and identify current areas of concern.
- Creating cross-sectoral safety insights: identifying transferable safety strategies applicable across industries, through the use of similar factors to be analysed in all sectors.
- Ensuring the analysis provides real results by integrating the proposed framework into SMS.

Following these approaches, this thesis contributes to the development of robust, evidence-based safety methodology that can inform future transport safety policies and interventions, as described in the following section.

5.4. Proposed research methodology

This section explains how the research philosophy and approaches established in the previous sections support the objectives of this thesis through the implementation of a robust methodology. This methodology will be implemented for the case studies that have been proposed in the previous section. Figure 5.4 outlines the methodology used in this thesis.

Figure 5.4. Research methodology for safety-related data analysis.



This methodology has been designed for the analysis of factors underlying safety in the transport industry, to answer the main research question "*How can transport safety be enhanced through data analysis to reduce the number of accidents, incidents, and associated lives lost, injuries and property damage?*". This is achieved by considering different case studies, modifying this research question to be specific for each study. These are minor modifications, for example the following research question applies to one of the case studies, and the modifications are underlined: "*How can seaplane safety be enhanced for private, recreational operations through data analysis, to reduce the number of accidents, incidents, and associated lives lost, injuries and property damage?*". The case studies mentioned have been described in the previous section (Section 5.3).

Having established the research question, different data sources will be used, and their quality and limitations will be assessed. If the data gaps are deemed unacceptable, new data will be collected through alternative methods such as surveys and interviews with industry professionals. As such, the design of the interviews and survey will be based on the findings from the accident and incident data analysis. The analysis will also provide areas of concern which will determine the selection of interviewed participants. Additional interviews will be conducted with industry professionals to validate the results and assess other potential limitations of the analysis. Having acceptable data gaps that are not expected to affect the capabilities of the subsequent analysis, the quality of the data will be assessed using the framework proposed in Section 5.6 of this chapter. In case the data quality is unacceptable, the research question will need to be redefined.

Having checked that the data is suitable for the subsequent analysis, mixed methods of quantitative and qualitative analysis will be used, as detailed in Section 5.2 of this chapter. If the method of analysis or the limitations are deemed unacceptable, alternative methods of analysis will be considered. If these are acceptable, a set of preliminary results is obtained. All results will be validated by industry professionals and, if found unacceptable, additional or alternative data sources will be considered. This will also ensure that these findings represent reality as far as possible, and all limitations and gaps are accounted for and acceptable. Then, the validated results will undergo a comparison process with findings from previous years, other countries or the literature. This will provide additional insights into the state of the system's safety, after which the final set of results will be achieved.

Based on the final results, policy recommendations could be formulated to enhance the safety of the transport sector in question. Finally, methods of safety mitigation and awareness to the relevant communities will be discussed, along with safety assurance.

In conclusion, this methodology aims to achieve a holistic understanding of a system's safety by utilising robust methods of analysis and by addressing all pillars of the Safety Management System. The following section provides a summary of the quantitative data sources that will be used in this thesis.

5.5. Data sources

This section provides an overview of the data sources used in this thesis, for each of the case studies outlined previously in Section 5.3, Figure 5.4. However, this section does not provide the data obtained by the researcher through interviews, focus groups and questionnaires, which are detailed in the relevant sections where they are used. Similar data categories are sought for both the maritime and aviation industries. However, the ideal (required) data fields will be different for each case study because of the differences between the two transport sectors and the requirements of the methods of analysis used. These ideal data fields are outlined in the data quality assessment section of each case study presented in the following two chapters.

Table 5.5 summarises the data sources obtained from national or international databases and investigation reports, which are used for different types of analysis previously presented in the Section 5.2, Figure 5.5. The data analysis methods employed using each source of data are also present in Table 5.5. The only generated data is qualitative, through interviews, focus groups and questionnaires with industry professionals, which are used in addition to the data sources presented in Table 5.5 and correspond to the starred (*) methods of analysis employed which are present in the same table.

All data have been cleaned and assessed for their quality, then adjusted to create data sets as complete and accurate as possible. The methodology for assessing the data quality is presented in the next section. Appendix F presents a more detailed version of Table 5.5, which includes the reasons behind choosing each method of data analysis.

Table 5.5. Description and use of different data sources.

Chapter & Case Study	Data source	Location, Years & Data type	Description	Method of Analysis
CH 6	**Maritime**			
CS 1	***Marine Accident Investigation Branch (MAIB)***	UK, 5,078 ship casualties and occupational accidents from 2013 to 2022	Database of marine casualties and incidents in and around ports	Clustering analysis
				Trend analysis
				Contingency analysis
				Three-way associations
				Logistic regression
				Bayesian Networks
				Complex Networks
				Narrative analysis
				*Content analysis
				*Thematic analysis
CS 2		UK, 74 investigation reports of crew navigation errors from 2012 to 2020	Data fields extracted from investigation reports to assess expected implications of AVs	Trend analysis
				Contingency analysis
				Three-way associations
				Narrative analysis
				*Content analysis
				*Thematic analysis
CS 1	***Automatic Identification System (AIS)***	UK, approx. 9 million vessel movements and 1.7 million gridded traffic densities, 2011-2017	Database of vessel movements and traffic densities on UK waters	Trend analysis
				Logistic regression
				*Content analysis
				*Thematic analysis

Chapter & Case Study	Data source	Location, Years & Data type	Description	Method of Analysis
CS 1	***Royal National Lifeboat Institution (RNLI)***	UK, approx. 17,000 occurrences, 2008-2019	Extracted vessel-related occurrences	Trend analysis
CS 3	***IMO's Global Integrated Shipping Information System (GISIS)***	West Africa and the Gulf of Guinea, 322 piracy related incident reports from 2017 to 2022	Data fields extracted from accident reports to analyse maritime piracy	Trend analysis
				Contingency analysis
				Three-way associations
				Narrative analysis
CH 7&8	**Aviation**			
CS 4	***Seaplane database***	Canada 2,021 GA seaplane accidents from 1990 to 2022	Database of GA seaplane accidents and incidents, to analyse the reasons of an increase in seaplane accidents in the last studied years	Trend analysis
				Contingency analysis
				Three-way associations
				Bayesian Networks *(unsuccessful)*
				Narrative analysis
				*Content analysis
				*Thematic analysis

** Content and thematic analyses were used to further enhance the findings from the data sources and determine data limitations. These were used for interviews, focus groups and questionnaires.*

Regarding the maritime data for the first two case studies which address UK port safety and autonomous vessels, a database of marine casualties and incidents that occurred in UK territorial waters is required. This data has been obtained from the MAIB, under the Freedom of Information Act 2000, and it was updated every year around July with new occurrences from the previous year, since the MAIB's accident reports are released to the public around that time. The database combines casualties with a ship and occupational accidents but, due to their differences in accident types and contributing factors, they were analysed separately. The Automatic Identification System (AIS) data has been used in addition to the MAIB data, since it provides additional information from which vessel movements in and around UK ports can be obtained. MAIB investigation reports have been considered for the second case study about autonomous vessels. Additional data has been obtained from IMO reports to analyse piracy-related incidents in West Africa and the Gulf of Guinea, which is the third case study.

With respect to the aviation data, a database of seaplane occurrences in Canada is required. This data has been obtained from Transport Canada (TC) and is available to the public. The database combines private, commercial and other types of operations but, for the purpose of the analysis, only occurrences during private operations have been analysed. Section 7.3 provides a detailed overview of the database and the data filtering procedure. Unlike the AIS data used for the maritime case studies for vessel movements, there was no similar data for private seaplane operations in Canada that could be obtained. Section 4.2.2 addressed this limitation.

5.6. Data Quality Assessment (DQA)

All data sources reviewed in the previous section are assessed for their quality and suitability for the methods of analysis proposed in Section 5.2. This section describes the process of Data Quality Assessment (DQA) and it is organised as follows. Section 5.6.1 offers an overview of the importance of assessing data quality of occurrence data, and Section 5.6.2 reviews the available literature, focusing on DQA in the transport sector. Then, Section 5.6.3 presents the methodology of the DQA and the developed framework, by describing the data quality dimensions and outlining the approach to applying this framework to safety data. With the primary interest in safety-critical industries, the transport domain is used as reference, but the findings are arguably extendable beyond the transport sector.

5.6.1. Overview

Incident and accident reports (or safety occurrence reports) are the primary types of safety data and have been extensively used to inform recommendations for review and revision of safety policy and

practice. Wilke, Majumdar & Ochieng (2014a) offer such an example by proposing a framework to analyse safety incident reports of runway incursions in order to identify latent contributory factors to airport surface operations. Furthermore, incident and accident reports have been used to monitor safety trends, as evident in annual safety reports published by stakeholders, such as transport regulators and service providers (EASA, 2018; EMSA, 2018; ORR, 2019; TSB, 2022). These are critical to the success of the SMS of any major transport industry, as outlined by Kyriakidis, Majumdar & Ochieng (2015b) for the railways industry. However, recent advances in technology have the potential to radically change the safety domain, with increasing amounts of data from a wide variety of sources being at the core of the safety management.

Safety occurrence reports are collected by various stakeholders including investigation bodies, transport service providers and transport regulators and they typically fulfil multiple purposes. Hence, the level of detail varies and this in turn affects the quality of any research analysis, as evident in Wilke, Majumdar & Ochieng (2014b). Datasets capturing little information offer little to aid the understanding of the underlying reasons for the occurrence. A thorough review of the capabilities of the dataset is unfortunately not often conducted and thus, data are usually used without questioning whether they are appropriate for the specific purpose of analyses (Wang, Quddus & Ison, 2011; Arnaldo Valdés et. al., 2018).

While safety databases are expanding in size and increasingly originate from different sources, e.g. sensors on-board vehicles, occurrence reports, onboard navigation safety device, CCTV, etc., there is no indication of the quality of the large pool of data, how well it reflects reality, or if the methods used to collect the data are appropriate. Data quality does not only refer to the missing values of a dataset, even though data completeness is used as a countermeasure of data quality as seen in the data quality assessment by Bye & Aalberg (2018). Data quality is affected by a variety of factors that can be described using a series of dimensions that consider, among others, the consistency, believability and relevance, as captured by researchers in information technology (Pipino, Lee & Wang, 2002).

5.6.2. Literature review on methods used for assessing data quality

To address safety data quality concerns in safety management, Dupuy (2012) developed a framework that systematically assesses the quality of the reported information relating to separation minimum infringement incidents in aviation. Dupuy (2012) explored ways to encounter issues relating to the following: the lack of information capturing in the reports, the reporting scheme of incidents of stakeholders and missing data. The framework consists of the following dimensions inspired by the data quality in information technology (Pipino, Lee & Wang, 2002): relevance, completeness,

consistency, accessibility, timeliness and credibility. The framework was developed based on the systematic analysis of incident reports originating from various safety databases. This framework was used to provide the database owner with an indication of the suitability of the data for the analysis of separation minimum infringements and further to recommend improvements that would enhance the quality of the database.

Dupuy (2012) quantified the five dimensions of relevance, completeness, consistency, timeliness and accessibility in an attempt to provide objective outcomes that will be easy to interpret and to enable comparison of the capabilities of safety datasets. This framework was successfully applied to other aviation occurrences including the offshore helicopter accidents (Nascimento, Majumdar & Ochieng, 2014), runway incursions (Wilke, Majumdar & Ochieng, 2014a), as well as to the railway sector in order to develop performance shaping factors (Kyriakidis, Majumdar & Ochieng, 2015b).

Wilke, Majumdar & Ochieng (2014b) further examined the impact of the data collection mechanism, the level of processing that the data required and the investigation processes on the data quality. They incorporated these aspects into their data quality assessment that examines among others whether the occurrences are reported using an electronic system and the type of procedures on how to report an incident. Such an assessment could benefit from the inclusion of further parameters that take into account the following: the type of investigation of incidents, the extent to which the reporter was trained to submit a report, the provision of guidelines of filling the incident form, the background of the narrator (e.g. involved in the incident, observer of the incident, investigator, etc.) and the just culture of the database owner. The latter poses considerable challenges to measurement and is not further developed in the present study.

Cheong et al. (2023) proposed a framework for a systematic data quality of secondary interview data using different metrics and dimensions. Cheong et al. (2023) consider the challenges faced when first hand data collection is not possible, so the researchers rely on data obtained from other sources, such as open sources easily accessible online. Cheong et al. (2023) identified 42 dimensions throughout the literature, from which only eight were repeated in the research of West (1993); Fox et al. (1994); Brackstone (1999); Pipino et al. (2002); Patton (2002); Mehrabi et al. (2009); Dupuy (2012); Chung et al. (2012); Laranjeiro et al. (2015); and Ehrlinger and Wöß (2022). Cheong et al. (2023) added three new data quality dimensions that are specific for interview data analysis: (self-)representation, (hyper-)emotivity and interactivity of the inquirer.

Neither framework evaluates the effectiveness of the narrative description of accidents and incidents, which provides key information that in many cases cannot be depicted from the other data fields. In

transport safety, human operators describe any occurrence to the best of their knowledge and the training and instructions that they were given. This has a significant effect on the content of the report. As outlined by Newnam et al. (2017), both the length of the text and the purpose of the report influence the content of the narrative description. However, the content of the narrative description has not been considered in the developed dimensions. Hence, the level of detail of the narrative description needs to be assessed.

Dupuy's (2012) framework would benefit from including the following dimensions to ensure high quality data that have already been identified as important by Pipino, Lee & Wang (2002): the importance of considering the size of the dataset, the need to select data that will add value to the analysis, security and interpretability of the data by the analyst. In particular, retrieving data from a well-known database whose owner possesses a mature SMS will increase the robustness of the analysis. Furthermore, data restricted from modifications should be more reliable than other data where information can be changed. Finally, the interpretability of the data fields should also be included in a data quality assessment as data can be provided in various languages, terminology, symbols and units, which can possess difficulties for the analysts in terms of understanding the true meaning of the captured information.

In conclusion, data gaps consist of uncollected, incomplete or scattered data. Datasets from different sources might also be incompatible, or some accident reports might be unavailable or only partly available to the author. These may influence the quality of the data and the validity of the results. To overcome these issues and determine whether the databases are suitable for the required analysis, they will be checked, cleaned and the scores of the data quality dimensions will be assessed, following the framework proposed in the following section.

5.6.3. Proposed framework for data quality

Data quality is assessed to check how an obtained data set matches the ideal one and whether the database is suitable for the analysis. The ideal data set comprises of the required data fields to answer a specific research question, which can be either intuitive or based on reviewed literature. They can be adjusted throughout the research to account for new challenges detected through the data analysis and interviews with professionals.

This section presents the scope of the proposed framework for DQA, and describes each data quality dimension that is checked for as part of the DQA.

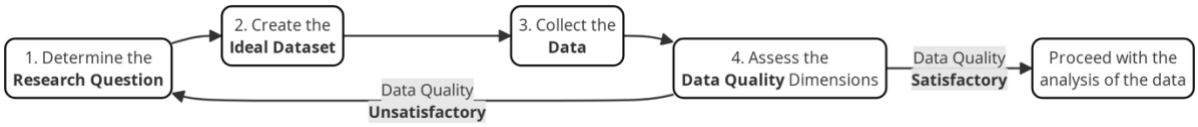
5.6.3.1. Scope of the proposed framework

Aiming to develop a framework for data quality assessment of safety data across industries, the data quality assessment described by (Wilke, Majumdar & Ochieng, 2014b; Pipino, Lee & Wang, 2002; Dupuy, 2012) has been elaborated and further enhanced, as follows:

i. Developed a dimension that determines the richness of the narrative description of the occurrence;
ii. Incorporated the external assessment developed by Wilke, Majumdar & Ochieng (Wilke, Majumdar & Ochieng, 2014b) into the dimension of credibility;
iii. Accounted for the amount of data, which was proposed by Pipino, Lee & Wang (2002), as it has an immediate effect on the statistical analysis; and
iv. Accounted for the value-added dimension, which was also proposed by Pipino, Lee & Wang (2002), to confirm the importance of a particular dataset in the analysis.

The process of assessing the quality of a dataset is built on four main pillars, as outlined in Figure 5.6. The initial step is to clearly define the research question, which guides the direction of the entire process. Based on the research question, an ideal dataset is conceptualised, outlining the data fields and types of data needed. Then, the actual data is gathered, ensuring it aligns with the parameters set in the ideal dataset, and more data sources can be included. The collected data is then evaluated against various data quality dimensions to determine its suitability for analysis. If the data quality is found to be satisfactory, the process moves forward with the analysis of the data. However, if the data quality is unsatisfactory and better quality data cannot be obtained, the research question may need to be revised, and the entire process repeated to ensure meaningful and reliable results.

Figure 5.6. Outline of the process of data quality assessment.



Before any data is collected, the research question shall be clearly defined to determine the anticipated data quality range. In particular, a lower threshold can apply for explorative research but not for any aggregation of the dataset. The scope of the assessment may include one or several of the following:

- Understand how and why accidents occur, i.e., explorative research;
- Develop metrics relating to incident reporting and safety management;
- Compare incidents where datasets need to be aggregated; and

- Manage the safety databases, e.g., maintenance.

The data quality assessment framework was validated using:

i. a wide array of occurrences both incidents and accidents (unauthorised entry of aircraft into airspace, fixed-wing aircraft ditching, weather related aviation occurrences, helicopter occurrences during training, seaplane occurrences, and occurrences at ports).
ii. databases originating from private companies, national services, regulators and independent organisations.
iii. mandatory and voluntary reporting systems.
iv. databases from European countries, Canada, the United States of America, Africa, Australia and New Zealand.
v. data that cover a long, continuous period of time.

5.6.3.2. Data quality dimensions

Table 5.6 summarises the data quality dimensions and where in the available literature these have been accounted for.

Table 5.6. Data quality dimensions.

Dimension Name	**Dimension definition**	**(Dupuy, 2012) *(12)***	**(Wilke, Majumdar & Ochieng, 2014b) *(7)***	**(Pipino, Lee & Wang, 2002) *(11)***
Accessibility	Data availability, ease and quick retrievability	☑ Quantified	n/a	☑ Accessibility ☑ Easy of manipulation ☑ Concise representation
Accuracy	Data is correct and reliable	☑	☑	☑ Free of error
Appropriate amount of data	Volume of data	n/a	n/a	☑
Completeness	Data is not missing	☑ Quantified	n/a	☑
Consistency	Data is presented in the same format	☑ Quantified	n/a	☑
Credibility	Data is regarded as true	☑	☑ Major form of reporting, level of investigation, bias, publication of statistics, consistency of the reporting system over time	☑ Believability ☑ Objectivity ☑ Originality/ Ownership ☑ Reputation
Interpretability (by the analyst)	Data is in appropriate language, symbols	n/a		☑ Interpretability ☑ Understandability

	and units; data is easily comprehended			
Relevance	Data is applicable and helpful for the task	☑		☑
Security	Data is restricted appropriately to maintain its security	n/a	n/a	☑
Timeliness	Data is sufficiently up-to-date	☑ Time of reporting	☑ Time of reporting	☑
Value-added	Data is beneficial and provides advantages from its use	n/a	n/a	☑
Richness of the narrative	Detail of the information captured in the narrative description of the occurrence	n/a	n/a	☑

The dimensions listed in Table 5.6 are described in detail below (Dupuy, 2012):

Accessibility

The dimension of accessibility determines that the data is available and quickly retrievable. This is defined by the number of data fields the dataset can provide without any further modifications. An Accessibility value of 1 indicates that all data is considered consistent. The arithmetic weighting system rewards explicit data fields (Equation 1). The lower the score of this dimension, the greater the number of data fields created by analysts, thereby increasing the time needed for the analysis.

$$accesibility = (1 \times N_{explicit} + 0{\cdot}80 \times N_{implicit} + 0{\cdot}20 \times N_{inferred} + 0 \times N_{not\ available}) / (Total\ number\ of\ required\ datafields) \quad \textit{Equation 1}$$

where:

- $N_{explicit}$: Information is already available in an existing data field and it can be used as is.
- $N_{inferred}$: Information is available in a relevant data field and thus, the information is not immediately available. Modifications need to be made to the data field, e.g., infringing altitude is written in the narrative and thus, a new data field is created.
- $N_{implicit}$: Information for this data field can be found in the dataset but it requires considerable effort, e.g. extract from a narrative description, computation, and/or it relies on the analyst's interpretation.
- $N_{not\ available}$: Information for this data field cannot be found in the dataset.

Accuracy

Accuracy defines whether data is correct, close to reality and free from error. It can be determined by assessing the agreement between the data fields, especially with that of the narrative description of the incident. For example, data fields of the flight phase or airspace class must match the information provided in the incident narrative. As it is time consuming to check every incident, a sample of incident records, e.g., 10%, can be randomly selected to confirm the agreement between the data fields. Inaccurate data, either incidents or data fields, shall be excluded from the analysis.

Appropriate amount of data

This dimension considers the efficacy of the size of the dataset and defines the volume of data depending on the scope of the analysis.

Completeness

Completeness estimates the rate of missing data and is equal to the difference in the percentage of the complete data. The percentage of data missing for each data field is estimated and the arithmetic average of all the missing data is calculated (Equation 2).

$$Completeness = 100 - arithmentic\ average\ of\ missing\ values\ percentage \qquad \textit{Equation 2}$$

Consistency

The dimension of consistency indicates that the information in a data field is reported in the same format. It is measured by the percentage of data that are presented in the same manner within each data field (consistent). If a data field has to be either recoded or newly coded for the purpose of this analysis, the quality of the data will be reduced as shown by the arithmetic weights (Equation 3). A lower score for this dimension indicates that the dataset suffers from inconsistent data implying that the data might be inappropriate for the analysis.

$$consistency = (\ 1 \times N_{consistent} + 0{\cdot}80 \times N_{recoded} + 0{\cdot}20 \times N_{newly\ coded} + 0 \times N_{not\ available}\ )/(Total\ number\ of\ required\ datafields) \qquad \textit{Equation 3}$$

where:

- $N_{consistent}$: Data field is consistent, and it can be used as is.
- $N_{recoded}$: Information is inconsistently reported. Hence, the structure of the data field needs to be revised.
- $N_{newly\ coded}$: Information for this data field can be found in the dataset but its structure needs major revisions, e.g. aircraft model is provided and a new data field is created to cluster the aircraft designs.

- $N_{not\ available}$: Information for this data field cannot be found in the dataset

Credibility

The dimension of credibility ensures that data is regarded as true by assessing the framework used to collect them in the first place. In the absence of such information, credibility is assessed by investigating whether data is obtained from reliable sources by seeking further information from database owners. For example, incidents can be assumed to come from reliable sources if they are reported by air traffic controllers who are trained to report incidents and the investigation follows the international procedures. The successful completeness of an investigation ensures that the reported information has been assessed at least for its truthfulness and relevance. On the other hand, for incidents reported by untrained individuals, the credibility is regarded as low. Nonetheless, if an incident was investigated, it could be assumed that the associated data is obtained from reliable sources.

Interpretability

Interpretability verifies that the data are in appropriate language, symbols and units and are easily comprehended by the analysts. For example, acronyms and coded information is defined by the data provider.

Relevance

Relevance determines whether the data can be applicable for further analysis. The required data fields are determined and compared with those in the dataset. In the case of airspace infringements, for example, the required data fields are grouped into eight categories: incident information, description, aircraft, ATCO, severity, environment, airspace and contributory factors. The lower the score, the less the information provided in the dataset (Equation 4).

$$relevance = \frac{1}{N\ categories} \sum_{i=1}^{N\ categories} \frac{N\ relevant,i}{N\ request,i}\ x\ 100 \qquad \textit{Equation 4}$$

Security

Security refers to the potential of changing information of the safety data whilst data is stored in the database. It aims to identify datasets that can be manipulated by unauthorised individuals.

Timeliness

Timeliness assesses the delay in providing and processing the incident/accident report. It can be defined as the elapsed time from when the occurrence of an incident to the point in time that the

incident was first recorded. It can be measured by comparing the dates on which the incident/accident occurred, the report was filed, and the investigation was completed.

Value added

This dimension defines whether data is beneficial and provide insights relating to the analysis, in order to encourage the selection of datasets that enrich findings. This is looked at for every data field before starting the analysis, so that the ones that do not add additional value are eliminated. For example, if there is interest in having the year and month of the occurrences, but have a separate "Date" data field, that can be eliminated as it does not add any value (the value needed is added by the "Year" and "Month" data fields, and the day is not needed).

Richness of the narrative

The narrative in the description of an occurrence is a key dimension towards extracting information about the underlying causes that led to the event. Rich narrative descriptions are considered those that present information about events prior to the incident, the response of the actors, the procedures, potential human errors and the environmental conditions which may have had an effect on the occurrence. An example of a rich incident narrative can be the following.

"A privately registered Cessna on amphibious floats, was conducting a VFR flight from Kamloops (CYKA), BC to Vanderhoof (CAU4), BC with only the pilot on board. The pilot departed from Runway 27 at CYKA at approximately 0800 PDT and the visibility, from the weather observation, was 3 statute miles (SM). Approximately 6 miles west of CYKA, visibility became worse and the pilot descended seeking better conditions. The visibility was still very poor so the pilot decided to do a precautionary landing straight ahead on Kamloops Lake. The aircraft touched down on the lake with the landing gear in the down position. The aircraft subsequently nosed over and came to rest inverted on the lake. The pilot egressed out the window of the left cockpit door and climbed up onto the float. A passing train acknowledged that they had seen the pilot and a train crew came later in the morning and, after the pilot swam to shore (the pilot was not wearing a PFD), transported him to the town of Savona. The pilot sustained minor injuries and no signal was received from the 406 MHz Emergency Locator Transmitter (ELT). The aircraft was subsequently recovered and is awaiting a maintenance estimate. During the recovery, a signal from the ELT was received by the Canadian Mission Control Centre."

Short descriptions, on the other hand, add little information to the existing knowledge of the incident and are considered rather ineffective for any further analysis. For example, a description such as "The aircraft crashed during a local flight." fails to provide any useful information.

Aiming at assessing a narrative's richness in a timely manner, a sample of narratives that represent at least 5% of narratives is used to determine those at are longer than 50 words and capture key information. In the example of seaplane accidents and incidents, the required key information is related to the details of any mechanical failure, the details of affected people including human

performance, and the environmental conditions. The score is calculated as shown in Equation 5, which is assigned to the following bands according to whether the narratives lie within:

- Detailed, i.e., they are likely to provide the majority of the required information if the score is greater than 75%.
- Moderate, i.e., some of them may provide limited information if the score is between 50% and 74%.
- Poor/Moderate, i.e., they are less likely to provide the required information if the score is between 25% and 49%.
- Poor, i.e., the narratives are unlikely to provide the required information if the score is less than 25%.

$$narrative = \frac{1}{N\ parameter} \sum_{i=1}^{N\ parameter} \frac{N\ incident\ that\ j\ lies\ within}{N\ incident}\ x\ 100 \qquad \textit{Equation 5}$$

5.6.4. Summary of data quality considerations

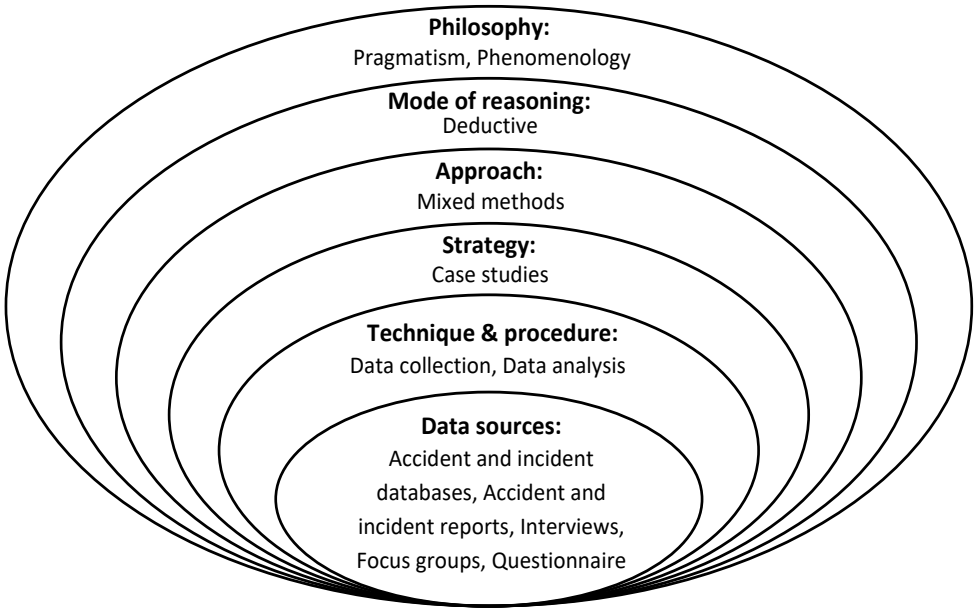
While safety occurrence data is critical to the effective management of safety, its quality often makes insightful analysis difficult. With increasing sources of data and a focus on "big data", questions on data quality have acquired greater importance. This section introduced a framework to assess the quality of a safety dataset, so that it could be used for subsequent analysis. The framework consists of a wide array of data quality dimensions that capture the multiple features that make a dataset to be of high or poor quality. The data quality dimensions range from data collection methods and database structures, to the added-value by the analysis and the content of the both the categorical and narrative descriptions.

The DQA framework is subsequently applied to the four case studies of this thesis, in Section 6.1.4, Section 6.2.3.3, Section 6.3.2 and Section 7.3.3.

5.7. Conclusions of Chapter 5

This chapter provides the research methodology, philosophy, approach and strategy used in this thesis. It also provides an overview of the data sources used and the methods employed to assure the quality of this data. Figure 5.7 presents the research paradigm for this thesis, depicted using an adapted research onion model based on Saunders et. al. (2019). This figure reflects the various choices made in this chapter that influence the methodology and design of this thesis. The methodologies of each subsequent case study and the reasons behind choosing them are provided in the methodology section of that particular chapter.

Figure 5.7. Research onion of this thesis, based on Saunders et al. (2019).



The following chapter comprises of the first three case studies which are related to different aspects of maritime safety. These apply the methodological framework established in this chapter, as well as the proposed framework for data quality assessment.

6. Analysis of Marine Accidents and Incidents

This chapter uses the methodology presented in the previous chapter and builds on the literature gaps found in Chapter 3 to enhance the safety of the maritime industry, by studying the factors which increase accident rates and their interactions. This is accomplished through three case studies:

1. Safety analysis of marine casualties and incidents at ports in the United Kingdom (Section 6.1).
2. Expected implications on maritime safety following the introduction of autonomous vessels (Section 6.2).
3. Safety analysis of piracy-related occurrences (Section 6.3).

The reason for choosing the maritime industry is that it is considered the most complex and dangerous worldwide, as previously explained in Section 5.3 (Celik and Selcuk, 2009; Hetherington, Flin and Mearns, 2006). Additionally, the United Kingdom has extensive maritime history and numerous significant ports, with the second largest maritime industry in Europe. This provides an ideal context for the first two case studies. Furthermore, choosing ports as a focus for the study of maritime safety is crucial due to their role in providing a protective refuge for vessels, facilitating the transfer of people and goods, promoting trade and economic growth, and serving as significant sources of employment. In particular, ports represent dynamic environments with a complex set of safety challenges. The case studies in the following sub-sections will employ the three main safety approaches previously described in Section 2.3 (reactive, proactive and predictive).

6.1. Safety analysis of accidents and incidents at ports in the United Kingdom

This section presents the results of the first case study, by applying the methodology of this thesis explained in the previous chapter to investigate the factors underlying safety in UK ports. The section begins by establishing the context, aims, objectives and methodology specific to this case study. Then, the selection of different data sources is discussed, ensuring data quality throughout the analysis. Multiple analytical methods are employed in subsequent sections, including trend analysis, contingency analysis, three-way associations, logistic regression, Bayesian Networks and Complex Networks. Lastly, insights from interviews with industry professionals are integrated with the findings, before reaching final conclusions.

6.1.1. Aim, objectives and methodology

Given the economic benefits previously mentioned of the maritime industry, there are understandable concerns about safety, with 1,530 marine casualties and incidents leading to 14

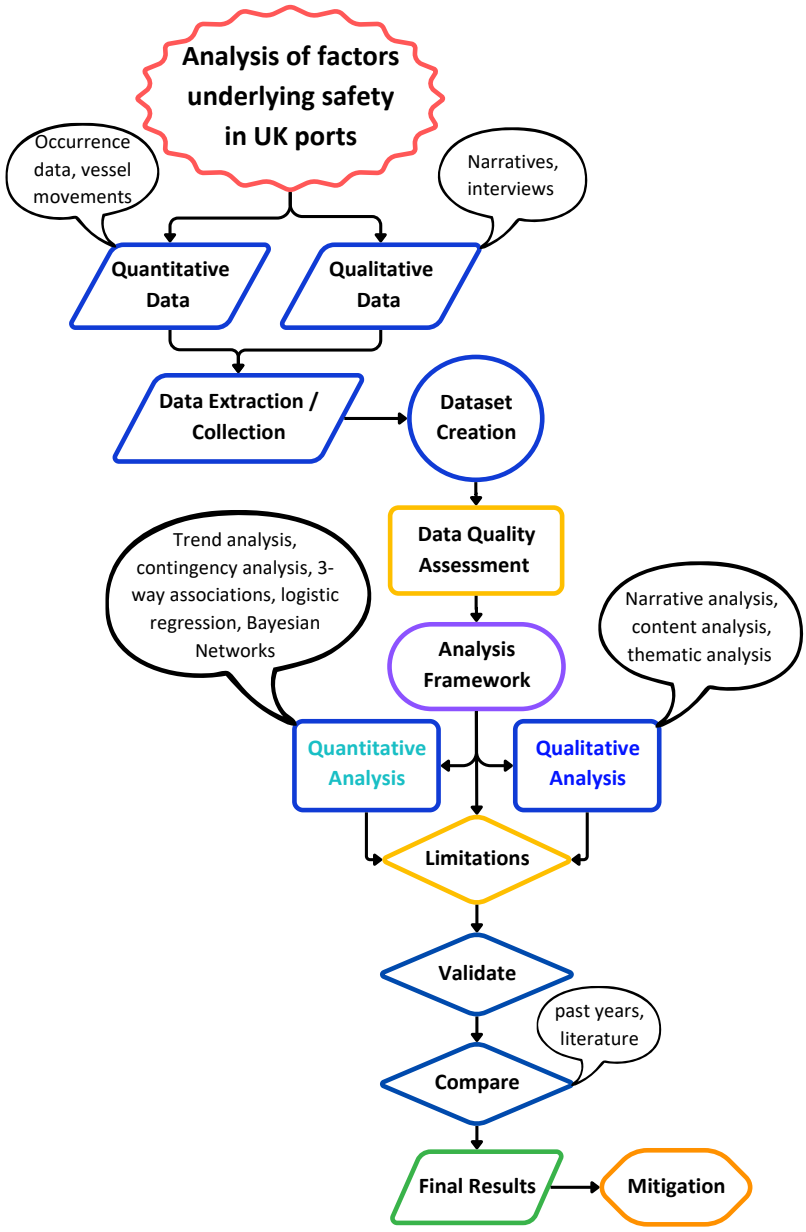
related fatalities in UK territorial waters reported in 2021 (MAIB, 2022). Furthermore, accidents are unevenly distributed in these waters and ports present a particularly vulnerable location, with their narrow concentration of maritime traffic. Given the importance of safety, an accurate picture of the state of safety of the country's ports, i.e., not just simple accident counts but accident rates given the vessel traffic at the ports, is not readily available. This is all the more surprising since data from the Automatic Identification System (AIS) tracks vessel locations by transceivers or satellite signals is readily available on vessels in UK waters.

Therefore, this case study aims to assess the safety of the UK's ports, with an emphasis on the largest ports, by analysing marine accidents and incidents normalised for movements using the AIS data. Following such an analysis, the factors that cause vessel transits to occur in an unsafe manner can be identified. Then, interviews with industry professionals are conducted to validate the results and get further insight into potential data limitations, and to assess the impact on port safety of factors not included in the MAIB or AIS data, such as port geometries and channel complexities. All methods of analysis which will be employed as part of this case study have been summarised in Figure 5.5 of Section 5.2. These are: trend analysis, contingency analysis, three-way associations, logistic regression, Bayesian Networks (BN), Complex Networks (CN), narrative analysis, content analysis and thematic analysis.

A reactive approach to safety will be employed initially, assuming that the system's malfunction has a cause which, throughout the literature, has been vastly linked to human, organisational and technical factors (Elliott, 2016). Two papers have been submitted for publication based on the work presented in this case study and received minor corrections, and they are expected to be published later this year (Majumdar, Manole and Garcia Sinobas, 2024; Yang et. al., 2024).

Figure 6.1-A summarises the methodology used for the analysis of factors underlying safety in UK ports presented in Section 6.1 of this chapter. It includes database description and data collection methods (Section 6.1.2), data quality assessment and quantitative data analysis (Section 6.1.4), qualitative analysis (Section 6.1.5), and limitations, comparison and methods of mitigation (Section 6.1.6). This methodology fits into the methodology of this thesis, and it represents a simplified version of Figure METHOD (Section 5.4), specific for this case study.

Figure 6.1-A. Methodology used for the analysis of factors underlying safety at ports in the United Kingdom.



6.1.2. Database description

This section presents the data sources that have been used and describes the databases. MAIB and AIS were the main data sources, but other sources that have been considered are also discussed. These data sources have previously been summarised in Table 5.5 of Section 5.5 of this thesis.

6.1.2.1. MAIB database

The original data set obtained from the MAIB includes 5,078 rows of maritime data in the United Kingdom, from 2013 to 2022. The 5,078 rows include 4,486 occurrences, around 4,979 vessels involved in those occurrences, and 1,638 details of affected people. These numbers different because

of the fact that there can be multiple vessels or people involved in one occurrence, details of which are provided separately. This data covers waterside accidents only, without considering health and safety accidents on the land side of ports, which are collected by the UK Health and Safety Executive (HSE). This is, however, outside the scope of this thesis.

The MAIB provided a comprehensive data set, however some of the data fields had to be derived from the narratives, such as for the number of ships involved (where missing). All data fields in Table 6.1-A are expected to add value to the analysis. Some of the ideal data fields have been removed from the analysis as they could not be obtained from other sources. The categories and data fields that would ideally be obtained from the MAIB (referred to as ideal database) are shown in Appendix G. This provides the information desired for the subsequent analysis, which is used as reference for the calculation of the data quality dimensions that assess how suitable the actual data obtained from different sources is for the desired analysis. The ideal dataset is based on findings from relevant literature, and the analyst's experience and intuition on further factors that can affect maritime accidents.

Table 6.1-A. The categories and relevant data fields obtained from the Marine Accident Investigation Branch of the United Kingdom.

Category	SC	OA	Data field	Data type	Description
General information and accident description	☑	☑	Occurrence ID	Continuous	Unique number of occurrence
			Date of casualty	Date	Day / Month / Year
			Investigation status	Categorical	Investigated, Not investigated
			Time of casualty	Categorical	Day divided into 6-hours intervals
			Nature of occurrence	Categorical	Casualty with a ship, Occupational accident
			Accident type	Text	Details about the type of accident
			Occurrence location	Categorical	Inland waters, Internal waters, Coastal waters, Repair yard. River, Port area, Channel, Channel, river, Lake.
			Narrative description	Text	Detailed description of accident & factors
Accident severity	☑	☑	***Occurrence severity***	Categorical	Marine incident, Less serious, Serious, Very serious
			Number of ships involved	Continuous	Number of involved ships
			Number of injuries	Continuous	Number of injuries of crew and passengers
			Number of deaths	Continuous	Number of deaths of crew and passengers
Mechanical errors	☑	☒	Equipment fault	Text	Narrative description
Details of affected people	☒	☑	Person ID	Continuous	Unique ID for injured/dead/missing person
			Gender	Categorical	Female, Male
			Person type	Categorical	Passenger, Crew, Other
			Age	Continuous	Age of affected person
			Personal protective equipment (PPE)	Categorical	Used, Inadequate, Not used

Category	SC	OA	Data field	Data type	Description
			Physical condition consequences	Categorical	Death, Injured, Missing, <72hr injury, Not a MAIB injury
			Injury description	Text	Narrative description of injury
			Place on board	Categorical	Accommodation, Bridge, Cargo & tank areas, Engine department, Pump room, Ship
Human performance	☑	☑	Fatigue	Text	People affected by fatigue
			Negligence or carelessness	Text	People affected by negligence or carelessness
			Alcohol	Categorical	Yes, No
			Training	Categorical	Done, Not done, Incomplete
Vessel details	☑	☑	Vessel ID	Continuous	Unique ID per vessel involved
			MAIB Vessel category	Categorical	Merchant Vessel ≥ 500gt, Merchant Vessel 100 - 500gt, Small Commercial <100gt, Fishing Vessel 15 - 24m, Fishing Vessel <15m, Non-Commercial recreational, Navy Ship, Fishing Vessel ≥24m, Not a MAIB vessel
			Ship craft type	Categorical	Cargo ship, Inland waterway vessel, Recreational craft, Fishing vessel, Service ship, Passenger ship, Navy ship
	☑	☒	Simple flag	Categorical	UK, Non-UK
			Place on board	Text	Accident place on vessel
			Gross tonnage	Continuous	Overall ship size
			Length overall	Continuous	Largest centreline longitudinal distance of ship
			Year of build	Categorical	≤1950, 1951-2000, >2000
			Hull material	Categorical	Steel, GRP, Aluminium alloy, Composite materials, Ferro cement, Wood, Wood - Primitive built, Other
			Damage description	Text	Narrative of vessel damage
	☑	☑	Did the ship sink?	Categorical	Yes, No, n.a.
Port details	☑	☑	National location	Categorical	England, Northern Ireland, Scotland, Wales
			Name	Text	Name of port
	☑	☒	Annual number of arrivals	Continuous	Annual number of arrivals at each port
Environmental conditions	☑	☒	**Natural light**	Categorical	Daylight, Night, Twilight
			Wind force	Categorical	Beaufort scale: 0-12
			Visibility	Categorical	Very good, Good, Moderate, Poor, Very poor
			Weather	Categorical	Clear, Fog, Rain, Overcast, Snow
			Sea state	Categorical	Scale 0-8

The 5,078 maritime occurrences have been cleaned and filtered, according to the following measures:

- The database has been split in two, for ship casualties (SC) and occupational accidents (OA).
- Checks for occurrences with over 50% incomplete data.
- Columns wilt over 4,500 blank cells have been removed.
- "Not available", "n.a.", "Unknown", etc. have been recoded as blank cells.
- For OA, days lost consequence has been assumed 0 if the cell was blank.

- It has been assumed that vessels did not sink unless stated otherwise.
- It has been assumed that there was no damage to the ship unless stated otherwise.
- It has been assumed that there was no pollution unless stated otherwise.
- Missing cells have been derived from the narratives, where possible, for the “Number of ships involved”.
- The categories ”Mechanical errors” and “Human performance” have been removed.

The reason for separating the database for CS and OA is the differences in the reported data fields for these two categories. For example, details of the affected people are not reported for SC, but they are for OA since they are relevant only for OA. However, details of people involved such as crew (e.g. age, experience, fatigue, etc.) were not present for SC. In addition, the categories ”Mechanical errors” and “Human performance” have been removed from the analysis as their data fields were mostly empty and that information could be obtained from the narrative only for a small proportion of the occurrences

The MAIB data has been used in other publications that provide insights into various aspects of maritime safety, accident analysis, and regulatory effectiveness. Baker and McCafferty (2005) review 100 accident reports from the MAIB, to study human elements in ship design and operation. Tirunagari (2015) also use MAIB reports to extract causal relations and analyse marine accidents. Zheng (2020) explores the effectiveness of various national marine accident investigation agencies, including the MAIB. Carter and Williams (2019) use historic MAIB data to statistically analyse ship accidents and fatalities on UK passenger ships. Loughney, Wang and Matellini (2024) use MAIB data to statistically analyse ship to platform collisions.

6.1.2.2. AIS database

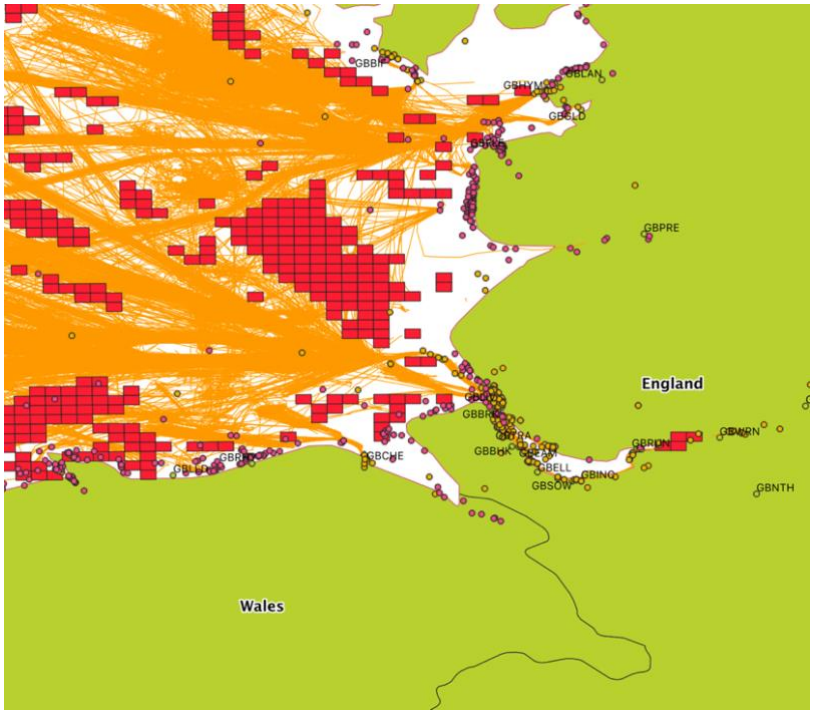
In addition to the MAIB data, publicly available AIS data for 2015-2017 has already been obtained and it includes almost nine million vessel movements in UK territorial waters and 1.7 million gridded traffic densities. The AIS data comprises of fewer data fields than the MAIB data. It includes only the date, time, vessel type, vessel route and average vessel density within a 2km grid resolution (Marine Management Organisation [MMO], 2014; MMO, 2017). The categories and data fields that would ideally be obtained from the AIS (referred to as ideal database) are shown in Appendix H. The ideal dataset is based on the MAIB database, as information for vessel movements that did not result in an accident or incident would be required in order to implement robust prediction models.

As previously mentioned in Section 3.7, the AIS tracks vessel locations by transceivers or satellite signals. Whilst the MAIB provides accident data along with possible contributing factors, the AIS

system helps identify ships, track their routes, and exchange information under certain circumstances. The International Maritime Organisation has implemented regulations which oblige all ships to use AIS except for commercial vessels below 300 gross tonnage (GT), recreational and fishing vessels, and military or governmental vessels. All ships under that group will use Class-A AIS, while all other ships which use AIS for voluntary purposes will use Class-B AIS. Data from both classes will be used for the analysis outlined in this thesis.

In Figure 6.1-B, the AIS derived vessel routes and density grid are shown for the port of Liverpool for illustrative purposes. The orange lines represent each of the vessel tracks for one year. The red rectangles show the less traffic dense locations, aiming to demonstrate how the grid is structured. For each of these rectangles, an average yearly traffic density is available. The yellow circles show MAIB's data, while the pink ones show RNLI's data which is described in the following section. All data sources used have been described in Section 5.5.

Figure 6.1-B. AIS data obtained from the UK government for the port of Liverpool (Majumdar, Manole and Sinobas, 2024).

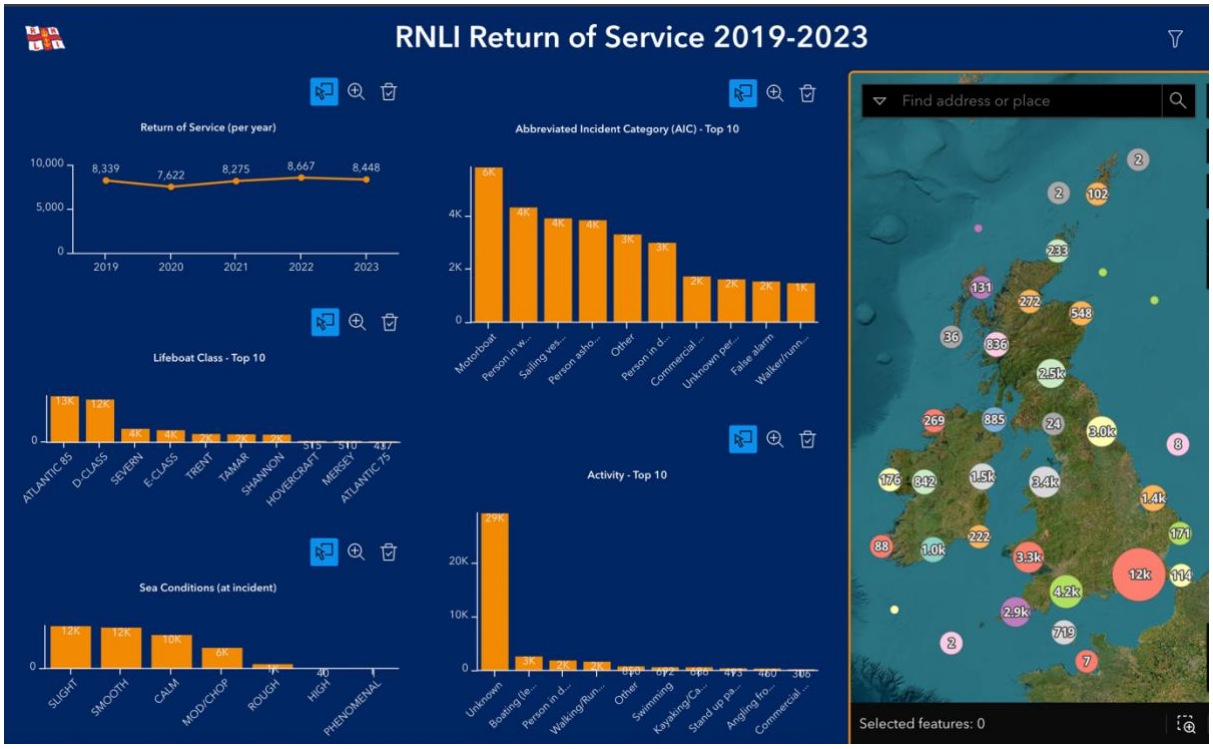


6.1.2.3. RNLI database

Because of the previously mentioned underreporting of less serious accidents and marine incidents to the MAIB, alternative sources have been sought. It was not possible to obtain local databases from individual ports or other authorities, the reason being that these are not publicly available and stored only for internal use. However, data from the Royal National Lifeboat Institution (RNLI) has been

obtained for 2008-2023. This is a charitable institution, as previously mentioned in Section 3.4, and is tasked with saving lives at sea. Figure 6.1-C is a screenshot of their website which shows their statistics for 2019-2023, emphasising the high number of occurrences compared to the MAIB database. As a comparison, the RNLI data contains 40,000 incidents between 2019-2023 (RNLI, 2024), so around 10,000 per year, while the MAIB data comprises of only 564 occurrences per year, on average, of which around one half are marine incidents.

Figure 6.1-C. Screenshot of the RNLI website showing statistics for 2019-2023 (RNLI, 2024).



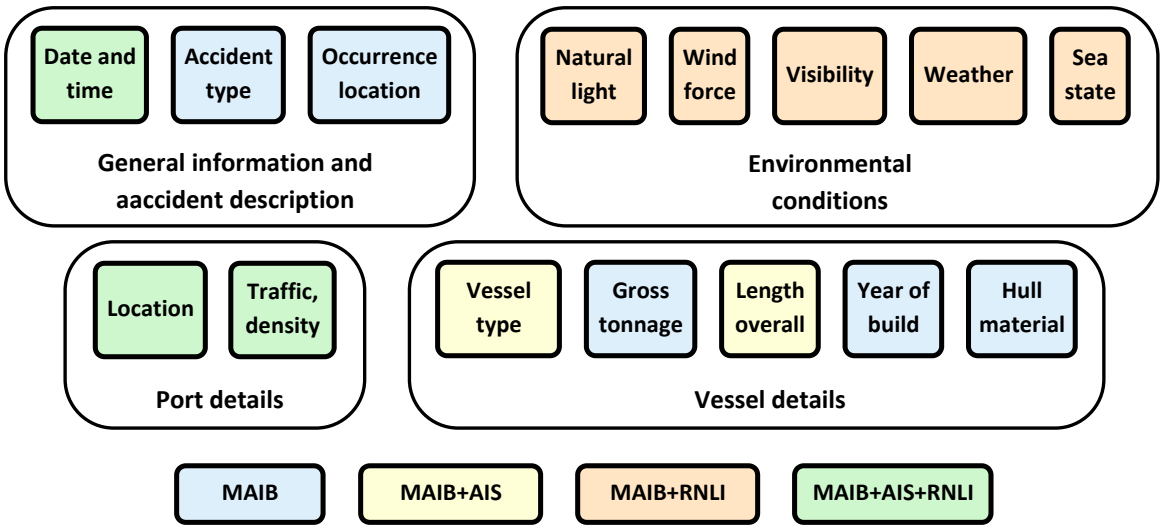
The database obtained from the RNLI has been filtered to consider marine incidents related to vessels only. Compared to the MAIB, RNLI's database includes substantially less data fields, making the analysis using this data limited. Moreover, the taxonomy and classification used by RNLI is different from the MAIB. The only comparable data fields between the RNLI and MAIB data sources are the date, time and coordinates. Apart from that, only weather conditions can be comparable: visibility, weather, sea state and wind. Therefore, the number of accidents is calculated using the MAIB data, without marine incidents. The number of injuries, however, is calculated as the marine incidents from the MAIB, to which the RNLI data is added.

6.1.2.4. Conclusions regarding maritime databases used

Having discussed the databases used in the subsequent analysis, Figure 6.1-D has been developed to summarise the factors investigated in this section, and the data sources used for each of them. All

factors previously mentioned of the MAIB dataset in Table 6.1-A are used for the trend analysis and associations. However, only the subset of ship casualties from the MAIB data will be used, as critical details for the study of occupational accidents, such as human-related factors, could not be obtained. Data of occupational accidents will only be used during trend analysis to provide relevant comparisons with the ship casualty events. Therefore, the 15 factors outlined in Figure 6.1-D are studied in this thesis, for this first case study presented in this section.

Figure 6.1-D. The studied contributory factors for safety-related maritime occurrences in the United Kingdom.



To summarise Figure 6.1.2.4, MAIB's accident database will be used for all factors. The RNLI data will be used in addition to the MAIB data for the environmental factors. MAIB and AIS data are used to study vessel type and length, while all three data sources are used to study the date and time of the occurrence, as well as the port details. Some port details, such as port and channel factors, will also be analysed based on interviews with industry professionals, since the available data sources do not provide details on port geometry and complexity.

6.1.3. Redefined vessel categories

The vessel categories in the MAIB and AIS databases have some differences. Table 6.1-B therefore describes the six vessel categories considered in this thesis that merge the eight vessel categories in the MAIB database with the ten categories in the AIS dataset. The category "High speed crafts" has been ignored in this thesis due to its low presence in both datasets.

Table 6.1-B. Redefined vessel categories consistent for both the MAIB and AIS data sources.

New Vessel Category	Vessel Category (MAIB)	Vessel Category (AIS)
1. Cargo Vessels	Cargo Ship	Cargo Vessels, Tankers
2. Fishing Vessels	Fishing Vessel	Fishing Vessels
3. Passenger Vessels	Passenger Ship	Passenger Vessels
4. Recreational Vessels	Recreational Craft	Recreation
5. Service Ships	Service Ship, Inland Waterway Vessel	Port and Non-Port Service Vessels, Vessels engaged in dredging or underwater operations
6. Military Vessels	Navy Ship	Military Vessels

6.1.4. Data quality assessment

This section provides the assessment of data quality for all maritime databases considered in Section 6.1.2. Table 6.1-C shows the DQA of the three databases used (MAIB, AIS and RNLI). As previously explained, because of the differences in the factors relevant for SC and OA, these are considered separately for the analysis.

Table 6.1-C. Results of the Data Quality Assessment for maritime occurrences in UK ports.

<table>
<tr><th colspan="5">Factors underlying maritime occurrences in UK ports</th></tr>
<tr><td>Agency</td><td>MAIB (SC)</td><td>MAIB (OA)</td><td>AIS</td><td>RNLI</td></tr>
<tr><td>Source</td><td>Database</td><td>Database</td><td>Database</td><td>Database</td></tr>
<tr><td>Area covered</td><td>UK</td><td>UK</td><td>UK</td><td>UK</td></tr>
<tr><td>Study period</td><td>2013 - 2022</td><td>2013 - 2022</td><td>2015 - 2017</td><td>2008 - 2023</td></tr>
<tr><td>Sample size</td><td>3,743</td><td>1,335</td><td>9 million movements
1.7 million densities</td><td>147,000</td></tr>
<tr><td colspan="5">Data Quality Dimension</td></tr>
<tr><td>Accessibility</td><td>93%</td><td>93%</td><td>96%</td><td>97%</td></tr>
<tr><td>Completeness</td><td>80%</td><td>65%</td><td>97%</td><td>54%</td></tr>
<tr><td>Consistency</td><td>94%</td><td>94%</td><td>85%</td><td>90%</td></tr>
<tr><td>Relevance</td><td>59%</td><td>51%</td><td>55%</td><td>45%</td></tr>
<tr><td>Accuracy</td><td colspan="2">High (the data is consistent with the narratives)</td><td colspan="2">Assumed high</td></tr>
<tr><td>Credentials / Credibility</td><td colspan="4">It is assumed that the data is obtained from a reliable and credible source</td></tr>
<tr><td>Interpretability</td><td colspan="4">It is assumed that the reporter, the agency and the analyst have similar understanding and interpretation of data fields</td></tr>
<tr><td>Timeliness</td><td colspan="4">Not available, as the date of notification is not available</td></tr>
<tr><td>Security</td><td colspan="4">Assumed secure</td></tr>
<tr><td>Value-added</td><td colspan="4">Assured for all data fields</td></tr>
<tr><td rowspan="3">Narrative richness</td><td>Moderate (56%)</td><td>Moderate (62%)</td><td rowspan="3">Not applicable</td><td rowspan="3">Not applicable</td></tr>
<tr><td>Narrative length (> 20 words) 78%</td><td>Narrative length (> 20 words) 65%</td></tr>
<tr><td>Vessel(s) involved 48%</td><td>Injured person 100%</td></tr>
</table>

	Location 55%	Location 74%		
	Actions before the occurrence 69%	Actions before the occurrence 74%		
	Actions after the occurrence 59%	Physical and mental state 11%		
	Physical environment 52%	Physical environment 47%		
	Human and organisational factors 31%			

The scores of “Accessibility” and “Consistency” are high, above 85% for all datasets. For OA and RNLI, "Completeness" scored under 80% (in fact, 65% and 54%, respectively), however these are still acceptable scores, but a decision has to be made whether the score is sufficient for RNLI and the impact this will have for the subsequent analysis. "Relevance" has, overall, the lowest scores for all datasets. While above 50% for the MAIB and AIS data, it scored only 45% for RNLI. In general, for this dimension, most data fields were explicit, and some were inferred from the narrative (e.g., the number of ships involved, human performance and mechanical failure). If the “Human performance”, “Mechanical failure” and “Environmental / External factors” categories are removed from the scope of the MAIB analysis, the scores for "Completeness" and "Relevance" would increase considerably. Therefore, alternative analysis will be conducted for these categories in addition to the analysis of these databases.

Section 6.1.9 presents the additional analysis undergone through interviews with industry professionals. It is important to conduct separate analysis for categories which lower data quality as they can provide misleading results, and the subsequent analysis may lead to incorrect conclusions and affect the overall credibility of the study. Hence the importance of undertaking a data quality assessment and redefining the scope of the study if necessary, as described in Section 5.6.

The dimension “Timeliness” could not be calculated, which is important as a longer time between when an occurrence happened and when it was reported might indicate that some information could have been forgotten and therefore missed. This dimension could be calculated for the majority of the MAIB data before January 2020, from when the “Date of notification” has been missing. Similarly, the “Weather” data field has been removed from January 2018.

Narrative descriptions of OA and SC were moderately detailed and, thus, only some of the narratives were comprehensive. Detailed narratives contained a description of the occurrence which explained how and why the accident or incident occurred. In the case of CS, the following information was needed: human factors (e.g. decisions made before and after the occurrence, situation awareness, fatigue), the impact of technologies on the occurrence (e.g. whether a new technology was used) and the procedures (e.g. expected communication), which were deemed relevant from the literature

review in Section 3.5.1. Instead, narratives of SC provided extensive information on the physical damage of the vessels involved. For OA, narratives generally described the *affected people* (e.g., gender, age, injury description, physical condition consequences, place on board). In conclusion, the reduced sample of detailed narratives prevents the analysis of human performance. Hence, only the remaining data fields were used for the subsequent analysis as their dimensions scored high values. These results are reported in the following section, separately for SC and OA.

Furthermore, the underreporting of less serious marine casualties, as well as marine incidents, poses a significant limitation. This underreporting can occur for several reasons, including individuals and operators not being required to report these levels of severity, fear of punishment or negative repercussions, and lack of awareness or understanding of reporting requirements. This results in incomplete datasets, which can skew the analysis and lead to an inaccurate understanding of the true safety conditions and risk factors associated with maritime operations. To mitigate this, efforts should be made to encourage comprehensive and accurate reporting of all incidents, regardless of their perceived severity, and to ensure that pilots and other stakeholders understand the importance of thorough reporting for improving overall safety. Another improvement would be the standardisation of taxonomies and requirements for different accident and incident data sources, at least at a national level.

Having conducted a satisfactory data quality assessment and reviewing the strengths and weaknesses of all datasets used, the following sections use this data to employ different analytical methods.

6.1.5. Trend and contingency analysis

This section employs the first analytical methods used to study port safety in the United Kingdom, and has three sub-sections. The first one describes the methods of analysis used, which are then employed for SC and OA separately.

6.1.5.1. Overview of the methods of analysis

Descriptive statistics, frequency analysis and distributions were used to analyse trends of occurrences in UK ports. The MAIB dataset contains the following types of data:

- Continuous (e.g. number of injured people);
- Categorical (e.g. vessel category);
- Textual (e.g. accident description).

Both continuous and categorical data were tested for normality using the Kolmogorov-Smirnov (sample>50) and the Shapiro-Wilk tests (sample<50) (Wilke, Majumdar and Ochieng, 2015). Non-

parametric statistical tests, such as Pearson's Chi Square test (χ^2), were applied for non-normally distributed data. For categorical variables, the Pearson's Chi Square test (χ^2) was used to compare the actual frequencies with the corresponding expected frequencies in the categories of the variables (Wilke, Majumdar and Ochieng, 2015). The χ^2 statistic is calculated using Equation 6:

$$\chi^2 = \sum \frac{(observed\ frequency - expected\ frequency)^2}{expected\ frequency} \quad (6)$$

where the expected frequency refers to the expected count if there was no association between parameters, while the observed frequency is obtained from the dataset. Moreover, the data fields are adjusted such that the expected frequencies less than five are under 20% (Uebersax, 2014). Otherwise, it is considered that there is not enough data to test the association.

The p-value indicates the statistical significance of the association, with lower p-values, meaning stronger evidence against the null hypothesis, for statistically significant relationships (p-value under 0.01 means 99% confidence level). In this case, the significance was set at $p<0.05$ for the statistical test, meaning a 95% confidence level. Consequently, the phi-value was used as a measure of the strength of the association, with higher phi-values indicating stronger relationships. Based on this, the strength of the relationship is determined (weak, moderate or strong). Table 6.1-D shows the interpretation of the phi-values.

Table 6.1-D. Interpretation of Phi value (Plummer, 2014).

Phi value	**Strength of relationship**
-1.0 to -0.5 and 0.5 to 1.0	Strong
-0.5 to -0.3 and 0.3 to 0.5	Moderate
-0.3 to -0.1 and 0.1 to 0.3	Weak
-0.1 to 0.1	None or very weak

An analysis is conducted to examine if accident severity, ship type and casualty event are statistically associated with details of vessels and affected people, port details and environmental conditions. Accident type and ship type were the dependent variables tested for associations with the other factors (independent variables). For each association, data values that were either missing or unknown were excluded. Moreover, to avoid the expected cell count to be less than five, the tested variables were transformed into binary categories. For example, casualty events were separated in collision/non-collision and contact/non-contact.

The following two sections present the main results of the trend and contingency analysis for ship casualties and occupational accidents, using MAIB data. The trend and contingency analysis results of the AIS and RNLI databases are presented in Section 6.1.7.

6.1.5.2. Results for ship casualties

This section presents relevant findings from the trend and contingency analysis of ship casualties at UK ports between 2013 and 2023, using MAIB data. These results are important as they form the baseline for more advanced analyses conducted in subsequent sections of this chapter.

Trend analysis

Figure 6.1-E illustrates that, while the overall number of SC increased over the studied period, this is mainly because the number of marine incidents, which account for just over half of the total occurrences, has been increasing over the years. Serious and very serious casualties remain relatively low and indicate a slight downward trend. These constituted only 5.21% and 1.2% of the accidents, respectively. Less serious SC, however, exhibited a decreasing trend, accounting for 43.28% of the occurrences. Considering the previous literature review, it has been assumed that the rise in marine incidents is due to efforts to increase the number of reported incidents of low severity.

Figure 6.1-E. Number of ship casualties per year, for different occurrence severities.

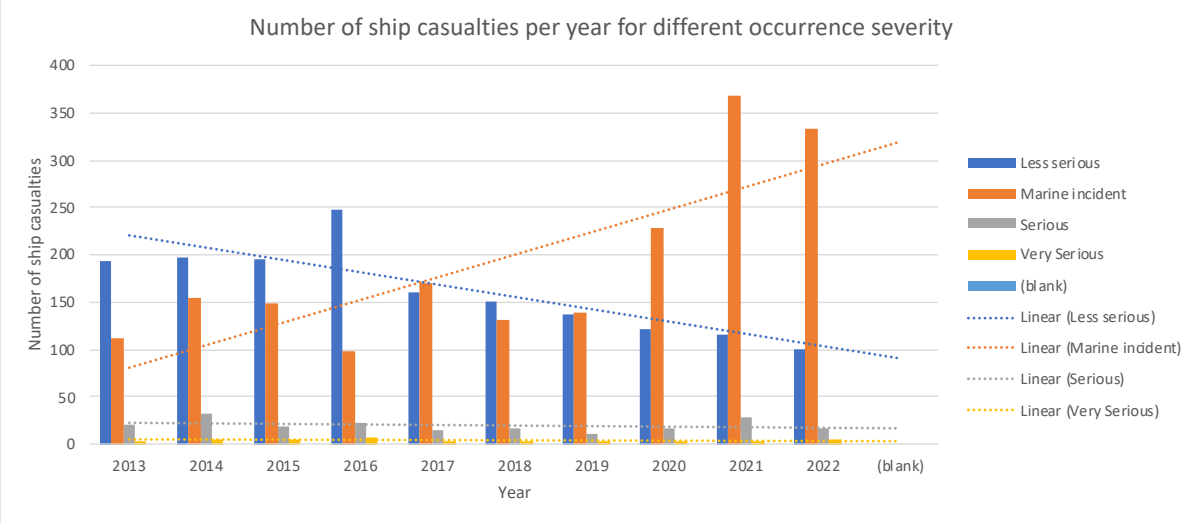


Figure 6.1-F depicts the number of ship casualties per year for different accident types, and reveals distinct trends in various categories. Collisions and contacts were the predominant accident types, collectively representing almost half of the ship casualties at 21.15% and 24.14%, respectively (Figure 6.1-G). These are, however, on a decreasing trend over the studied period. The most common type of collision involved two ships, whereas the most frequent type of contact occurred when a ship collided with a fixed object, such as a pier or breakwater. The most notable trend is the significant spike in "Damage / loss of equipment" occurrences after 2019, which drastically increased compared to previous years. However, the 87.33% of these are marine incidents which, as previously mentioned, are likely to have seen an increase because of better reporting systems in place.

Figure 6.1-F. Number of ship casualties per year, for different accident types.

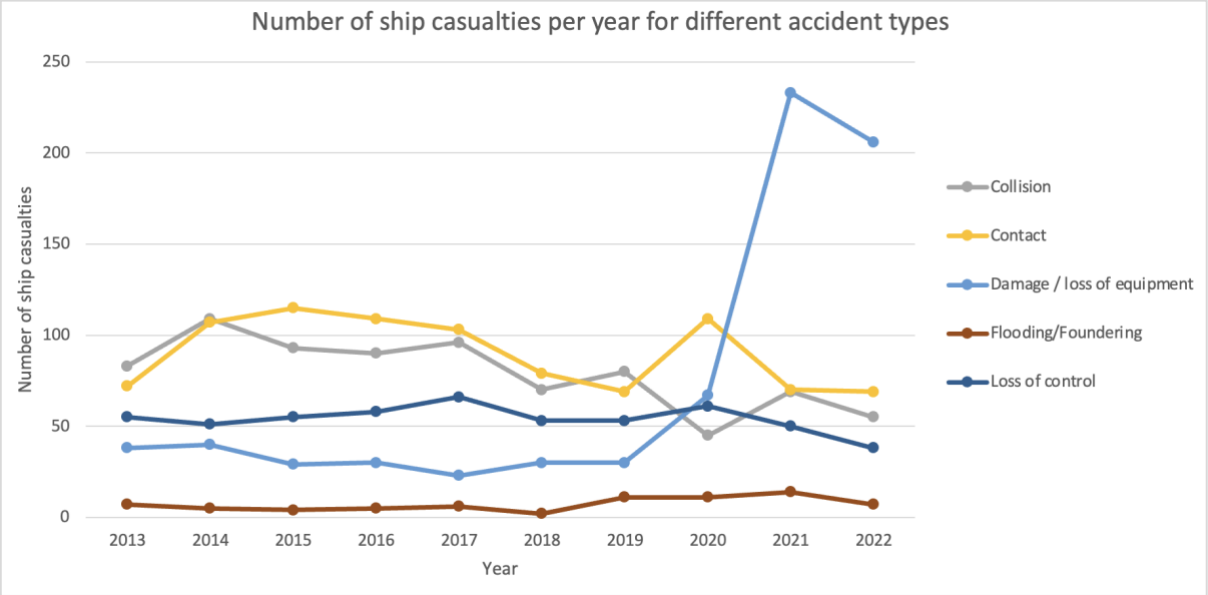


Figure 6.1-G. Distribution of accident types.

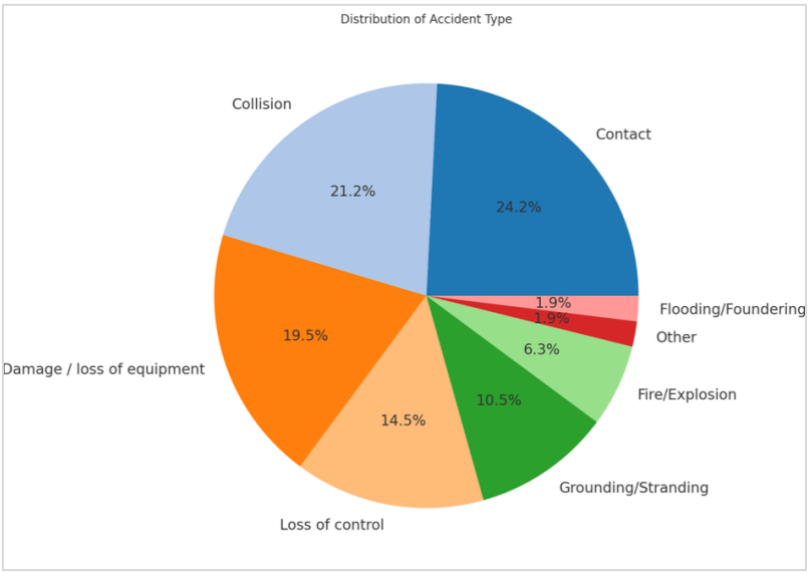


Figure 6.1-H shows the change in number of ship casualties per year for different vessel types. Cargo ships were predominantly involved in SC, averaging 43.84% and showing an increasing trend over the studied period. Service ships (24.79%) and passenger ships (14.35%) followed (Figure 6.1-I). The low number of occurrences on military vessels is expected, and this will be later emphasised by the interviewed professionals in Section 6.1.9.

Figure 6.1-H. Number of ship casualties per year, for different vessel types.

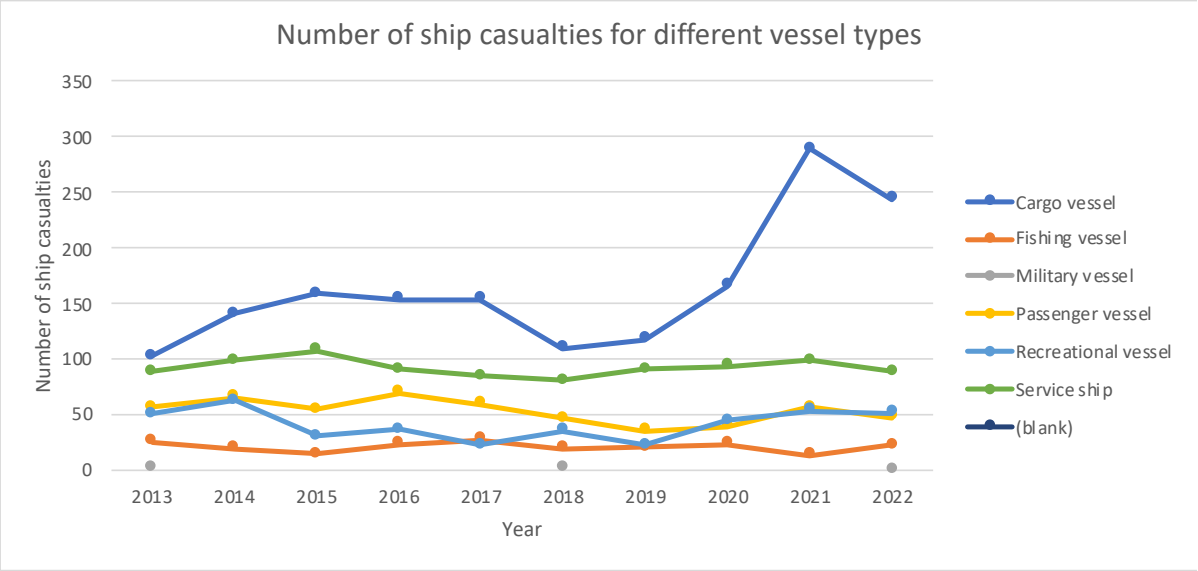


Figure 6.1-I. Distribution of vessel types.

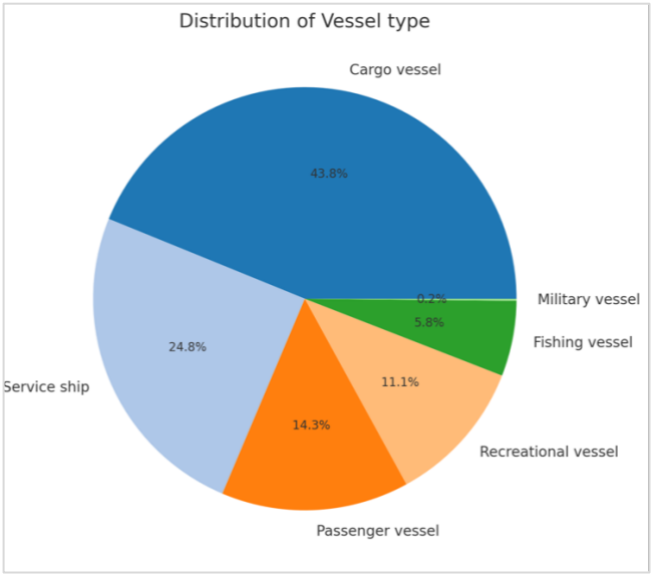
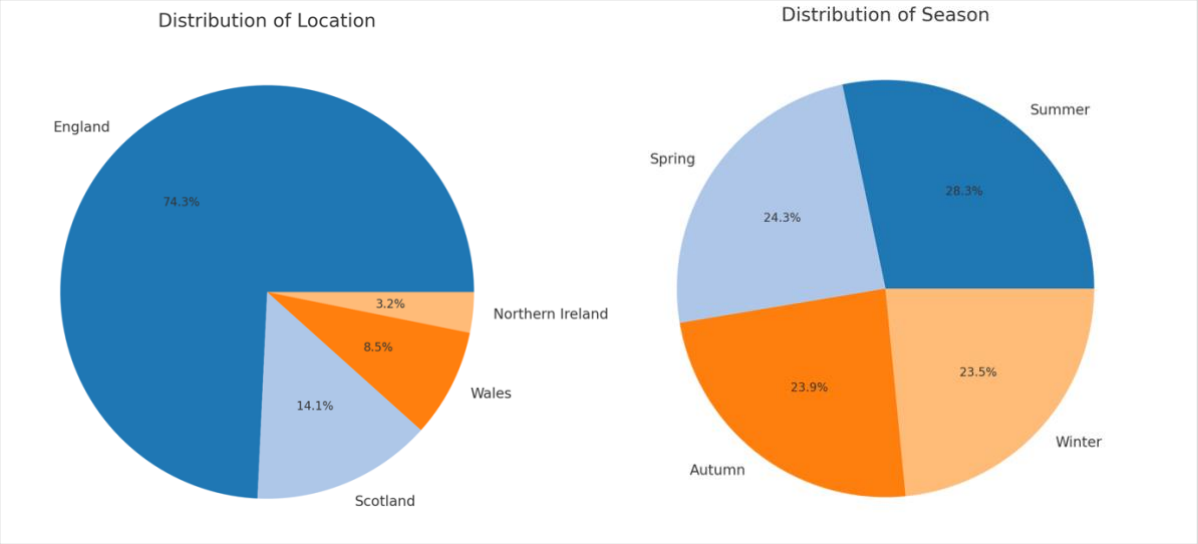


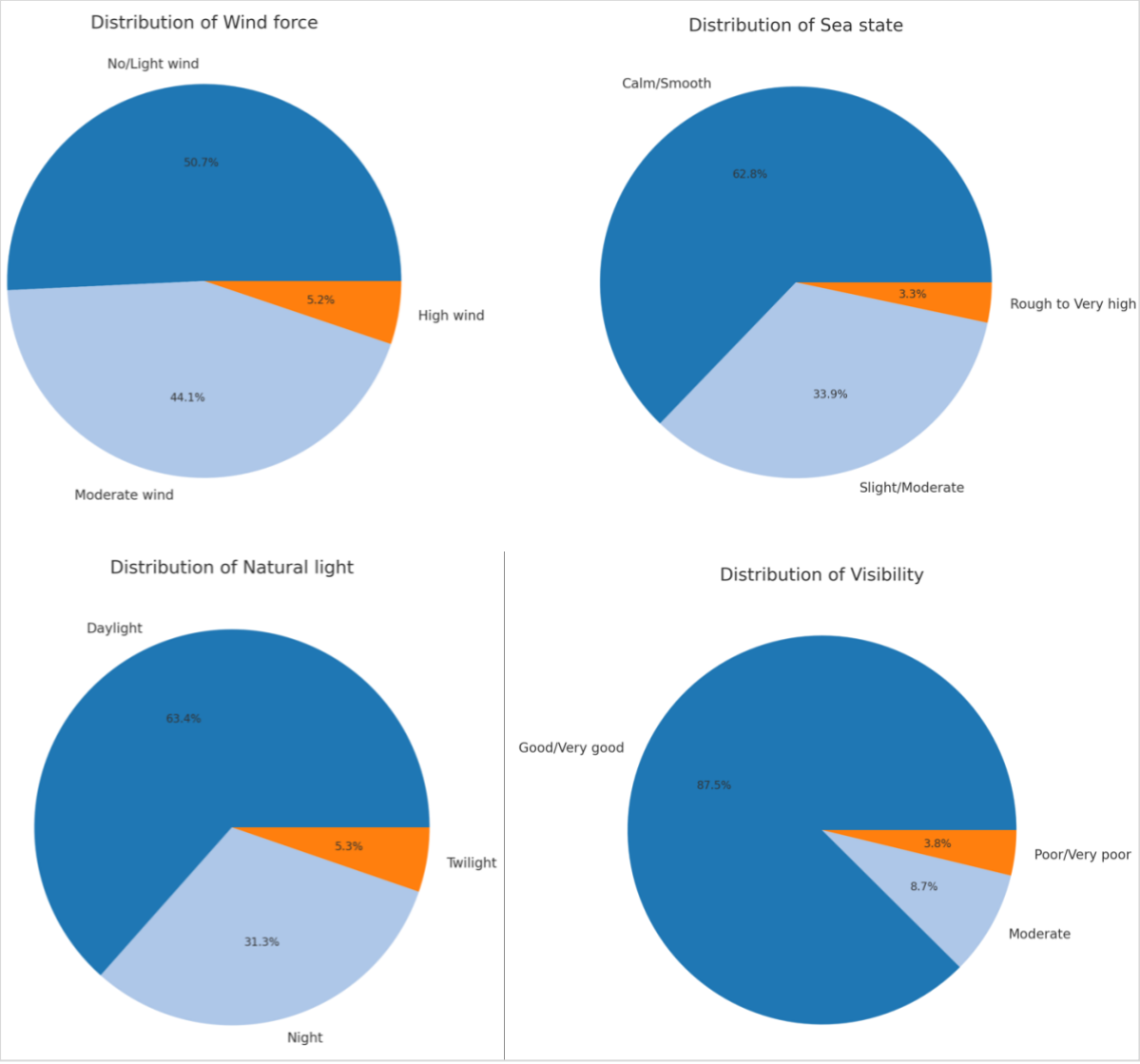
Figure 6.1-J represents the distribution of SC for different locations and seasons, to provide a better understanding of where and when ship casualties happen. Most of them occur in England, which is expected as it has the highest number of vessel movements, while the distribution over seasons is quite even.

Figure 6.1-J. Distribution of SC for different locations and seasons



The distribution of different environmental conditions is shown in Figure 6.1-K. 63.4% of SC occurred in daylight, while 31.3% occurred at night. Weather conditions, such as fog, overcast, rain, and snow, were reported for only 51.6% of accidents, although the completeness rate improved by 23% during the studied period. Excluding unknown values (average 23.95%), most SC occurred under good wind, sea state and visibility conditions (50.7%, 62.8% and 87.5%, respectively).

Figure 6.1-K. Distribution of different environmental conditions.



Other relevant statistics include the following. Most injured individuals were male (73.7%) and aged between 25 and 54 years old (32.3%). Crew members were involved in 70.7% of SC, with 62.6% being on duty prior to the occurrence. Onboard the vessel, most SC (38.4%) were recorded on the ship, followed by cargo and tank areas (14.1%) and accommodation (12.1%). Injuries to the whole body or multiple body parts occurred in 18.2% of SC, followed by head (16.2%) and upper extremities (14.1%) injuries. Personal protective equipment (PPE) usage was reported in only 7.1% of CS, with data provided for just 17.2% of the occurrences.

Contingency analysis

A contingency analysis was conducted to examine if accident severity, ship type, and accident type were statistically associated with the time of occurrence, port location, vessel details (e.g., hull material, ship type, ship flag), and environmental conditions. For each association, only occurrences

without unknown values were used to maximise accuracy. As previously mentioned, to avoid expected cell counts of less than five, input data fields were transformed into binary categories. For example, accident types were categorised as collision/non-collision, or contact/non-contact.

Approximately 45.2% of the tested 2-way associations were significant at the 95% confidence level, although their strength was mostly weak or very weak. Serious and very serious accidents were more likely to involve UK vessels, occur between 20:01 and 08:00, or during twilight/night. In addition, SC on cargo ships were more likely to be less severe, while contacts were more likely to involve non-UK vessels and occur during twilight/night, and collisions were more likely during daylight, involving UK-flagged vessels. The Chi-square analysis also revealed a strong relationship between ship type (cargo/non-cargo) and ship flag (UK/non-UK), meaning that cargo ship accidents are most likely to involve non-UK vessels.

The relationship between different parameters and accident severity has been tested to identify the factors which lead to more serious occurrences. This studies an accident/incident database and not the whole vessel population, meaning that any statistical figure obtained will not necessarily represent a causation pattern for accident occurrence. For example, if a third of SC occurred under sunny / clear conditions, and 95% of all vessel movements occur under sunny / clear weather conditions, what it should be deducted is that movements under other types of weather conditions could potentially be more dangerous. Comparisons against the whole vessel population is also considered.

It has been found that most occurrences happen during day-time, however, during night time (22h to 7h), SC are more serious. This is proven by a 99% confidence level that there is a relationship between accident severity and the time of the day. However, there is no relationship between seasonality and accident severity. Regarding the impact of environmental conditions on accident severity, poor visibility, a rather good sea state, moderate wind conditions and clear weather were found to be the conditions when an accident is most prone to occur. Furthermore, occurrence severity was determined to be related to visibility, sea state and wind force, such that a higher accident severity is directly correlated with worse visibility, a higher wave height and bad weather conditions. Accident severity and wind force are also directly correlated, but less significant.

Vessel-specific parameters such as age, tonnage, length, material and flag state were also tested against accident severity. The results show that UK registered vessels seem to have more severe accidents than non-UK flagged vessels. As expected, a strong correlation is found between accident severity and vessel material (steel) or flag state. There is also a significant direct relationship between

vessel age and accident severity (i.e., the older the vessel, the higher the accident severity). On the other hand, vessel length and tonnage do not have any correlation with accident severity.

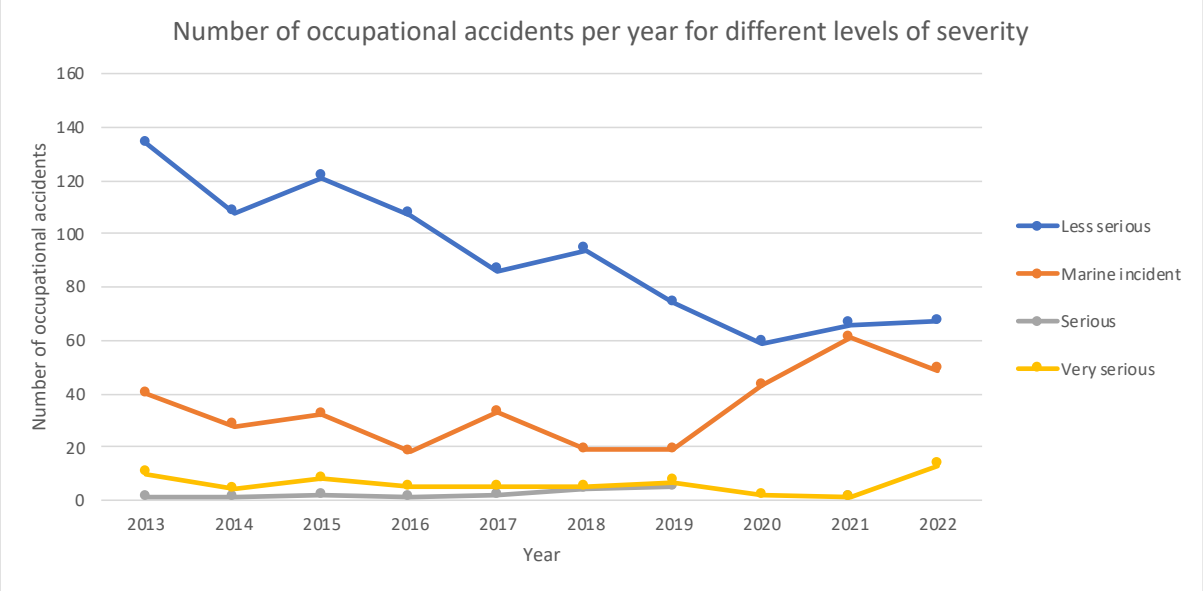
6.1.5.3. Results for occupational accidents

Having reviewed the results of trend and contingency analyses for ship casualties, this section presents a summary of the results for occupational accidents.

Trend analysis

Overall, the number of reported OA increased over the studied period. Less serious OA followed a decreasing trend, however, they still accounted for the majority of the occurrences (68.61%). Serious and very serious accidents only accounted for 1.27% and 4.49% of the reported accidents respectively, while marine incidents represented 25.62% of the number of OA. The variation of different severity OA over the years is shown in Figure 6.1-L. A similar increase in the number of marine incidents is observed, as for SC, which is assumed to be due to improved voluntary reporting systems for near-misses.

Figure 6.1-L. Variation of different severity levels for occupational accidents between 2013-2022.



75% of OA involved members of crew, of which 86.9% were on duty. On average, 60% of the injured crew members were aged between 22 and 54 years, with 37.4% over the age of 55. The most frequent causes of OA involving crew were slipping, stumbling and falling (45.4%), which coincides with HSE's observation (2019) for injuries at work in Great Britain. 60% of the OA involving crew occurred on the ship, 11.26% occurred in cargo and tank areas and 15.74% in accommodation areas. External injuries from body movement without physical stress were more common (22.6%) than internal injuries

(12.9%), usually caused by body movements under or with physical stress. External injuries were often resulted from body movement without any physical stress. The following represent typical injuries reported by crew members: bone fractures, dislocation, sprains and strains, wounds and superficial injuries.

OA involving passengers accounted for 15.09%. OA equally occurred at the accommodation area on stairway/ladders, at the ship boat deck or at the ship freeboard deck. Slipping accounted for 78.5% of the accidents involving passengers. Most of these OA occurred during daylight and good weather conditions. In general, passengers were injured while onboard a passenger (55.8%) or recreational ship (16.9%).

Contingency analysis

As for SC, a contingency analysis was conducted to examine if accident severity, ship type and accident type were statistically associated with time of occurrence, port location, details of vessels (e.g. ship type), affected people (e.g. occupation, place on board, gender) and environmental conditions. 54.8% of the tested associations were significant with 95% confidence level, but their strength was mostly weak or very weak.

It has been determined that high severity OA are less likely to occur on passenger and service ships. In addition, OA on cargo ships are less likely to happen in Northern Ireland or Wales, and less likely to involve passengers. In Scotland, casualties of crew members on fishing vessels are more likely. Passenger injuries are more likely on an inland waterway vessel in England and Scotland compared to the other areas. Moreover, passengers are more likely to be injured between 20:01 and 8:00 while on either a passenger ship or a recreational boat. Slipping, stumbling and falling are more likely to occur during the same time (20:01 to 8:00), for passengers.

The Chi-square analysis established a moderate relationship between ship type (inland waterway vessel or not) and person type (passenger/non-passenger). This means that OA on inland waterway vessels are more likely for passengers. When associating ship type and place on-board, passengers on passenger ships have been found less likely to get injured on the ship area.

Regarding the relationship between vessel types and accident severity, it has been determined that cargo vessels and service ships are strongly correlated with ship casualties (as previously mentioned, these exclude marine incidents). Still, cargo, passenger and service ships represent the main vessel types where the majority of OA occur.

Occupational accidents are determined to be mostly caused by human-related factors, in most cases under working conditions, in contrast with the findings for SC. Because of the previously mentioned lack of information on human-related factors, the following sections using more advanced methods of analysis consider only ship casualties.

6.1.5.4. Conclusions

Section 6.1.5 analysed the safety at UK ports using CS and OA reported in the period 2013 – 2022 using trend and contingency analysis. These results provide the basis of the subsequent analyses, contributing to their methodologies, data choices and assumed limitations. Therefore, the following sections use more advanced methods of analysis to provide a more comprehensive understanding of safety patterns in UK ports, the first one being three-way associations between parameters.

6.1.6. Three-way associations

Given the categorical nature of most of these variables, the Chi-Square test was also used to provide possible associations between any three of the binary variables in Table 6.1-E of the first sub-section of this section. This test is employed to expand on the trend and contingency analyses, for a deeper dive into how associations of different parameters affect the outcome of an occurrence. The first sub-section reviews the methods used and provides an overview of the studied parameters, while the second sub-section describes the results of the three-way associations.

6.1.6.1. Overview and methodology

Results are initially obtained for 95%, then 99% confidence level. For each combination of three variables from Table 6.1.6, the following steps have been employed:

- Recode the columns into binary variables.
- Construct a contingency table.
- Perform a Chi-Square test.
- Compute the p-value.
- Compute the strength of the association (using phi-value).

Permutations of the parameters in Table 6.1-E have been used to test for three-way associations. These have been recoded and converted into binary variables, as shown below in Table 6.1-E, to help understand the meaning of the associations. Table 6.1-E is based on Figure 6.1-D (in Section 6.1.2.4) which outlined the factors (parameters) studied in this thesis. In some cases, such as for the “Time” parameter which had many possible outcomes, these were grouped to reflect the part of the day (day-time and night-time), and therefore have only 2 possible outcomes that are more suitable for the

analysis. This is represented as "*Reason 1*" in the table. In other cases, such as for the "Vessel type" parameter, some possible outcomes were grouped into a "Other" binary variable, so that the focus can be on the other vessel categories which were deemed of interest during the trend and contingency analyses. This was done in general for the least frequent outcomes, to avoid parameters with a low expected count, as those would not provide accurate results. This is represented as "*Reason 2*" in the table.

Table 6.1-E. Parameters used to test for three-way associations, for SC.

Parameter	Binary variables	Count	Description / Reasoning
Season	Winter	878	Grouped according to the four seasons. Reason 1.
	Spring	910	
	Summer	1,060	
	Autumn	895	
Vessel type	Cargo vessel	1,638	Changes according to Table 6.1.3 in Section 6.1.3. Reason 1.
	Fishing vessel	215	
	Passenger vessel	536	
	Recreational vessel	415	
	Service ship	926	
	Military vessel	6	
Vessel size	Small (<8m)	135	Grouped in three categories. Reason 1.
	Medium (8m-40m)	1,084	
	Large (>40m)	2,340	
Year	2013 - 2017	1,812	Separated the years into 2 groups of equal number of years. Reason 1.
	2018 - 2022	1,931	
Severity	Very serious	45	Unchanged
	Serious	195	
	Less serious	1,620	
	Marine incident	1,883	
Accident type	Contact	902	Categories grouped into the "Other" category: "Capsizing/Listing", "Floating object", "Flooding/Foundering", "Hull failure" and "Non-accidental event". Reason 2.
	Collision	790	
	Damage / loss of equipment	726	
	Loss of control	540	
	Grounding/ Stranding	392	
	Fire/Explosion	234	
	Other Accident type	144	
Location	England	2,748	Unchanged
	Northern Ireland	117	
	Scotland	522	
	Wales	314	
Natural light	Daylight	1,950	Unchanged
	Night	962	
	Twilight	162	
Sea state	Calm/Smooth	1,442	Grouped in three categories. Reason 1.
	Slight/Moderate	778	

	Rough to Very high	76	
Visibility	Good/Very good	2,067	Grouped in three categories. Reason 1.
	Moderate	205	
	Poor/Very poor	89	
Wind force	No/Light wind	1,222	Grouped in three categories. Beauford scale groups: 0-3, 4-7, 8-12. Reason 1.
	Moderate wind	1,061	
	High wind	125	
Flag	UK	1,923	Unchanged
	Non-UK	1,812	
Year of build	Very old (<1980)	256	Grouped in three categories. Reason 1.
	Old (1980-2000)	1,036	
	New (>2000)	1,829	
Hull material	Steel	2,855	Grouped in two categories as "Steel" represents the majority (76.3%). Reason 2.
	Other	720	

6.1.6.2. Results of the three-way associations

The results of the three-way association analysis are presented in Appendix I, and the main findings are discussed in this section. In Figure 6.1-M, the three-way associations with 95% confidence level for ship casualties are plotted according to their p and phi values. Figure 6.1-N represents a heatmap of the relevant associations with 99% confidence level. The blue shades indicate moderate relationships, while the red shades indicate strong relationships.

Figure 6.1-M. Three-way associations with 95% confidence level for ship casualties according to their p and phi values.

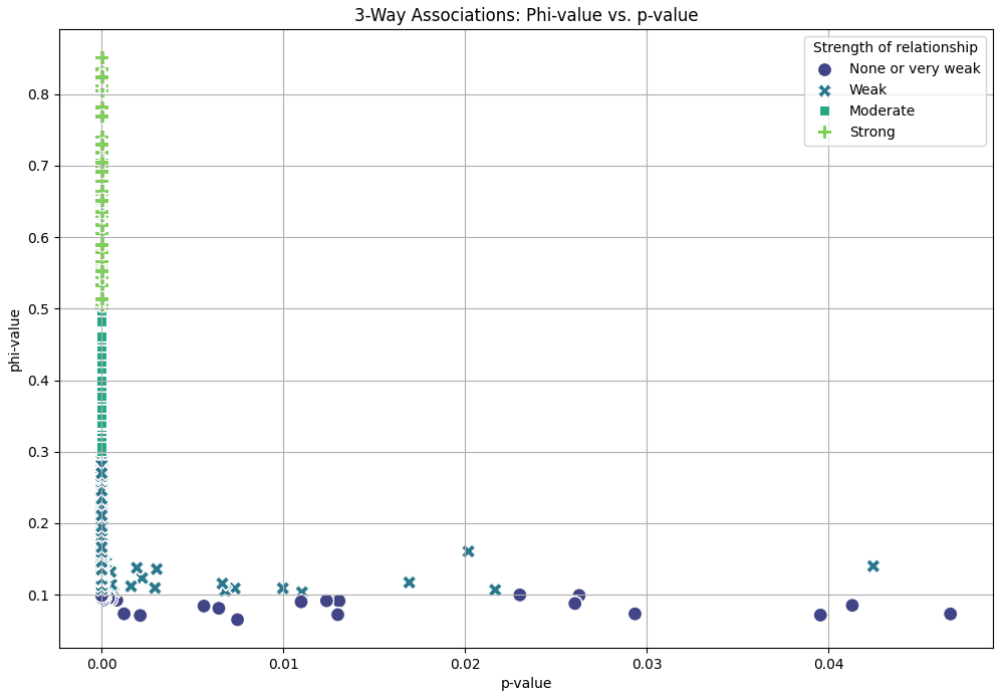
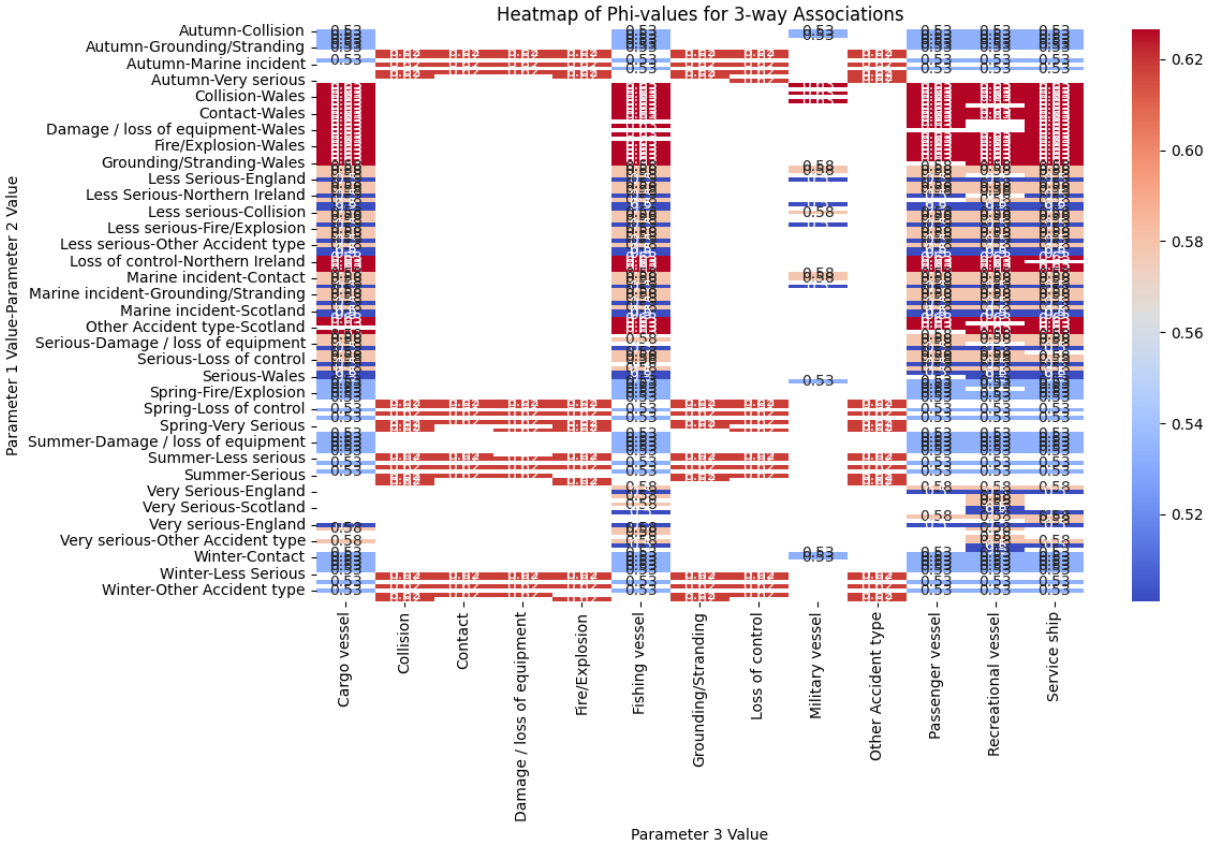


Figure 6.1-N. Heatmap of the three-way associations with 99% confidence level, for ship casualties.



Some findings that are similar to the findings already presented in the previous section are excluded. Moreover, the associations where one of the parameters was marine incident or military vessel were excluded, as it was previously determined that the data is unreliable for them. The “other” parameters were also excluded as they are irrelevant (e.g., “Other Accident type”). Taking these into account, the main findings for strong relationships with a 99% confidence level are explained below, and are grouped according to severity, location, accident and vessel types, season and environmental conditions.

For serious accidents, the data reveals strong associations across a variety of accident types and vessel types. For instance, collisions involving recreational vessels, service ships or passenger vessels exhibit strong associations with serious accidents, as indicated by consistent p-values close to zero and a phi-value over 0.5. Similarly, contacts involving recreational vessels, service ships, fishing vessels, and cargo vessels also show strong associations with serious incidents. This pattern extends to other accident types such as fire/explosion and loss of control, which are strongly associated with other vessel types like fishing vessels and passenger vessels.

Less serious occurrences follow a similar pattern, with strong associations observed for contacts involving fishing vessels and collisions involving recreational vessels. Additionally, occurrences involving damage or loss of equipment and fire or explosion show strong associations with service ships and fishing vessels, respectively. In England, less serious occurrences are strongly associated with recreational vessels, service ships, fishing vessels, passenger vessels. In Wales, there are strong relationships between less serious incidents and service ships, fishing vessels, passenger vessels, cargo vessels, and recreational vessels.

Very serious accidents demonstrate robust associations with different combinations of accident types and vessel types. For instance, collisions involving recreational vessels and service ships are strongly linked to very serious outcomes. Additionally, occurrences involving damage or loss of equipment and fire or explosion show strong associations with service ships and fishing vessels, respectively.

Geographically, specific vessel types display strong associations with accidents in different regions of the UK: England, Scotland, Northern Ireland, and Wales. For example, grounding/stranding incidents involving recreational vessels have a strong association with Wales, while loss of control incidents involving various vessel types show strong associations with regions like Scotland and Northern Ireland. These geographic trends are consistent across different types of accidents and vessel types, highlighting regional variations in maritime incidence patterns. In England, serious accidents involving recreational vessels have shown a strong relationship, as have service ships, fishing vessels, passenger vessels, and cargo vessels. Similarly, in Wales, serious accidents involving recreational and fishing vessels have been strongly associated. Northern Ireland demonstrates a strong relationship between serious accidents and recreational vessels, passenger vessels, and cargo vessels.

Accident types also vary by vessel size and weather conditions. Calm/smooth sea state is strongly associated with occurrences involving medium-sized service ships. Rough to very high sea state conditions show a strong relationship with large recreational vessels, medium-sized service ships and medium-sized fishing vessels. Slight/moderate sea state, on the other hand, is strongly linked to medium and large passenger vessels, as well as medium and large cargo vessels.

Wind conditions further influence accident and incident patterns. Moderate wind conditions show a strong association with medium and large fishing vessels, medium and large passenger vessels and medium and large cargo vessels. High wind conditions are strongly linked to medium-sized recreational vessels and medium and large passenger vessels.

Seasonality also plays a role in the occurrence of accidents and incidents. During summer, grounding/stranding incidents involving recreational vessels have shown a strong relationship.

Similarly, damage/loss of equipment incidents involving recreational vessels and service ships are strongly associated with the summer season. Contact incidents involving fishing vessels, passenger vessels and cargo vessels also show a strong relationship with the summer season. Fire/explosion incidents are strongly associated with summer, particularly involving recreational vessels, service ships, fishing vessels, passenger vessels, and cargo vessels.

In conclusion, these findings highlight the significant associations between various types of vessels, severity, accident type, season, and geographical and environmental conditions. The strong relationships observed suggest specific patterns and risk factors that can inform safety measures and prevention strategies in maritime operations. For example, the geographic associations underscore the need for region-specific safety measures. Therefore, these findings can inform targeted safety interventions and policy decisions to enhance maritime safety across different regions and vessel types. While, so far, a reactive approach to analysing maritime occurrences in the UK has been adopted, the following section adopts a predictive approach and adds value to the mixed methods approach employed in this thesis.

6.1.7. Logistic regression

This section aims to further analyse the data using discrete choice models, to predict behaviours by observing previous decision makers' decisions. This is achieved through five sub-sections which address the following: description of the methodology, initial statistical results using additional databases (AIS and RNLI), model development for logistic regression, reasons for integrating multiple data sources and discussion of the main results. A paper including this analysis has been accepted with minor revisions and is expected to be published in 2024 (Majumdar, Manole and Garcia Sinobas, 2024).

6.1.7.1. Overview and methodology

A binary logit model (or logistic regression) is used to predict accident occurrences based on different variables. The vessel density will be found with AIS data, which provides the date and time at which a specific vessel type made a movement. The MAIB SC database is used for accident data, and it excludes marine incidents. In using a binary logit model, the error components are assumed to be identically and independently distributed according to a Weibull distribution. Also, accident occurrence is considered deterministic (i.e., the accidents occur or do not occur), and the data fields are assumed to be representative of reality after performing the data cleaning. The current model and the already mentioned paper (Majumdar, Manole and Garcia Sinobas, 2024) used AIS data from 2015, 2016 and

2017 and accident data from 2013 to 2019 to represent the population of vessel movements and accidents, respectively. It has been assumed that vessel movements are similar throughout the years.

The different variables under consideration for accident causation are: seasonality, type of vessel, vessel length and visibility (day-time (7h to 22h) or night-time (22h to 7h)). Seasonality and visibility can be inferred from the date and time present in both databases. The vessel categories from both databases have been redefined in Section 6.1.3. Finally, vessel length is a continuous variable given in both datasets which is converted into three different categories (small (<8m), medium (8-40m), large (40m+)). The variables in the model will have a value of 0 or 1, depending on whether an accident had such variable characteristics (value of 1) or not (value of 0). The model categorisation and the presence of the variables in each of the databases has been represented in Table 6.1-F.

Table 6.1-F. AIS and MAIB samples and variables used.

Model Categorisation		AIS data		MAIB data	
Category	Variable / Name in model	Amount	% of Category	Amount	% of Category
Season	Winter / Season1	1,407,239	15.9%	482	25.6%
	Spring / Season2	2,258,546	25.5%	480	25.5%
	Summer / Season3	3,023,345	34.1%	515	27.3%
	Autumn / Season4	2,169.077	24.5%	406	21.6%
Time	Night-time	3,847,228	43.1%	779	42.1%
	Day-time	5,078,965	56.9%	1073	57.9%
Vessel Type	Cargo Vessels / Type1	3,229,379	45.0%	584	31.1%
	Fishing Vessels / Type2	1,436,074	20.0%	138	7.3%
	Passenger Vessels / Type3	1,132,631	15.8%	462	24.6%
	Recreational Vessels / Type4	417,481	5.8%	177	9.4%
	Service Ships / Type5	880,478	12.3%	515	27.4%
	Military Vessels / Type6	75,838	1.1%	3	0.2%
Vessel Size	Small (1m-8m) / Size1	608,480	6.8%	114	6.2%
	Medium (8m-40m) / Size2	3,173,519	35.6%	592	31.9%
	Large (40m+) / Size3	5,144,219	57.6%	1147	61.9%

Two models are analysed. Model I will consider all vessel types, while Model II will only consider the vessel types best captured by MAIB's and AIS' databases, which are vessel types 1, 3 and 5 from Table 6.1-B in Section 6.1.3 (Cargo, Passenger and Service ships, respectively). Table 6.1-G shows the sample sizes and number of parameters estimated for each model.

Table 6.1-G. Binary Logit Models performed.

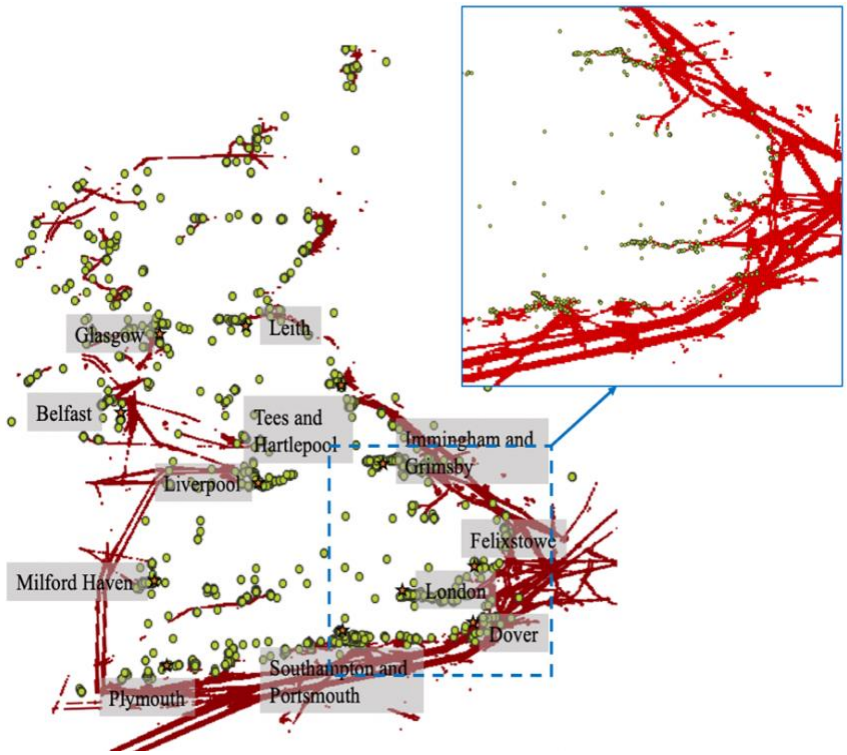
	Model I	Model II
AIS sample (2015-2017)	8,923,339	6,994,391
Accident sample (2013-2019)	1883	1561
Number of variables used	12	9

6.1.7.2. Initial statistical results

This section provides trend and contingency analysis using AIS data, to understand its capabilities and why this data source has been integrated with the MAIB.

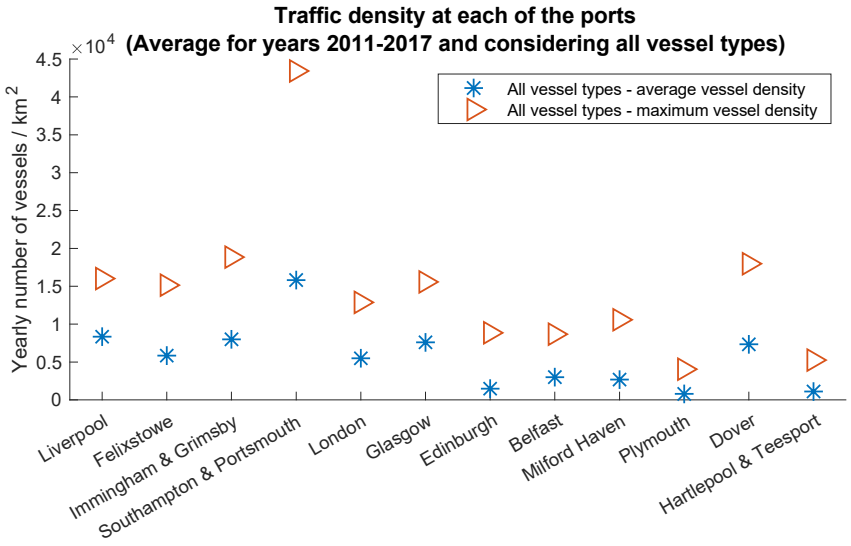
Figure 6 reveals that the highest traffic densities are located along the coast and in the English Channel. Red-coloured grids in the figure represent traffic densities exceeding 600 vessels per square kilometre annually, with each dot indicating an accident. Predictably, the majority of accidents occur in ports and areas with the highest traffic densities, particularly in the South-East region of the UK. Despite this, the densely trafficked English Channel does not experience a correspondingly high number of accidents. This suggests that traffic density significantly impacts accident occurrences mainly in spatially constrained locations such as ports. These insights are corroborated by analyses of MAIB and AIS data, with Figure 6.1-O serving an illustrative purpose.

Figure 6.1-O. Traffic densest areas in the UK and all maritime accidents (Manole, Majumdar and Garcia Sinobas).



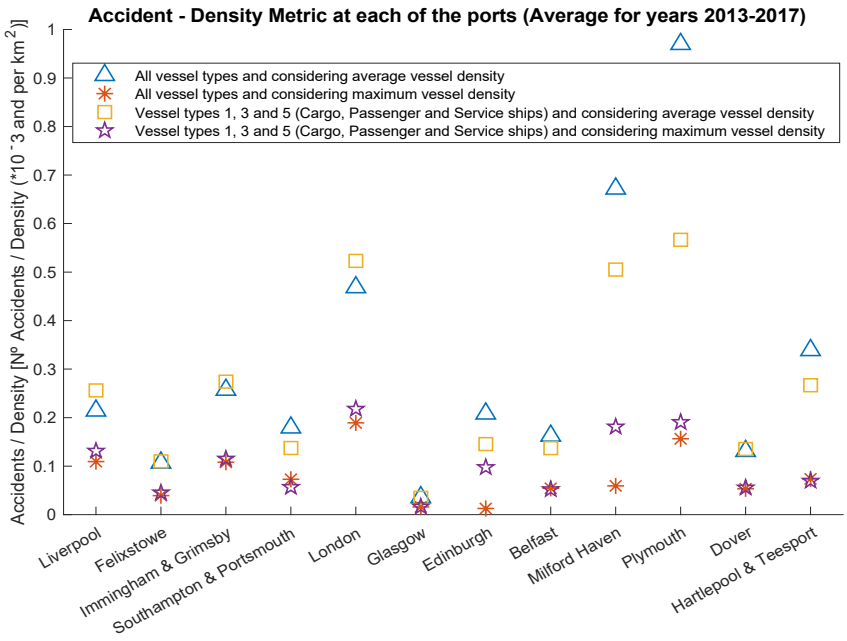
For the ports represented in Figure 6.1-O (with highest traffic densities), Figure 6.1-P indicates their average vessel densities between 2013 and 2017 using the AIS data, highlighting a clear direct relationship between each port's traffic density and number of accidents.

Figure 6.1-P. Vessel Traffic Densities in the 12 UK ports considered (Manole, Majumdar and Garcia Sinobas).



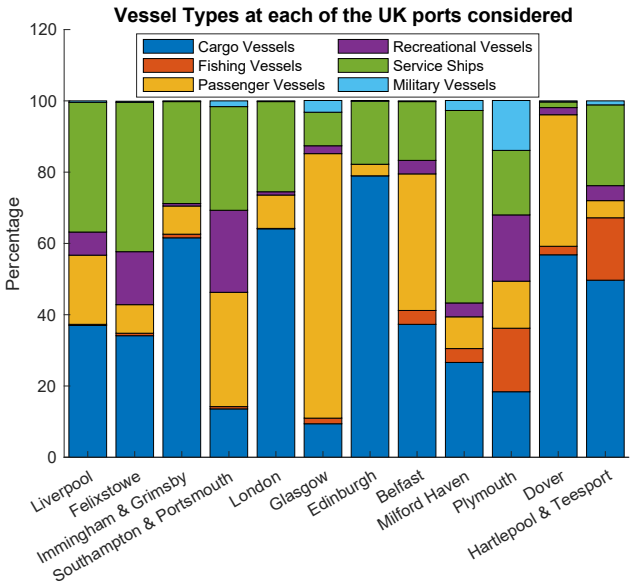
To further elucidate the impact of traffic density on accident rates, Figure 6.1-Q presents the accident-to-traffic density metrics. For all vessel types, Plymouth, London and Milford Haven exhibit the highest accident rates when average vessel densities in ports are considered. However, when maximum densities are taken into account, Milford Haven no longer falls into this category, suggesting that it has very localised high-traffic areas. A similar pattern is observed in the port of Edinburgh, where the accident-to-density metric approaches zero when maximum vessel density is considered, as indicated by the red stars in Figure 9. Conversely, the ports of Felixstowe, Glasgow and Dover demonstrate the safest metrics. Analysis of specific vessel types (cargo, passenger, and service ships) reveals substantial variations in accident-to-density relationships, particularly in ports with a high prevalence of fishing, recreational and/or military vessels, such as Plymouth.

Figure 6.1-Q. Accident to Traffic density metrics for the 12 UK ports considered (Manole, Majumdar and Garcia Sinobas).



Comparison of each port's accident-to-density metric with its traffic density reveals no clear relationship, indicating that a higher traffic density does not necessarily correlate with a higher accident rate. The types of vessels arriving and departing from the twelve ports under consideration are illustrated in Figure 6.1-R. Ports with the highest accident-to-density metrics predominantly accommodate cargo and service vessels, whereas Plymouth has a significant proportion of military vessels. In contrast, ports with a higher proportion of passenger vessels tend to be safer.

Figure 6.1-R. Vessel Traffic in the 12 UK ports considered (Manole, Majumdar and Garcia Sinobas).



Trend and contingency analyses, as well as three-way associations have already been used in previous sections of this chapter to identify those factors most likely to result in adverse outcomes. It should be noted that this section examines an accident database rather than the entire vessel population. Consequently, the statistical figures obtained do not necessarily indicate causation. For example, if one-third of all accidents occur under sunny/clear conditions and 95% of all vessel movements take place under these conditions, it implies that movements under other weather conditions can potentially be more hazardous. Such aspects are addressed in Section 6.1.8. The findings from this section, as well as from the reactive methods of analysis already employed, are used to develop a robust logistic regression model in the next section.

6.1.7.3. Development of the model

The deterministic utility functions used to predict accident occurrence in Model I are shown below. As expected, Model II will exclude the respective variables and parameters for vessel types 2, 4 and 6 (fishing, recreational and military vessels respectively). βs are the attributes which represent the sensitivity of its corresponding variable with respect to the variable of the dimension which is not being considered. ASC_{acc} represents the Alternative Specific Constant.

$$V(accident) = ASC_{acc} + \beta_{Season1} \times Season1 + \beta_{Season2} \times Season2 + \beta_{Season3} \times Season3 + \beta_{Nighttime} \times Nighttime + \beta_{Type1} \times Type1 + \beta_{Type2} \times Type2 + \beta_{Type3} \times Type3 + \beta_{Type4} \times Type4 + \beta_{Type5} \times Type5 + \beta_{Type6} \times Type6 + \beta_{Size1} \times Size1 + \beta_{Size2} \times Size2 \quad (7)$$

$$V(No\ accident) = 0 \quad (8)$$

Maximum likelihood estimation has been used to find the attributes by running the model in Biogeme software. The goodness of fit must be checked. A corrected version of McFadden's log likelihood goodness of fit method which considers the impact of the number of degrees of freedom will be calculated. The formula used is:

$$\bar{\rho}^2 = 1 - \frac{LogL(\beta) - k}{LogL(0)} \quad (9)$$

Where k represents the number of parameters estimated in the model (or the number of degrees of freedom in the model). A value close to 1 will prove a high accuracy of the model. Attributes' accuracy will also be checked with the t-test, by testing the hypothesis that the value obtained is significantly different from 0. As the number of observations is around 7 million, the t-values found must be larger than 1.96 to have at least 95% confidence on each attribute.

Finally, the probabilities will be calculated for accident occurrence under the different season, vessel size, time of the day and vessel type variables, after substituting the respective variable values (1 for yes, 0 for no) in the deterministic functions:

$$P(accident) = \frac{e^{V(accident)}}{e^{V(accident)} + e^{V(No\ accident)}}$$	(10)

6.1.7.4. Impact of Traffic Density on Accident Causation

As previously mentioned, AIS data allows an accurate representation of traffic vessel density within UK territorial waters. Traffic density and accidents will be related for UK's 12 largest ports. These ports were chosen according to different metrics, such as the traffic density or accident rate metrics calculated with AIS and MAIB data in multiple UK ports, or the ones shared by UK's Department for Transport which include the tonnage handled or the vessel arrivals per port. These 12 ports are: Leith, Glasgow, Belfast, Liverpool, Milford Haven, Plymouth, Southampton & Portsmouth, Dover, London, Felixstowe, Immingham & Grimsby, and Tees & Hartlepool. These have previously been shown in Figure 6 in Section 6.1.5.2.

The direct relationship between traffic density and accidents was studied in these twelve ports, where traffic densities were calculated. Firstly, the location of the centre of the port in the coast was found. Then, over 240,000 2km^2 grid cells which cover UK waters were modelled and given their respective coordinates. AIS grid cell locations were different for different years, so alternative approaches have been taken to locate the grid cells. Once all cells were located, the individual analysis for each of the ports was completed as follows.

i. Two different types of traffic vessel densities have been calculated in each of the ports: the maximum vessel density of the port, which considers the port's 5 grid cells with the highest traffic density; and the average traffic vessel density of the port, which considers all of the transited grid cells around the port. Using the same model which finds the limiting coordinates of the 450km^2 around the port's centre, the number of accidents were calculated for each of the years between 2013 and 2017 using the MAIB's database.
ii. For each port, an area of 450km^2 around the centre of the port was considered. The 2km^2 grid cells surrounding the port were identified with their respective annual traffic densities. Since it was desired to calculate traffic densities in UK ports and their immediate vicinity, the 2x2km^2 spatial resolution does not affect the results as no 2 ports that have been studied are that close to each other to have duplicate inputs. Selecting such a large area has enabled high risk locations,

capturing interactions between vessels entering or exiting the port. The grid cells where the traffic density is 0 or close to 0, representing land or inaccessible locations, have been removed. For the Port of London, to account for its larger dimensions, a much greater area of around 95 kilometres along River Thames, which congregated all port locations that are part of the Port of London, was chosen.

Then, for each year, the ratio of accidents to traffic density was calculated in each port:

$$Accident - Density\ metric = \frac{Total\ number\ of\ accidents\ in\ that\ year}{Yearly\ traffic\ density\ \ (Maximum\ or\ Average)} \quad (11)$$

Having calculated each year's metric, the average was determined for comparative purposes across the 12 ports. To achieve greater confidence in the results, the current metrics were first calculated for all vessel types, and then for only cargo, passenger and service ships, which are best represented by the used databases. Each of the grid cells also contained the average weekly traffic density for each vessel type, enabling the average weekly densities for each vessel type at each port to be calculated. These densities will provide an understanding of the main vessel types transiting in the ports, and subsequently, the main operations at each port.

6.1.7.5. Results

This section summarises the results of the logistic regression method of analysis. The attribute values and their corresponding p-values have been found for each of the models, and are presented in Table 6.1-H.

Table 6.1-H. Attributes found after maximum likelihood estimation.

	Model I			**Model II**		
Parameter	Value	t-value	p-value	Value	t-value	p-value
$\mathrm{ASC_{acc}}$	8.86	146.72	0	8.8	139.51	0
β_{Season1}	-0.759	-12.18	0	-0.788	-11.75	0
β_{Season2}	-0.149	-2.38	0.02	-0.167	-2.43	0.02
β_{Season3}	0.193	3.09	0	0.138	2.02	0.04
β_{Size1}	0.364	3.73	0	1.82	7.99	0
β_{Size2}	0.603	10.69	0	0.645	10.46	0
β_{type2}	-0.0714	-0.74	0.46			
β_{type3}	-1.25	-21.72	0	-1.21	-21.17	0
β_{type4}	-1.77	-19.92	0			
β_{type5}	-1.85	-30.69	0	-1.87	-30.46	0
β_{type6}	1.17	2.03	0.04			
$\beta_{\mathrm{Night-time}}$	0.154	3.48	0	0.275	5.66	0

The attributes from the table above have been used to find the probabilities of an accident occurring. The lower the coefficient for each category, the higher the probability for an accident occurrence and vice versa. These were calculated with reference to one of the parameters in each category, for which the value is zero (Season4, Size3, Type1, Day-time). Season 1, Vessel Type 5 (service ships), Size 3 (largest vessel size group, > 40m) and transits during day-time represent in both models the lowest coefficients. It is important to note the low p-values (i.e. the high confidence of the attribute values) except for Vessel Type 2 (fishing vessels). Table 6.1-I highlights the accuracy of the model with the corrected goodness-of-fit parameter being around 0.4, which is considered strong for multinomial logit models.

Table 6.1-I. Accuracy of both models.

	Model I	**Model II**
$\mathrm{LogL}(\beta)$	-19,585.6	-16,193.1
$\mathrm{LogL}(0)$	-6,186,492.5	-4,849,224.4
$\bar{\rho}^2$	0.3968	0.3966

Using the parameter values from Table 6.1-I, the probabilities are calculated for different variables under consideration. For illustrative purposes, Table 6.1-J indicates those variables which give the highest and lowest accident probabilities for each model. All probability values observed must be multiplied times 10^{-4}. It is important to note that these values are not accident rates, as only AIS data from 3 years is used, and accident data for seven years is considered. Hence, the current data only serves for comparison purposes amongst the different variables.

Table 6.1-J. Accident probabilities for Model I.

Model I	**Season 1**				**Season 3**			
Ship type	**Small**		**Large**		**Small**		**Large**	
All values $*10^{-4}$	Night-time	Day-time	Night-time	Day-time	Night-time	Day-time	Night-time	Day-time
Cargo	1.8	2.1	2.6	3.0	0.7	0.8	1.0	1.2
Fishing	1.9	2.3	2.8	3.3	0.7	0.9	1.1	1.3
Passenger	6.3	7.3	9.1	10.6	2.4	2.8	3.5	4.1
Recreational	10.6	12.4	15.2	17.8	4.1	4.8	5.9	6.9
Service	11.5	13.4	16.5	19.2	4.4	5.2	6.4	7.4
Military	0.6	0.7	0.8	0.9	0.2	0.3	0.3	0.4

The results of Model I show that large service ships during day-time and Season 1, have a 27 times greater probability for an accident occurring, than a cargo vessel during night-time in Season 3. The other probabilities can be compared accordingly for the different variables. It is important to note the

limitations of the data used: smaller vessels are underrepresented by AIS data, and fishing, recreational and military vessels are largely underreported in accidents.

As explained in the methodology (Section 6.1.7.1), to avoid the vessel type related inconsistencies, Model II has been created, where only Cargo, Passenger and Service ships are analysed. Although small vessels have been considered in Model II's analysis, the comparison is performed between medium and large vessels only, which are best represented by AIS data, see Table 6.1-K.

Table 6.1-K. Accident probabilities for Model II.

Model II	**Season 1**				**Season 4**			
	Medium		**Large**		**Medium**		**Large**	
All values $*10^{-4}$	Night-time	Day-time	Night-time	Day-time	Night-time	Day-time	Night-time	Day-time
Cargo Vessels	1.32	1.74	2.52	3.3	0.60	0.79	1.14	1.5
Passenger Vessels	4.43	5.83	8.44	11.1	2.01	2.65	3.84	5.1
Service Ships	8.56	11.27	16.31	21.5	3.90	5.13	7.42	9.8

Under the current model, the comparison between large service ships during daytime and season 1, and medium cargo vessels during night-time and season 4, show a more than quadruple risk of an accident occurring in the former scenario. The remaining values can be compared for illustrative purposes. These tables indicate that day-time movements, during the winter season, for larger sized vessels, and specially, the vessel category of service ships, largely increase accident occurrence.

Even though AIS offers several advantages in providing far greater resolution and details of vessel movements, significant limitations have been highlighted through the literature (Iphar, Ray, & Napoli, 2020; Yang et al., 2019). These include limitations of:

i. reception range and coverage between vessels and terrestrial receiving stations or message collision in busy areas such as the North Sea.
ii. transmitted data can be false, with one study finding that 8% of AIS transmissions contained some form of error, including vessel identity, length, position, type or draught (Harati-Mokhtari et al., 2007).

6.1.7.6. Conclusions of the implementation of the logistic regression model

Section 6.1.7 proved that logistic regression is a powerful tool for binary classification problems, providing interpretable results regarding the influence of predictor variables on the probability of an outcome. It quantified the relationships between independent variables (such as environmental conditions or vessel characteristics) and the likelihood of maritime occurrences. However, the impact

of certain factors such as those related to port characteristics on accident causation could not be obtained. Hence, this topic will be part of the qualitative study presented in Section 6.1.9, which uses the experience of industry professionals to answer questions the analysed data could not.

This model of analysis used reports of safety occurrences at UK ports to determine both the capabilities of reports for historical safety analysis and the prominent features of the accidents at the ports. Adding dynamic movement data such as AIS has advantages which have already been described, but also computational and representation challenges. Given the low frequency of accident occurrence, additional years of AIS data would be required for more accurate results, which are costly to obtain and challenging to handle.

The following section provides additional methods of analysis for an even deeper dive into factors underlying maritime safety.

6.1.8. The use of other analytical tools, focusing on Bayesian and Complex Networks

While logistic regression offered valuable insights in the previous section, it assumed that the factors were independent and directly influenced the outcome. Bayesian networks, on the other hand, allow for the modelling of more complex dependencies among variables. By transitioning to Bayesian networks, conditional dependencies between multiple factors can be incorporated and analysed, which were treated independently by logistic regression. This shift adds value towards achieving a holistic understanding of the maritime safety system.

Bayesian Networks (BN) and Complex Networks (CN) are more powerful analytical tools used to model and understand intricate systems, which are employed in this section to complement the other more traditional methods of safety data analysis used in the previous sections of this chapter. BN focus on probabilistic relationships and dependencies, while CN emphasise the structure and dynamics of interconnected nodes. A paper which uses complex networks in the study of ship casualties has been accepted with minor reviews and it is attached in Appendix J (Yang et. al., 2024). The content of this paper is not duplicated in this section, so this section includes BN only.

This section is divided into three sub-sections, as the available literature on these methods of analysis has already been presented in Section 3.5.3. The first sub-section provides an overview of BN to help understand this method. In the second sub-section, the results of the application of BN for analysing port accidents and incidents will be discussed. Finally, the limitations of BN will be addressed.

6.1.8.1. Overview of Bayesian Networks and proposed methodology

This sub-section provides an overview of Bayesian Networks and the methodology used to employ this method of analysis using the MAIB data of maritime occurrences that has been used in the previous methods of analysis.

A Bayesian Network is a powerful method for data processing and analysis that helps reveal causal relationships between different factors. This model is built by maintaining known conditional probabilities between random variables, which have been determined in the previous sections. The use of directed edges in a graph model allows the Bayesian Network to explicitly reflect these known conditional dependencies and to establish conditional independencies for all unknown connections within the model.

The structure of a Bayesian Network includes nodes representing factors, with links showing the causal relationships between these factors (Hu, 2019). Nodes are categorised into parent nodes and child nodes. Child nodes serve as sub-nodes of parent nodes which can be analogised as the relationship between wind force and weather. BN can illustrate the dependency relationships between factors through directed arcs and probability distributions in a graph. Furthermore, the conditional probability table (CPT) quantitatively defines the relationships based on probability dependencies within individual factors and parent nodes, ensuring coherence among all nodes.

Therefore, the initial step in developing the Bayesian Networks involves defining the graphical representation of the nodes. This graphical model, known as a probability influencing diagram, visually depicts the relationships between various factors represented as nodes (Pearl, 1985). As previously mentioned, the structure of this diagram uses the results of the previous methods used to determine associations between different factors using historical data (e.g., conditional probability of a certain vessel type being involved in an occurrence). Approximations based on other findings of the literature or discussions with industry professionals can also be included, to mitigate against the limitations of data analysis (Korb & Nicholson, 2010). This diagram is pivotal in modelling decision-making processes and assessing the utilities associated with different factors (Jensen & Nielsen, 2007). Each utility node within the diagram has an assigned utility function that quantifies its value. By establishing these utility functions and the associated decisions, one can compute the expected utility for each decision (Neapolitan, 2003). Following the principle of maximum expected utility, the decision that yields the highest expected utility is ultimately selected (Russell & Norvig, 2010). This method ensures a systematic approach to decision-making by leveraging probabilistic relationships and utility evaluations.

Once the structure and parameters of the BN are identified from the dataset, the network can infer relationships and make predictions. This involves updating the probabilities of various nodes based on new evidence, thus dynamically adjusting to reflect the latest information. The following equations are used or the joint probability, marginalisation rule and Bayesian rule:

i. The joint probability:

$$P(Y = y_i, X = x_{ij}) = P(X = x_{ij}) * P(Y = y_i, X = x_{ij}) \quad (12)$$

ii. The marginalisation rule:

$$P(Y = y_i) = \sum_j^n P(X = x_{ij}) * P(Y = y_i | X = x_{ij}) \quad (13)$$

iii. The Bayesian rule:

$$P(X = x_{ij} | Y = y_i) = \frac{P(X = x_{ij}) * P(Y = y_i | X = x_{ij})}{P(Y = y_i)} \quad (14)$$

The binary logistic regression calculated in the previous section has provided the coefficients β_n, while the conditional probability in Equation 12 can be calculated using the probability formula in the previous section on logistic regression. Finally, the sensitivity analysis is modelled to validate the results, separately for each factor.

Since this methodology builds upon the previous ones, all the factors (data fields) used for the logistic regression, three-way associations and contingency analysis are included in the BN model. The following section discusses the main results after employing the methodology presented in this section for factors included in the CS MAIB dataset presented in Table 6.1.2.1. The categories of mechanical errors, human errors and port characteristics were excluded because of their large underreporting which have been discussed in the data quality assessment of this dataset in Section 6.1.4.

6.1.8.2. Results and discussion of the main findings

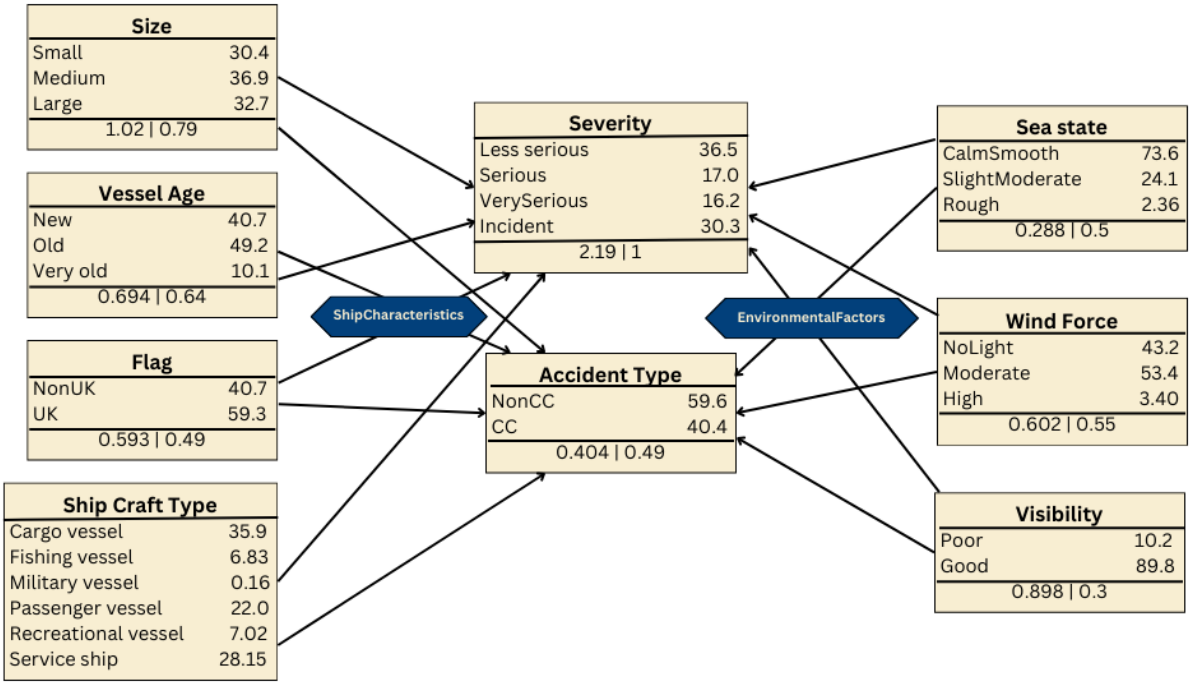
This section summarises the results of the BN model described in the last section. A detailed analysis of the influencing factors that resulted in the two more common accident types, collisions and contacts, are presented in Appendix K. The reason for including only these two types of accidents is that they represent just under half of the occurrences (according to the findings in Section 6.1.5.2), and provide a sufficient number of entries to ensure the accuracy of the model. Additionally, due to the nature of these types of occurrences, their risk influencing factors are consistent.

As previously mentioned, this method uses the findings from the previous sections on associated factors. Based on those and the level of completeness of these factors for contacts and collisions, the

data fields selected for the BN model are: date, accident type, severity, flag, vessel factors (type, age, size), environmental factors (wind force, sea state, visibility). The other factors were not deemed significant enough for this analysis, with little impact on the severity of maritime occurrences, and the addressed accident types.

Having identified these factors, for each configuration of decision options based on the results for associations between factors, the previously mentioned CPT and utility table are established. These determine the resulting state in the Bayesian Network model and necessitate that the probability values are non-zero and the combined value for each parameter equals 100% (Li et. al., 2014). These probabilities are called prior probabilities and are presented in Appendix K and are based on Table 6.1.6 in Section 6.1.6 about the parameters and binary variables used for three-way associations. Figure 6.1-S summarises the prior probabilities of these variables. Netica software is used for the BN model as it normalises the data after receiving input from both these tables automatically.

Figure 6.1-S. Prior probabilities of the variables considered.



The effects of each of the parameters (e.g. vessel type, vessel size, etc.) have been studied separately and are detailed in Appendix K, while the main findings are summarised in Table 6.1-L. The bolded text indicates that there is a higher occurrence probability of contact/collision and serious casualty for those variables.

Table 6.1-L. Main results for all variables, highlighting the highest increases in the posterior probability compared to the prior probability (in bold).

Parameter	Variables	Prior probability	Posterior probability: Accident type	Change rate: Collision/ contact	Posterior probability: Severity	Change rate: Very serious accidents
Vessel size	Small (<8m)	30.4%	39.5	-0.0223	14.1	**0.160494**
	Medium (8m-40m)	36.9%	42.2	**0.0446**	18.8	-0.12963
	Large (>40m)	32.7%	39.3	-0.0272	16.2	0
Sea state	Calm/Smooth	73.6%	38.8	-0.0396	15.2	-0.06173
	Slight/Moderate	24.1%	44.6	0.1040	18.6	0.148148
	Rough to Very high	2.36%	49.5	**0.2252**	24	**0.481481**
Visibility	Good	89.8%	39.7	-0.0173	15.6	-0.03704
	Poor	10.2%	46.8	0.1584	22.1	**0.364198**
Wind force	No/Light wind	43.2%	38.2	-0.0545	16	-0.01235
	Moderate wind	53.4%	41.6	0.0297	15.9	-0.01852
	High wind	3.4%	50.6	**0.2525**	25.8	**0.592593**
Flag	UK	59.3%	37.4	-0.0743	15.3	-0.05556
	Non-UK	40.7%	44.8	**0.1089**	17.6	**0.08642**
Year of build / Vessel age	Very old (<1980)	10.1%	44.2	**0.0941**	20.4	**0.259259**
	Old (1980-2000)	49.2%	38.5	-0.0470	15.1	-0.0679
	New (>2000)	40.7%	41.8	0.0347	16.6	0.024691

Results for different parameters are explained in detail in Appendix K, while this section focuses on the main findings for the parameters in Table 6.1-L.

Summary of Results – Vessel size

The analysis concludes that vessel size impacts both the likelihood of collision / contact and the severity of these accidents. Larger vessels are more prone to collisions and contact due to their limited manoeuvrability, while smaller vessels are more likely to experience more severe accidents. This information is crucial for maritime safety management, as it highlights the need for size-specific safety measures and protocols.

Summary of Results – Sea state

The analysis confirms that adverse sea conditions escalate the risk and severity of maritime accidents. This finding underscores the necessity for implementing stringent weather-related safety management measures and regulations to mitigate risks in severe sea states.

Summary of Results – Visibility

Visibility is found to be a critical factor in maritime safety, influencing the likelihood of contact and collision accidents. Poor visibility conditions, such as fog, haze, snow and storms, reduce a pilot's visual range, complicating the identification of landmarks and sea objects. This impairment increases accident probability, as evident from the BN analysis showing that improving visibility conditions can markedly decrease the occurrence probability of contacts and collisions, with a 15.17% change rate, and serious accidents with a 26.46% change rate. Additionally, the likelihood of very serious accidents decreases from 22.1% to 15.6% as visibility improves.

Summary of Results – Wind force

Strong winds significantly impact ship manoeuvrability and collision avoidance, particularly due to the large wind area affecting berthing safety. As wind strength increases, the probability of contact and collision increases by 12.4%. The likelihood of very serious accidents increases by 7.8%, while the likelihood of marine incidents slightly decreases by 4%. Intuitively, strong winds create challenging conditions for vessels, making them more prone to serious accidents caused by difficulty in maintaining control and avoiding obstacles.

Summary of Results – Flag

Non-UK vessels are found to be more likely to be involved in collisions or contacts, with more severe outcomes compared to UK vessels. This disparity can be attributed to the unfamiliarity of non-UK ships with UK port geometries, sailing regulations or weather conditions, making them more susceptible to an occurrence. This highlights the importance of familiarising international crews with local aspects of navigation and safety protocols.

Summary of Results – Vessel age

The analysis concludes that vessel age significantly impacts both the likelihood and severity of maritime accidents. Older vessels are more prone to severe accidents due to their deteriorating condition and lack of adequate maintenance. This highlights the importance of rigorous maintenance protocols and safety management systems, especially for aging vessels, to mitigate the risk of serious occurrences.

The following section provides a summary of the BN results.

6.1.8.3. Conclusions of the Bayesian Networks analysis

In this thesis, Bayesian Networks have been integrated with the findings from logistic regression and associations to assess the risks associated with maritime occurrences in UK ports. Establishing the relationships between variables and specifying the conditional probability distributions is essential for this method of analysis. This has been accomplished using the results from the previous methods of analysis employed in this case study (Sections 8.1.5, 6.1.6 and 6.1.7).

Table 6.1-M provides a summary of the main findings for each parameter included in the BN model.

Table 6.1-M. Summary of the main findings for each parameter included in the analysis using Bayesian Networks.

Category	Parameter	Main findings
Vessel-related parameters	**Vessel size**	Medium vessels are more likely to be involved in contacts / collisions. Small vessels are more likely to be involved in serious accidents.
	Vessel age	Older vessels are more likely to be involved in contacts / collisions and more severe occurrences.
	Flag	Non-UK vessels are more likely to be involved in contacts / collisions, as well as more serious occurrences when compared to UK-flagged vessels.
Environmental parameters	**Sea state**	Largest impact on severity, with highest change rate (57.89%). Worse sea state is more likely to result in contacts / collisions, as well as more severe accidents.
	Visibility	Good visibility lowers the likelihood of contact / collision, as well as accident severity.
	Wind force	Largest impact on contact/collision, with highest change rate (32.46%). Even larger impact on severity (48.13% change rate). The stronger the winds, the higher the likelihood of contact/collision, as well as serious accidents.

Strong winds can often be linked to extreme weather conditions (e.g., storms). In such conditions, it is intuitive that contact and collision are more likely to occur compared to other accident types, as these required precise human control of the vessel which can be weakened significantly by extreme weather. However, the impact of a vessel's age and size on the occurrence of a contact or collision is determined to be less significant, with the lowest change rates of prior probabilities.

Adverse sea state conditions have been found to have a higher probability of causing a more serious accident. This finding can be attributed to several factors. Firstly, high waves and strong currents make vessel navigation significantly more challenging, increasing the chances of instability and loss of control. In such conditions, the crew must constantly adapt to the unpredictable movements and forces of the sea, which can elevate the risk of accidents (Smith et al., 2019). Secondly, rough seas can impair visibility and reduce the effectiveness of navigational aids, complicating the detection and

avoidance of obstacles or other vessels (Jones, 2020). Thirdly, the increased physical demands and stress on the crew under these conditions can lead to fatigue and human error, further raising the probability of severe accidents (Brown & Lee, 2018). Therefore, adverse sea state conditions inherently create a more hazardous environment for maritime operations.

Similar to the other methods of analysis employed, the use of BN in this case study has associated limitations. The underreporting of less severe occurrences is, again, a significant limitation that decreases the accuracy of the analysis of the MAIB dataset. In addition to this, this method includes some subjectivity in the selection of parameters and variables. Hence, only some of the possible influencing factors are included in the analysis because of previously mentioned data limitations.

Overall, the environmental parameters seem to have a higher impact on the occurrence of contacts / collisions and more severe accidents than the vessel-related parameters. However, the latter have higher links to accident severity. These results prove the importance of setting up long-term mechanisms to effectively respond to bad weather, and bring awareness on these issues, how these can be avoided and what can be done in such emergency scenarios.

In conclusion, these results show that the tested parameters impact the occurrence probability of contact / collision and different levels of severity. These findings provide a deeper understanding of risk influencing parameters and their connections. It can be concluded that this model was successful as it built on previous assumptions of associations between parameter from the previous methods of analysis and further determined the variability in their degree of influence on contact / collision and severity.

6.1.9. Interviews with professionals from the maritime industry

The previous mixed-methods approach of analysing accident data and vessel movements is critical for improving safety and ensuring the prevention of future accident, by addressing the factors affecting past occurrences and their frequency, along with associations between different factors. However, highly valuable insight can be missed by such databases and analyses. There are gaps in the available data which have already been mentioned in this chapter and in the literature review in Chapter 3, especially related to the quality of accident databases, and the effect of human factors and port-related factors such as channel depth, width or complexity on port safety. Hence, further data is to be collected from industry professionals, not only to validate these results, but also to complement the insights from data analysis.

The following sub-sections present details of the participants, interview design and analysis of the responses.

6.1.9.1. Participants

Semi-structured interviews have been conducted with ten industry professionals, with the following qualifications:

- 2 x harbour master;
- 2 x safety managers;
- mariner;
- former mariner;
- director within the UK maritime sector;
- director within the European maritime sector;
- MAIB database admin;
- institutions researching maritime safety.

The participants have been chosen based on their qualifications, so that different stakeholders in the port industry could be reached. The interviews were informal and have not been recorded, however two participants decided to also respond to the questions via email. Moreover, the responses have been kept anonymously. Among the participants, there are 8 males and 2 females, and their ages range from 35 to 70.

6.1.9.2. Interview design

The topics used as a baseline for the interviews follow the uncertainties encountered during the previous analysis of the different databases. These topics are:

1. Personal details (age, gender and experience in the maritime industry).
2. Quality of the AIS, MAIB and RNLI databases.
3. Quality of local databases.
4. Opinion on the mixed methods of analysis used and validity of the results.
5. Expected effects of port related factors that could not be obtained from data sources on port safety (e.g., channel depth, width, complexity).
6. The importance of Safety Management Systems within ports to reduce accident rates.

To ensure the trustworthiness of the interview answers, the principles of credibility, dependability, transferability, and confirmability were applied (Bengtsson, 2016). Credibility guarantees that all reliable data is included, and dependability accounts for the differences in the opinions and answers of the interviewed participants. In addition, transferability assesses whether the responses can be

generalised to others in similar positions, while confirmability ensures the answers are objective and neutral. The interview findings are discussed in the following section.

6.1.9.3. Analysis of the interview responses

This section summarises the answers of the participants to the last five topics mentioned in the previous section. The personal details of the participants have already been summarised in the previous section. The results have been validated and, in fact, the introduction of the RNLI database in the analysis was after considering the suggestion of one of the participants.

The accuracy of the datasets have been confirmed by the industry professionals. Regarding the MAIB database, participants agreed that accident reporting is accurate and consistent only for specific vessel categories, such as UK merchant vessels over 100GT and other main vessel categories used for commercial purposes, but it less accurate for other vessel categories, including non-UK vessels, and UK military, recreational, and fishing vessels. It was noted that ports send reports to the MAIB annually or for accidents, but the marine incidents of this dataset are seen as underreported, which was also evident from the literature review. For example, one of the participants mentioned the MAIB's 2017 annual report which revealed that only 13.5% of the UK marine accidents and incidents were reported to the MAIB, compared to data from Scottish Boatowners (MAIB, 2018).

Apart from the highlighted underreporting of minor incidents and near misses, some participants brought up the internal database of ports, which can be ten times larger than what is reported to the MAIB. However, underreporting varies between ports, with some reporting more frequently than others. Therefore, the decision to remove marine incidents from the MAIB data for the previous analysis has been taken following these discussions.

Another decision previously made during the analysis based on the feedback from participants includes vessel types. Regarding the AIS data, the literature review already highlighted the limitations concerning the absence of AIS in many smaller recreational and fishing vessels. Industry professionals also indicated that AIS data would be inaccurate in areas with high recreational usage. Thus, the account of vessel types in the analysis has been filtered to account for the significant underreporting of occurrences involving recreational, fishing, and military vessels in the MAIB database, as well as the low AIS usage among smaller recreational and fishing vessels. This is why these vessel categories have been excluded from the analysis, and the vessel categories used for the logistic regression analysis are cargo, merchant, and service ships, to increase the accuracy and credibility of the results.

As previously discussed, industry professionals were also consulted about the impact of port-related factors on accidents, as this information was not available from the data. They emphasised the

importance of the channel's depth, traffic density and the port's protection from sea state or wind force. It has been mentioned that regular hydrographic surveys are believed to effectively manage these port-related factors. In addition, when asked about measures to reduce accident rates, participants focused more on addressing human factors rather than implementing regulations targeting the factors analysed in this thesis.

6.1.9.4. Conclusions of interviews with maritime safety professionals

In conclusion, the semi-structured interviews revealed that accurate analysis could be achieved by focusing on cargo, merchant, and service ships, excluding smaller recreational and fishing vessels due to their underreporting in the MAIB database, as well as their low AIS usage. Participants confirmed the accuracy and consistency of the MAIB database for specific vessel categories but highlighted underreporting of minor incidents and near misses. In addition, the participants emphasised human factors as crucial for reducing accident rates, over regulatory measures addressing port-related factors such as channel depth, traffic density, and protection from sea state or wind force.

6.1.10. Conclusions of the first case study

This section presented the analysis of port casualties and incidents in the United Kingdom, using mixed quantitative and qualitative methods of analysis in line with the methodology of this thesis previously described in Chapter 5. The mixed-methods approach employed in this section, combining accident, incident and vessel movement data analysis, is essential for enhancing maritime safety and preventing future incidents. This methodology addresses factors influencing past occurrences and their frequencies, alongside associations between various factors and predictive approaches to prevent future occurrences. For this, the datasets and their limitations have been defined, and data quality checks have been employed. However, it has been proven that valuable insights can be missed due to gaps in available data, as noted in this section and in Chapter 3. For example, such limitations include insufficient reporting of certain risk influencing factors, the most notable being human factors and port characteristics. These statistics would have been interesting, but impossible to achieve. To bridge these gaps, additional data from industry professionals has been obtained and analysed, both to validate existing results and to enrich the data analysis insights. Nonetheless, the achievable results of the analysis of factors underlying port safety have been explained and detailed.

This case study provided a critical advancement in the UK port industry, especially since, compared to the previous literature, this thesis represents the most recent analysis of such historical data, with the last study being conducted in 2004 (Darbra & Casal, 2004) with significantly less data and methods of analysis employed. Since then, the understanding of the complex socio-technical maritime system has

grown and accidents continue to be reported both in the UK and around the world with annual number of reports reaching over 1000 in the UK (MAIB, 2018b).

The following section includes the second case study on maritime safety, which also looks at the safety of UK ports, but from a different perspective.

6.2. Expected implications on maritime safety following the introduction of autonomous vessels

Section 6.2 includes the second case study of this thesis which assesses the expected improvements and challenges of the introduction of autonomous vessels in the near future. A paper on this topic has been presented at the European Safety and Reliability conference in 2023, which was also published (Manole and Majumdar, 2023).

One of the factors contributing to occurrences in ports that has been discussed in the relevant literature review section (Section 3.5) is the introduction of advanced or new technology. All other factors that have been reviewed are recurrent, so that lessons can be learned from studying past accidents and incidents, using a reactive approach. This approach has been the main approach used in the previous case study, along with a predictive approach. When introducing new technologies such as Autonomous Vessels (AVs), the new hazards and risks need to be forecasted using a predictive approach. This will be the main approach used in developing the methodology of this case study. In addition, the other pillars of the SMS discussed in Section 2.2 need to be addressed in order to develop a robust Safety Management System framework to effectively manage these risks.

The case study presented in this section is structured as follows. The first sub-section provides an introduction to the case study and its aims, leading to the development of its methodology. The required data is then selected and assessed for its quality in providing insightful results. Afterwards, the data is analysed and the results are discussed, which provides insights into the expected improvements associated with the introduction of AVs. Lastly, qualitative analysis is performed using interviews with industry professionals to further explore the expected impact of AVs and determine additional main benefits and discuss potential difficulties, such as the lack of adequate legislation and regulations or possible cyberattacks. It is predicted and verified by subject matter experts that autonomous vessels will have positive effects, creating less human dependent actions, therefore reducing accident frequency.

6.2.1. Introduction

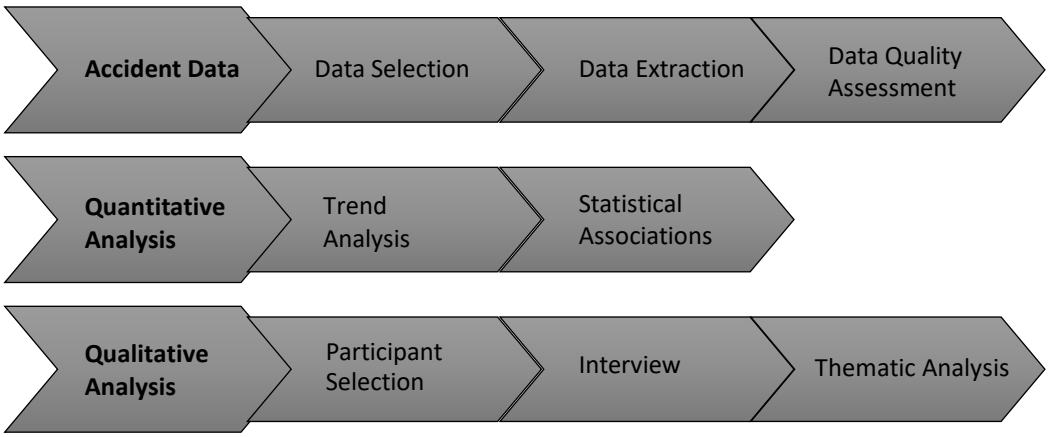
AVs are expected to commission and become operational within the next decade, in response to the declining supply of seafarers and increasing demand for seaborne trade. It is widely assumed that the introduction of autonomy would reduce the occurrence of human-related accidents on ships, as evident from the relevant literature review conducted in Section 3.6. However, as concluded after assessing the literature on AVs, there is a lack of studies on the impact that autonomous vessels would have on the safety of maritime transportation.

A hybrid methodology is used to critically assess the impacts of AVs on maritime safety, along with challenges and changes that are expected to follow. Quantitative analysis of marine accident investigation reports is used to determine the current factors that contribute to marine casualties. Then, thematic analysis of interviews with industry professionals will provide a realistic perspective on the expected positives and negatives of automation in the maritime industry. Therefore, this case study identifies important considerations regarding the implications of unintended consequences, challenges to automation, and a realistic description of what automation can and cannot deliver in terms of reduced maritime incidence. In order to achieve this, a robust methodology has been developed for this case study which is described in the following section.

6.2.2. Methodology

Figure 6.2-A summarises the methodology of this case study to assess the impact of AVs on maritime transportation safety, which fits into the methodology of this thesis, which has been detailed in Section 5.4. This case study also uses mixed methods of analysis, in line with the methodology of this thesis.

Figure 6.2-A. Methodology on the case study assessing potential impacts of autonomous vessels.



Data is extracted from investigation reports and subsequently analysed to determine the influence of human errors. The data source used is described in the following section. The quality of the dataset is then assessed, and a preliminary descriptive analysis is conducted, finding the frequency of each factor and any association between them and the occurrence of navigational human errors. The qualitative method comprises of semi-structured interviews with industry professionals of different backgrounds, to explore the expected future impact of AVs and determine the main benefits and difficulties. These are analysed using thematic analysis.

6.2.3. Database description

This section describes the data source used, the process of data collection, data extraction and data quality assessment.

6.2.3.1. Data selection

This case study uses MAIB accident data from investigation reports related to navigation errors caused by vessel crew. The accident type is limited to collision, contact or grounding. This decision follows the findings from the literature review in Section 3.6 that these three types of accidents normally follow navigational errors. This new data source has been described previously in Section 5.5, which summarises the data sources used in this thesis. The reason investigation reports are used in this case study and not the MAIB database is because of the data limitations on human-related factors of the MAIB dataset, as mentioned in previous sections.

6.2.3.2. Data extraction

Since accident reports contain a wide variety of information, a process was derived to extract the necessary data. First, the factual information was reviewed to obtain details of the event, such as location, time and environmental conditions. Then, the narratives of the reports are reviewed, and the obtained dataset is analysed to determine the influence of human error of accident causation, and improvements AVs would make on preventing these accidents. As such, the immediate cause and other underlying contributory factors are found.

For the same reasons as in the previous case study, marine incidents (near misses) have been excluded. Therefore, the investigation reports have been classed according to their severity as less serious, serious and very serious marine casualty (MAIB, 2019), while the “type of occurrence” selected is collision, contact, or grounding (MAIB, 2020). Only the MAIB investigation reports which resulted from human error that directly affected navigational decisions have been considered. As

such, mechanical malfunction such as the loss of control of the controllable pitch propeller, or loss of propulsion control are outside of the scope of this case study.

The technical and conceptual reasons for the accidents are also described, along with the necessary improvements AVs may require to eliminate human error. It should be noted that, when the pilot is onboard and the Master present, the Master is considered the officer of the watch (OOW) (Royal Navy, 2008). Furthermore, it is assumed that AVs are at least degree 3 and their sensemaking, decision making, and execution of manoeuvres are without error.

The information that has been extracted from the investigation reports has been categorised into different data fields which are presented in Table 6.2-A.

Table 6.2-A. Data fields extracted from MAIB investigation reports.

General description
Serial number, Case title
Marine casualty information
Date, Time, Location, Accident severity, Casualty event, Place on board, Fatalities, Serious injuries, Minor injuries, Damage/ Environmental impact, Ship operation, Voyage, Persons onboard
Vessel details
Name, Flag, Vessel type, Construction, Age of vessel, Length overall, Displacement, Minimum safe manning, Authorised cargo
Voyage details
Type of voyage, Cargo information, Manning
Environmental conditions
Visibility, Wind, Sea state, Swell height, Weather, Light, Tidal stream
Human error analysis
Appointment of OOW, Years of nautical experience, Time with vessel involved, Presence of alcohol/drug, Fatigue, Human error (Navigational), Technical accident reason, Conceptual accident reason, Would autonomy help, Autonomous vessel improvements

6.2.3.3. Data quality assessment

After the necessary data has been obtained from the MAIB investigation reports, its quality is checked using the methodology previously described in Section 5.6. The following data quality dimensions are included: accuracy, consistency, timeliness, accessibility, relevance, completeness, interpretability, credentials and detail of the narrative (Majumdar, Manole & Nalty, 2022).

Table 6.2-B. Data quality assessment results.

Dimension	Collision	Contact	Grounding
Accessibility	71.35%		

Completeness	86.02%	82.80%	81.45%
Consistency	95.46%	96.17%	96.17%
Relevance	84.52%		
Accuracy	High		
Credentials	High		
Interpretability	High		
Timeliness	Unknown		
Narrative	Detailed		

All dimensions are well above the 50% threshold (Table 6.2-B). The lower accessibility score (71.35%) is due to a lack of analytical data required, however it is still high and considered satisfactory. For completeness, vessel details had unknowns, which might be due to underreporting (Majumdar, Manole & Nalty, 2022). The environmental conditions were also incomplete, despite the good practice to maintain hourly and four-hourly logs. However, reporting such data may not be mandatory unless it was thought to be a critical factor. The investigation reports were detailed and consistent in the manner of reporting. The format of report, analysis and information included are similar across accidents. However, the quantity of information varies upon the uncovered evidence and accident severity. The Marine Accident Investigation Branch (MAIB) is a government branch and the investigation reports are official documents that highlight safety concerns, seeking to improve safety. Thus, these reports are assumed to be reliable and accurate. Overall, the data is deemed to be of high quality and suitable for further analysis in the following section.

6.2.4. Data analysis and discussion of the results

Having checked the data for its quality, this section provides the quantitative analysis undergone to determine the expected changes in the frequencies of types of occurrences after the introduction of Avs.

The categorical variables that have been collected are examined for associations, so that the relationship between the variables can be analysed. This is calculated using Pearson's chi-squared test, which compares the actual counts of events with the expected counts if the variables were independent. The null hypothesis is rejected with a level of confidence of 95%. The methodology is the same as for the previous case study, and can be found in Sections 6.1.5 and 6.1.6.

6.2.4.1. General details of the accidents

After filtering the investigation reports based on the previously mentioned requirements, 74 accidents between 2013 and 2020 have been reviewed: 28 collisions, 13 contacts and 33 groundings. Of these, three are less serious, 53 serious and 18 very serious marine casualties, which resulted in eight fatalities, five serious injuries and 36 minor injuries. 106 vessels were involved in these accidents: 37.7% cargo ships, 20.8% ferry, 16% fishing vessels and 17% smaller ships for recreational and operational activities. Most accidents occurred when the vessels were on passage (67%) or manoeuvring while berthing or unberthing (21.7%). This result concurs with the identification of risk influencing factors of Fan et. al. (2020), having found them most prevalent at the ocean passage phase. Even though manoeuvring is navigationally more challenging, vessels spend most of their time on passage, explaining their higher frequency. This also makes it more likely for the crew to be susceptible to distraction and boredom, as they are less challenged during the process.

The highest accident rate was from 00:01 to 03:59, which is expected since humans tend to become increasingly tired towards twilight ([Fletcher et. al., 1988). As such, most companies have a policy for watchkeepers to have a minimum of six hours rest before their watch, but this is often not strictly enforced. Furthermore, vessels at sea and other objects are less conspicuous with the absence of daylight, hence visual assessment of collisions becomes less effective. It is common for watchkeepers to be disoriented by the array of lights displayed by vessels at night as it is not possible to visually assess how far vessels are. Of the ten accidents reported to be affected by fatigue, six occurred between 00:01 - 04:00 and four between 04:00 - 08:00, the conventional sleeping hours.

6.2.4.2. Analysis of accident reasons

Of the 74 accidents, 57 were a result of human error, nine were not (poor design, instability, or malfunction of equipment) and eight were outside the scope of the study. Regarding the human-error-related accidents, the predominant contributing factor is the lack of situational awareness (64%). Table 6.2-C summarises the different types of human errors, and the severity of the accident they caused. Besides error in execution of the passage, improper or insufficient passage planning represents 14% of accidents. The next most identified factor is inaction or insufficient action (11%). This is tied with the lack of situation awareness, as most OOWs are unaware that they are in a collision course or heading for shallow waters, which results in no action being taken or the action being taken too late.

Table 6.2-C. Human errors, counted for different severity levels.

Human error factor	Less serious	Serious	Very serious	Total
Lack of situational awareness	3	30	15	47
Improper/insufficient passage planning	2	6	2	10
Inaction/Insufficient action		5	3	8
Poor decision making		4	2	6
Poor crew resource management		1	3	4
Lack of understanding of vessel manoeuvring characteristics		4		4
Misinterpretation of other vessel intention		2		2
Own vessel intention ambiguous		1		1
Underestimated weather conditions		1		1
Unfamiliar with ship emergency drills		1		1

The lack of situational awareness reflects the loss of position awareness, lack of identification of other vessels in collision course and shallow waters in the vicinity. It may happen due to incorrect equipment set up (charts not used, radar not set for long-range scanning, or no additional lookout role delegated), distraction (using entertainment devices, or preoccupied with other operational duties), fatigue, alcohol or poor seamanship (bridge left unattended, navigating by eye, visual navigation in poor visibility, not using navigational aids or radar, ECDIS, GPS etc., over-reliance on AIS, not verifying course on chart or not accounting for weather/tidal stream).

6.2.4.3. Analysis of the impact of environmental conditions

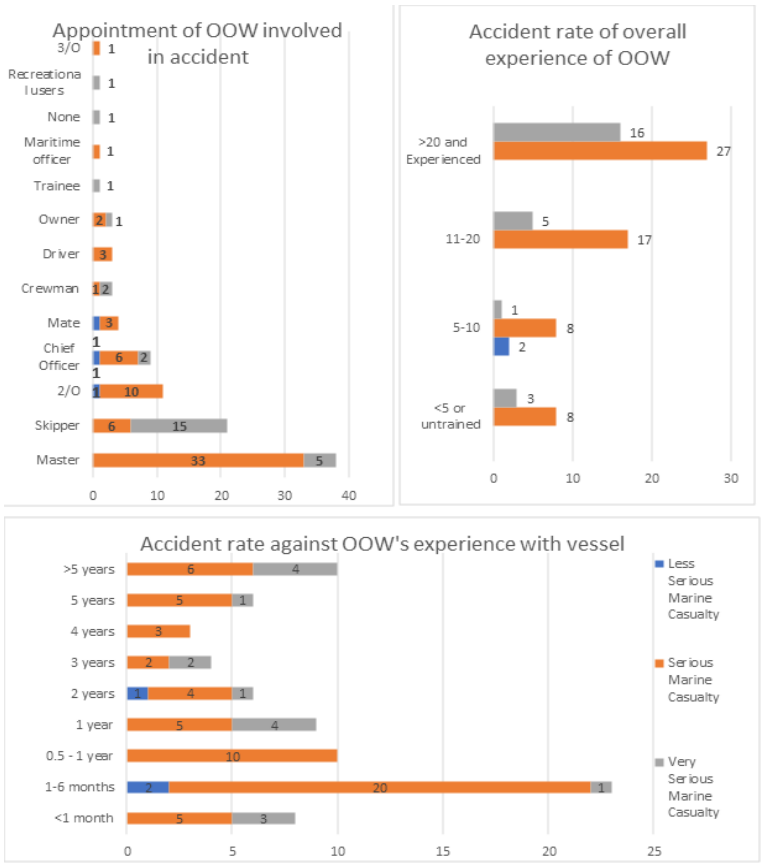
Generally, poor environmental conditions were not a major contributary factor to accidents. Only 4% of the studied accidents occurred in poor visibility, being either serious or very serious marine casualties. This can be mitigated by RADAR equipment aboard ships, where most crews learn to navigate blind, without the aid of visual references and only through the use of radar, GPS and chart plotting. 44.6% accidents took place in light wind conditions and included most very serious casualties. Sea state, swell height, weather, light and tidal stream were not as widely reported as visibility and wind, even though it is generally required by watchkeepers to record these at a 4-hour frequency.

6.2.4.4. Analysis of the impact of human experience and performance

13.5% of the studied accidents reported that fatigue was a contributory factor, while 8.1% cited alcohol or drug use. These resulted in serious or very serious casualties. During the accidents, 38 of the OOWs at the time were the Master of the vessel, which makes up 35.8% of the vessels involved. The second highest identity is the skipper (21 for 19.8% of the vessels), who is also the highest appointed, and typically most experienced personnel on smaller craft. Following are less experienced

appointments such as the Second Officer (2/O) and Chief Officer. It is also observed that more than half of the vessels involved in very serious marine casualties involved the Skipper. This could be because most skippers' responsibilities also include fishing and other high intensity work, and they do not receive the same level of navigational training as merchant vessels. The breakdown of accident frequencies is presented in Figure 6.2-B.

Figure 6.2-B. Appointment and level of experience of OOW.



In line with this analysis, the majority of the OOWs were individuals with more sea time even though it would be intuitive to expect the less experienced mariner to contribute the most to accidents. In this instance, 40.6% of the accidents involved OOWs working at sea for over 20 years. On the other hand, less experienced individuals of less than five years and untrained members form only 10.3% of the group. This is in concurrence with the finding that many of the OOWs were Masters or Skippers, who are the most experienced on the vessel and take on the largest responsibilities.

The highest proportion of OOWs have only had experience with the vessel, or the class of vessel, for less than a year. As presented in Figure 5, the number of accidents when the OOW has only been on for less than a month, between one to six months, and between half a year and a year, is 8, 23 and 10,

respectively. However, an increase in experience does not result in lower frequencies, and the shorter time period does not reflect a lack of navigational competence in the OOW.

6.2.4.5. Contingency analysis and three-way associations

There was a significant relationship between fatigue and the time of occurrence. It was also found that shorter, lighter vessels are more likely to be involved in very serious accidents, involving total loss of ship, loss of life or severe pollution. This is expected, as smaller ships are more vulnerable to capsizing and damage, especially upon impact with larger vessels. The next section summarises the results of this section (Section 6.2.4) and emphasises on the expected improvements in maritime safety after the introduction of AVs.

6.2.5. Improvements of autonomous vessels

As proved in the previous section, accidents affected by human error could have been avoided if it the vessels had been operated with autonomy. This can be achieved through the artificial intelligence (AI) onboard AVs. Firstly, to counter the lack of situational awareness, all information from the vessel's sensor suite would be constantly monitored and assessed by the AI for real-time sense-making of traffic conditions and safe water. For example, the AI can visually identify surrounding vessels through electro-optical or infrared systems and assess their relative course and speed through changes in the relative bearing and recognise any vessels on a collision course. This information would also be cross-checked with radar and AIS information to gather a complete picture. The AI can also conduct position checks through GPS and visual fixes along with the planned track and available safe water. Secondly, AI could avoid collisions depending on the traffic condition, which is automatically monitored by the system. Through the radar and automatic radar plotting aid (ARPA) outputs, it can adjust the vessel's heading until it can pass another vessel with a satisfactory lateral distance, which can be computed through 'Closest Point of Approach' or ARPA. It can also ensure that it is in safe waters through real-time adjustments upon position checks.

The sensor equipment already exists on most operational vessels, but the OOW may not use them due to distraction, fatigue, stress, and unfamiliarity. The benefit of the AI over humans is that the computer has a higher capacity and is less likely to be overloaded. Even if offshore operators of AVs mistakenly direct the vessels due to inexperience, fatigue or alcohol, the onboard AI can be configured to automatically take over control and redirect the vessel to a safer path. This is similar to self-driving cars with automatic collision avoidance.

11 of the accidents can only be avoided with specific configurations on the AVs, and they serve as improvements that would be necessary. Firstly, the chart database on vessels must be up to date,

following chart revisions and Notice to Mariners updates. This would highlight any unsafe waters from recent shipwrecks, ongoing construction, and other sea hazards. Secondly, the AI should be able to plan tracks that are tailored to the specific vessel characteristics, such as its draught and turning angles. This allows the vessel to know exactly the depth required for safe water, areas of dangerously shallow water, and thus the flexibility for vessels to deviate from their planned tracks. Lastly, dangerous manoeuvres such as high-speed turns in the presence of other vessels and shore platforms in close proximity can be prevented.

6.2.6. Qualitative analysis and discussion of the results

Having assessed the potential improvements of AVs on maritime safety in the previous section, this section reviews interviews with industry professionals to further assess expected improvements, as well as identify potential areas of concern and new risks. It starts with providing an overview of the aim, objective and methodology of this qualitative side of this case study. Then, details of the participants are provided, as well as the design of the interviews. Then, the responses are analysed, before reaching final conclusions.

6.2.6.1. Aim, objectives and methodology

A common issue in quantitative analysis is research subjectivity. To overcome this, qualitative research is also performed. After analysing several AV projects around Europe and reviewing accident data to understand the present situation, the interview questions are designed to capture the effects AVs would have on maritime safety, according to industry professionals. The interviews were recorded, transcribed and analysed using the NVivo program, which helps perform thematic analysis by categorising answer topics in themes.

Individual self-completion questionnaires have been used prior to the interviews. These are open-ended self-report measures where the participants could answer questions remotely at any convenient time, which was preferred by the participants as they could get familiar with the questions before the actual interview. Another advantage compared to structured interviews is the absence of interview effects, such as the ethnicity, gender or social background of the interviewer, that can affect the answers that people give (Bryman, 2016). The self-completion questionnaire includes more closed questions as they are easier to answer, At the same time, the format is easy to follow and designed to reduce the risk of "respondent fatigue".

Thematic analysis is used to distinguish themes within the questionnaire data (Maguire and Delahunt, 2017). This method has been chosen because it offers flexibility when identifying patterns and themes. The analysis is conducted based on the methodologies of Braun and Clarke (2006), Bryman (2016),

and Erlingsson and Brysiewicz (2017). Using NVivo, codes are created for assigning sentences from the participants, allowing for a better organisation of the information. A code is a word or group of words used to describe the topic of various sentences from the participants. Different codes with similar meaning units are grouped to form categories which, in this case, entail the main themes of the study. Figure 6.2-C outlines the thematic analysis approach suggested by Erlingsson and Brysiewicz (2017), showing how from a general answer or raw data, high levels of abstraction can be obtained.

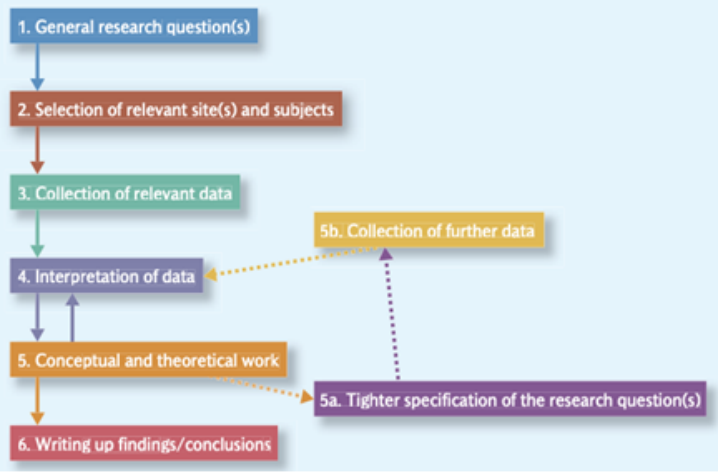
Figure 6.2-C. Thematic qualitative analysis outline (Erlingsson and Brysiewicz, 2017).



Theme	Navigating the nascent legal landscape of automated vessels
Category	Legal Challenges & Responsibilities
Code	Challenges
Condensed Meaning Unit	Responsibilities will be very important when something goes wrong, one of the biggest challenges to place responsibilities such as the owner, flag or operator.
Meaning Unit	That will be very important as to place responsibilities when something goes wrong. the biggest challenge will be to place responsibilities i.e., owner, flag or operator!

Figure 6.2-D proves that the research can suffer from generalisation due to the small sample size, which is a common issue in qualitative research. However, the participants have been carefully selected, with diverse backgrounds and professional experience, making the analysis more realistic. They are presented in the following section.

Figure 6.2-D. Main steps of qualitative research (Bryman, 2016).



6.2.6.2. Participants

The participants for the questionnaire and interviews were selected from Spain and Denmark (Table 6.2-D), based on their experience in the maritime industry. They were acquired through snowball

sampling, where the researcher made connections with individuals with relevant experience, through whom other contacts were established (Bryman, 2016).

Table 6.2-D. List of interviewed participants.

ID	Experience	Country	Gender	Role
1	16 years	Spain	Male	Chief Engineer
2	6 years	Spain	Male	Chief Engineer
3	6 years	Spain	Male	Loading Master
4	43 years	Denmark	Male	Nautical Superintendent
5	12 years	Spain	Male	Harbor Pilot
6	2 years	Spain	Female	Naval architect and maritime engineer

6.2.6.3. Design of the questionnaire

Having reviewed the methodology and participants, and taking into account findings from the literature (Section 3.6) and accident data analysis (Section 6.2.4), this section introduces the design of the questionnaire. Some participants agreed to a follow-up interview, which had the aim to further expand on their answers to the questionnaire. The questions are presented in Appendix L, while the question categories are summarised below:

- Personal details
- Safety Management System and Safety Risk Management
- Safety policy and objectives
- Safety assurance
- Safety culture and promotion
- Incident data collection
- Equipment
- Autonomous vessels

6.2.6.4. Analysis

In this section, the responses of the questionnaires and interviews that have just been described are analysed. The results are based on the encounters, remarks and feelings of six professionals. Figure 6.2-E shows the themes, while Table 6.2-E discusses the findings for each of these themes. These are linked to findings from the literature and quantitative analysis, to provide a full image of the effects AVs are expected to have on maritime safety.

Figure 6.2-E. Main themes of the qualitative analysis of maritime professionals regarding expected implications of the introduction of autonomous vessels.

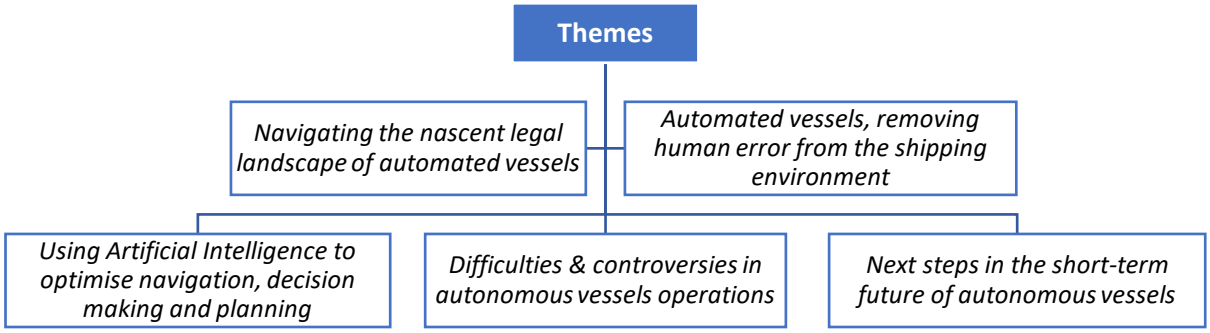


Table 6.2-E. Qualitative analysis discussion using quotes and links to relevant literature, regarding expected implications of the introduction of autonomous vessels.

Quotes	**Discussion**
Navigating the nascent legal landscape of automated vessels	
'Situations of human errors, we can know who is responsible, but in AVs who will be responsible if there is a machine error?' 'Who will be responsible in case of an accident when no one is onboard? The software engineers? If no one is on board besides pilot – who is responsible and in charge? That will be very important as to place responsibilities when something goes wrong.' 'International regulations will have to be developed together with new technologies. Achieve a global agreement over the world and all the necessary changes in laws for responsibilities.' 'To develop a new regulatory framework for AVs. For example, SOLAS needs to be expanded to allow AVs (right now, it says that someone physically onboard is needed for a ship to operate, which does not allow AVs to be a reality).'	The dependence on autonomous systems will lead to a gain in terms of importance in the insurance policies. Nowadays, the most common error is the human error. In the future, it will be a technical error so the insurance will need to change too. From the point of view of regulation of responsibility in automation, AVs have common aspects with autonomous cars. In a hypothetical accident between self-driving cars and pedestrians or drivers, the car factories argue that the responsibility lies only with the company that designed the software, so long and complex courts are ahead to discuss responsibility of the accidents. The list of laws that apply will vary depending on different factors such as the place of the accident, the type of accident, the nationality of the ship, etc. Implementing AVs will cause a before and after in which the consideration of this aspect must be changed, since at this time the limitation of liability goes hand in hand with human fault. In the future, the use of smart devices will increase, so the responsibility is more likely to be due to technical failures. The new considerations will include responsibility for errors made by operators on land, in a similar way to the faults of the ship's crew members in conventional vessels. However, there will be new laws and conventions that will link to technical failures, as software errors, data loss, system break, etc. Human intervention can often solve these errors and overcome technical problems, but in cases where the human cannot do anything (as in the case of a loss of communication), the

	distribution of responsibility will become a problem and the IMO will have an important role in this new area.
Automated vessels, removing human error from the shipping environment	
'With AVs can estimate a great part of future situations based on previous data, technology always offers solutions, improves people's lives and more efficiency in process engineering.' 'An efficient way to eliminate all this common error human factors is to have complete automation of the vessels. Unmanned vessels will reduce human error, which is the most common cause of accidents, so we will improve the safety at ports.'	In the last two decades, the human error has been present in most marine accidents. In around 60-70% of maritime accidents the human has intervened. Whether it is due to poor management of the on-board systems, poor decision-making or incorrect action, distractions, poor maintenance, incorrect stowage, or any other cause, it is a problem that is present every day today and is a risk to life and safety at sea (European Maritime Safety Agency, 2023). These quotes emphasise on the findings from studies carried out in recent years about maritime accidents and their causes, which found that over 60% of maritime occurrences are due to human errors such as fatigue, errors of judgment or personal decision, negligence, or inadequate training (Kim and Mallam, 2020). It is reasonable to assume that AVs would reduce the human-error-related accidents, eliminating risks faced by offshore crews that can end in injury or death.
Using Artificial Intelligence to optimise navigation, decision making and planning	
'Situations where the ability of a worker with his/her intuition after all the experience save the ship only will be possible with a good artificial intelligence a lot of time and a big dataset.' 'Reducing human error due to artificial intelligence.' 'The algorithm will be frequently updated through new training data that is continuously collected navigation based on Artificial Intelligence technology and all the decisions are programmed into the software according to the COLREG regulation'	An autonomous surface vessel can navigate without human intervention, being controlled by artificial intelligence (AI) that algorithmically solves any problems arising during navigation. AI would connect to a network with several devices and use data about the weather, sea and dangerous obstacles to make a shorter route and therefore save on consumption (Shulerm, 2018). The technology used is based on machine learning and creates a self-adaptive and predictive management system on the ship behaviour. It manages monitoring and controls a large part of the ship's systems in real time, carrying out tasks quickly and efficiently. The system can inform the captain of stabiliser recommendations, speed and route planning (Austal, 2023). This facilitates decision-making during port operations and navigation, reducing the frequency of human errors.
Difficulties & controversies in AV operations	
'Communications between crew and machines and could be a big problem, especially at the beginning with the first levels of autonomy.' 'I can see cargo vessels without crew, but automated operations should always be supervised by the crew. The crew will be reduced to a minimum but if there aren´t changes in the vessel the reduction of crew will not be as much as we think.'	AVs could improve safety by diminishing human error in the long term. However, during the transition phase, these vessels will work closely with conventional vessels. The way these will interact can create great difficulties when it comes to navigation in the event of a potential collision scenario. Another problem is the transmission of data between the ship and the control centre, increasing the possibilities of saturation due to the high amount of image or video data and the large information flow through the sensors on board.

'A lot of things that can be done at port with land crew but the time at port will be increased and the vessel will be done with fewer journeys, due to that reason the maintenance (in the engine room and deck) are made in sailing time.'	Another great uncertainty comes with the change in the way of working and in the preparation of these workers. The passage to land should be done gradually, and Lloyd's Register define the steps to be taken before completing full automation between on-board decision making, shared decision making with the ground, reduction of crews and full automation.
'I do not see it as feasible, since you will always need a crew for maintenance of the ship, this is affected by weather conditions, machinery wear and in the best of cases the crew would be reduced even more.' 'Job losses, economic and social impact.' 'The possibility of remote-control failure and cybersecurity are main issues that need to be solved for complete safety. Special attention (…) about Cybersecurity, we must be aware of hackers attacks.' 'Adapt to possible problems created by automation of industries like the cyber-attacks. With AVs, one of the main goals is to reduce human error but the company has to empathise Cybersecurity aspects.'	One of the biggest disadvantages that come with automation is the drastic reduction of workers, since a small team of maritime workers and engineers will be able to manage and coordinate several vessels. Although the work will be diversified in many aspects and the people who work on the ship will come from external companies, it has been argued by the interviewees that the generation of indirect employment will not supply the decrease in the demand for personnel, and although the companies allege that the number of officers decreases alarmingly, the reality for active mariners would be very uncertain. In addition, cyberattacks have become a growing danger in shipping, where programmers hack frameworks like AIS, to alter the GPS signal. Due to the increased reliance of an AV on innovation, network safety turns into a significantly more major issue that organisations should address. Onboard controls and data can be undermined and powerless against computer-based attacks, as self-governing vessels require a steady relationship for checking and control (Komianos, 2018).
Next steps in the short-term future of AVs	
'In the next 10 years we will see big cargo vessels with no crew. The crew is one of the most expensive costs they have.' 'We will see it increase year by year until it will become a reality. Of course, right now, we are in the design and testing phase and this implies testing with small-medium ships.' 'When a good foundation is created in safety regulations and the study of the behaviour of AVs in the face of adversity.'	Crew expenses are typically around 20-30% of the total expense of a cargo ship, including salaries, diet, insurance, contracts, provisions and other essential components. AVs can reduce or eliminate these costs, making an incentive for shipping companies seeking cost decrease in an aggressive market. Some countries and organisations are already involved in the study and analysis of the implementation of AVs. The European Union allocated 3.5 million Euros to finance the MUNIN project, to investigate the costs and benefits of unmanned vessels. Moreover, a vice president of innovation at Rolls Royce said that the technological trend is towards the automation of processes, affirming that technology is at an appropriate level to revolutionise the maritime industry society.

Similar advantages of automation were brought up, the most recurring being the increased safety. However, cost reduction and efficiency improvements were also mentioned. Automation will involve a series of changes in the human behaviour of a ship's crew. The automation of a ship does not mean that the human element no longer exists since, in a direct or indirect way, it will always be present (Ahvenjärvi, 2016). Moreover, although some jobs are eliminated, new ones will be created.

On the other hand, legislation uncertainty and cyberattacks were the most recurring difficulties and controversies mentioned by the participants. At the moment, there is no adequate legislation, so companies interested in developing this technology do not have clear instructions, and the development of new laws related to AVs is a slow process. Interim guidelines could be developed according to the results from MUNIN and YARA Birkeland projects, amongst others. Once the authorities and organisations related to the maritime sector have a clear idea of the new autonomous regulations, DNV GL suggests that a new Autonomous Ship Code should be developed, commanded by SOLAS (Johan, Lera and Skjong, 2018).

6.2.7. Conclusions of the second case study

This case study presented a preliminary analysis of how AVs may impact maritime safety in the future, based upon mixed methods of quantitative and qualitative analysis. The former involved the analysis of over 70 maritime investigation reports sourced from the MAIB. This revealed that 77% of the accidents studied could be prevented with the introduction of autonomy, and thus the elimination of human errors that influenced decisions and behaviour in navigation. However, 12% of the navigation accidents would not be prevented, being caused by mechanical malfunctions. To eliminate human errors, the AVs must mitigate them by design, through a wide array of sensor equipment such as electro optics and radar, and properly designed AI. For this to happen, deep learning is crucial to ensure adequate depth of knowledge for robust and resilient decision making in AI systems. Programmers will also have to look upon existing seamanship practices and rules to design the behaviour of autonomous vessels.

The qualitative analysis provided further insights on the impacts of AVs. Most participants highlighted similar advantages of automation, the most recurring being the increased safety. Cost reduction and efficiency improvement were also mentioned. However, new challenges and controversies arise. The lack of adequate legislation and regulations or possible cyberattacks can be some obstacles in the maritime environment. In the short run, shipping crews should focus on upholding a strong safety culture and maintain currency in their navigational skills through frequent and targeted trainings. It may be impossible to eliminate human error, since it may exist in other forms in the process of maritime transport, such as in the design, construction and remote operation of vessels. These findings generally assume that AVs are perfectly designed and do not run the risk of compromise of cyber-security attacks. Table 6.2-F summarises the positive and negative impact of AVs, expected after their introduction.

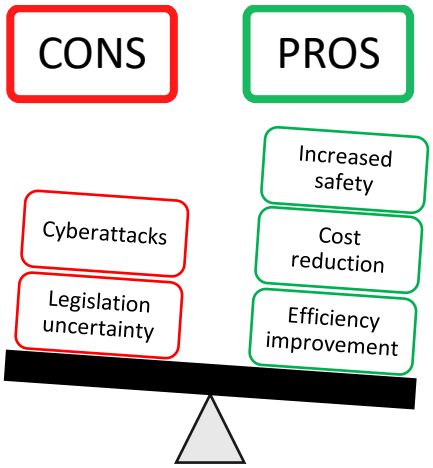
Table 6.2-F. Expected positive and negative impact of autonomous vessels.

Positive	Negative
'Lower operating costs'	**'Safety in navigation and liability'**
'Higher revenue'	**'Cyber security (a completely new world for shipping industry)'**
'Lower voyage expenses'	**'Job losses'**
'Higher efficiency of ships (operating and design, where accommodation of crew + bridge could be removed and a higher aerodynamic structure + more cargo space could be achieved)'	**'Regulatory framework (unclear how we are going to regulate the autonomous ships)'**
'Reduced human error and risk'	**'Economic and social impact'**
'Reducing the risk of piracy'	**'Communications between crew and machines'**
'Green shipping'	**'Ability to react to external adversities'**

When AVs start navigating around the world, many interests may be affected, especially for insurers. The new threats must be included in the MAIB data fields, such as AI malfunction and cyberattacks, while, as suggested by Bimco et. al. (2023), distinguishing between untargeted and targeted attacks. To improve future data quality assessment and overcome the mentioned challenges, a new data field related to the sensor's connectivity must also be added to the reporting scheme as a text category to provide detailed descriptions of the sensor's performance. Due to ship digitalisation, many sensors will be operating during navigation and, under bad environmental conditions, some can lose communication and connectivity with the software, or even stop working, due to computational issues.

Figure 6.2-F summarises the most notable positives and negatives expected after the introduction of autonomy in shipping operations, which have been addressed through this case study.

Figure 6.2-F Main positive and negative aspects of autonomous vessels expected after their introduction in the future.



6.3. Safety analysis using IMO data (for piracy-related occurrences)

This section presents the third case study, which introduces a new database (from the International Maritime Organisation), as well as a new safety topic (that of piracy). A conference paper has been written on this topic and it is attached in Appendix M. Unlike the previous sections with the first two case studies, this one presents only a summary of the main results, focusing on the limitations of the IMO dataset.

The reason for choosing to analyse the IMO data source is the fact that many published studies include such data obtained from the IMO. A reason could be that it contains more entries since it comprises of safety data from the majority of the countries in the world. Data limitations of more localised data sources have been described in detail so far, for different databases and also investigation reports. Therefore, even though the IMO provides more quantity of data, questions arise regarding the quality of this data and whether it can provide accurate results.

The reason for focusing on piracy-related occurrences is the threat these pose on maritime safety, and the fact that their number has seen an increase in recent years for the area of the Gulf of Guinea (GoG). The following sub-section provides an introduction into this topic and literature, which leads to the aim and objectives of this case study. The review of West African piracy and the main factors driving piracy in that region are not present in this section, and can be found in Appendix M. The second sub-section summarises the methodology of this case study and the data source. Lastly, the main findings are discussed, and the limitations addressed.

6.3.1. Introduction, aim and objectives

Maritime transport is critical to international trade, accounting for over 80% of its volume. As previously emphasised, ensuring the safety of maritime routes, cargo, and crew is paramount. However, piracy remains a persistent threat, particularly in the Gulf of Guinea, which has seen a sharp rise in both the incidence and severity of pirate attacks.

History highlights that the main factors underlying piracy occurrences are episodic wars and unstable, fluctuating economies. These factors, which are often linked by a causal relationship, generally cause a surge in unemployment and instability of the labour markets, triggering a rise in the black-market demand for goods stolen and provided by pirates. As ships laid idle and less profitable opportunities were available for sea merchants, piracy offered a suitable alternative that would match their skills and expertise and offered an escape from starvation and bankruptcy (Anderson, 1995).

In certain regions of the world, these conditions are prevalent. For example, Western Africa and the Gulf of Guinea have experienced a sharp rise in piracy during the past 30 years, characterised by increasing violence against crew members. Other key factors that should be highlighted are the poverty rate and political instability of this area. About 3% of the population of West Africa lives under 1.90$ per day, which is a 3% rise compared to 2020's level (United Nations, 2022). Furthermore, the region has witnessed its fair share of instability over the past few decades as several countries experienced civil wars, extensive corruption, civil unrest, coups and the rise of terrorism (Marc, Verjee and Mogaka, 2015).

Table 6.3-A summarises the main factors driving piracy in West Africa and the GoG, according to the literature review in Appendix ML.

Table 6.3-A. Main factors driving piracy in West Africa and the Gulf of Guinea.

Factors	**Description**
Illegal Fishing	Displacement of small-scale fisheries by foreign industrial fishing fleets.
Youth Bulges	High youth population with limited job opportunities.
Political Instability	Political unrest and weak state structures.
Military Capacity	Limited naval capacity to patrol and secure waters.

Previous studies have extensively explored the factors behind piracy, the efforts to combat it and potential solutions. Notably, Fattah (2017) provided a qualitative analysis and descriptive statistics of piracy incidents from 2010 to 2016, highlighting the importance of inter-state cooperation and military presence. Liwång (2016) analysed trends and patterns in pirate attacks from 2010 to 2014, identifying key phases of piracy incidents and the effectiveness of pre-emptive measures. Jiang and Lu (2020) utilised Bayesian Networks to analyse maritime piracy in Southeast Asia for deeper statistical analysis.

In conclusion, piracy accounted for more than 95% of kidnappings at sea in 2020 (International Maritime Bureau, 2021) and poses a serious danger to maritime transport on the Atlantic seaboard of Africa. The importance of piracy can be seen through the fact that the IMO collects data on such occurrences in considerable detail. Therefore, this case study aims to analyse the factors driving piracy in the GoG, using data from the International Maritime Organisation and providing insights into the complex relationships between different piracy-related parameters. The study seeks to offer recommendations for improving defensive strategies and technologies to counteract piracy, while also addressing data limitations.

6.3.2. Methodology, data and main findings

The study's methodology involves several key steps: creating a dataset from the IMO's Global Integrated Shipping Information System (GISIS), assessing data quality, segmenting incidents based on severity, and conducting statistical and contingency analysis to identify patterns and associations. The data has been described in Section 5.5, and the methods of analysis have been explained and used in the previous case studies. The dataset is categorised by factors such as ship type, attack location and incident severity, facilitating a detailed examination of piracy incidents.

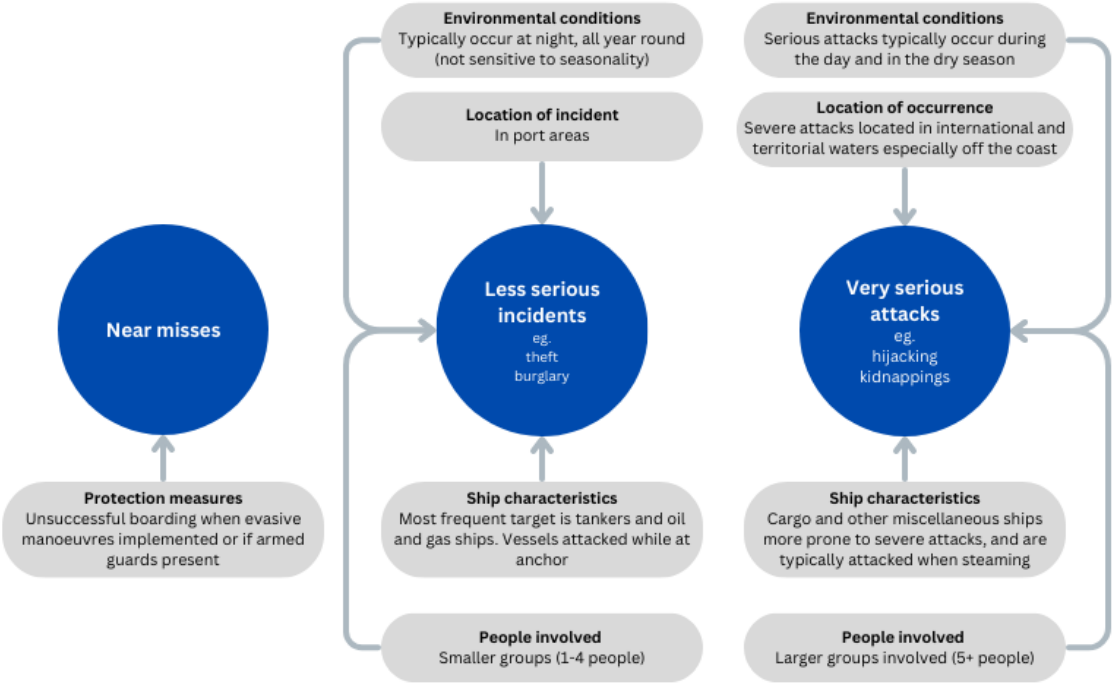
Data for this case study was sourced from the IMO's GISIS, covering 322 piracy-related incidents in the GoG from 2017 to 2022. The dataset includes detailed information on each incident, such as the type of ship, location, time of attack, weapons used and the number of people involved. The occurrences are categorised into three threat levels: Level 1 (most severe), Level 2 (serious), and Level 3 (less serious). The parameters were reformatted for analysis, considering factors like seasonality, time of day, and ship status. Figure 6.3-A summarises the data fields obtained from the IMO database and narratives.

Figure 6.3-A. Accident characteristics compiled in dataset, using the IMO database and narratives.

General information	Location data	Accident severity	Accident details	Response and aftermath	Accident description
• Ship name • Ship flag • IMO number • Type of ship • Gross tonnage • Date • Time • Time zone	• Longitude • Latitude • Coastal state • Area • Position of occurrence	• Threat level • Weapons used • Lives lost • Missing crew • Wounded crew • Hostages	• Action taken by coastal state • Consequences to ship, crew and cargo • Details of the attack	• Action taken by crew • Reporting to authorities • If yes, which authorities were involved • Reporting state or international organisation	• Narrative of events • Consequences to ship, crew and cargo

The analysis reveals that severe piracy incidents, such as hijacking and kidnapping, are more likely to occur in international waters during the daytime. These often involve organised gangs and occur off the coasts of countries in the GoG. They are also more frequent during the dry season. However, less severe attacks, like theft and burglary, typically happen in port areas at night. Moreover, the presence of armed guards and evasive manoeuvres by ship crews were found to be effective deterrents against piracy. Figure 6.3-B outlines the main results of this case study, for different levels of severity.

Figure 6.3-B. Main results of the analysis of piracy occurrences in West Africa and the Gulf of Guinea, for different levels of severity.



The results of the case study also highlight the underreporting of occurrences, which affects the accuracy of the data. This and other limitations are detailed in the following section.

6.3.3. Limitations of the results

One of the primary limitations of this study is the inconsistency and underreporting of piracy occurrences in the data provided by the International Maritime Organisation. While the analysis provided some interesting results, this issue is compounded by several factors that contribute to data inaccuracies and gaps, affecting the reliability and comprehensiveness of the findings.

Firstly, the IMO relies on voluntary reporting from member states and commercial shipping companies. This voluntary nature means that many incidents, especially less severe ones, may go unreported. As previously discussed, the national bodies responsible with accident investigation, such as the MAIB, do not require themselves the reporting of non-serious occurrences. Therefore, even fewer of these can reach the IMO database. Aside from the reasons of underreporting already mentioned in previous chapters of this thesis, specific for piracy, shipping companies might choose not to report such occurrences to avoid negative publicity or increased insurance premiums. Some states might also underreport to downplay the severity of piracy within their jurisdiction to protect their maritime trade reputation.

Secondly, the variability in the length and detail of the reported narratives also poses a challenge. Therefore, not only are the occurrences underreported, but the depth and detail in the majority of the reported occurrences are also insufficient. Some reports contain rich, detailed narratives that provide valuable insights into the dynamics of an occurrence, while others are brief and lack substantive content. This variability affects the depth of qualitative analysis that can be performed and may lead to an over-reliance on quantitative data, which might not capture the complexities of piracy incidents.

Thirdly, the quality of the reports submitted to the IMO vary significantly. It has been previously mentioned that the IMO aims to standardise reporting in Section 3.4, however there is still a lot of room for subjectivity and inconsistent taxonomy. As evident from this case study, some reports provide comprehensive details about the occurrence, including the type of ship, exact location, time of day and nature of the attack. However, many reports are sparse, lacking critical information such as the tactics used by pirates, the response by the crew and the presence of security measures. This inconsistency hampers the ability to perform a thorough analysis and draw reliable conclusions about the patterns and factors driving piracy.

Fourthly, there is a significant time lag in the reporting process. Delays in reporting can lead to outdated information that does not reflect the current state of piracy in the region. This time lag can skew the analysis, making it difficult to implement timely and effective countermeasures. Moreover, the lack of real-time data limits the ability to conduct predictive analyses that could help in forecasting future piracy trends and preparing proactive responses.

Another limitation is the absence of socio-economic data related to piracy incidents. Understanding the socio-economic backgrounds of pirates, including factors such as unemployment rates, income levels and local political instability is crucial for determining the root causes of piracy. The IMO dataset does not include such information, making it challenging to develop comprehensive socio-economic models that could better explain the motivations behind piracy and inform targeted interventions.

Additionally, the study is limited by its reliance on a single data source. While the IMO's database is extensive and widely used in the literature, it is not exhaustive. Integrating data from other sources, such as records from shipping companies, maritime security firms and insurance companies could provide a more holistic view of piracy in the region. Access to these sources could enhance the robustness of the findings and allow for cross-validation of reported occurrences, thereby increasing the accuracy and reliability of the data. However, this data is kept confidential which limits its capabilities. While this data is analysed locally, releasing it to the public in a way that certain aspects

remain confidential, it is yet to reach its highest potential which can be achieved through further analysis using diverse perspectives.

Furthermore, the IMO dataset does not account for the technological advancements in piracy countermeasures. As evident from the previous case study, new technologies can have significant impacts on a sector, both good and bad, so it is crucial to address these in a proactive and predictive way. This is also relevant for piracy since, over the years, shipping companies have adopted various technologies to combat this issue, such as advanced radar systems, automated distress signals and fortified ship designs. However, the IMO dataset does not provide information on the presence or absence of these technologies during piracy incidents. Therefore, this omission limits the ability to assess the effectiveness of technological interventions and to recommend improvements based on empirical evidence.

Finally, geopolitical factors are not adequately represented in the data. The Gulf of Guinea is a region with diverse political landscapes, and the political context in which piracy occurs can significantly influence its prevalence and nature. Factors such as regional cooperation, international naval presence and domestic maritime policies play a crucial role in shaping the piracy landscape. The lack of detailed geopolitical data in the study limits the ability to fully understand the broader context of piracy and to propose comprehensive, context-specific solutions that address aspects of the SMS such as safety policy, assurance and promotion.

6.3.4. Conclusions of the third case study

In conclusion, while the study of the IMO database can provide valuable insights into different factors and accident patterns, in this case related to piracy in the Gulf of Guinea, it is constrained by numerous data limitations. Addressing these limitations in future research would require more consistent and comprehensive reporting, integration and increased public availability of other data sources, inclusion of socio-economic and geopolitical factors, and consideration of technological advancements. These improvements would enhance the ability to develop more effective strategies for combating specific issues and enhancing maritime safety.

6.4. Conclusions of Chapter 6

This chapter presented the analysis of three case studies related to different aspects of maritime safety, using different safety approaches and mixed methods of quantitative and qualitative analysis. The datasets and their limitations have been defined, and data quality checks have been employed.

Considering the results of mixed methods of data analysis, as well as the additional insights from the interviews, a holistic understanding of accident causation patterns in UK ports has been achieved in this section. At the same time, databases widely used in the literature have been studied and criticised for their limitations and, where possible, alternative sources have been provided. Nonetheless, the data filtering procedures that have been considered for the analysis in the three case studies included in this chapter achieved a high accuracy of the results.

Tables 6.4-A, 6.4-B and 6.4-C summarise the main findings of the three case studies, for each of the methods of analysis employed. These tables also provide an overview of unique, specific safety challenges and risks associated with the case studies.

Table 6.4-A. Main findings for the analysis of safety data for marine casualties and incidents in UK ports.

Category	Main findings
Data quality and limitations	Improvement in MAIB reporting completeness by 23% over the studied period.
	PPE usage reported in only 7.1% of SC, with data completeness of 17.2%.
Trend analysis (SC)	Overall increase in the number of SC at UK ports from 2013 to 2023.
	Marine incidents account for over half of SC, with an increase likely due to improved reporting systems.
	Collisions and contacts are the most frequent accident types (21.15% and 24.14%).
	Damage/Loss of equipment saw a significant increase after 2019, with 87.33% classified as marine incidents.
	Even distribution of SC across different seasons. No relationship between season and accident severity.
	31.3% of SC occurred at night. Most SC happen during the day, but night-time SC are more severe.
	51.6% of accidents reported conditions like fog, overcast, rain, or snow.
	Majority of SC occurred under good wind (50.7%), sea state (62.8%), and visibility (87.5%) conditions.
Contingency analysis (SC)	Serious and very serious accidents are more likely with UK vessels, between 20:01-08:00, during twilight/night.
	Strong relationship between cargo ship accidents and non-UK vessels.
	Poor visibility, moderate wind, and clear weather correlated with higher severity.
	Older vessels are more prone to severe accidents.
	No correlation between vessel length/tonnage and severity.
	Cargo vessels and service ships are strongly correlated with ship casualties, excluding marine incidents.
Trend analysis (OA)	Occupational accidents are predominantly caused by human-related factors under working conditions.
	Overall increase in reported occupational accidents (OA) between 2013 and 2022.
	Marine incidents account for 25.62% of OA, with an increase likely due to improved reporting systems.
	75% of OA involved crew members, with 86.9% on duty at the time.
	Slipping, stumbling, and falling were the most common causes of OA for crew (45.4%).

	Most OA involving crew occurred on the ship (60%), followed by cargo and tank areas (11.26%) and accommodation areas (15.74%).
	Passenger OA commonly occurred in accommodation areas, on stairways/ladders, ship boat decks, or freeboard decks, with slipping being the main cause (78.5%).
	Most passenger OA occurred during daylight and good weather conditions, primarily on passenger ships (55.8%) or recreational ships (16.9%).
Contingency analysis (OA)	High severity OA are less likely on passenger and service ships.
	Passenger injuries are more likely on inland waterway vessels in England and Scotland, especially during the night.
	Crew casualties on fishing vessels are more common in Scotland.
Three-way associations	Results obtained for 95% and then 99% confidence levels.
	Significant associations between occurrence severity, collisions/contacts and ship type.
	Significant associations between occurrence severity, UK regions and vessel type.
	Significant associations between environmental conditions, vessel size and vessel type.
	Significant associations between seasonality, type of occurrence and vessel type.
Logistic regression	Estimated accident probabilities based on various attributes.
	Proven as a powerful tool for binary classification, quantifying relationships between independent variables and likelihood of maritime occurrences.
Bayesian Networks	Medium vessels more likely to be involved in contacts/collisions. Small vessels are more likely to be involved in serious accidents.
	Older vessels more likely to be involved in contacts/collisions and severe occurrences.
	Non-UK vessels more likely to be involved in contacts/collisions and severe occurrences.
	Sea state has the largest impact on severity, with highest change rate (57.89%). Worse sea state is more likely to result in contacts/collisions, as well as more severe accidents.
	Good visibility lowers the likelihood of contact / collision, as well as accident severity.
	Wind force has the largest impact on contact/collision, with highest change rate (32.46%). Even larger impact on severity (48.13% change rate). The stronger the winds, the higher the likelihood of contact/collision, as well as serious accidents.
Complex Networks	This method emphasises the complexity and interconnectedness of risk factors in maritime safety, highlighting the small-world characteristics of accident RIFs networks.
	Ship age and environmental conditions highly influence occurrences.
	Key ship-related factors such as hull materials, gross tonnage, and ship length significantly influence accident occurrences.
	Small ships (e.g., small fishing vessels) are more vulnerabe in high-risk scenarios such as high winds, waves, collisions or emergencies.
Interviews	Participants confirmed the strengths and limitations of the MAIB, AIS and RNLI datasets.
	Industry professionals emphasised the importance of channel depth, traffic density and port protection from sea state or wind force.
	Participants focused more on addressing human factors rather than implementing regulations targeting the analysed factors.

Table 6.4-B. Main findings for the analysis of safety data for the expected impact of autonomous vessels on the safety of ports.

Category	Main findings
Data quality and limitations	Data limitations determined by comparing the number of MAIB investigation reports to their database.
	Data limitations on impact of human factors, which was assumed from literature.
Quantitative analysis	Determined the percentage of occurrences that would be eliminated using AVs in an ideal case.
Interviews	Determined new challenges of using AVs (e.g., cyberattacks, legislation uncertainty).
	Determined further benefits of AVs (cost reduction, efficiency improvement).
Additional findings	Quantitative data needed to be obtained from MAIB investigation reports to maximise the completeness of human-related factors.
	Uncertain field, needs to be addressed using predictive approaches.

Compared to the first case study, the second case study used a different data source (investigation reports) and focused on human-related factors. It employed a different, predictive-oriented methodology.

Table 6.4-C. Main findings for safety data analysis for piracy occurrences, using IMO data of investigation reports.

Category	Main findings
Data quality and limitations	Highlighted the capabilities and limitations of IMO investigation reports.
	Data inconsistency and underreporting, as the IMO relies on voluntary reporting from member states and commercial shipping companies. Shipping companies might avoid reporting to prevent negative publicity or increased insurance premiums.
	States might underreport to downplay piracy severity to protect maritime trade reputation.
	Quality of reports varies significantly. Reported occurrences often lack depth and detail.
	Lack of data on critical factors for this study, such as socio-economic data, geopolitical factors or technological advancements.
Main findings	Could obtain some insightful statistics.
	Very serious attacks associated with daytime, cargo vessels and large groups of attackers.

Compared to the previous case studies, the third one addressed a new issue in order to reflect on the capabilities and limitations of IMO investigation reports. This is because this data source is widely used in the literature, and the findings are assumed to reflect reality.

In conclusion, this chapter achieved a high level of analysis of different data sources. It used mixed methods of analysis and multiple data sources. The limitations of these methods and other methods used in the literature have been emphasised, along with specific limitations of different data types and sources. The following chapter includes the fourth case study of this thesis which addresses a new transport sector, aviation, and a new methodology tailored for the specific needs of the studied field.

7. Analysis of Accident and Incident Data for Private, Recreational Seaplanes

This chapters aims to address the gaps in existing research presented in Chapter 4, by providing GA-specific insights that could lead to improved safety measures and training programs specifically tailored for private, recreational seaplane operations. As previously concluded in Chapter 4, there are currently no comprehensive studies that concentrate on the safety of private, recreational seaplanes, hence the development of the case study presented in this chapter.

General Aviation (GA) is a vital component of the global aviation ecosystem as it is crucial for various purposes, including flight training, agriculture, law enforcement, recreational flying, and emergency medical services. General aviation (GA) plays a significant role in connecting remote communities in Canada, and supporting various economic activities. Its safety is crucial given the large geographical expanse and the reliance on aviation for transportation and logistics (AOPA, 2023). A significant problem of GA is related to seaplane operations, as they carry additional risks due to the environments in which they operate.

The only two studies from the TSB on seaplane occurrence safety analysis mentioned in Section 4.5.2 use data of 1,432 occurrences between 1976 and 1990 (TSB, 1993; TSB, 1994). From 1990 through 2022, there were an additional 1,005 occurrences involving privately registered seaplanes, with a considerable number (118) ending in the aircraft being destroyed. In the 30 years between 1993 and 2022, seaplane accidents in Canada led to 179 fatalities and 401 injuries. This is significant considering that seaplanes make up less than five percent of all GA aircraft.

According to TC (2015), achieving corrective action in aviation has five steps: problem definition, cause identification, corrective action development, corrective action implementation and corrective action impact evaluation. A similar approach is implemented, but only the first three steps are covered in this thesis. This chapter (Chapter 7) analyses occurrences of private, recreational seaplanes in Canada, identifying problems in the system. Further issues are identified in Chapter 8 using a different method. Possible causes are discussed, so that specific mitigation strategies can be proposed.

7.1. Aim and objectives of the aviation case study

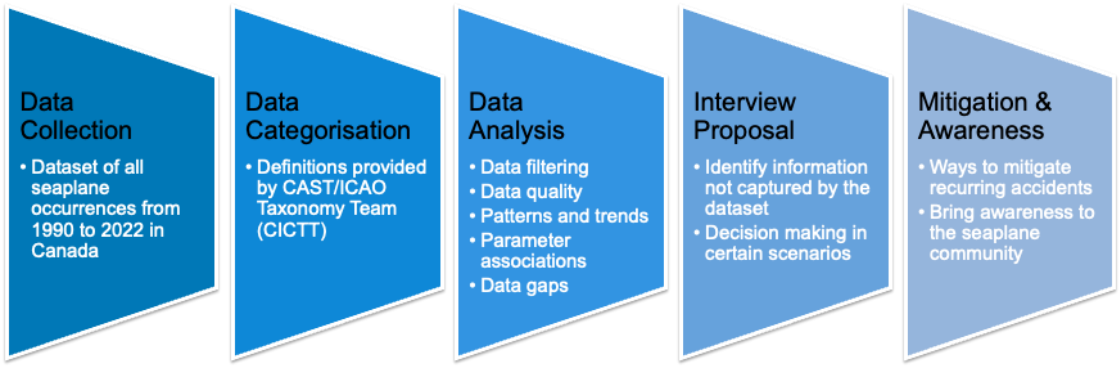
The aim of this case study is to diminish the number of seaplane occurrences in Canada, by meeting the following objectives:

- Collect and filter accident and incident data to create a dataset relevant for private, recreational seaplane operations in Canada.
- Categorise the occurrences to determine their root causes.
- Perform an in-depth analysis of past accidents and incidents of private, recreational seaplane operations.
- Determine further details that had not been captured by the previously analysed data, such as pilot concerns and decision making during pre-determined scenarios.
- Enhance safety awareness within the seaplane GA community in Canada.

7.2. Methodology of the aviation case study

This section briefly describes the methodology used for the aviation case study presented in Chapter 7, in Figure 7.2. It includes data collection methods (Section 7.3), data categorisation (Section 7.4), data analysis (Section 7.5), interview proposal (Chapter 8), and proposed mitigation and safety awareness (Section 7.7). This methodology fits into the methodology of this thesis, which is shown in Figure 5.4 (Section 5.4) and follows the analysis framework presented in Section 5.2.

Figure 7.2. Methodology used for the aviation case study of seaplane accidents and incidents in Canada.



7.3. Description of the database of seaplane occurrences in Canada

This section describes the database used in this chapter for the study of factors underlying private, recreational GA seaplane occurrences in Canada. Then, data quality is assessed using the methodology proposed in Section 5.6 of this thesis.

7.3.1. Database description – Seaplane occurrences

The original data set obtained from Transport Canada (TC) includes 1,771 seaplane occurrences (accidents and incidents) in Canada, from 1990 to 2022. Before obtaining the data, a set of ideal data fields has been created, which can be compared to the actual data set and see how accurate the subsequent analysis can be. Certain data fields that were ideal but missing from the actual data set could be obtained from the occurrence narratives, such as number of injuries and deaths. Table 7.3-A shows a breakdown of the data fields, sorted according to different categories and compared to the ideal data fields that were initially required for a high quality analysis of seaplane occurrences. TC provided a comprehensive data set, however some of the data fields had to be derived from the narratives, such as the cause of the occurrence (categorisation), number of injuries and fatalities and route. All data fields are expected to add value to the analysis.

Table 7.3-A. Data fields of seaplane occurrences obtained from Transport Canada, compared to the desired information for the analysis (ideal data fields)

Category	Ideal data fields		Data field topic
General information	Case ID	✓	Occurrence Number
	Date of occurrence	✓	Occurrence Date
	Date of notification	✗	n.a.
	Time	✓	Occurrence Time
	Accident type (Categorisation)	✓	1st Occurrence Category (inferred from narrative)
	Severity	✗	n.a.
	Number injuries	✓	(inferred from narrative)
	Number fatalities	✓	(inferred from narrative)
	Phase of Flight	✓	Phase Category
	Economic Cost	✗	n.a.
	Accident Description	✓	Narrative (EN)
Surrounding environment details / Context	Route – Direction	✓	(inferred from narrative)
	Latitude & Longitude	✗	n.a.
	Location	✓	Occurrence Province/State
	Location description	⚠	(can sometimes be inferred from narrative)
Aircraft details	Identification	✓	Aircraft Mark
	Category	✓	Aircraft Category
	Damage Level	✓	Aircraft Damage Level

	Amateur build	✓	Aircraft Amateur Built Flag
	Tonnage	✓	Aircraft Weight Category
	Registration Type	✓	Aircraft Registration Type
	Number of Engines	✓	Number of Engines
	Landing Gear	✓	Aircraft Landing Gear
	Speed at Occurrence	✗	n.a.
	Age	✗	n.a.
	Flag State	✓	Aircraft Country of Registration Name
	Mechanical Failure Details	⚠	(can sometimes be inferred from narrative)
Details of affected people	ID Injured Person	✗	n.a.
	Gender	⚠	(can sometimes be inferred from narrative)
	Age	✗	n.a.
	Type (pilot or passenger)	✓	(inferred from narrative)
	Part of Injury	⚠	(can usually be inferred from narrative)
	Actions, PPE, precautions, etc.	⚠	(can sometimes be inferred from narrative)
	Physical Condition of Injury	⚠	(can sometimes be inferred from narrative)
Human performance	Experience	✗	n.a.
	Training	✗	n.a.
	Fatigue	✗	n.a.
	Mental Status/health of Captain	✗	n.a.
	Accident History of person involved	✗	n.a.
	Negligence or carelessness	✗	n.a.
	Blood Alcohol Content	✗	n.a.
Environmental conditions	Visibility	⚠	(can sometimes be inferred from narrative)
	Weather	✓	Weather Condition
	Wind Force	⚠	(can sometimes be inferred from narrative)
	State of the Water Surface	✗	n.a.
	Light	✗	n.a.

7.3.2. Data filtering and cleaning – Seaplane occurrences

After data cleaning and filtering through the 1,771 seaplane occurrences, a new data set of 1,005 occurrences from 1990 to 2022 has been created. The following filters have been used, to include occurrences only for private, recreational seaplane operations:

- Aircraft category - Glider and Helicopter occurrences have been removed, to focus on float and amphibious recreational seaplane operations only. The reasons are that gliders are not capable of having floats attached to them, and that there are very few helicopters with floats attached in Canada. Additionally, the analysis focuses on fixed wing aircraft and not helicopters, to allow for a deeper dive into occurrences of these aircraft categories.

- Aircraft Registration Type - Only “Private” is considered (“Commercial”, “Corporate”, “Manufacturer”, “State”, and “Other” are removed).
- Aircraft Weight Category - Only “0 – 2,250 kg” aircraft are considered, to include only recreational operations.

Data cleaning comprised of the following:

- Checks for occurrences with too much incomplete data.
- "Unknown", "Missing" or "No Data" have been recoded as blank cells.
- Missing cells have been derived from the narratives, where possible, for the “Phase of flight” and “Aircraft damage level” data fields.
- “Aircraft Manufacturer Model Series” - completed as "Amateur Built Aircraft" as, for those, the cells were left empty.
- The number of injuries and fatalities has been derived from the narratives.

One reason for including only occurrences for private, recreational seaplane operations in the analysis is that the training and regulatory requirements differ between commercial and private operations. This can influence pilots’ decision-making process, as private pilots may be indirectly affected by a variety of factors that are not as prevalent in commercial aviation, and conversely. For instance, private pilots might have less rigorous training, or they might not fly as often as commercial pilots.

Another reason is that there is a gap in existing research when it comes to the safety of private, recreational seaplanes, which has been addressed in Section 4.4. This is a very important sector since it includes flight training units, which play a vital role in shaping the skills and safety practices of new pilots, and it represents the majority of seaplane occurrences (in this case, 57.04%). This is significant considering that seaplanes make up less than five percent of all GA aircraft. By addressing this gap, this case study aims to provide insights that could lead to improved safety measures and training programs specifically tailored for flight training units and private, recreational seaplane operations.

Given the unique challenges and risks associated with recreational seaplane flying, such as varying levels of pilot experience and the diverse environments in which recreational seaplane pilots may operate, it is imperative to conduct a thorough analysis of this sector. The analysis of this subset of occurrences is important so that specific challenges can be understood and addressed. This will not only help in identifying specific safety issues, but also in formulating targeted recommendations to enhance the overall safety of private seaplane aviation. Ultimately, the goal is to ensure that pilots, trainees, and other stakeholders in the private seaplane community can benefit from improved safety

practices, thereby reducing the number of accidents and enhancing the overall safety of this important sector.

7.3.3. Data quality assessment – Seaplane occurrences

Table 7.3-B shows the DQA and the scores obtained. While the scores of “Accessibility” and “Consistency” are high, above 70%, "Completeness" and "Relevance" scored 62.77% and 47.4%, respectively. Most data fields were explicit, but some were inferred from the narrative (Number of injuries and fatalities, Route and some Details of affected people), and one was implicit (Accident type, which had to be deducted from the narrative according to the Aviation Occurrence Categories definitions of the International Civil Aviation Organisation). However, if the “Human performance” and “Environmental conditions” categories are removed from the analysis, the scores for "Completeness" and "Relevance" increase to 73.85 % and 66.1%, respectively. Therefore, alternative analysis will be conducted for these categories in addition to the analysis of the seaplane database from TC. Chapter 8 presents the additional analysis undergone that includes the “Human performance” category.

Table 7.3-B: Results of the Data Quality Assessment for private, recreational seaplane occurrences in Canada.

Factors underlying seaplane occurrences in Canada	
Agency	Transport Canada (TC)
Source	Database
Area covered	Canada
Study period	1990 - 2022
Sample size	1,005
Data Quality Dimension	
Accessibility	73.6 %
Completeness	62.77 % [73.85 %]
Consistency	70.4 %
Relevance	47.4 % [66.1 %]
Accuracy	High (the data is consistent with the narratives)
Credentials / Credibility	It is assumed that the data is obtained from a reliable and credible source
Interpretability	It is assumed that the reporter, TC and the analyst have similar understanding and interpretation of data fields
Timeliness	Not available, as the date of notification is not available
Security	Assumed secure
Value-added	Assured for all data fields
Narrative richness	Detailed (75.48%)
	Narrative length (> 50 words) 88.36%
	Mechanical Failure 75.12 %
	Details of affected people 75.87%
	Environmental conditions 62.55%

The dimension “Timeliness” could not be calculated, which is important as a longer time between when an occurrence happened and when it was reported might indicate that some information could

have been forgotten and therefore missed. The date an accident is reported is not a requirement when reporting an occurrence. However, according to Transport Canada Civil Aviation (Transport Canada, 2024), because of the Civil Aviation Daily Occurrence Reporting System (CADORS), detailed input of a reported accident or incident should be expected within one week.

Keeping categories that are incomplete such as “Human performance” and “Environmental conditions” in this case can provide misleading results. The analysis of accident data is often limited by the completeness and accuracy of the available data. If certain critical categories are incomplete or missing, the analysis may lead to incorrect conclusions and affect the overall reliability of the findings, which highlights the importance of undertaking a data quality assessment and redefining the scope of the case study if necessary, as described in Section 5.6.

Although TC’s database is official and reliable when it comes to seaplane activities, a data gap can be observed when it comes to “Human performance”. Thus, in order to be able to have results of high quality, since obtaining data related to human performance is not possible, another method that will complement the data analysis has to be considered. A relevant study is the paper by Irwi, Sedlar and Hamlet (2019), which aims to understand how pilots evaluate risks relevant to flight, by looking at their assessment and management strategies across various risk types. The study uses an online vignette method, presenting pilots with 12 go/no-go take-off decision scenarios across four risk categories. This type of analysis, focusing on pilots' decision-making processes, adds a crucial dimension to accident data analysis. It provides insights into the subjective nature of risk perception and decision-making, offering a deeper understanding of the factors influencing pilots' choices in different scenarios. In our case, this approach is vital as it complements traditional accident data analysis, so a series of interviews, focus groups and a questionnaire are conducted to determine the extent in which the category “Human Performance” in Table 7.4.1 contributes to a seaplane occurrence and its severity (detailed in Chapter 8).

Even though the level of detail of “Environmental conditions” narrative was 62.55%, the “Environmental conditions” category is not reliable for full analysis, so it is also removed from the scope of the analysis. Even though “Visibility” and “Wind force” can sometimes be inferred from the narratives, in cases where these data fields actively impact the occurrence, they do not offer enough information or any information at all, and information about them is often available in occurrences that have not been impacted by visibility or wind (e.g. “no wind”, “clear sky”, “good visibility”). This category has therefore been removed from the scope of this analysis.

Although the level of detail of “Mechanical Failure” narrative was 75.12 %, this is mainly made of occurrences where mechanical failure was not a contributory factor and, in most cases where this information would have been relevant, details of mechanical failures were missing. This highlights the importance of separately looking into the completeness of data fields that are specific for only certain accident / incident types, or a portion of the occurrences, as a high score may be misleading since for most occurrences this information is not applicable and is recorded as such. Therefore, the mechanical failure needs separate analysis so areas of concern can be determined, and this becomes outside the scope of this thesis.

Furthermore, the underreporting of seaplane accidents and incidents poses a significant limitation. This underreporting can occur for several reasons, including pilots not being required to report minor incidents, fear of punishment or negative repercussions, and lack of awareness or understanding of reporting requirements. This results in incomplete datasets, which can skew the analysis and lead to an inaccurate understanding of the true safety conditions and risk factors associated with seaplane operations. To mitigate this, efforts should be made to encourage comprehensive and accurate reporting of all incidents, regardless of their perceived severity, and to ensure that pilots and other stakeholders understand the importance of thorough reporting for improving overall safety.

7.4. Occurrence categorisation

The narratives of all seaplane occurrences have been read and analysed in order to identify their root cause or causes (up to 4 causes). These could be related to weather conditions, visibility, wind, loss of control, mechanical errors, human errors in making decisions or in operating the plane, the reason for pilots making certain decisions (such as to fly low), missing emergency equipment from the plane and so on. This was a particularly timely task and included all 1,771 seaplane accidents and incidents from January 1990 to December 2022. Table 7.4 shows the categorisation for the private, recreational seaplane occurrences that are considered for analysis in this chapter. Section 4.3.4. explains the categories used during this process.

Table 7.4. Categorisation of private, recreational seaplane occurrences in Canada, from 1990 to 2022.

Categorisation	Description	Count	%
LOC-I	**Loss of Control–Inflight**	**165**	**16.4%**
SCF-PP	**System/Component Failure or Malfunction (Powerplant)**	**141**	**14.0%**
ARC	**Abnormal Runway Contact**	**139**	**13.8%**
LOC-G	**Loss of Control–Ground**	**122**	**12.1%**
SCF-NP	System/Component Failure or Malfunction (Non-Powerplant)	77	7.7%
CTOL	Collision with Obstacle(s) During Take-off and Landing	71	7.1%
UNK	Unknown or Undetermined	65	6.5%
FUEL	Fuel Related	48	4.8%
UIMC	Unintended Flight in IMC	32	3.2%
LALT	Low Altitude Operations	25	2.5%
AMAN	Abrupt Manoeuvre	24	2.4%
OTHR	Other	24	2.4%
CFIT	Controlled Flight Into/Toward Terrain	12	1.2%
RAMP	Ground Handling	11	1.1%
GCOL	Ground Collision	8	0.8%
RE	Runway Excursion	7	0.7%
TURB	Turbulence Encounter	7	0.7%
WSTRW	Wind Shear or Thunderstorm	7	0.7%
MAC	Airprox/TCAS Alert/Loss of Separation/(Near) Midair Collisions	6	0.6%
USOS	Undershoot/Overshoot	4	0.4%
ICE	Icing	3	0.3%
F-NI	Fire/Smoke (Non-Impact)	2	0.2%
ATM	ATM/CNS	1	0.1%
ADRM	Aerodrome	1	0.1%
BIRD	Bird	1	0.1%
EXTL	External Load Related Occurrences	1	0.1%
MED	Medical	1	0.1%

Since the document used for categorisation is not specific for seaplanes, and in particular not tailored for private, recreational operations, there were some difficulties categorising some of the occurrences. Below are some examples of challenging categorisation, the assumptions made, and the proposed mitigation:

- Occurrences such as collisions with obstacles during take-off and landing (such as logs or submerged rocks) were categorised as CTOL, even if the aircraft was not airborne when the

collision occurred (as per the definition of CTOL), as it was in line with the category's objectives and it could not be fitted in any other occurrence category.

- When loss of control in flight was mentioned, but there was no information about other possible causes such as the condition of the engine or fuel, LOC-I was used. In this case, it was assumed that all relevant information was present in the narratives.
- When a seaplane attempts a forced landing on a body of water and the aircraft lands short of the runway, the definition of USOS specifies that it should not be used for emergency landings off airports, however, seaplanes are a special case since they are able to land on any body of water, so USOS was used (unless emergency landing was mentioned in the narrative).
- Overweight aircraft could not be fitted in any of the categorisation definitions.
- Occurrences with pilots who do not hold any permit or licence to operate an aircraft could not be fitted in any of the categorisation definitions. In this case the fact that the pilot did not have a licence was disregarded and the occurrence was categorised according to the narrative.
- Engine failure after one fuel tank was ran dry, when trying to switch to the other tank, which was not empty, was categorised as SCF-PP. It was assumed that, since fuel was present in one tank, the engine should not have failed.

TSB reports have also been checked when present, as they include this categorisation. In a few cases, the categorisation in the TSB report was unexpected after reading only the narrative from the dataset, as new information was present in the TSB report. Generally, where a TSB report was not available, it was assumed that all relevant information about the occurrence was present in the narrative.

7.5. Analysis of seaplane occurrences in Canada

Mixed methods of analysis have been used to analyse the dataset of seaplane occurrences in Canada, as previously presented in Section 5.2. Table 7.5-A describes the dataset and types of analysis employed.

Table 7.5-A. Description of the accident / incident dataset for private, recreational seaplanes, and types of analysis employed

Location, Years, Data count/type, Source	**Method of Analysis**	**Reason**
- Canada - 1990 to 2022 - 1,005 private, recreational GA seaplane occurrences - Transport Canada	Narrative analysis	To extract further information and improve the quality of the analysis. It includes the occurrence categorisation.
	Trend analysis	Calculate trends and determine patterns. These results are used in the subsequent analysis.
	Contingency analysis	To detect potential associations and relationships between two variables.
	Three-way associations	To detect potential associations and relationships between three variables.
	Bayesian Networks	More advanced tool for modelling probabilistic relationships between variables.
	Prediction models	To predict accidents based on associations of different accident causation factors.
Chapter 8	Interviews with industry professionals	Engagement with industry professionals to discuss the data analysis results and assess mitigation methods.
	Focus groups with pilots and industry professionals	Engagement with seaplane pilots to determine potential factors not included in the database and bring awareness on current areas of concern.
	Questionnaire for pilots	Engagement with seaplane pilots to determine potential factors not included in the database

7.5.1. Narrative analysis

An extensive narrative analysis has been undergone to identify information missing from the dataset in order to increase data completeness and quality. An example is the occurrence categorisation, which was explained in Section 7.4 and required a timely analysis of all narratives. Additionally, the missing cells of the “Phase of flight” and “Aircraft damage level” data fields were derived from the narrative, where possible. The narratives have also been used to infer the number of injuries and fatalities, which is an important metric in determining the severity and implications of seaplane occurrences.

Most narratives offered detailed but concise information about the occurrence. The word count of the narratives ranged from 7 to 1,350 words, with an average of 108.79 words. The low number of words in some cases (under 50 words for 11.64% of the narratives) did not have an impact on occurrence categorisation, and the average word count for the narratives of the occurrences categorised as “Unknown” is 99.53.

The languages used are either English or French, since these are the official languages spoken in Canada, with equal status and rights in federal institutions. Consequently, occurrences can be reported in either English or French. Below is an example of a narrative, in the most common format:

"*C-IGSC, a privately registered float-equipped Spectrum Aircraft Beaver RX 550 basic ultra-light aircraft, was conducting a takeoff on Setting Lake, MB with only the pilot on board. During the initial climb at approximately 75 feet AGL, the engine (Rotax 503) completely lost power. While attempting to conduct a forced landing on the lake, a float dug into the water and the aircraft capsized. The pilot was able to evacuate the aircraft with a minor injury. The aircraft sustained substantial damage. The pilot was pulled out of the water by local cottagers and then taken to hospital for observation.*"

7.5.2. Trend and contingency analysis

The dataset of seaplane occurrences for private, recreational operations has been analysed around the following variables:

- Year
- Landing Gear
- Phase of Flight
  - Take-off
  - Climb
  - Landing
- Aircraft Damage Level
- Injuries and Fatalities

Trends / Year of occurrence:

Even though the USA has the most seaplanes in the world, on average, their number of seaplane occurrences is decreasing over the years, as shown in Figure 7.5-B. In Canada, a similar overall trend is observed, with the average number of seaplane occurrences decreasing over the years, but higher yearly numbers are observed compared to the USA (Figure 7.5-A). Moreover, when specifically looking at private, recreational seaplanes, the data tells a different story. The number of occurrences involving recreational GA seaplanes is actually showing an increase over the years. This indicates that, while general seaplane safety may be improving, especially in the commercial world, there are unique challenges and risks associated with private, recreational seaplane operations that need to be addressed through research and focused safety initiatives. It should also be noted that Covid restrictions impacted the number of flights in 2020-2021.

The accurate calculation of occurrence rates for seaplanes presents a significant challenge due to the deficiency of data on seaplane movements, or on the yearly number of hours flown by seaplane pilots.

This issue is particularly relevant in the context of private recreational seaplanes in Canada, where specific data is not available. One of the primary issues highlighted by Ison (2024) is the lack of detailed data on the seaplane fleet and the cadre of seaplane pilots in the US, which makes it difficult to calculate accurate accident rates because comprehensive records of flight hours, pilot experience and operational contexts are often incomplete or unavailable. During the Seaplane Working Group meetings, the same issue was brought up for Canada.

Figure 7.5-A. Number of seaplane occurrences per year, for all seaplane occurrences vs for only private, recreational operations.

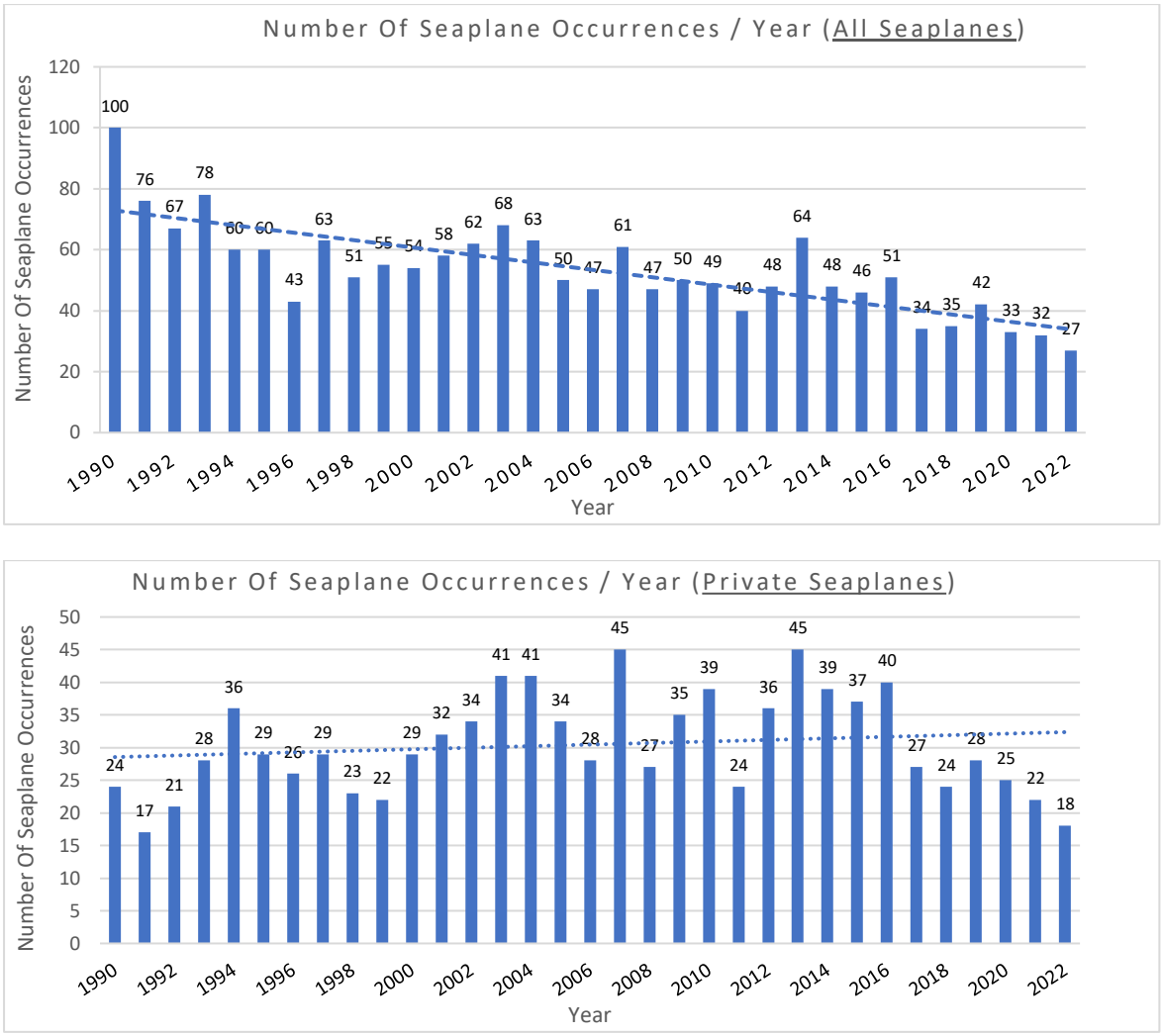


Figure 7.5-B. Number of seaplane occurrences per year in the United States of America (Ison, 2024).

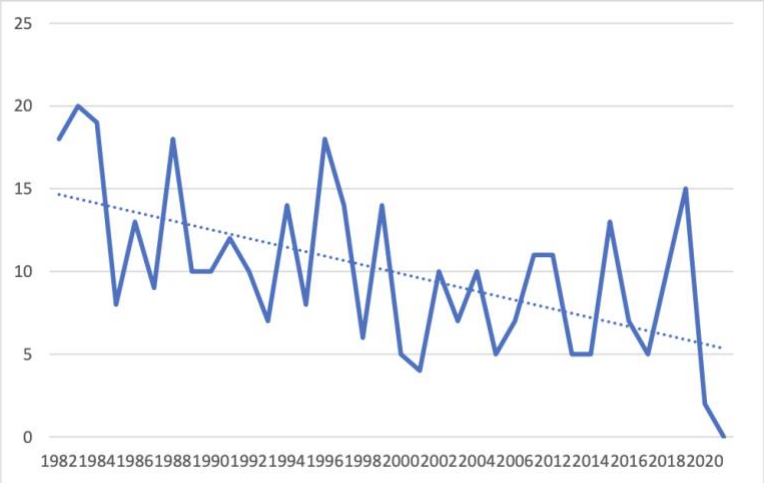
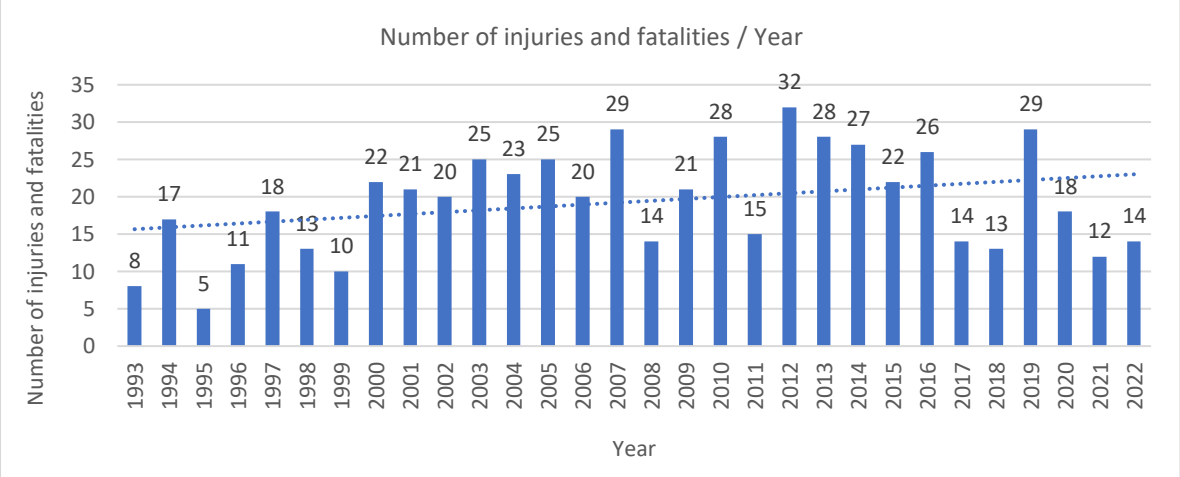


Figure 7.5-C. shows how the number of injuries and fatalities fluctuates over the years, with an ascending trendline. Since it is not possible to calculate the number of injuries and fatalities per hours flown or number of flights, the aim of this case study became to reach an overall decrease in the number of lives lost and injured people in the coming years, by adopting relevant measures based on the work in this thesis. The probable impact of Covid restrictions on the number of flights in 2020-2021 should be noted. Also, a high number of narratives for 1990-1992 made it impossible to determine the number of injuries and fatalities, so these three years have been removed.

Figure 7.5-C. Number of injuries and fatalities per year, for private, recreational seaplane operations in Canada.



The number of occurrences per year for private, recreational seaplane operations using amateur built aircraft shows an increasing trend over the years. Before 2003, this could be due to the rising popularity and, therefore, activity in the sector. After 2003, the numbers stabilise around a consistent average, which can be attributed to improved safety and a more experienced and knowledgeable

community, along with regulatory enhancements. However, improvements can be made so that, in the future, amateur built aircraft become safer, with a decreasing trend in terms of number of occurrences.

Figure 7.5-D. Number of occurrences per year for private, recreational seaplane operations using amateur built aircraft, in Canada.

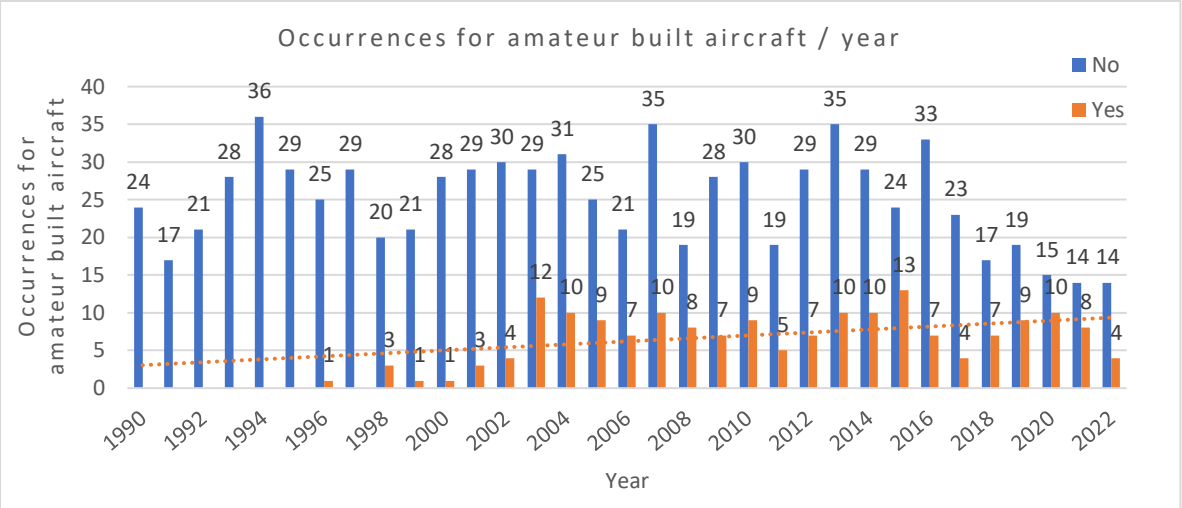


Figure 7.5-E illustrates the annual occurrences of different damage levels to aircraft from 1990 to 2022. 85% of the damage levels are "substantial", followed by 11.6% for “destroyed” aircraft. This proves that no matter what the cause of the accident is, there is a great possibility of causing serious damage or even destruction of the seaplane. The most notable trend is the fluctuation in the number of substantially damaged aircraft, which, in the last 10 years, has seen a gradual decline. The number of destroyed aircraft remains relatively stable and low throughout the period, but with an increasing trendline (Figure 7.5-F). The concerning aspect is the high and variable rate of "Destroyed" aircraft, indicating potential severe safety issues in these operations. Occurrences with less than major structural problems with the aircraft are not required to be reported, unless there has been a death, injury, missing aircraft or collision (Transport Canada, 2024), which is reflected in the low numbers of occurrences where the aircraft had minor or no damage.

Figure 7.5-E. Aircraft damage level per year, for private, recreational seaplane operations in Canada.

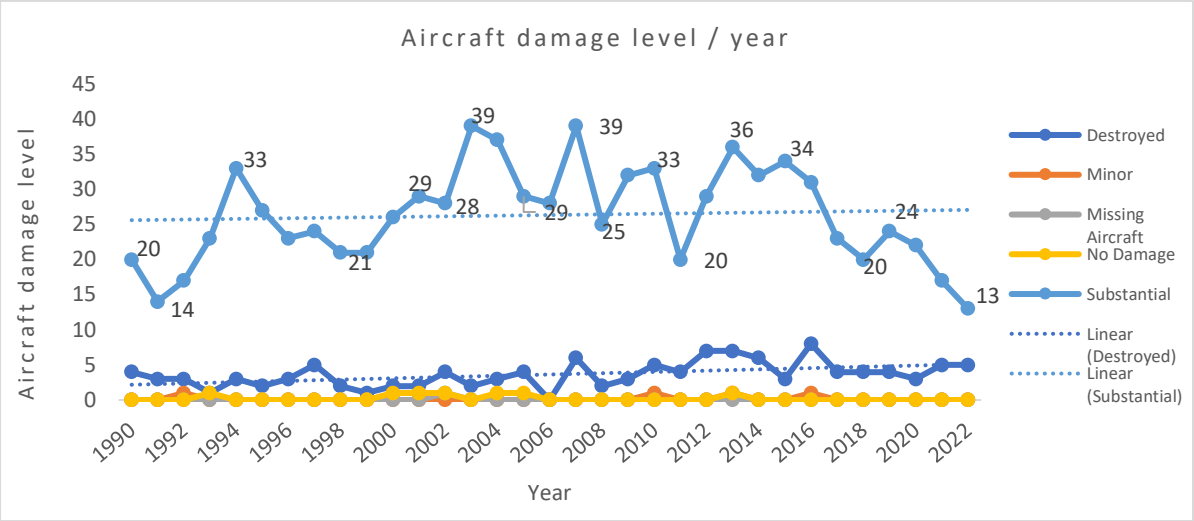


Figure 7.5-F. Number of destroyed aircraft per year, for private, recreational seaplane operations in Canada.

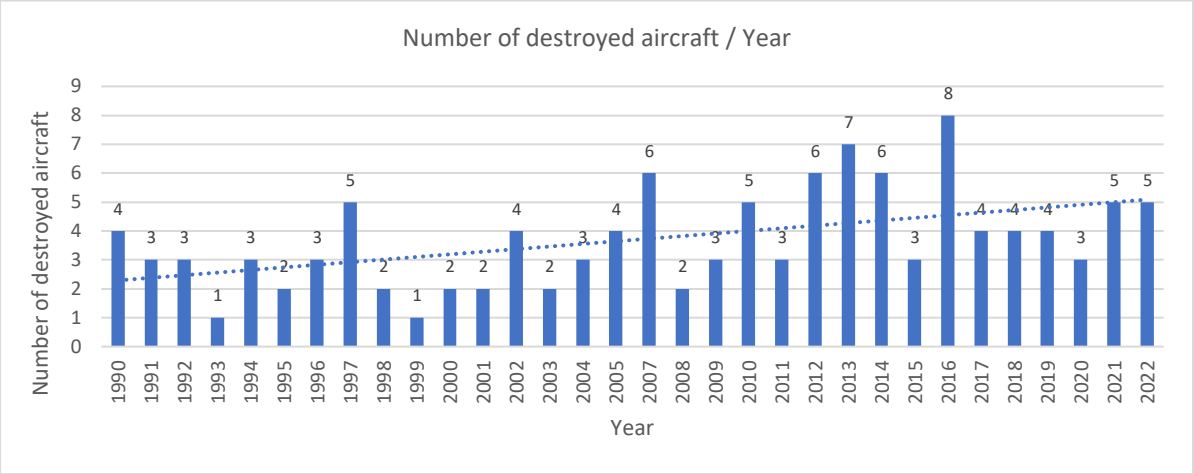
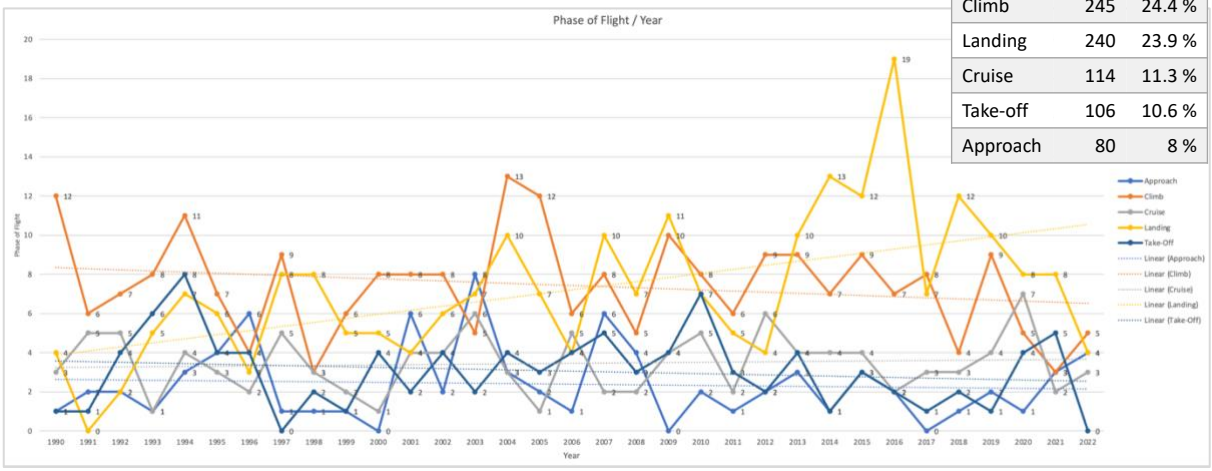


Figure 7.5-G shows that the climb and landing phases are the most hazardous for private, recreational seaplane operations in Canada, accounting for 24.4% and 23.9% of occurrences, respectively. The trendlines for climb, take-off and approach are slightly decreasing, and constant for cruise, but the one for landing is increasing sharply, following a peak period between 2013 and 2019. Loss of control during climb is the most recurring occurrence, and it could be because pilots tend to fly very slow, there is a lot of drag, and also a lot of things happening as the aircraft is into transition towards a stable position.

Figure 7.5-G. Number of occurrences during the top 5 phases of flight, for private, recreational seaplane operations in Canada.

Phase	Count	%
Climb	245	24.4 %
Landing	240	23.9 %
Cruise	114	11.3 %
Take-off	106	10.6 %
Approach	80	8 %



Trends / Landing Gear

The distribution of the landing gear across the private, recreational seaplane occurrences is: 67.36% float, 28.26% amphibious (float-wheel and hull-wheel), 4.08% water landing aircraft and 0.3% hull. The last occurrence for a water landing aircraft was in 2005, and this category was used for unknown landing gear. Hull landing gear refers to flying boats, which are not used that often in Canada anymore.

The number of float seaplanes in Canada is expected to be higher than amphibious aircraft, even though exact numbers could not be obtained, hence the difference in the number of occurrences for these categories. Figure 7.5-H illustrates the number of occurrences across different phases of flight, for different landing gear. The data indicates that seaplanes with float landing gear experience the highest number of occurrences, particularly during the climb (27.32%) and landing (20.38%). Amphibious float-wheel and hull-wheel configurations show a notable number of occurrences during landing (32.75%) and climb (18.31%).

Figure 7.5-H. Phases of flight for occurrences of recreational GA seaplanes with different landing gear.

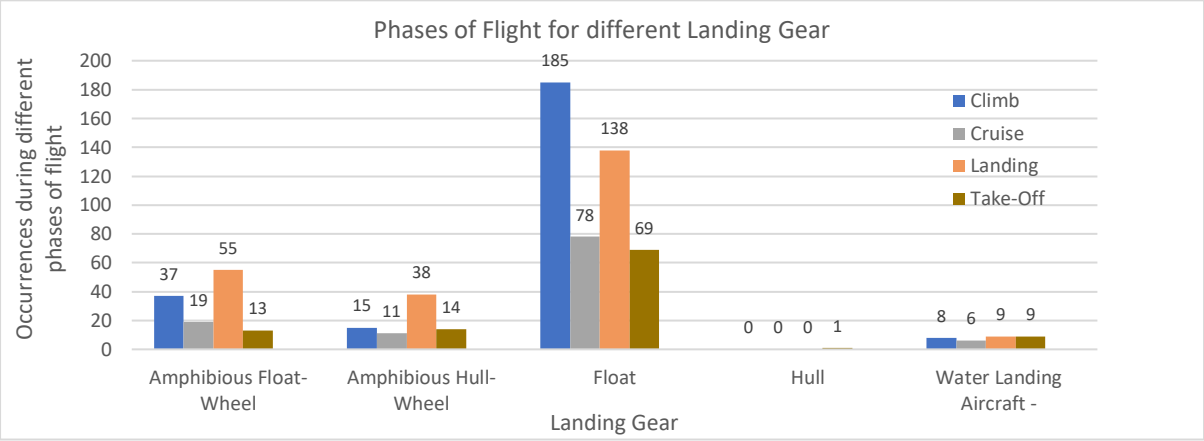
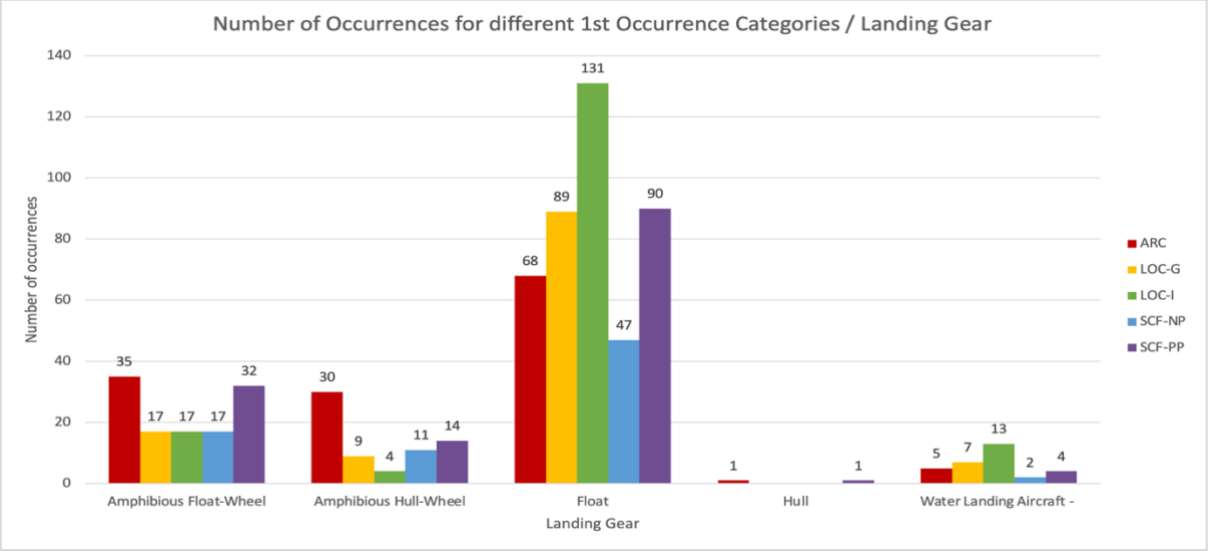


Figure 7.5-I illustrates the number of occurrences for different first occurrence categories, per different landing gear. The data shows that float-equipped seaplanes have the highest number of occurrences across all categories, particularly in "LOC-I" (Loss of Control in Flight) with 131 incidents, followed by “SCF-PP” (System Component Failure - Powerplant) and "LOC-G" (Loss of Control-Ground). Amphibious float-wheel and hull-wheel configurations also show significant numbers of occurrences, though to a lesser extent.

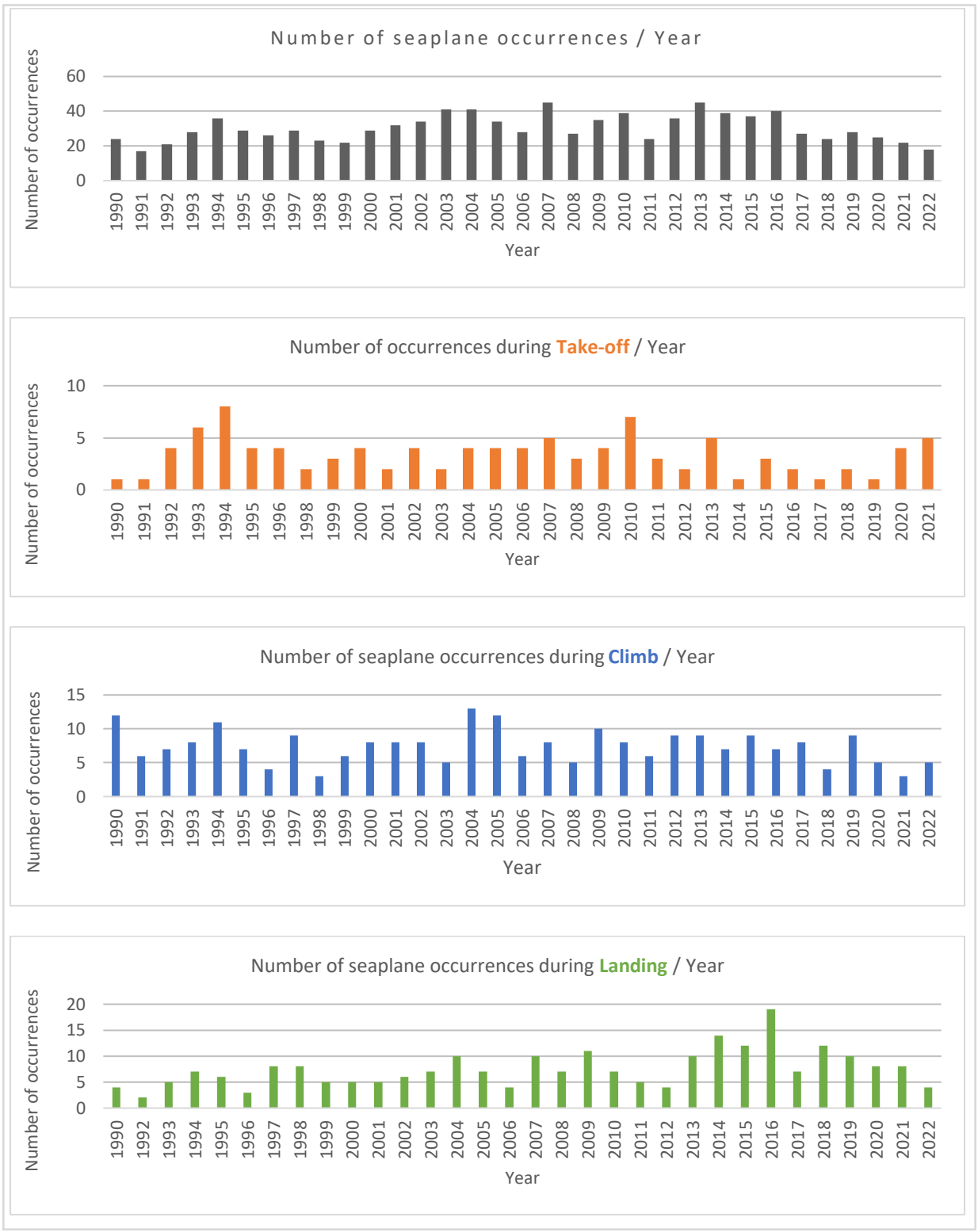
Figure 7.5-I. Number of occurrences for different categorisation, per different landing gear, for private, recreational seaplane operations in Canada.



Trends / Phase of flight

Figure 7.5-J shows trends for the most concerning phases of flight, in terms of number and severity of occurrences, compared to the trend for the total number of private, recreational seaplane occurrences (this includes all phases of flight). These are Take-Off, Climb and Landing. Compared to the overall trend in seaplane occurrences, which shows fluctuations over the years, with notable peaks and declines, the take-off phase shows varied occurrences with several peaks, indicating intermittent periods of increased risk. Despite a low profile for take-off in 2011-2019, 2020 and 2021 show the highest number of occurrences in the past 10 years, despite covid restrictions in those years. The climb phase also presents significant numbers, with fluctuating numbers across the studied period. The data for **landing** shows an increasing trend in occurrences from around 2013 onwards, peaking notably in 2016. This indicates a possible shift in the underlying factors contributing to landing incidents, such as changes in operational procedures, increased seaplane activity, or variations in reporting practices.

Figure 7.5-J. Number of occurrences per year, for Take-Off, Climb and Landing, for private, recreational seaplane operations in Canada.



Other trends related to phases of flight show that the climb phase has the highest number of destroyed aircraft (43 or 17.55% of the occurrences during climb result in destroyed aircraft, and

35.83% of the number of destroyed aircraft occurred during climb), followed by the cruise phase (22 or 19.13% of the occurrences during climb result in destroyed aircraft, and 18.33% of the number of destroyed aircraft occurred during climb).

Trends / Aircraft Damage Level

Exploring the relationship between different accident causes and Aircraft Damage Level can reveal whether there are significant differences in the degree of damage suffered by aircraft under different accident causes, thereby providing information for safety management and flight operations. Some statistics including the number of destroyed aircraft have already been presented, and the main results are summarised here. Over the years, most the studied occurrences resulted in the aircraft being substantially damaged (87.02%), followed by destroyed (11.87%). 63.56% of the accidents where the aircraft was destroyed involved float landing gear, while 21.17% involved amphibious. However, when compared to the number of accidents for these landing gears, only 11.08% of the float occurrences resulted in destroyed aircraft, compared to 14.44% for amphibious. The majority of destroyed aircraft was as a result of an accident during climb (36.44%), or caused by loss of control in flight (25.42%) and unknown cause (23.73%), followed by engine failure. This means that loss of control and engine failure pose a significantly greater threat to the aircraft in a seaplane accident. These numbers are important because they highlight the gravity of seaplane accidents.

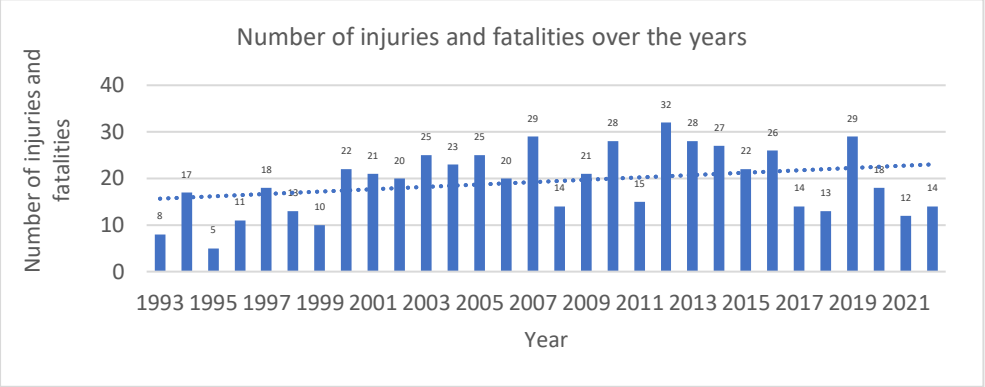
Trends / Injuries and Fatalities

In the past 30 years (between 1993 and 2022), private, recreational seaplane occurrences in Canada led to 179 fatalities and 401 injuries. This is significant considering that seaplanes make up less than 5% of all GA aircraft, and the percentage for private, recreational is even lower. Most injuries and fatalities occur after loss of control in flight (20.34%), followed by engine failures (14.31%) and unknown cause (12.07%). When considering the number of injuries alone, the proportions are similar for loss of control in flight (21.2%) and engine failures (18.7%), but these are followed by abnormal runway contact (12.72%). However, when looking at fatalities alone, the majority occurred during unknown circumstances (32.96%), followed by loss of control in flight (18.44%).

Regarding the number of injuries and fatalities by phase of flight, the climb phase shows the highest number of injuries (255 or 63.59%) and fatalities (73 or 40.78%), followed by the cruise and landing phases. These figures indicate that the climb phase not only has a high number of occurrences, but also results in significant injuries, fatalities and destroyed aircraft, highlighting the critical need for enhanced safety measures during this phase to mitigate severe outcomes.

Figure 7.5-K outlines the number of injuries and fatalities over the studied period, showing an increasing trendline.

Figure 7.5-K. Number of injuries and fatalities per year, for private, recreational seaplane operations in Canada.



7.5.3. Three-way associations

Given the categorical nature of most of these variables, the Chi-Square test was chosen to provide possible associations between any three of the binary variables in Table 7.5-B. The Chi-Square test was employed to expand on the trend and contingency analyses for a deeper dive into how associations of different parameters affect an occurrence.

The p-value indicates the statistical significance of the association, with lower p-values, meaning stronger evidence against the null hypothesis, for statistically significant relationships (p-value under 0.01 means 99% confidence level). The phi-value measures the strength of the association, with higher phi-values indicating stronger relationships. Based on this, the strength of the relationship is determined (weak, moderate or strong).

Results are obtained for 99% confidence level. Lower confidence levels of 95%, 90% and 80% were also tested for, even though these are less significant, but have not been presented in this thesis. For each combination of three variables, the following steps have been employed:

- Recode the columns into binary variables.
- Construct a contingency table.
- Perform a Chi-Square test.
- Compute the p-value
- Compute the strength of the association (using phi-value).

Permutations of the parameters in Table 7.5-B have been used to test for three-way associations. These have been recoded and converted into binary variables, as shown in Table 7.5-B, to help

understand the meaning of the associations. In some cases, such as for the "Time" parameter which had many possible outcomes, these were grouped to reflect the part of the day (morning & evening, daytime and night-time) and therefore have only 3 possible outcomes that are also more relevant for the analysis. This is represented as "Reason 1" in the table. In other cases, such as for the "Phase of Flight" parameter, some possible outcomes were grouped into a "Other" binary variable, so that the focus can be on the other phases of flight which were deemed of interest during the trend and contingency analyses. This was done in general for the least frequent outcomes, to avoid binary parameters with a low expected count, as those would not provide accurate results. This is represented as "Reason 2" in the table.

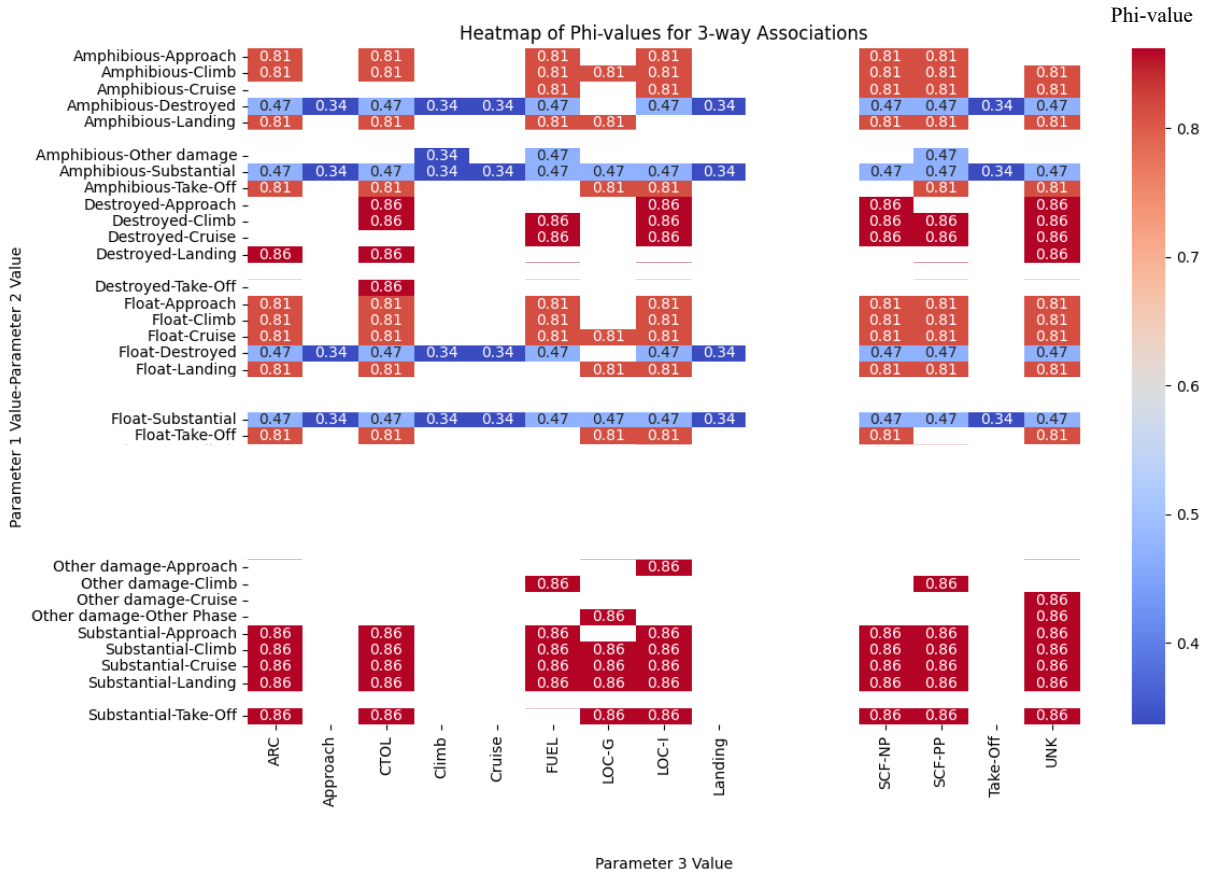
Table 7.5-B. Parameters used to test for three-way associations.

Parameter	Binary variables	Count	Description / Reasoning
Year	1990-2000	284	Separated the years into 3 groups of equal number of years. Reason 1.
	2001-2011	380	
	2012-2022	341	
Month	May-October	935	Grouped into flying season (May-October) and outside flying season (November-April). Reason 1.
	November-April	70	
Time	Daytime (11:00-17:59)	602	Grouped to reflect the part of the day. Reason 1.
	Morning & Evening (05:46-10:59 & 18:00-21:59)	367	
	Night-time (10pm-05:45am)	36	
Occurrence Province/State	Alberta	40	Categories grouped into the "Other" category: "New Brunswick", "Northwest Territories", "Nova Scotia", "Nunavut", "Saskatchewan" and "Yukon". Reason 2.
	British Columbia	155	
	Manitoba	36	
	Newfoundland and Labrador	37	
	Ontario	343	
	Quebec	330	
	Other Province/State	64	
Aircraft Category	Aeroplane	857	Unchanged.
	Ultralight	71	
	Advanced Ultralight	77	
Aircraft Amateur Built Flag	Yes Amateur Built	826	Reason 1.
	Not Amateur Built	179	
Aircraft Landing Gear	Amphibious	284	"Amphibious Float-Wheel" and "Amphibious Hull-Wheel" were grouped into "Amphibious". Categories grouped into the "Other" category: "Hull" and "Water Landing Aircraft". Reasons 1&2.
	Float	677	
	Other (landing) gear	44	
Aircraft Damage Level	Substantial	869	Categories grouped into the "Other" category: "Minor", "No Damage", "Missing Aircraft". Reason 2.
	Destroyed	120	
	Other damage (level)	16	
Phase of Flight	Approach	80	Categories grouped into the "Other" category: "Descent", "En-Route", "Manoeuvring", "Parked", "Post-Impact", "Roll-Out", "Standing", "Taxi". Reason 2.
	Climb	245	
	Cruise	114	
	Landing	240	
	Take-Off	106	

	Other Phase (of Flight)	220	
1st Occurrence Category	ARC	139	Categories grouped into the "Other" category: "ADRM", "AMAN", "ATM", "BIRD", "CFIT", "EXTL", "F-NI", "GCOL", "ICE", "LALT", "MAC", "MED", "OTHR", "RAMP", "RE", "TURB", "UIMC", "UNK", "USOS", "WSTRW". Reason 2.
	CTOL	71	
	FUEL	48	
	LOC-G	122	
	LOC-I	165	
	SCF-NP	77	
	SCF-PP	141	
	UNK	65	
	Other (1st Occurrence) Category	177	

The results of the three-way association analysis are presented in Appendix N, and the main findings are discussed in this section. Figure 7.5-L represents a heatmap of the relevant associations with 99% confidence level. The blue shades indicate moderate relationships, while the red shades indicate strong relationships.

Figure 7.5-L. Heatmap of the three-way associations for 99% confidence level.



Some findings that are similar to the findings already presented in the previous section are excluded. Moreover, the associations where one of the parameters was daytime, May-October or non-amateur built were excluded, as it was previously determined that the majority of accidents and incidents happen then, meaning the associations are, in fact, for the other two parameters only. Taking these

into account, the main findings for strong relationships with a 99% confidence level are explained below:

- A seaplane is more likely to be destroyed for the following occurrences:
  - CTOL, SCF-NP and UNK on approach
  - CTOL, LOC-I, SCF-NP and UNK on climb
  - FUEL, LOC-I, SCF-NP and SCF-PP on cruise
  - ARC, CTOL and UNK on landing
  - CTOL on take-off
- A seaplane is likely to have substantial damage for the following occurrences:
  - ARC, CTOL, FUEL, SCF-NP, SCF-PP and UNK on approach
  - ARC, CTOL, LOC-G, LOC-I, SCF-NP and UNK on climb
  - ARC, CTOL, FUEL, LOC-G, LOC-I, SCF-NP and SCF-PP on cruise
  - ARC, CTOL, FUEL, LOC-G, LOC-I, SCF-NP, SCF-PP and UNK on landing
  - ARC, CTOL, LOC-G, LOC-I, SCF-NP, SCF-PP and UNK on take-off

Other notable findings for moderate relationships with a 99% confidence level are:

- Occurrences involving abnormal runway contacts of advanced ultralight seaplanes are more likely to result in the destruction of the aircraft.
- Occurrences involving amphibious advanced ultralight seaplanes have a moderate association with abnormal runway contacts.
- For 2012-2022, a moderate association was present for the likelihood of an occurrence during take-off to result in destroyed aircraft, which was not obtained for previous years.
- A seaplane is more likely to be involved in CTOL in the following situations:
  - Amphibious aircraft on approach, climb, landing, take-off
  - Float seaplane on approach, climb, cruise, landing, take-off
- A seaplane is more likely to be involved in FUEL in the following situations:
  - Amphibious aircraft on approach, climb, cruise, landing
  - Float seaplane on approach, climb, cruise
- A seaplane is likely to have substantial damage after an occurrence for:
  - Amphibious aircraft after ARC, CTOL, LOC-G, LOC-I, SCF-NP and UNK
  - Amphibious aircraft during take-off, cruise, approach and landing phases of flight
  - Float seaplanes after ARC, CTOL, FUEL, SCF-NP and SCF-PP
  - Float seaplanes during climb, take-off and landing phases of flight
- A seaplane is more likely to be destroyed for the following occurrences:
  - Amphibious aircraft after ARC, CTOL, LOC-I, SCF-NP and UNK occurrence categories
  - Amphibious aircraft during take-off, cruise, approach and landing phases of flight
  - Float seaplanes after ARC, CTOL, FUEL, SCF-NP and SCF-PP
  - Float seaplanes during climb and landing phases of flight
- A seaplane is likely to have minor or no damage for the following occurrences:
  - Float seaplanes after LOC-G

More findings are included in Appendix N.

7.5.4. Bayesian Networks and Prediction Models

The findings of the trend and contingency analysis, along with the three-way associations, provide the foundation for the proposed subsequent analysis using Bayesian Network and prediction models.

Bayesian Networks (BN) are more powerful tools for modelling probabilistic relationships between parameters, but there are certain situations where their use might not be recommended for accident/incident data. As such, the characteristics of the dataset and the objectives of the analysis have been carefully evaluated before attempting to use this method of analysis. For example, BNs are not suitable in cases of complex dependencies, lack of causal knowledge, and when simpler or more appropriate methods are available. For the study of private, recreational GA seaplane occurrences in Canada using 1990-2022 data, complex relationships between variables are expected especially related to human performance, but crucial parameters such as pilot experience, human errors, environmental condition and pilot decision making are missing. Based on the literature for transport safety, these are expected to have very high impact on the outcome of an occurrence, and their interactions with variables from the dataset can be significant. The data is also limited as minor incidents and near misses are not recorded. Therefore, it is challenging to construct a meaningful Bayesian Network without additional data fields. For this case study, the three-way associations provided meaningful results for the analysed dataset, and it is considered sufficient for the purpose of the analysis.

The following parameters have been chosen for the predictions of the decision tree and random forest models: aircraft damage level (substantial or destroyed), number of injuries and fatalities (0 or non-0), and initiating occurrence category (top 5 only). Similar methods have been employed as for the maritime case study in Section 6.3. However, for the development of these models, more factors are required, in addition to the number of annual movements per different landing gear (which, as mentioned in previous sections, could not be obtained). These factors can be related to the environment (e.g. wind, visibility, water surface, temperature), the pilot (e.g. demographics, different levels of experience, timespan from the previous seaplane flight, fatigue), aircraft (e.g. last maintenance checks, age, previous incidents, last time it was used), or any other external factors. Moreover, the majority of the possible factors in the studied dataset, such as the time of occurrence, month, year, region, aircraft category, amateur built or landing gear, do not have any enough strong correlations between their associated binary variables. The development of decision trees and random forest models was attempted, however, it was determined that the possible factors in the studied dataset are not sufficient for an accurate, comprehensive result. Hence, these are not presented here, but instead it is discussed why these methods are not appropriate.

7.6. Conclusions of Chapter 7

This chapter presented the analysis of private, recreational seaplane occurrences in Canada, using different methods. The dataset and its limitations have been defined, and data quality checks have

been employed. For example, such limitations include the correlation between the number of occurrences and pilot experience, or if any of those seaplane pilots were flying land planes outside the summer season. These statistics would have been interesting, but impossible to achieve. The achievable results of the quantitative analysis have been explained and detailed. Chapter 8 expands on this analysis and uses the results as the basis for collecting further qualitative data from recreational GA pilots.

Table 7.6 summarises the main findings of this chapter and provide an overview of unique safety challenges and risks specific to private, recreational GA seaplane operations in Canada. These emphasise the need for targeted interventions and improved reporting mechanisms.

Table 7.6. Main findings for the analysis of accident and incident data for private, recreational seaplanes in Canada.

Category	Main findings
Data quality and limitations	Underreporting of less serious accidents and incidents.
	Need for improved safety reporting standards.
Narrative analysis	Environmental factors play a significant role in the severity of an occurrence.
	Impossible to assess the impact of human errors and pilot-related factors such as training, experience, frequency of flying, currency and proficiency.
Occurrence categorisation	All occurrences have been categorised for a deep dive into what causes different types of occurrences.
	The document used for categorisation is not specific for seaplanes, and in particular not tailored for private, recreational operations.
	Overweight aircraft could not be fitted in any of the categorisation definitions.
	For occurrences leading to a TSB reports, in some cases, the report provided new, unexpected information missing from the narratives that led to different categorisation.
Trend and contingency analysis	Trend and contingency analysis have been accomplished around different parameters.
	The number of occurrences shows an increasing trend.
	The climb and landing phases are the most hazardous
	The climb phase shows the highest number of destroyed aircraft, injuries and fatalities.
	Loss of control and engine failure are the leading types of occurrences. These lead to a high number of fatalities and substantial damage/destruction of aircraft. However, industry professionals claim that they should not.
Three-way associations	Associations accomplished between any three parameters with high confidence level.
	Proved that certain occurrence categories are most likely to result in destroyed aircraft or substantial damage for different phases of flight, amongst other findings.

Additional findings	Seaplanes make up less than five percent of all GA aircraft but have significant accident rates and numbers of injuries and fatalities.
	Regulatory frameworks for private operations are less stringent compared to commercial aviation.
	Inability to calculate occurrence rates.

Despite insightful findings from safety data analysis, this is insufficient for understanding why such accidents happen in order to enhance the safety of this sector. Because of the previously discussed data limitations in Section 7.3, factors such as pilot experience, decision making and critical thinking in adverse scenarios are not captured by the dataset. To ensure that the robust thesis methodology explained in Section 5.4 is properly followed, because of these unacceptable limitations after data analysis, a new framework of analysis that addresses these limitations will be proposed. This will be the topic of the next chapter, which explores these critical factors missed in the analysis of safety data.

8. Qualitative Analysis of Private, Recreational Seaplane Safety - What can be learnt that could not be captured by data analysis?

As explained in the previous chapter, the analysis of accident and incident data in aviation is critical for improving safety and ensuring the prevention of future accident, however, it has certain limitations that do not allow a comprehensive understanding of all underlying safety factors. There are gaps in the available data which have been mentioned previously, especially related to the people involved in the occurrence, such as decision-making, concerns, and other contributory factors that can influence safety outcomes. Hence, this chapter collects new data and employs a robust methodology tailored for the GA seaplane industry in Canada. This will complement the insights from accident and incident data analysis through direct engagement with pilots and other safety professionals in the field, who can help reveal the answers that are missed.

Data on seaplane accidents and incidents has already been analysed, revealing key safety issues and data gaps that will be addressed by adopting a mixed-methods approach. In this chapter, qualitative data is collected through interviews, focus groups and a questionnaire.

8.1. Aim and Objectives

By engaging with the pilot community, not only new risks and concerns can be flagged and then prevented, but also safety awareness can be shared. The qualitative analysis presented in Chapter 8 expands on the data analysis of seaplane occurrences in Canada that has been presented in Section 7.5, and is referred to in the rest of this chapter as a “study”. Therefore, this study aims to enhance safety awareness within the seaplane GA community in Canada, using the results from an in-depth analysis of seaplane GA past accident and incident data, as well as to determine further details that had not been captured by the previously analysed databases, such as pilot concerns and decision making during pre-determined scenarios.

This study covers a wide range of scenarios during take-off, climb, cruise, approach and landing, based on the most recurring accident types seen after analysing data between 1990 and 2022 of privately registered seaplanes in Canada. This format encourages pilots to think critically about their actions in different conditions, while bringing awareness on current safety issues. This study contributes significantly to safety awareness and training improvements.

This study has the following objectives:

- Determine factors contributing to accidents and incidents that had not been captured by the previously analysed databases, such as pilot concerns and decision making, by asking pilots and other seaplane safety professionals to think critically about what could happen in different conditions, and flag any potential current issues that should be addressed.
- Determine whether the actions pilots take in certain scenarios differ among age groups and level of experience with flying seaplanes.
- Bring awareness to the pilot community on what is part of the bigger picture of private, recreational seaplane safety by sharing the main factors contributing to past seaplane occurrences, their implications and the results of data analysis.
- Determine which methods of safety promotion are preferred, which will be used in the future to maximise the outreach and visibility of safety issues and recommendations.

This proposal has been presented to the Seaplane Working Group online meeting by the principle investigator (Iulia Manole) of the study, after being reviewed internally in Imperial College by Prof. Arnab Majumdar. This working group is part of the General Aviation Safety Program launched by Transport Canada to enhance safety in the GA community and comprises of pilots, experts in the field and members of academia that together can make flying safer in Canada. The response to the proposal was positive from all members.

8.2. Methodology

In this study, the pragmatic research philosophy is employed to address seaplane safety issues, as it focuses on practical solutions and real-world applications, so that actionable recommendations can be developed for the GA seaplane community in Canada. As previously mentioned in Section 5.1, pragmatic research is a practical approach that emphasises the outcomes and applications of the research process. It is characterised by flexibility in choosing research methods and approaches, based on what seems suitable for the research in question. This method allows the use of a mix of qualitative and quantitative techniques to gather data, analyse findings, and develop solutions that are directly applicable to real-world problems.

The flexibility of pragmatic research allows for the use of various data collection methods, such as interviews, focus groups and questionnaires. This approach ensures comprehensive data collection and a deeper understanding of safety issues. Pragmatic research is conducted in real-world settings, which is crucial for understanding the actual safety concerns and practices of seaplane pilots. This approach ensures that the recommendations are relevant and feasible. Engaging with stakeholders,

such as seaplane pilots and industry representatives, is a key aspect of pragmatic research, ensuring that the research addresses the needs and concerns of those directly affected by the safety issues.

Semi-structured interviews were used as they use a mix of pre-determined questions and the flexibility to explore topics that arise during the conversation. This approach allows flexibility during the interviews, while following the topics and questions determined of importance after the accident and incident data analysis, which are consistent through all three methods of qualitative data collection, maintaining comparability across the associated data.

Phenomenological focus groups explore and understanding the depth and richness of personal experiences of participants (Savin-Baden & Howell Major, 2013). This approach seeks to uncover the essence of experiences and how individuals perceive different scenarios, making it suitable for this study. The discussion was guided by open-ended questions that encourage participants to share detailed and personal accounts of their experiences, in a safe, non-punitive and non-judgemental environment. In this way, the subjective, lived experiences of the participants in the pre-defined scenarios that are discussed can be captured. The data collected is then analysed to identify common themes and patterns that describe the essence of the experiences shared.

Phenomenological questionnaires aim to explore the lived experiences and perceptions of respondents (Major, 2013). This type of questionnaire is used to gather in-depth qualitative data about how pilots perceive safety and risk in their operations using personal experiences, during pre-defined scenarios. It aligns with phenomenology, which focuses on understanding phenomena from the perspective of those experiencing them (Major, 2013).

Content analysis and thematic analysis are both valuable methods for analysing qualitative data, but they serve different purposes and are used in complementary ways in this study. Content analysis is a systematic method for quantifying and summarising the content of qualitative data by categorising responses into predefined themes or codes. It provides a way to measure the frequency and significance of specific issues or concerns raised by seaplane pilots, making it particularly useful for analysing responses from the online questionnaire where patterns and trends need to be quantified. On the other hand, thematic analysis involves identifying, analysing, and reporting patterns (themes) within the data, allowing for a deeper exploration of the underlying themes and the context in which these themes emerge. This method is more interpretative, providing rich, detailed insights into the experiences and perceptions of the participants, making it ideal for the in-depth interviews and round table discussions. In summary, content analysis offers a broad overview of prevalent issues, while thematic analysis provides a nuanced understanding of the complex interactions and contextual

factors influencing these concerns (Savin-Baden & Howell Major, 2013; Major, Savin-Baden & Haynes, 2022).

Summary of the methods used for the qualitative analysis:

- Content Analysis - to systematically categorise and quantify responses from the online questionnaire, identifying key safety issues and trends.
- Thematic Analysis - to explore in-depth themes from interviews, focus group discussions and free-text answers of the questionnaire, providing detailed insights into the experiences and perspectives of recreational GA seaplane pilots.

By combining these methods, this study aims to provide a thorough analysis of what can be amiss with seaplane operations, contributing to both theoretical knowledge and practical applications in aviation safety management. It provides the results needed for recommendations for changes in regulations, flight training and safety practices. Additionally, this analysis will facilitate the creation of materials for bringing awareness to the seaplane community on the identified issues, ultimately aiming to diminish the number of accidents, destroyed aircraft and lives lost. This analysis is conducted for Canada, but the methodology can be adjusted for other countries in the future.

The methods were chosen based on informal discussions with representatives of the seaplane industry during the Seaplane Working Group meetings. Hence, the use of interviews, focus groups and a questionnaire has been decided to maximise the study's reach to GA seaplane pilots. Individual semi-structured interviews have been conducted in-person and online, two focus groups were held, one in-person and one online, and one online questionnaire has been distributed to the GA seaplane pilot community in Canada. Section 7.7.5. shows the participants for these and the reasoning behind it.

In summary, the three methods used to gather qualitative data from recreational, private GA pilots in Canada are: semi-structured interviews, phenomenological focus groups and a phenomenological questionnaire. Thematic and content analysis are employed to identify key safety issues and in-depth understanding of the processes and interactions affecting GA seaplane safety. The data is coded and analysed, allowing for themes to emerge naturally from the data. This approach ensures a comprehensive understanding of the participants' perspectives and experiences.

8.3. Data quality and integrity of the interviews, focus groups and questionnaire

To ensure the overall quality of the data obtained through this study, different data quality dimensions have been considered and detailed below.

Completeness - Although the participants are free to withdraw at any time, it is expected that the majority of them complete all the questions. Responses that are incomplete may be deleted if they do not provide any useful insights.

Consistency - There are multiple answers from different participants for each question and, for some sections of the questionnaire, recoding is not needed since they have pre-defined multiple choice answers. For the questions with comment boxes, as well as for the interviews and focus groups, the data has been categorised to match the questions and answers of the questionnaire, and any additional data will be analysed separately.

Accuracy - All participants are seaplane pilots, meaning that they have the knowledge required to answer all questions accurately and from experience. It is assumed that they understand the questions and answer truthfully.

Interpretability - It is assumed that all questions are interpreted in a correct and similar manner by the investigators and participants. The participants are given opportunities to ask for clarifications.

Credibility - The participants are selected from different ranges of seaplane flying experience and age groups, to ensure that the collected data reflects reality for the population of seaplane pilots.

To mitigate against things that could go wrong, the collected data has been cleaned before being used for further analysis.

To ensure good data management for this study, a well-defined data management plan has been put in place. It outlines how data will be collected, validated, stored, protected, and processed:

- clear protocols have been established for data entry and validation to minimise errors (data has been consistently formatted and easily accessible for analysis; the interview and focus group questions may differ as possible follow up questions will depend on the answers given by participants, but their core question categories will be consistent with the questionnaire)
- measures to protect data integrity and confidentiality have been implemented (the questionnaire, interviews and focus groups are anonymous and personal details such as names are not required, however pilots have the option to share their email address if they wish to be contacted for future research, or about the results of this study).

Regular backups were used for preventing data loss. Additionally, detailed documentation of all data management processes and decisions has been kept throughout the time from when the study was planned to when the final analysis of the gathered data was completed, to ensure transparency and reproducibility.

By adhering to these checks and practices, the quality and integrity of the obtained data can be ensured, thereby enhancing the quality of the findings.

8.4. Ethics considerations

Approval from the Head of Department and favourable opinion from the Research Governance and Integrity Team (RGIT) have been obtained. The documents approved by the Imperial College ethics committee are attached in Appendix O.

The confidentiality of participants taking part in the study has been preserved, and the transparency requirements under the General Data Protection Regulation for health and care research have been fulfilled.

8.5. Participants

The initial goal was to recruit minimum 15, but ideally 30 recreational seaplane pilots with different seaplane flying experience for the questionnaire, and 5 for individual interviews, so that the collected data is representative for the GA seaplane community in Canada. The seaplane flying experience (in years and also hours flown) would ideally be evenly distributed between the following 3 categories: under 5 years (including participants with less than 2 years of experience), 6-20 years and over 20 years, and under 100 hours flown (including new seaplane pilots with under 10 hours flown), 100-500 hours and over 500 hours. These goals have been met, and the number of participants exceeded the initial ideal number of 35 participants, totalling 80 (Table 8.5). This demonstrates the interest of private, recreational GA seaplane pilots in Canada in safety.

8.5.1. General details of the participants

Initially, the study aimed to achieve interviews with 5 individuals with specific experience and place of work, and responses for an online questionnaire from an additional 15-30 participants (seaplane pilots). However, based on the preferences of seaplane pilots involved in the SPWG, it was decided that the questions asked in the questionnaire could also be used in a different format, which is focus groups. There, GA seaplane pilots of different backgrounds and experiences can meet and talk about areas of concern. Hence, a presentation was created to include all questions of the questionnaire, and also some key results of the data analysis presented in Chapter 7. These can be found in Appendix P.

Aside from this, other pilots that are highly experienced in flying seaplanes and aviation safety were considered for separate interviews, to get a deeper dive into specific concerns. It was sought to interview individuals from different GA seaplane communities, which included representatives from the Canadian Owners and Pilots Association (COPA), Aviateurs Quebec, Ontario Seaplane Association,

Northwest Territories Flying Association, and Transport Canada (in particular, the General Aviation Safety Program). These associations have the focus and primary training in seaplane operations around Canada, and are the associations which the majority of GA seaplane pilots in Canada are members of. Aviateurs Quebec was the only one not reached, however, another interview was conducted with a chief pilot of a seaplane base and flight training unit at Constance Lake seaplane base. Representatives from COPA have not been interviewed separately, however COPA was represented at the online focus group.

The third method chosen is focus groups, for which the positive response from pilots was overwhelmingly high. These had a presenter (Iulia Manole) and a moderator. This particular moderator was chosen as they are the lead of the Seaplane Working Group, and a very experienced pilot. Even though an in-person focus group was preferred, travelling to multiple parts of Canada was not possible. Hence, it was decided to have one in-person focus group at Arnprior Airport in Ontario, and one online for the people from other parts of Canada. 19 people were present from the beginning of the in-person focus group, and three joined later, hence the two different numbers in Table 8.5. The online focus group was advertised through the SPWG and COPA and had 85 people who expressed interest. Of these, 29 joined the focus group online, however everyone who expressed interest was emailed copies of the presentation, data analysis and results of the study. This way, awareness on current issues has been brought to the attention of 136 people, some of whom mentioned sharing it with others, while this study had 80 participants (Table 8.5).

Flying experience or demographics of the attendees of the online focus group are unknown, however these were part of most stakeholders presented in Section 4.4.2, including: seaplane pilots and owners, Transport Canada, COPA, flight training units, different seaplane pilot associations and even insurers. In addition, flying experience or demographics of 4 of the attendees of the in-person focus group are unknown.

Table 8.5. The number of participants for the interviews, focus groups and online questionnaire.

Method	**Location**	**Number of participants**	**Seaplane flying experience**							
			Years				**Hours**			
			0-2	**3-5**	**6-20**	**20+**	**0-10**	**11-100**	**101-500**	**500+**
Interview	Online	3	0	0	3	1	0	1	1	2
	In-person	1								
Focus group	Online	29 (85)	-	-	-	-	-	-	-	-
	In person	22	0	2	3	13	0	7	3	8
Questionnaire	Online	25	7	1	6	11	3	6	6	10

Total	80 (136)	7	3	12	25	3	14	10	20

8.5.2. Exclusion criteria for the participants

Minors and people considered vulnerable were denied taking part in this survey. Pilots who have not flown in Canada were also excluded, as well as people without the right to fly a seaplane. Excluding minors and individuals considered vulnerable from participating in this survey was a decision grounded in ethical considerations and the responsibility to protect the wellbeing and rights of potential participants. Minors and vulnerable populations often require special considerations to ensure their safety, understanding, and consent in research contexts. They may have limited capacity to fully comprehend the purpose, risks and implications of their participation, or they may be in positions that limit their ability to give informed consent freely. Furthermore, research involving these groups necessitates additional regulatory approvals and protective measures that aim to safeguard their interests and welfare. By excluding these groups, this study aims to prevent any potential risk or harm that could arise from their participation, ensuring that the research is conducted within ethical bounds and respects the vulnerability and rights of all individuals.

8.5.3. Advertisement of this study

This study was firstly advertised to the Seaplane Working Group. Then, members of this group advertised it to their seaplane/pilot communities, and other GA seaplane pilots. Participants have also been recruited through advertisement by COPA.

8.6. Design of the questionnaire, interviews and focus groups

The questionnaire, focus groups and interviews have been designed such that they complement the seaplane occurrence data that was analysed in Chapter 7, so that the quality of the research including both the quantitative data (which is already of good quality) and the qualitative data obtained through the questionnaire, focus groups and interviews is overall of high quality and more representative of reality.

The questionnaire is meant to fill the gaps in the accident data and address issues found after analysing the data on seaplane occurrences in Canada. The focus groups and interviews will be based on the same questions as those proposed in the survey, but it gives the participants the opportunity to expand on certain issues and, for the focus group, discuss with other pilots different areas of concern.

Informed consent had been obtained from all participants, before proceeding with the questions. The study began with a short description of its purpose, then the participants have been assured of

confidentiality and explained their freedom to withdraw without giving a reason. The completion of the study was entirely voluntary.

8.6.1. Design of the questionnaire

The questionnaire was conducted online using Qualtrics, which is the approved survey platform for Imperial College London and meets all General Data Protection Regulation (GDPR) requirements and wider security requirements of the College. It could be easily accessed through a link or QR code from any device (e.g., laptop, smartphone, tablet), and paused and resumed at the convenience of the participant.

The questionnaire has multiple choice or open-ended questions, and has been structured into eight parts:

1. Participant information & Consent
2. General details
3. Information gathering – Safety training and concerns
4. Scenario discussion – Take-off
5. Scenario discussion – Climb
6. Scenario discussion – Approach
7. Scenario discussion – Landing
8. Ending questions

Part 1 “Participant information & Consent" includes information that can be found in the Participant Information Sheet and Consent Form, as mentioned in Section 8.4. Part 2 “General details” and Part 8 “Ending questions” were presented in Section 8.5.1, and contain questions about participants’ age group, experience, seaplane ratings, safety training and methods of safety awareness preferred. Sections 4-7 consist of scenarios which include the questions “What have you done to mitigate this?” and “What would you do to mitigate this?”, regarding different hazardous situations that may happen during different phases of flight. These have been decided based on the results from the data analysis and discussions during the Seaplane Working Group. The questionnaire is attached in Appendix Q.

This phenomenological questionnaire aims to gain information related to pilot decision making during different scenarios, as well as other details about safety training and practices, and ways in which pilots stay current and proficient. Pilots can express current safety concerns and propose ways for safety prevention and awareness. All answers are anonymous, increasing the chance pilots answer truthfully.

8.6.2. Design of the focus groups

Two focus groups have been conducted, one online using Microsoft Teams and one in-person, which were led by a presenter from Imperial College London and a moderator from Transport Canada and the SPWG, with high level of experience in GA seaplane flying and safety. Even though the moderator works for the regulator (TC), they emphasised on the anonymity of the responses and a non-punitive environment was created. The discussions were guided by open-ended questions that encourage the participants to share personal accounts of similar experiences and express areas of concern. The environment was non-punitive and non-judgemental, to give participants freedom to express their thoughts.

The focus groups started with a presentation of the results from the data analysis. A booklet with these results was given to the participants to keep, either as a printed copy or as an online shared file. The booklet is attached in Appendix P, Part 2. The focus groups followed the same parts of the online questionnaire, but more possible scenarios were brought to the attention of the participants. The participants discussed these issues, shared personal experiences and speculated on the possible reasons behind seaplane occurrences in Canada.

8.6.3. Design of the interviews

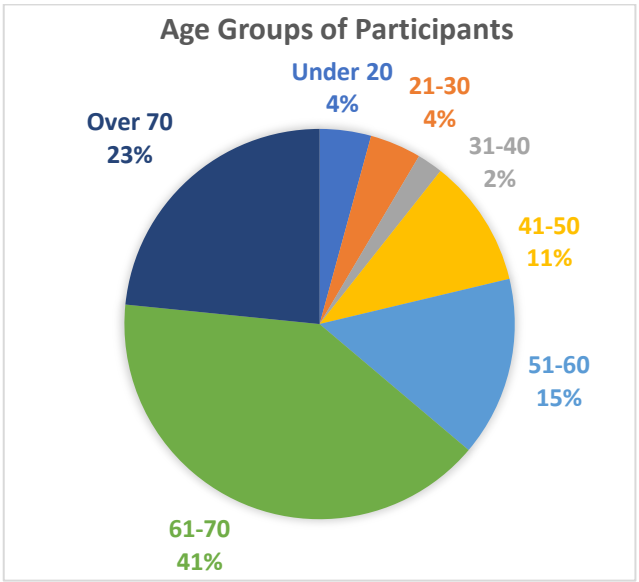
Semi-structured interviews have been conducted either online, using Microsoft Teams, or in-person. The interview questions are the same as for the questionnaire, but a smaller number of questions is addressed with every participant so that, overall, they provide detail information on all scenarios in the questionnaire. The interviewer had the flexibility to explore new topics that arose during the conversation. Each participant brought insight into issues around different parts of Canada, or regarding flight training, based on their experience.

8.7. Quantitative data analysis

The data obtained through the questionnaire has been analysed quantitatively and qualitatively, depending on the nature of the questions. The participants of the interviews and in-person focus group were asked the same questions for gathering pilot information, which are attached in Appendix P Part 1. The quantifiable data is presented in this section and uses descriptive statistics and content analysis. The number of responses in each category has been tallied and frequency distribution tables created. Then, bar charts and pie charts have been used to visualise the distribution of responses. The qualitative analysis is presented in Section 8.8.

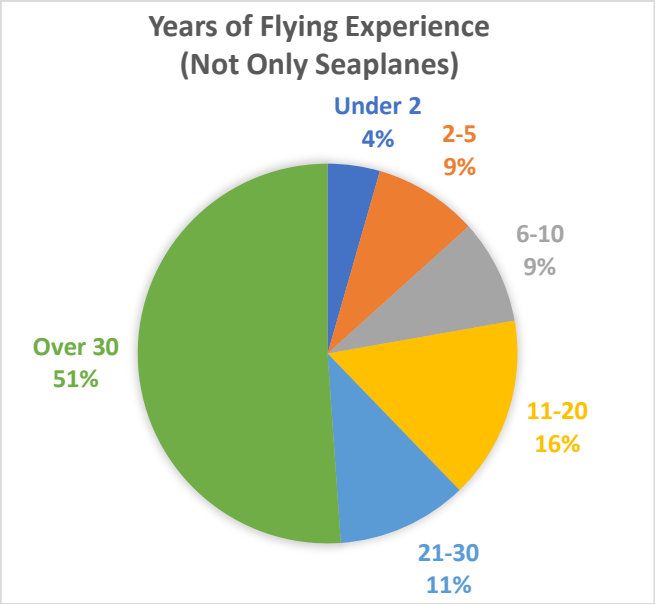
The number of participants who responded to the quantifiable, multiple-choice questions is 47, as four pilots who joined the in-person focus group did not complete this information. These are GA seaplane pilots with different backgrounds and flying experience. Participants ranged from under 20 to over 70 years old, with the majority of them falling in the 61+ age range (Figure 8.7-A). One reason could be that the population of seaplane pilots is decreasing, while at the same time they are currently likely to be working and thus unable to attend the interviews or focus groups. However, 10% of the participants are under 40 years old, and every age group was reached. Moreover, their experience in flying seaplanes is not directly proportional to their age, which can be seen in Figures 8.7-C and 8.7-D.

Figure 8.7-A. Distribution of the age groups of the participants.



Experience varied from under 2 years to over 30 years, as shown in Figure 8.7-B. Many participants had over 30 years of flying experience.

Figure 8.7-B. Distribution of the years of experience flying of the participants.



Experience flying seaplanes ranged from under 2 years to over 30 years, with a significant number of participants having over 30 years of experience (Figure 8.7-C). One participant stood out, having flown float planes for 50 years, with 11,600 hours of experience.

Figure 8.7-C. Distribution of the years of experience flying seaplanes of the participants.

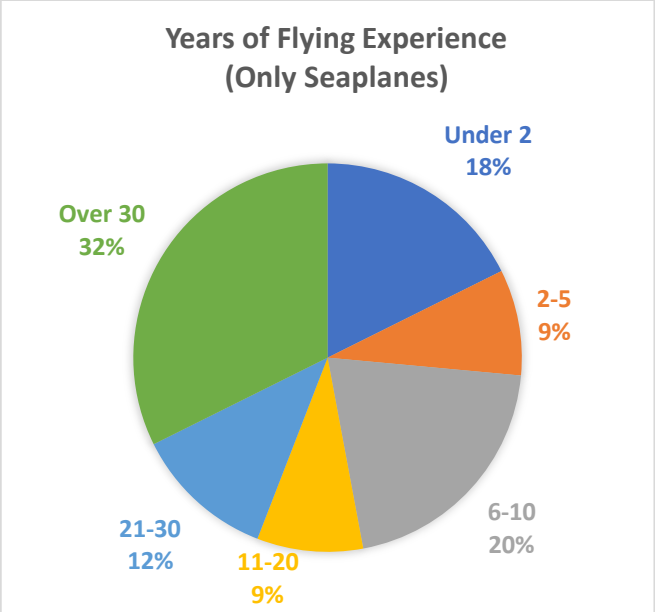
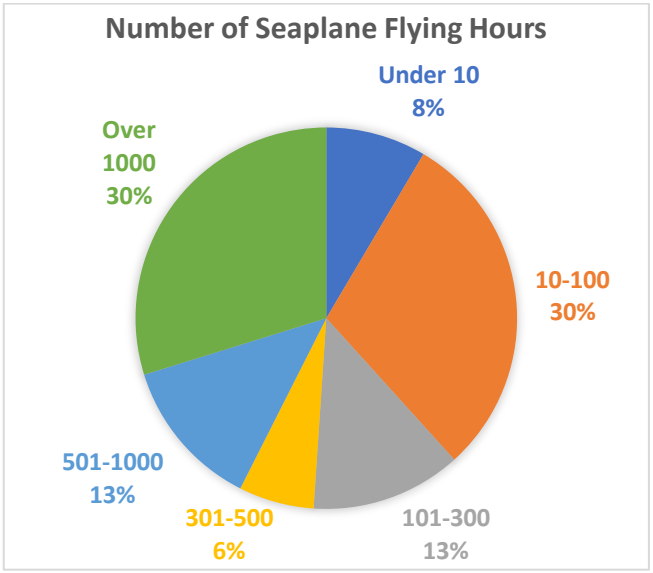


Figure 8.7-D shows the distribution of the number of seaplane flying hours, which ranges from under 10 to over 1,000 hours. Several participants had accumulated over 3,000 hours of seaplane flying time. This chart demonstrates a good distribution of seaplane flying experience amongst the participants.

Figure 8.7-D. Distribution of the number of hours flying a seaplane of the participants.



All participants had Seaplane Rating, and some of the had other types of training, as follows: Insurance Checkout(s) on Type (29.79%), 25 Hour Bush Pilot Course (8.51%), 50 Hour Bush Pilot Course (8.51%), Underwater Egress Training (42.55%) and Other (27.66%), such as 10 hour bush course and other training outside the scope of our study, such as CL-415 Pilot Simulation Training, Instructor commercial, IFR Flight Instructor Training (Figure 8.7-E).

Figure 8.7-E. The types of seaplane training completed by the participants.

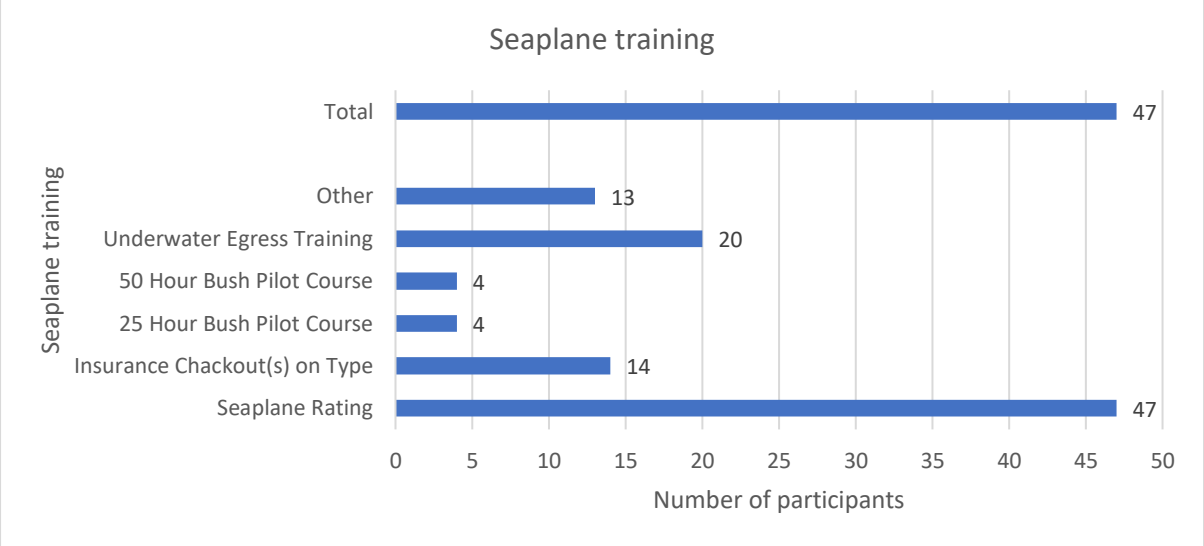


Figure 8.7-F shows the last time the participants completed a safety course/training related to seaplane operations. The majority of pilots did not consider any other safety training after completing the mandatory trainings.

Figure 8.7-F. The last time a safety course/training related to seaplane operations was completed by the participants.

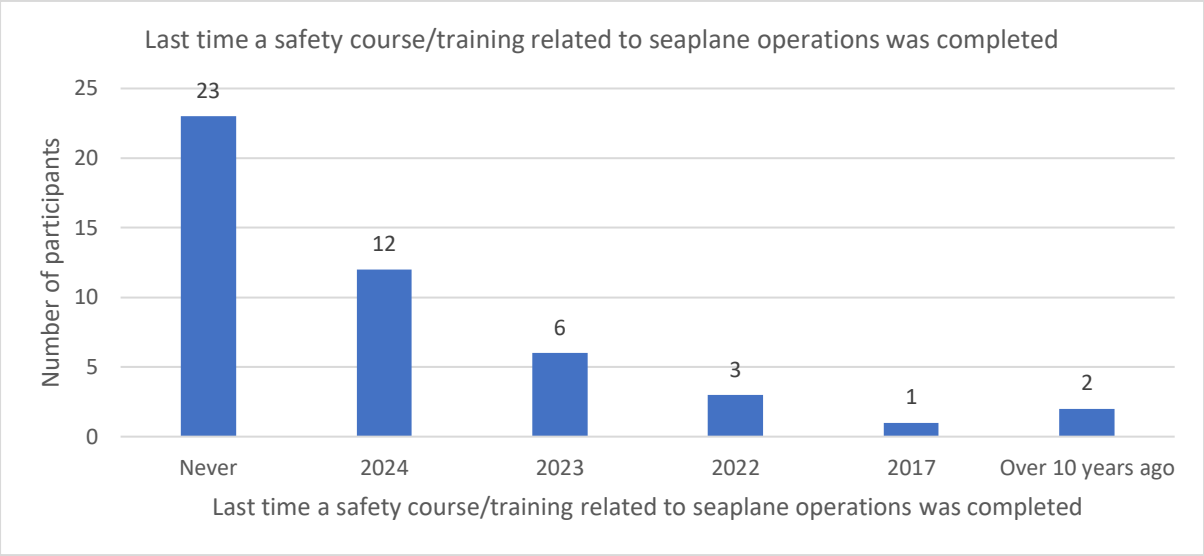
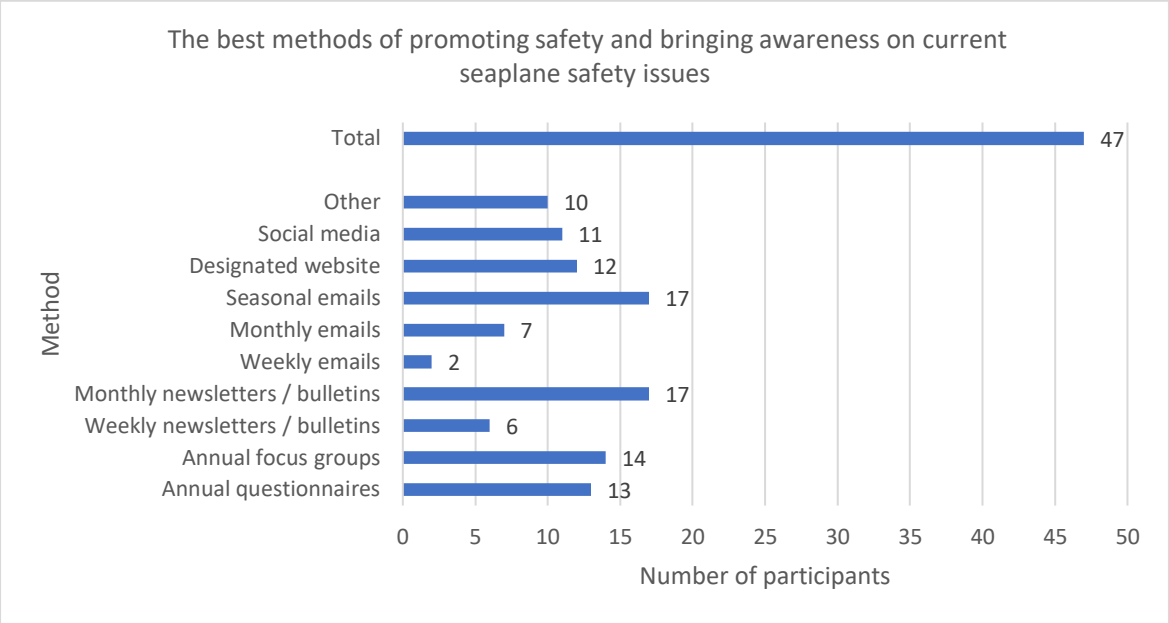


Figure 8.7-G shows the best methods of promoting safety and bringing awareness on current seaplane safety issues amongst the GA seaplane pilot community in Canada, according to the participants. Seasonal emails and monthly newsletters are preferred and, in general, more frequent contact is unwelcomed. In-person methods such as focus groups where pilots meet and discuss safety issues are also preferred compared to virtual, which was observed based on the feedback and participant engagement of the in-person versus online focus groups.

Figure 8.7-G. The best methods of promoting safety and bringing awareness on current seaplane safety issues, according to the participants.



8.8. Qualitative data analysis

The qualitative data obtained through the questionnaire, interviews and focus groups has been analysed using content and thematic analysis. Some responses for the open-ended questions of the questionnaire were incomplete, especially for the scenarios during different phases of flight. Content analysis was used to analyse the open-ended questionnaire responses, and to summarise and quantify the content of qualitative data. Codes have been assigned to different recorded quotes based on recurring themes or topics. Similar codes obtained from the questionnaire responses were grouped into broader categories or themes. Thematic analysis was employed to identify safety concerns by refining and analysing codes and themes (patterns) within the data, and themes have been redefined to be consistent for all three methods of data collection used. The results are compared with the existing literature.

Firstly, content analysis has been employed. All quotes and notes from the focus groups and interviews have been recorded in a format consistent with that of the questionnaire. Hence, all input for each question has been recorded in the same place, to facilitate the subsequent analysis. For open-ended questions, recurring words and phrases have been identified and categorised, then their count has been calculated.

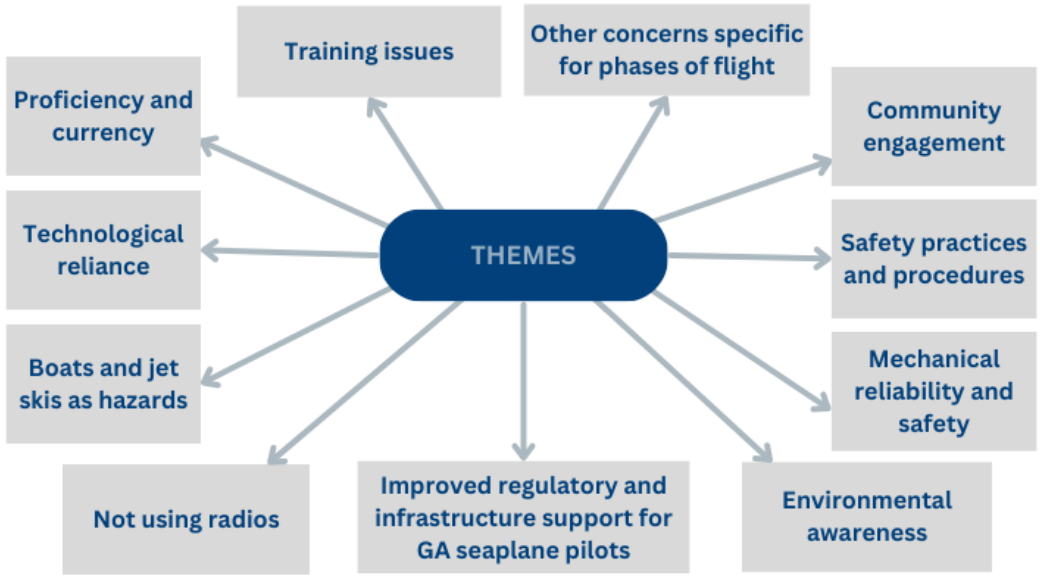
Secondly, thematic analysis has been pursued to reveal detailed codes and key themes. By identifying and analysing these themes, the concerns and experiences of seaplane pilots can be understood

better and specific recurring issues can be addressed. This analysis provides valuable insights that can inform the development of targeted safety programs, training initiatives, and regulatory changes to enhance the overall safety of seaplane operations.

Before the start of the scenarios, the participants of the questionnaire were asked about personal safety concerns. The notable responses are: “Too many aircraft crashing and people getting killed”. “The current number of accidents is too high”. “Loss of control on climb”. “Amphibious safety, landing gear configuration on landing”. “Staying current on type”. “Concerns about pilot attitudes in general”. "We don't want to think it will happen to us". "It takes meticulous care finding out what you don't know yet - flying new aircraft e.g. ultralight." “Proficiency of seaplane pilots”.

The results of the content and thematic analysis are summarised below, and grouped into themes and codes. Figure 8.8-A summarises all themes, while the subsequent figures include the codes of each theme. Each code has quotes recorded from either interviews, focus groups or the questionnaire.

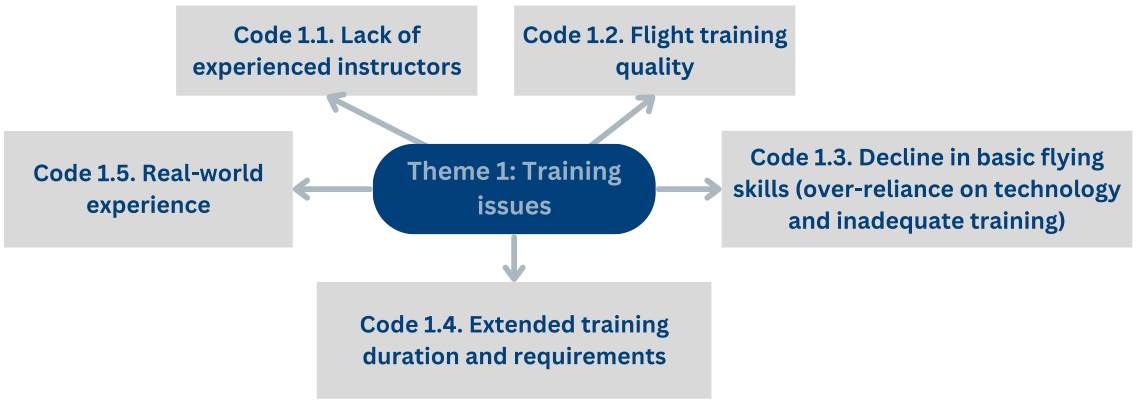
Figure 8.8-A. Themes from interviews, focus groups and questionnaire with seaplane industry operators and other professionals.



Key Themes and Codes:

Theme 1. Training Issues (Figure 8.8-B)

Figure 8.8-B. Training issues.



Code 1.1. Lack of Experienced Instructors:

- "We're seeing people in my demographic...we're either retiring or we don't have a valid medical anymore. And so the industry is losing a lot of us baby boomers."
- "The loss of experienced instructors is a major concern."
- "We clearly now have more than ever before rookies teaching rookies."
- “Lack of available flight instructors […] if it is not close to them, they won't do it”.

Code 1.2. Flight Training Quality:

- "It's not something where you should just be taking somebody coming out of training and say there you go, seven hours later you're off and running".
- “Lacking funding for training”.
- “Make it mandatory that an instructor has a complete check sheet of what the pilot has achieved or has not accomplished properly […] make this a transport exam and check sheet”.

Code 1.3. Decline in basic flying skills due to over-reliance on technology and inadequate training.

- "People are mesmerised by the technology and they forget how to fly an airplane."
- "One of the things we need to do is try and figure out how to better teach the new generation".
- “Too much reliance on new technologies”.

Code 1.4. Extended Training Duration and Requirements: More comprehensive training before allowing pilots to fly solo;

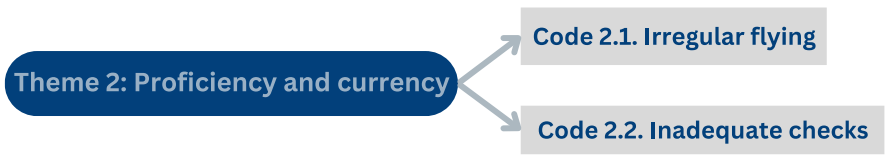
- "Update the Seaplane Rating document to include items which are currently not covered. Provide standards for guidance. Include the completion of a written exam for the rating."
- The 7 hours requirement is not enough and can be done in one day, which is not enough time to practice enough emergency procedures. The training should be spread through different days, to allow the new pilot to experience flying in different conditions and environments.
- "One needs 100 hours to really get to know a seaplane".
- "Pilots are cheap […], and so they'll just do the cheap stuff they can. But if there is a way that if they took a water egress and paid […], if they see that there could be an insurance reduction. […] That's a motivator to actually get that rating". With motivators from the private industry, recreational seaplane pilots can be determined to do more training, as commercial float plane pilots need to do.
- "Training programs need to be more comprehensive and cover all aspects of seaplane operations."

Code 1.5. Real-World Experience

- "Real-world experience is the best teacher when it comes to seaplane flying."
- "Practical experience is just as important as theoretical knowledge."
- "Learning from real-world scenarios helps prepare pilots for unexpected situations."

Theme 2. Proficiency and Currency (Figure 8.8-C)

Figure 8.8-C. Proficiency and currency.



Code 2.1. Irregular Flying: Seasonal flying leads to a decrease in proficiency.

- "A lot of float plane pilots only bring their airplane out in May or June and they put it away in October".
- "Many seaplane pilots are not maintaining proficiency, often only flying seasonally."
- "Pilots flying only three months a year in the same conditions."

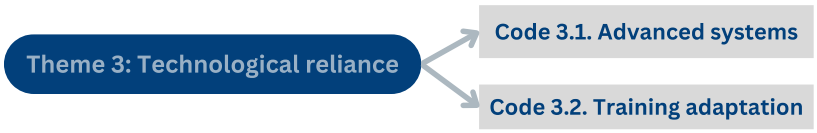
Code 2.2. Inadequate Checks: Insufficient proficiency checks for pilots.

- "Proficiency checks are not frequent or thorough enough." "Proficiency checks should be mandatory and frequent."

- "Every day we fly […] it's a different day out there".

Theme 3. Technological Reliance (Figure 8.8-D)

Figure 8.8-D. Technological reliance.



Code 3.1. Advanced Systems: Over-reliance on G1000 and similar systems, leading to poor basic skills.

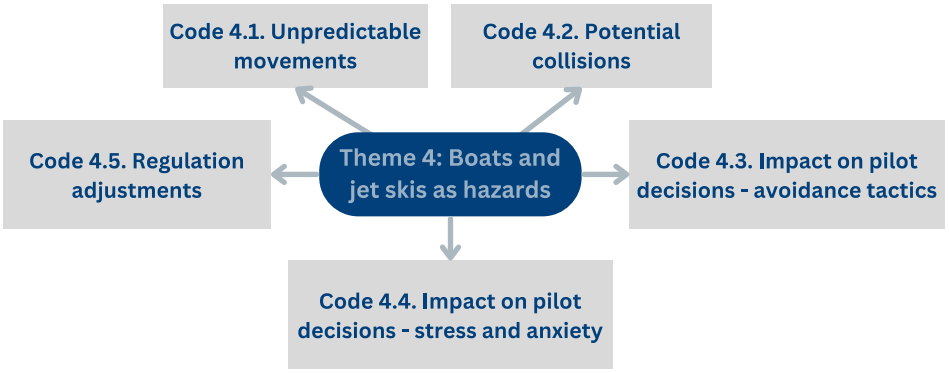
- "People are mesmerised by the technology and they forget how to fly an airplane."
- "With the new technology, more training aircraft are being equipped with G1000."

Code 3.2. Training Adaptation: Need for training to adapt to include both technology and fundamental flying skills.

- "We need to balance training between technology and fundamental flying skills."
- "Training programs should include both traditional flying skills and the latest technologies."
- "There is too much reliance on technology, which can be a problem if the technology fails."

Theme 4. Boats and Jet Skis as Hazards (Figure 8.8-E)

Figure 8.8-E. Hazards of boats and ski jets.



Code 4.1. Unpredictable Movements:

- "The worst are Sea-doos and boats towing a tube since they often have an erratic and unpredictable course."
- "Boats and jet skis can suddenly change direction, creating dangerous situations for seaplanes during take-off and landing."

Code 4.2. Potential Collisions:

- "I've had a few close calls with jet skis while trying to land. It's terrifying because they don't seem to be aware of the seaplane's approach."
- "Boats often don't realise the risk they pose to seaplanes, especially when crossing paths during critical phases of flight."
- Pilots expressed concerns regarding the right of way on take-off and landing, and argued that the "[…] aircraft must have priority by law".

Code 4.3. Impact on Pilot Decisions - Avoidance Tactics:

- Pilots may need to delay their landing until the water is clear of boats and jet skis. However, it is not always possible.
- Pilots choose landing areas away from busy water traffic to minimise the risk of collisions.

Code 4.4. Impact on Pilot Decisions - Stress and Anxiety:

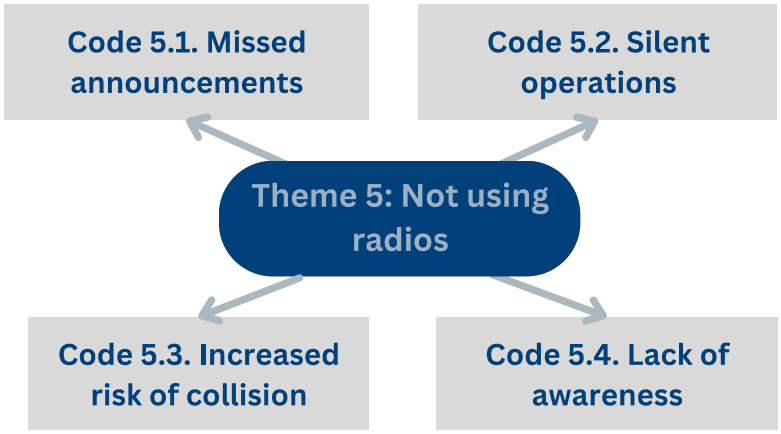
- The presence of boats and jet skis adds a lot of stress to seaplane operations. "It's a constant worry."

Code 4.5. Regulation Adjustment

- "The regulations need to be adjusted so that an aircraft on take-off and landing has priority over other vessels."
- "Understanding maritime regulations is essential for seaplane pilots."
- "Navigating busy waterways requires knowledge of maritime regulations."

Theme 5. Not using radios (Figure 8.8-F)

Figure 8.8-F. Misuse of radios.



Code 5.1. Missed Announcements:

- Many pilots do not use their radios consistently, leading to missed announcements about their intentions and positions.
- "I've noticed a lot of pilots don't communicate their movements, which increases the risk of misunderstandings and accidents."

Code 5.2. Silent Operations:

- "Silent operations are common, especially among older pilots who are not used to relying on radios."
- There seems to be a culture of not using radios, which is dangerous in busy areas.
- "You have a common frequency […], use it!"

Code 5.3. Increased Risk of Collision:

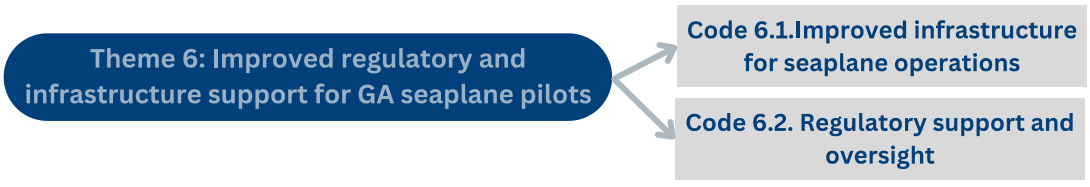
- Not using radios increases the risk of mid-air collisions, especially in areas with mixed traffic.
- Without proper communication, it is difficult to coordinate with other seaplanes and boats, leading to potentially dangerous situations.

Code 5.4. Lack of Awareness:

- When pilots don't use their radios, it creates a lack of situational awareness for everyone in the vicinity.
- "I've had situations where I was on final approach and another plane suddenly appeared, unaware because they weren't monitoring the radio."
- "We don't talk to each other, why is that?"

Theme 6. Improved regulatory and infrastructure support for GA seaplane pilots (Figure 8.8-G)

Figure 8.8-G. Improved regulatory and infrastructure support for GA seaplane pilots.



Code 6.1. Improved infrastructure for seaplane operations.

- "The infrastructure for seaplane operations needs to be improved."
- "We need more seaplane bases with proper facilities."
- "The existing infrastructure is outdated and needs significant improvements."

Code 6.2. Regulatory Support and Oversight.

- The regulations need to be updated to reflect the current state of the industry.
- "There should be more frequent inspections to ensure compliance with safety standards."
- "More regulatory oversight is needed to ensure safety standards are met."
- "Advocating for regulatory changes is important for long-term safety."

Theme 7: Environmental Awareness (Figure 8.8-H)

Figure 8.8-H. Environmental awareness.



Code 7.1: Unpredictable Weather

- Unpredictable weather conditions have often been a challenge.
- "Weather forecasting and awareness are critical for safe seaplane operations."
- Adverse weather conditions require careful planning and decision-making.
- "Pilots need to be trained to handle sudden weather changes."
- Weather-related issues are a significant concern for seaplane pilots.

Code 7.2: Wildlife Hazards

- Wildlife, such as birds and marine animals, pose risks during take-off and landing.
- "Encounters with wildlife are not uncommon and can be dangerous."
- "Pilots must be aware of the potential for wildlife interference."
- Wildlife strikes are a real threat and “require constant vigilance."

Theme 8. Mechanical Reliability and Safety (Figure 8.8-I)

Figure 8.8-I. Mechanical reliability.



Code 8.1: Engine Failures

- "There's a lot of engine failures occurring during take-off."

- Engine reliability is a major concern for seaplane operations.
- Training should include handling engine failures at low altitudes.

Code 8.2: Maintenance Issues

- Maintenance issues and the reliability of seaplane equipment are significant safety concerns.
- "Neglecting maintenance can lead to serious safety risks."
- "Maintenance protocols must be strictly followed."

Code 8.3: Equipment Reliability

- "The reliability of seaplane equipment is a key factor in ensuring safety."
- "Equipment failures can have catastrophic consequences."
- "Pilots need to trust that their equipment will perform as expected."
- "Investing in high-quality equipment is essential for safety."
- "Equipment reliability should be a top priority for all seaplane operators."

Theme 9: Safety Practices and Procedures (Figure 8.8-J)

Figure 8.8-J. Safety practices and procedures.



Code 9.1: Emergency Procedures

- "Emergency procedures should be practiced regularly to ensure readiness."
- "Pilots must be familiar with all emergency procedures."

Code 9.2: Checklists

- "Pilots should use checklists for all phases of flight."
- "Strict adherence to checklists can reduce human error."

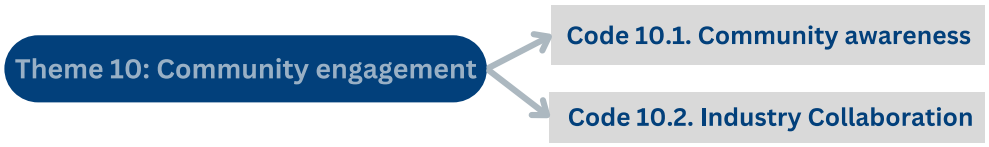
Code 9.3: Best Practices

- "I think we need more focus on practicing engine failures and other emergency procedures regularly."
- "Sharing best practices among pilots can improve safety."
- "Learning from others' experiences is valuable."

- "Best practices should be documented and disseminated widely."

Theme 10: Community Engagement (Figure 8.8-K)

Figure 8.8-K. Community engagement.



Code 10.1: Community Awareness

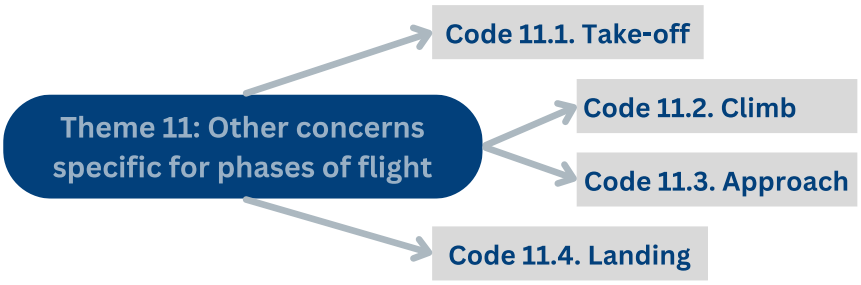
- "Raising awareness within the community can enhance safety."
- "Community engagement is key to understanding safety concerns."
- "Involving the community in safety initiatives is beneficial."
- "Community awareness programs can promote a safety culture."

Code 10.2: Industry Collaboration

- "Sharing information and resources among operators is beneficial."
- "Industry partnerships can enhance safety training and protocols."
- "Working together, we can create a safer environment for seaplane operations."

Theme 11. Other concerns specific for phases of flight (Figure 8.8-L)

Figure 8.8-L. Other concerns specific for phases of flight.



Code 11.1. Take-off:

- Misjudge of distances and visual reference: “Hill too close”.

Code 11.2. Climb: "Not all people have the money to get a plane that climbs like an angel"

- Overweight aircraft: “One had passenger jump off so he could climb faster over power lines. It was a near-death experience”. "Weight is heavy so no good climb rate".

Code 11.3. Approach

- Familiarity leads pilots to tend to do shortcuts.
- "The reluctance to go around is still huge!"

Code 11.4. Landing

- “Glassy water is challenging”. "Glassy water took me a few years to get around. Then you don't fly for five months."
- Misjudge of distances and visual reference: "I was surprised how close the shore was after I landed on glassy water."
- "When they know they're not being watched and they can land anywhere […] more disregard for safety"

Other notable findings:

- Poor communication, considering the vast geography of Canada with numerous lakes: "People announcing taking off a lake, where is that lake?"
- Language barriers: “In Montreal they speak in French. I am not bilingual”.
- “In Toronto especially, the majority of GA like to fly below flying space”.
- Drone concerns have been mentioned by two participants.
- Not wearing shoulder harnesses is a known problem. “TC cannot relax rules when it comes to safety”.

The general aviation seaplane pilot community in Canada identified **training** issues as the most significant concern. Participants highlighted a lack of experienced instructors, with a prevalent issue of "rookies teaching rookies" due to the retirement or medical disqualification of seasoned pilots. This shortage leads to insufficient flight training quality, as new pilots often receive minimal instruction time and lack comprehensive training. Additionally, there is a noted decline in basic flying skills attributed to an over-reliance on technology and inadequate training. To address these issues, participants suggested extending training durations and making requirements more comprehensive, including mandatory proficiency checks and updated seaplane rating documents. Enhancing training programs to cover all aspects of seaplane safety thoroughly would help bridge the current gaps in pilot preparation.

Proficiency and **currency** issues were prominent among the participants, who noted that irregular, seasonal flying leads to a decline in proficiency. Many seaplane pilots only fly during the summer season, which impacts their skills and readiness. The need for regular and rigorous proficiency checks

was emphasised to maintain pilot competence. These checks should be frequent and thorough to ensure that pilots remain proficient throughout the year. The variability of flying conditions, including changes in weather and density altitude, underscores the necessity for ongoing practice and checks. Participants also highlighted the importance of extensive retraining programs for pilots who have been inactive, ensuring they are fully prepared before resuming flying.

Participants expressed concerns about the over-reliance on advanced systems like the G1000, which has led to a deterioration of basic flying skills. While **technology** can enhance flight safety and efficiency, there is a critical need for training programs to balance technological proficiency with fundamental flying skills. This issue is not unique to seaplanes but is part of a broader training problem across aviation. Participants emphasised the importance of integrating traditional flying techniques with modern training to ensure pilots can handle manual flying when necessary. The reliance on technology should not overshadow the need for robust basic flying skills, which are essential for safe seaplane operations.

The interaction with **boats** and **jet skis** poses significant hazards for seaplane pilots. Participants reported unpredictable movements of these watercraft, creating dangerous situations during take-off and landing. Potential collisions are a major concern, with pilots recounting close calls and expressing the need for better awareness among boat operators about the risks they pose to seaplanes. To mitigate these risks, pilots often employ avoidance tactics, such as delaying landings or choosing less busy areas. However, the presence of boats and jet skis adds considerable stress and anxiety to seaplane operations, underscoring the need for improved regulations and awareness to enhance safety.

A lack of **radio communication** between float planes was identified as a critical safety issue. Many pilots do not use their radios consistently, leading to missed announcements and increasing the risk of misunderstandings and accidents, while creating a culture of non-communication. The absence of radio communication significantly raises the risk of mid-air collisions and reduces situational awareness for all pilots in the vicinity. Participants stressed the importance of using common frequencies and ensuring all pilots communicate their intentions and positions to improve overall safety.

Participants highlighted the need for improved **infrastructure** and **regulatory support** for seaplane operations. The current infrastructure is outdated and inadequate, necessitating the development of more seaplane bases with proper facilities. Additionally, there is a call for more regulatory oversight and support, with updated regulations that reflect the current state of recreational flying. Seaplane

pilots expressed a feeling that they are left out when decisions are made by the regulators or insurers. Enhanced regulatory frameworks specific for GA seaplanes and better infrastructure would significantly improve the operational environment for these pilots, contributing to overall safety and efficiency. It has also been mentioned that the number of seminars and educational materials for seaplane pilots is minimal and does not address the needs of the private, recreational seaplane community.

Participants discussed various concerns specific to different **phases of flight**. During take-off, misjudgement of distances and visual references, such as proximity to hills, were common issues. In the climb phase, overweight aircraft and financial limitations on aircraft performance were highlighted. Approach phase concerns included pilots taking shortcuts due to familiarity and reluctance to go around. Landing on glassy water presented challenges in judging distances and visual references.

Additional notable findings included concerns related to unpredictable changes in environmental conditions, such as changing winds and poor weather. Language barriers and concerns about drone interference have also been mentioned. The importance of practicing emergency procedures was also discussed, in particular engine failures. These insights underscore the complexity and variability of private, recreational GA seaplane operations, highlighting the need for tailored training and regulatory measures to address these specific challenges.

8.9. Mitigation and safety awareness

Determining the right methods for mitigation is important, as these goals need to be practical and achievable. Likewise, the correct methods of bringing safety awareness to the GA seaplane pilot community should be adopted, to maximise their reach and effectiveness. This section proposes mitigation measures and ways to bring safety awareness.

8.9.1. Mitigation strategies - Training issues and technological reliance

To mitigate the **lack of experienced instructors**, the GA seaplane community in Canada can implement strategies to retain seasoned instructors and ensure their knowledge is passed on effectively. This includes offering better compensation and support, creating mentorship programs, and providing career development opportunities. Encouraging retired pilots to contribute as part-time instructors or mentors can also help. Increasing the availability of flight instructors through improved incentives and support will address the concerns of "rookies teaching rookies" and the overall decline in experienced personnel.

Improving **flight training** quality involves extending the duration and comprehensiveness of training programs. Implementing mandatory proficiency checks and using detailed checklists can ensure that pilots meet the required standards before flying solo. Allocating more funding for training programs and ensuring that training includes a wide range of scenarios will better prepare pilots for the real world. Making it mandatory for instructors to have a complete check sheet of a pilot's achievements and areas needing improvement will enhance accountability and training effectiveness.

To address the decline in basic flying skills due to over-reliance on **technology**, training programs should balance the use of advanced systems with fundamental flying techniques. Emphasising the importance of manual flying skills and incorporating more hands-on experience into training can help. Regularly updating training materials to include both new technologies and traditional flying methods will ensure that pilots are well-rounded and capable of handling situations where technology may fail.

Extending **training duration** and enhancing requirements before allowing pilots to fly solo is crucial, and this was brought up by the majority of participants. Updating the Seaplane Rating document to include currently uncovered items, such as practicing a variety of unsafe scenarios, and providing clear standards for guidance can improve training quality. Spreading the training over different days to cover various conditions will ensure comprehensive preparation, encouraging pilots to gain practical experience in varied conditions and scenarios. Creating opportunities for pilots to participate in real-world flying exercises, such as simulated emergency scenarios, can provide valuable hands-on learning. Highlighting the importance of both theoretical knowledge and practical experience in training programs will ensure well-rounded pilot preparation. Additionally, incentivising additional training through insurance reductions for pilots who complete more safety-related courses can motivate recreational pilots to pursue more thorough training.

8.9.2. Mitigation strategies - Proficiency, currency and safety practices

To mitigate the effects of irregular flying on **proficiency**, implementing regular proficiency checks and mandatory retraining programs before the flying season starts is essential. Seasonal pilots should undergo refresher courses to regain their skills. Encouraging continuous education and practice sessions, even during the off-season, can help maintain proficiency. Developing standardised proficiency checklists and ensuring that these checks cover all critical aspects of flying can enhance pilot competence. Establishing a system for continuous monitoring and feedback can help identify areas needing improvement and ensure that proficiency checks are effective. Moreover, providing incentives, such as insurance savings for pilots who regularly participate in proficiency checks and training programs, can motivate pilots to stay engaged in their training.

Practicing **emergency procedures** regularly is crucial to ensure pilots are ready to respond to emergencies effectively. Training programs should include frequent drills and simulations of various emergency scenarios. Encouraging pilots to stay familiar with all emergency procedures and providing refresher courses can help maintain readiness. Promoting a culture of continuous practice and preparation will enhance overall safety. Awareness campaigns can emphasise the importance of regular emergency procedure practice and share success stories where proper training has prevented accidents.

The use of **checklists** for all phases of flight is a fundamental safety practice. Pilots should be trained to use checklists consistently and understand the importance of each step. Developing standardised checklists for various types of operations and ensuring they are easily accessible to pilots can enhance adherence. Reinforcing the use of checklists through training and regular briefings can help reduce human error. Sharing examples of occurrences where checklist use has prevented accidents can underline their importance and promote their use.

Sharing **best practices** among pilots can significantly improve safety. Creating platforms for pilots to exchange experiences and learn from each other is beneficial. Documenting and disseminating best practices through safety bulletins and workshops, among other methods, can reach a wide audience. Encouraging pilots to participate in safety initiatives and contribute their insights can foster a culture of continuous improvement.

8.9.3. Mitigation strategies – Interactions with boats and jet skis

Mitigating risks from boats and jet skis involves raising **awareness** among boaters about the presence and operations of seaplanes. This can be achieved through community outreach programs and collaboration with local maritime authorities. Adjusting **regulations** to give aircraft priority during take-off and landing can reduce conflicts with boats and jet skis. Establishing clear right-of-way rules and ensuring they are communicated to both pilots and boaters will help reduce conflicts and potential collisions. Educating both pilots and boaters on maritime regulations and their impact on seaplane operations is essential.

To address the impact on pilot decisions, pilots should be trained to identify high-traffic water areas and to employ avoidance tactics effectively. This includes developing clear **protocols** for avoidance tactics and ensuring that pilots are familiar with them. Encouraging pilots to report near-miss incidents and sharing these reports can help identify common risk areas and improve avoidance strategies.

8.9.4. Mitigation strategies – Use of radios

Improving **radio communication** among pilots is essential for situational awareness and collision avoidance. Consistent radio use can be promoted through education, emphasising its safety benefits. Installing and maintaining reliable radio infrastructure in seaplane operating areas will support this effort. Addressing silent operations, particularly among older pilots, requires targeted training and awareness programs to encourage regular radio use. Highlighting case studies where communication failures led to incidents can further stress the importance of radio communication. Enhancing situational awareness through consistent radio use can prevent misunderstandings and accidents, with pilots encouraged to report communication issues to help identify areas for improvement.

8.9.5. Mitigation strategies - Regulatory and infrastructure support for GA seaplane pilots

Improving **infrastructure** for seaplane operations involves developing more seaplane bases with proper facilities and updating existing infrastructure to support safe and efficient operations. Collaborating with local authorities and industry stakeholders to identify areas needing improvement and prioritising infrastructure projects can enhance safety. Providing resources and support for infrastructure development, including funding and technical assistance, can facilitate these improvements.

Enhancing **regulatory support** and oversight involves updating regulations to also reflect the current state of the GA seaplane industry. Working with regulatory bodies to develop and implement these changes is essential. Providing training and resources to ensure compliance with new regulations and encouraging feedback from pilots and operators on regulatory issues can lead to continuous improvement. Advocating for regulatory changes that support long-term safety and addressing the specific needs of the seaplane community can enhance overall safety and efficiency.

8.9.6. Mitigation strategies – Environmental awareness

Mitigating risks from **unpredictable weather** involves emphasising weather awareness and decision-making skills in training programs. Training should include scenarios simulating sudden weather changes, fostering proactive weather planning, and thorough pre-flight checks. Awareness campaigns should highlight the importance of staying informed about weather conditions. On a different note, addressing **wildlife** hazards combines pilot training and environmental management. Pilots need education on wildlife risks and mitigation techniques especially during take-off and landing. Implementing wildlife management programs at seaplane bases and tracking wildlife encounters through reporting systems can reduce hazards. Regular updates on wildlife activity and incorporating wildlife hazard awareness into safety briefings can enhance vigilance.

8.9.7. Mitigation strategies – Mechanical issues and equipment reliability

Mitigating **engine failures** requires regular, thorough maintenance and pilot training on handling failures at low altitudes. Standardised emergency procedures in training programs, routine engine checks and adherence to maintenance schedules are crucial. Educating pilots on the consequences of neglecting maintenance is essential.

Ensuring **equipment reliability** involves investing in high-quality components, regular inspections and thorough pre-flight checks by pilots. Reporting equipment issues immediately and fostering a safety culture prioritising equipment reliability can reduce risks. Sharing best practices and failure case studies would highlight the importance of equipment maintenance and reliability.

8.9.8. Awareness initiatives

Raising awareness within the seaplane community about safety issues and best practices is essential. Organising in-person **community engagement** events, such as safety seminars, workshops and focus groups, can facilitate knowledge sharing and discussion. This is supported by the level of positive feedback received during and after the in-person focus group, compared to the other methods used for data collection. Moreover, involving the community in safety initiatives and encouraging active participation can promote a safety culture. Developing community **awareness programs** that highlight the importance of safety and share practical tips can enhance overall safety consciousness. Utilising various **communication channels**, including social media, newsletters, and seasonal emails can reach a broader audience and keep the community informed.

Collaborating with industry stakeholders, including seaplane operators, regulatory bodies and flight training units can enhance safety training and protocols. Sharing information and resources among operators can lead to the development of standardised safety practices and recurring training programs. Establishing partnerships for joint safety initiatives and research can drive improvements in safety standards. Working together, the seaplane community can create a safer operating environment and achieve higher safety standards.

8.10. Conclusions of Chapter 8

In this section, a pragmatic approach has been employed to address safety issues of private, recreational seaplane pilots in Canada. This has been achieved through three methods of data collection: semi-structured interviews with industry professionals, phenomenological focus groups with pilots and other stakeholders, and a phenomenological questionnaire which was distributed among the relevant pilot community. The methods employed to analyse the qualitative data were

content analysis and thematic analysis. By combining these methods, the study provided a thorough analysis of recreational GA seaplane operations, contributing to both theoretical knowledge and practical applications in general aviation safety management. Recommendations for mitigation have been proposed, including specific changes in regulations, flight training and safety practices. Adopting these would lead to the improvement of GA seaplane safety in Canada and potentially other countries.

Engaging with the pilot community through focus groups, interviews, and a questionnaire proved essential for gathering crucial safety-related information that complemented accident and incident data. Creating opportunities for pilots to discuss safety issues and share experiences in-person proved the most effective, and it was the method preferred by the majority of participants. Encouraging young pilots to participate in these discussions could ensure that the next generation of seaplane pilots is well-informed and safety-conscious. In addition, the preferred methods of safety communication varied between participants, most preferring occasional contact (seasonal emails and monthly newsletters), among having a designated website for GA seaplane safety and social media. Using a mix of safety awareness and safety promotion methods will maximise the reach to the community.

Using mixed methods of analysis proved useful in studying the safety of private, recreational seaplane pilots. The methods employed complemented each other and added value to the study. All feedback received during the interviews, focus groups, questionnaire and via email was positive, proving the willingness of the community to learn more about current safety issues and collaborate to ensure future recommendations and regulations address the specific needs of the community.

9. Discussion and Implications

This chapter discussed the methodology used and results achieved, while considering the implications of this research and how the discovered issues could be addressed. It starts with an overview of the capabilities and limitations of transport safety data, including findings specific for the studied databases. Afterwards, the implications of using mixed methods of analysis are addressed, with examples from the case studies. Finally, a framework for holistic safety data analysis is proposed.

9.1. Overview of capabilities of transport safety data

This section reviews the capabilities of transport safety data, taking into account the ideal factors for a robust safety data analysis, data limitations and other safety barriers observed throughout the PhD.

Each case study presented in this thesis included a set of specific ideal factors necessary for a comprehensive analysis. Despite the efforts to combine data sources, none of the cases had all the required information which, along with other issues such as differences in taxonomies, imposed significant limitations on the capabilities of data analysis. Furthermore, the case studies focused only on factors deemed to have a potentially significant contribution to either an occurrence, a specific type of occurrence or its severity. This approach overlooks the inherent complexity of the transport system as a socio-technical system, where accidents and incidents rarely occur under the same conditions given the vast array of contributing factors, as well as different personnel and environments involved. Additionally, these factors interact in complex ways, further complicating the analysis and emphasising the need for the holistic approach to address transport safety.

While the use of mixed methods of data analysis helped achieve a better understanding of the safety systems involved, despite data limitations, it would be ideal to employ mixed methods of analysis on more complete datasets. Because of this, an exhaustive list of factors relevant for transport safety analysis has been compiled and is presented in Figure 9.1-A. This list has been developed based on the findings from the literature and data analysis presented in previous chapters of this thesis. For example, the “degree of manoeuvrability” factor has been introduced following the qualitative analysis on seaplane safety in the previous chapter. This was deemed to be especially important when different types of vehicles interact. For example, seaplanes have very limited manoeuvrability, as well as restricted forward and peripheral visibility during the take-off run, which is not reflected by the regulations for priority on the water in place. This becomes even more concerning when increased boat traffic and lack of awareness of boat operators are considered.

Figure 9.1-A. Main data categories and contributory factors relevant for studying safety occurrences in the transport industry.

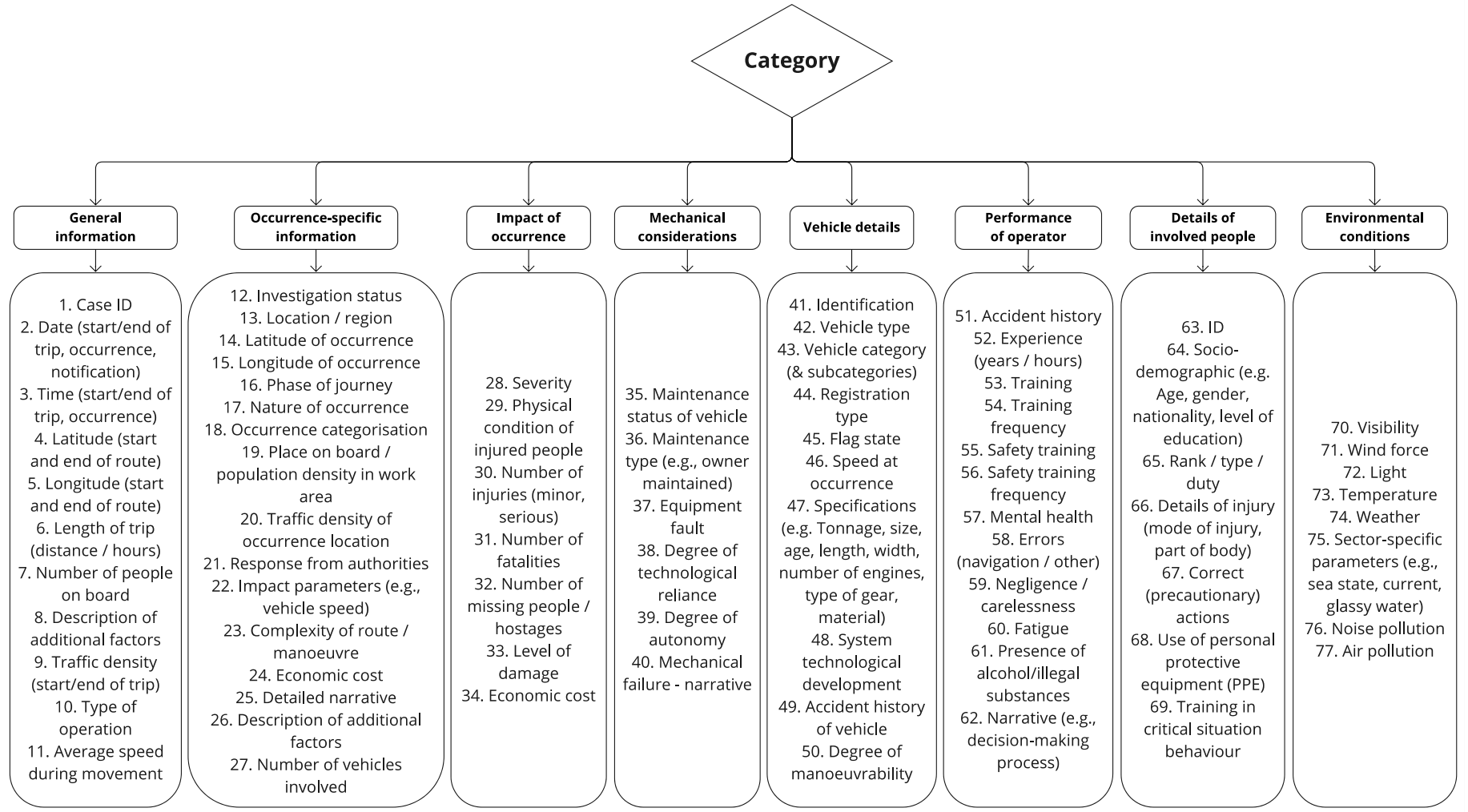
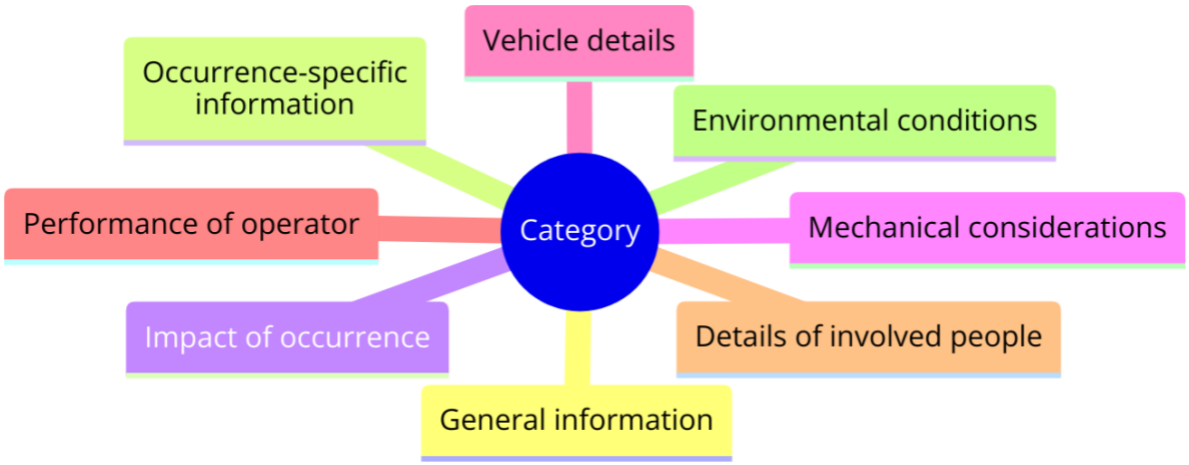


Figure 9.1-B summarises the main categories of these factors relevant for studying safety occurrences.

Figure 9.1-B. Main categories of factors relevant for studying safety occurrences in the transport industry.



Each category within the list presented in the above serves a critical role in ensuring a holistic understanding of transport safety. Furthermore, the large number of factors allows for a "deep dive" into any of them, to discover specific issues and then implement targeted mitigation strategies. However, the literature indicates that these categories and factors are only partially addressed, mostly because of the previously mentioned data limitations, which fail to address the "big picture" of safety. The following summarises these categories and offers examples of academic publications which consider them:

- The General Information category includes essential data such as dates, times and geographical coordinates, providing the fundamental context for any analysis. This information helps establish a baseline for the conditions under which the transport activity occurred. (see Pak et. al., 2015; Li et. al., 2019; Yip, 2008)
- Occurrence-Specific Information details the circumstances of the accident or incident, including the investigation status, location and specifics of the event. This category is crucial for pinpointing the exact conditions and context that led to the occurrence, enabling targeted interventions. (see Chauvin et al., 2013; Mansson, Lutzhoft & Brooks, 2017; Mansoor, 2011; Mou et. al., 2010; Kujala et. al., 2009)
- The Impact of Occurrence category assesses the severity and consequences of the event, such as injuries, fatalities, and economic costs. Understanding the impact helps in prioritising safety measures based on the potential for harm and associated costs. (see: Chauvin et. al., 2013; Hänninen, 2015; Kujala et. al., 2009)

- Mechanical Considerations examine the technical aspects of the vehicles involved, including maintenance status and equipment faults which are vital for identifying mechanical failures that could contribute to occurrences. (Wang & Pillay, 2001)
- Vehicle Details provide comprehensive information about the vehicles, such as category, registration type, specifications and level of reliance on autonomy. This data is essential for understanding how vehicle characteristics influence safety. (see: Mou et. al., 2010; Ziarati and Ziarati, 2007; Mallam et. al., 2019; Hashimoto and Okushima, 1990)
- The Performance of the Operator category focuses on the human element, including the operator's experience, training and influences on decision making. This helps understand how human factors contribute to safety outcomes. (see: Macrae, 2009; Hetherington et. al., 2006; Hanzu-Pazara et. al., 2008; Seafarers, 2019; Project Martha, 2016)
- Details of Involved People include socio-demographic information, as well as the specific roles and injuries of those involved, including but not limited to the vehicle operator. This assists in understanding the demographics of affected people and consequences of an occurrence, so that tailored safety measures can be adopted to protect vulnerable populations. (see: Chauvin et. al., 2013)
- Environmental Conditions encompass external factors such as visibility, weather and temperature, which can significantly affect transport safety. The importance of addressing environmental factors has been demonstrated by the analysis in the previous chapters. (see: Pak et. al., 2015; Balmat et. al., 2009; Clinton et. al., 2013; Hetherington et. al., 2006; Gultepe et. al., 2019)

It is important to acknowledge that not all factors in the above categories (Table 9.1b) have the same impact on an occurrence. This highlights the importance of a robust literature review and eliciting expert opinion prior to assessing which factors to consider in an analysis. However, it is usually the case that for many of these factors their effect cannot be determined because of insufficient recording of factors, underreporting, inconsistencies in reporting and other constraints. These data-related limitations are discussed below.

Given the importance of the categories of factors in Table 9.1b for assessing the underlying reasons of an occurrence, for robust predictive approaches, certain information is also needed from vehicles that are not involved in an occurrence. For example, from Figure 9.1b, the factors of the following categories need to be collected to allow for accurate development of advanced models that could predict an accident, so that precautionary measures could be taken in real-time: “General information”, “Mechanical considerations”, “Vehicle details”, “Performance of operator” and

“Environmental conditions”. This has been a significant data challenge encountered throughout this doctoral research. For example, for the case study on private, recreational seaplane safety in Chapter 7, not even the number of annual movements or hours flown could be obtained.

9.1.1. Summary of data-related limitations

Having reviewed the ideal set of categories and factors for a comprehensive data analysis, this section explains data-related limitations and reflects on possible reasons. Five categories of limitations are addressed below, including the related findings of this thesis.

i) Underreporting of certain factors or variables within factors:

Underreporting in safety databases presents a significant challenge in the transportation sector, impacting the reliability and accuracy of safety data. This phenomenon occurs when accidents or incidents are either not recorded or inadequately documented, resulting in a skewed understanding of safety performance and risk factors. Several factors contribute to underreporting, including regulatory gaps, fear of legal consequences, lack of standardised reporting procedures and organisational culture.

The implications of underreporting on safety management and policy-making are profound. It results in the underestimation of the frequency and severity of accidents, which subsequently affects risk assessments and the development of effective safety interventions. Numerous studies have highlighted the prevalence and consequences of underreporting in transportation safety data.

For instance, Folke and Melin, (2024) discuss the challenges of accident and incident underreporting in aviation, noting that many minor incidents go unreported due to fears of punitive actions or job loss. This underreporting hinders the identification of patterns crucial for preventive measures. Similarly, in the maritime sector, Chauvin et. al. (2013) highlight that underreporting is prevalent due to the decentralised nature of maritime operations and the variability in national and international reporting standards.

In the maritime sector, the MAIB's requirement to report only serious and very serious accidents inherently leads to underreporting of less severe occurrences. This issue is exacerbated by a culture within the maritime industry where seafarers are often reluctant to report incidents. This reluctance can stem from fear of blame or disciplinary action, lack of perceived importance of minor incidents, and a desire to avoid additional paperwork. Such underreporting skews the data, making it difficult to fully understand the prevalence and causes of various types of incidents and to develop effective safety interventions (Anderson, 2003).

Seaplane operations face similar challenges with underreporting as other maritime sectors. Pilots may not report minor incidents due to fear of punishment, lack of awareness of reporting requirements, or a perception that minor incidents are insufficiently important to report. This leads to incomplete datasets that fail to accurately reflect the safety conditions and risk factors associated with seaplane operations. Improved education and outreach to seaplane pilots, as well as simplifying the reporting process, could help address these issues.

In road transport, Elvik and Mysen (1999) note that traffic accidents involving minor injuries or property damage are frequently underreported. They argue that this underreporting leads to a significant underestimation of the societal costs of road accidents and misallocation of resources for road safety improvements. Amoros, Martin, and Laumon (2006) further support this by demonstrating that the true incidence of road traffic injuries is much higher than reported statistics, particularly for non-fatal injuries.

The railway sector faces similar issues. The European Railway Agency (2013) reported discrepancies in accident data due to underreporting, especially in cases of minor incidents or those involving third parties. This affects the reliability of safety performance indicators and the effectiveness of safety management systems.

Underreporting impacts both the quantity and quality of data. The lack of detailed information on reported occurrences impairs the ability to conduct thorough investigations and root cause analyses. Edwards et. al. (2013) and Majumdar, Manole & Nalty (2022) emphasise the need for improved reporting systems that encourage the reporting of all occurrences, regardless of severity, and ensure the collection of comprehensive data to facilitate better safety analysis and decision-making.

While voluntary reporting systems like CHIRP and MARS aim to address underreporting and fear of punishment, their voluntary nature means that participation is not guaranteed. Mariners may still be hesitant to report incidents, fearing that their reports may somehow be traced back to them despite assurances of confidentiality. Additionally, voluntary systems rely on the mariners' initiative to report, which may not always occur, especially in busy or high-pressure work environments. Consequently, these systems may not capture a comprehensive picture of safety incidents (Lloyds List, 2016).

Addressing underreporting requires a multifaceted approach. Enhancing regulatory frameworks to mandate comprehensive reporting, implementing non-punitive reporting systems and fostering a safety culture that prioritises transparent and accurate reporting are crucial steps. The Aviation Safety Reporting System in the USA, for instance, has successfully encouraged voluntary reporting by protecting the identities of reporters and providing immunity from enforcement actions (NASA, 2020).

In conclusion, underreporting in safety databases poses a significant challenge to the accurate assessment of safety in the transportation sector. Addressing this issue requires regulatory enhancements, cultural shifts, and improved reporting mechanisms to ensure that safety data accurately reflects the true state of transportation safety and supports effective safety management and policy-making.

The following limitation reflects another issue, that of unavailability of more complete data sources to researchers, which leads to an overreliance on data of lower quality.

ii) Lack of publicly available detailed databases - Reliance on lower quality data:

This thesis, has discussed that local databases from individual ports or authorities were not publicly available, limiting access to potentially valuable data for analysis. These local databases may contain detailed information on incidents that is not captured in national databases such as the MAIB. However, efforts to obtain local databases were unsuccessful, as they seem to be stored only for internal use. This limits the scope and depth of analysis for researchers, reinforcing the need for improved data reporting and sharing practices.

Encouraging ports and authorities to make their data more accessible, either through public databases or data-sharing agreements, could improve the quality and comprehensiveness of safety analyses. Additionally, making this data available to researchers not only has benefits for them, but also for the ports. While this data is analysed locally, releasing it to the public in a way that certain aspects remain confidential would help reach its highest potential which can be achieved through further analysis using diverse perspectives. This will provide a detailed analysis into accident causation patterns to identify local risk factors that may not be apparent in national or international databases.

Because of the data limitations already mentioned, throughout the literature, much research is focused on analysing a high number of occurrences rather than the quality and limitations of the data. This phenomenon has been critiqued in this thesis, and a data quality assessment framework has been proposed to address this issue. It is vital that the selection criteria for the factors to be used in any analysis must be primarily based on the research requirements and not available data.

Having mentioned the reasons for the concentration of research on data quantity, such detailed, comprehensive databases are often either not publicly accessible or not recorded to the necessary high standard. Consequently, researchers frequently rely on international data sources such as IMO reports. This phenomenon is also encountered with databases like MAIB, which often lack information on specific categories and parameters, particularly those related to the operator performance and human factors.

As evident from all case studies of this theses, as well as the reviewed literature, the majority of maritime occurrences and their severity has been influenced by human decision making or other human errors. This applies to the other sectors of transportation, such as the aviation sector. Because of the importance of such data, much of the research reviewed in this thesis has depended on manually extracting data from investigation reports. Although this method can provide more detailed datasets on certain factors and facilitate the use of international data, it is crucial to recognise that not all occurrences lead to investigation reports. In fact, as previously discussed in this thesis, only a small proportion of incidents meet the criteria for such reports, making sole reliance on them insufficient for an accurate representation of reality.

iii) Practical considerations of the level of detail of datasets:

Despite the comprehensive nature of the list of ideal factors underlying safety and evident advantages, practical limitations must be addressed to make it feasible in real-world applications.

Collecting such detailed information requires substantial time and effort, potentially leading to increased underreporting as individuals may be reluctant to spend additional time for a thorough documentation. Informal chats with different operators highlighted this issue, as some expressed that safety checklists and reporting forms are already too lengthy and time consuming. Moreover, the complexity and volume of data necessitate robust systems for data management and analysis, which might not be available in all contexts.

iv) Variability in reporting schemes:

In the maritime industry of the UK, for example, the decentralised nature of reporting schemes means that ports and terminal operators develop their own procedures for safety evaluation and enforcement. This not only leads to the underreporting in national databases, but also to inconsistencies in the categorisation and reporting of occurrences. Smaller ports may lack the resources to implement comprehensive reporting systems, while larger ports may have more sophisticated schemes that are not standardised across the industry. This variability complicates the aggregation and comparison of data across different ports and regions, reducing the overall quality and usefulness of the data for national safety analyses (Port of London Authority, 2023; Forth Ports, 2016; Nalty, 2017).

v) Taxonomy differences:

Local variations in hazard identification schemes can lead to differences in how safety occurrences and risks are categorised and reported. For example in maritime safety, smaller ports and private

terminal operators may develop their own taxonomies that differ from those used by larger ports or national authorities. This lack of standardisation can result in fragmented data that is difficult to compare or aggregate, hindering comprehensive safety analyses. Efforts to standardise taxonomies across the industry could improve the consistency and quality of reported data (Port of London Authority, 2023).

9.1.2. Importance of data quality

In this thesis, data quality issues posed significant challenges for transport safety analysis, including the following errors (Wegman & Oppe, 2010):

i. Incomplete reporting
ii. Inconsistent data collection methodologies, and
iii. Data entry errors.

These problems can lead to inaccurate risk assessments, hinder the identification of safety trends and undermine the effectiveness of safety interventions (Elvik, 2008). For example, underreporting and misclassification of safety data can obscure the true extent and nature of safety issues, resulting in misguided policy decisions and resource allocations (Amundsen & Elvik, 2004). Furthermore, the lack of standardised data formats and terminologies complicates the integration of data from different sources, further hampering analysis (Fleury & Brenac, 2001).

In general, databases lack information on less severe accidents and incidents which are not mandatory to report. They also lack information about the people involved, the performance of operators and mechanical information. This could be because it is hard to quantify such information and have pre-defined answers easy to choose, the person reporting either does not know how to report these factors, or does not think they are relevant for the occurrence. In this thesis, these underreported categories have been addressed through engagement with the relevant maritime or aviation communities. Moreover, the variability in the length and detail of the reported narratives also poses a challenge. Therefore, not only are the occurrences underreported, but the depth and detail of the reported occurrences are also insufficient. Hence, important safety insights are missed from databases and, as concluded in previous literature review, the study of such factors relies on extracting information from investigation reports. Two of the case studies of this thesis used such reports, from the MAIB and the IMO, and addressed their limitations.

Mentioned data incompleteness can result from inconsistent reporting practices, lack of mandatory reporting requirements for certain data elements, or the variable quality of logs kept by different operators. Ensuring that all relevant data is reported consistently and accurately would improve the

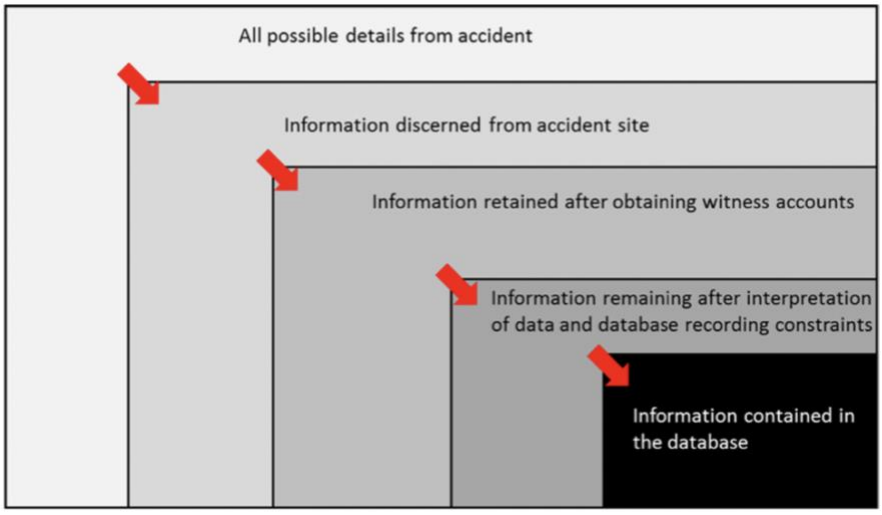
quality of safety analyses and enable better identification of risk factors (Majumdar, Manole & Nalty, 2022). In addition, local databases may contain much larger amounts of data than reported to national investigation bodies such as the MAIB or TC. Similarly, international databases contain less occurrences than the national databases. Standardising reporting practices and encouraging more comprehensive reporting could help address this issue.

Another common limitation is that datasets fail to properly account for technological advancements. As evident from the case study on autonomous vessels, new technologies can have significant impacts on a sector, both good and bad, so it is crucial to address these in a proactive and predictive way.

Furthermore, occurrence reports rely on the thoroughness of the investigator and the determined accident cause is through the investigator's perspective and competence level. Some information can also be omitted and only the factors deemed relevant by the investigator would be studied in the accident report (de Voogt and van Doorn, 2007). Moreover, investigators often focus on the apparent cause of the accident and do not investigate root causes (EHEST, 2010). This can lead to incomplete findings and misleading accident reports, making any other analysis using the information in these reports inaccurate.

Figure 9.1-C shows the level of information available in databases, through the stages of the analysis. It starts with the time when the accident occurs, which contains all the related information, then shows how this information passes through different layers (where accident information is lost) before being included in a database. Hence, all the analysis that uses the database may not be fully accurate and so there is a need to combine different methods of analysis in order to be able to understand what the root causes of each accident are, and obtain as much lost information as possible. This is why mixed methods of analysis are used in this thesis, to provide a deeper understanding of accident causation patterns that gets as close as possible to reality. These mixed methods comprise of qualitative and quantitative analysis methods that have been presented in Section 5.2 of this thesis.

Figure 9.1-C. Level of information available in a database (Rao and Marais, 2018).



The previous section mentioned that ensuring the accuracy and reliability of the data collected is a significant challenge, as is maintaining consistency across different reporting entities. Given this and other data-related limitations previously mentioned, the evaluation of data quality is critically important for safety data analysis. A framework for data quality assessment has been proposed in Section 5.6 of this thesis and subsequently applied for all case studies. The following section addresses data limitations specific for the databases studied in this thesis.

9.1.3. Limitations of the studied data sources

This section summarises the data limitations that have been found through reading accident reports, analysing accident and incident data, understanding accident reporting procedures and regulations, and interviewing field experts. Specific data limitations for the data sources used in this thesis from the maritime and aviation sectors (MAIB, AIS, RNLI, IMO and TC) are summarised below. Detailed explanations of these limitations for the analysis in each case study have been presented in the sections where they were used.

<u>MAIB database</u>

- Underreporting (for example, in 2017, only 13.5% of the accidents provided by the insurance provider Scottish Boatowners were reported to MAIB):
  - Underreporting of less serious accidents and near misses, since they are not mandatory to report (in accordance with (Nalty, 2017; Transportation Safety Board Canada., 2021).
  - Underreporting of vessels under 8 metres, as well as fishing, recreational and military vessels, while the data is complete for commercial vessels.
  - Lower reporting requirements for non-UK vessels not carrying passengers to a UK port.

- Lower completeness for vessel details and environmental conditions.
- MAIB does not consider health and safety accidents on the land side of ports.
- The MAIB database is accurate and consistent for specific vessel categories, such as UK merchant vessels over 100GT and other main commercial vessel categories.
- However, it is less accurate for other vessel categories, including non-UK vessels, and UK military, recreational, and fishing vessels.
- Ports report to the MAIB annually or for accidents, but marine incidents are underreported.
- The MAIB's 2017 annual report highlighted that only 13.5% of UK marine accidents and incidents were reported to the MAIB compared to data from Scottish Boatowners (MAIB, 2018).
- Internal databases of ports are larger than what is reported to the MAIB.
- Underreporting varies between ports, influencing the decision to exclude marine incidents from the MAIB data in previous analyses.
- Human factors hard to quantify and very rarely included in accident narratives.

<u>MAIB investigation reports</u>

- A small proportion of accidents/incidents in the MAIB database lead to an investigation report.
- Rely on reported occurrences, so similar limitations of underreporting apply as for the MAIB database.

<u>AIS</u>

- Underrepresentation of small commercial vessels under 300 GT, fishing vessels, small recreational fishing vessels and military/governmental vessels, which are not required by IMO regulations to use AIS. However, these categories of vessels can voluntarily use AIS.
- Low number of data fields available.
- Small errors may occur when vessel operators input the vessel data fields in the AIS system incorrectly (around 1% according to interviewed participant).
- MMO project 1042:
    - Incorrectly identified recorded vessels – around 2% (Marine Management Organisation, 2014).
    - When compared to Lloyds List:
        - 37% of the vessels were not matched
        - 13% of the ship types were incorrect

    - 14% of the vessel draughts were incorrect.
- Deficiencies which impact AIS data validity.
- The literature review highlighted the absence of AIS in many smaller recreational and fishing vessels.
- Industry professionals indicated inaccuracies in AIS data in areas with high recreational usage.
- These vessel categories were excluded from the analysis to increase accuracy and credibility, focusing on cargo, merchant, and service ships for logistic regression analysis.
- Potential for false data transmissions, with errors found in vessel identity, length, position, type, or draught in 8% of AIS transmissions (Harati-Mokhtari et al., 2007).

RNLI

- More complete than MAIB or AIS for underreported occurrences, but it has a very limited number of data fields.
- Not specific for port activities.

IMO

- Reliance on voluntary reporting from member states and commercial shipping companies.
- Data inconsistencies.
- Similar underreporting of less severe occurrences.
- Reporting subjectivity.
- Inconsistent taxonomy.

Having addressed the data sources used for the three maritime case studies, the limitations of the following data source are important for the aviation case study.

TC

- Human factors hard to quantify and very rarely included in accident narratives.
- No details about pilots.
- Data is not categorised unless the occurrence is further investigated.
- Could not obtain any information on movements to calculate accident rates.
- Similar underreporting of less severe occurrences.

This thesis provided three maritime and one aviation case study which considered different methodologies and data sources, and addressed distinct safety issues specific for those sectors. The most common data limitations in transport safety, as well as those that have been encountered during the use of the MAIB, AIS, RNLI, IMO and TC datasets, have been discussed.

9.1.4. Conclusions

In conclusion, ensuring high data quality is essential, as it enhances the reliability and validity of safety analyses, supports informed decision-making and ultimately contributes to the development of more effective safety management practices (Hauer, 1997). Establishing rigorous data collection frameworks, implementing robust data validation processes, and fostering a culture of accurate reporting are critical steps in addressing these data quality challenges (Elvik, 2008).

While the detailed and exhaustive list of ideal factors presented provides a robust framework for transport safety data analysis, practical implementation requires overcoming significant challenges. Addressing these challenges is crucial for improving data quality and ensuring that safety measures are both effective and feasible across various contexts.

In the context of Safety Management Systems, this section proved the interconnections among the four foundational pillars outlined in Section 2.2 of this thesis: safety policy, safety risk management, safety assurance, and safety promotion. As such, to achieve robust risk management, it is imperative to address the challenges posed by data limitations. This can be accomplished by implementing comprehensive safety policies that prioritise data reporting, integrity and accuracy, ensuring thorough safety assurance processes to continuously monitor and improve data quality, and promoting a culture of safety that emphasises the importance of high-quality data. By tackling data limitations through these integrated approaches, the effectiveness of risk management strategies can be enhanced, and the overall safety objectives of an organisation support.

Having reviewed the main data categories and contributory factors relevant for studying safety occurrences in the transport industry and addressed the capabilities of safety data, the following section provides the main findings of the mixed methods of data analysis.

9.2. Main findings of data analysis

While the limitations of the datasets used in this thesis have been summarised in the previous section, this section focuses on what could be achieved using this data, emphasising on the benefits of using each method of quantitative and qualitative analysis employed.

9.2.1. Main findings from quantitative methods of data analysis

The following quantitative methods of data analysis have been used in this thesis, and their contributions are summarised below.

- Trend analysis
- Contingency analysis and three-way associations

- Logistic regression
- Bayesian Networks
- Complex Networks
- Clustering analysis

Trend analysis is the most widely used method of analysis in the transport sector and is what the annual reports of national and international investigation bodies mostly consist of. It is an easy method that involves examining historical data to identify patterns and changes over time. This method is crucial for understanding long-term developments and fluctuations in accident and incident data. It highlights general trends, such as increases or decreases in accident frequencies and severities, providing a baseline for further, more detailed analysis. In this thesis, trend analysis provided an understanding of what factors the datasets could offer, in what detail, and statistics could be obtained around specific variables.

Having established general trends and getting an understanding of the data, contingency analysis and three-way associations were used to examines the interactions between pre-determined sets of two or three categorical variables, using Chi-Square tests to assure statistical significance and high association strengths. This method goes beyond trend analysis by uncovering hidden relationships and dependencies among multiple factors, offering a deeper understanding of the complexity within the data.

Logistic regression is a statistical method used for binary classification problems, quantifying the influence of predictor variables on the probability of an outcome. It builds on the findings from the previous methods of analysis by providing a model that quantifies how specific factors, such as environmental conditions and vehicle characteristics, impact the likelihood of accidents. This method offers a more predictive approach, helping to identify high-risk scenarios based on historical data.

Bayesian Networks model the probabilistic relationships between variables, offering a structured way to understand causality and dependencies. BN builds on logistic regression by incorporating both prior knowledge and observed data to update the probabilities of outcomes dynamically. This method is particularly effective in dealing with complex interactions and allows for influences from field experts to alter the relationships between factors, providing a robust framework for risk assessment and decision-making. Despite its capabilities, this method requires large amounts of data that were not available in all case studies. In this thesis, the capabilities of BN have been proven for the analysis of safety data.

Complex network analysis examines the interconnectivity and structural properties of safety data, revealing how different risk factors interact within a network. This method introduces a new perspective, identifying key nodes and pathways that significantly influence accident propagation. Compared to BN, CN offer a broader view of the systemic vulnerabilities and potential cascading effects within the transport safety systems. However, this method also relies on high amounts of complete datasets.

Clustering analysis groups similar data points based on predefined criteria, uncovering natural groupings within the dataset. This method adds value by identifying clusters of accidents with common characteristics, providing a focused examination of homogeneous groups within the data. In this thesis, this method was used to group occurrences of different severities and demonstrate the applicability of Heinrich's theory in the transport sector. The clustering analysis results confirmed that the analysed data did not match Heinrich's original severity ratios and pyramid shape. One of the biggest differences was that the Very Serious to Serious accident ratio was 4:1 and 1:5 for the two subsets of data studied, in contrast with Heinrich's 1:29. However, because of the mentioned issue of underreporting, if incidents were to be excluded, the data could indeed be pyramid shaped. Nonetheless, the importance of addressing less severe occurrences in order to prevent more serious ones stands for the transport systems.

Despite the capabilities of accident and incident data and the insightful results obtained in this thesis, because of the mentioned data limitations, a holistic understanding of accident causation patterns could not be achieved as the effects of many of the ideal factors could not be captured. Hence, mixed methods of analysis have been employed, and these are presented in the next section.

9.2.2. Main findings from qualitative data analysis

The following qualitative methods of data analysis have been used in this thesis, and their contributions are summarised below. All of these methods have been employed for three of the case studies, as the one related to piracy had a different aim – to address IMO data limitations rather than obtaining a thorough analysis of this issue.

- Narrative analysis
- Content analysis
- Thematic analysis

Narrative analysis has been used to capture information thar was not separately addressed in the data fields of the studied databases. Furthermore, this method was used to extract information from investigation reports. This helped with the completeness and relevance of the subsequent analyses.

The thematic and content analyses are described below, for each case study where they have been used.

For the first case study related to safety in UK ports, semi-structured interviews have been conducted with ten industry professionals, including harbour masters, safety managers, mariners and directors within the maritime sector. The aim was to validate and complement the insights from the quantitative data analysis. The results provided detailed perspectives on the accuracy and consistency of accident reporting, the quality of various databases, and the impact of human and port-related factors such as channel depth and traffic density on maritime safety as these were missing from the used databases.

In the second case study, that on autonomous vessels, content and thematic analysis have been used. This involved analysing transcribed interviews with industry professionals to identify themes and patterns regarding the expected implications associated with AVs on maritime safety, to complement the results of the quantitative analysis. This offered in-depth insights into the potential benefits and challenges of AVs, including regulatory concerns, technological reliance and implications on human factors. It also highlighted areas of concern that might not be evident from quantitative data alone, such as the responsibility in case of machine errors and the impact of automation on job security. This analysis included perspectives of professionals involved in AV projects and those with direct experience in the maritime industry. This analysis emphasised the importance of people to not rely too much on the new technology, or at least do so gradually, and continue to do what goes right, adopting a proactive approach to safety.

The fourth case study of this thesis included the most comprehensive qualitative research, using semi-structured interviews, phenomenological focus groups and phenomenological questionnaires to gather data from seaplane pilots and other safety professionals. These qualitative methods were chosen based on informal discussions with industry representatives, ensuring that the study addressed the specific needs and preferences of the GA seaplane community. Thematic and content analysis were used to identify key safety issues and inform practical recommendations. The aim was similar as before, to address gaps identified in the quantitative data analysis, but this qualitative study also aimed to gain insights into pilot concerns and decision-making, and reach out to the community of private, recreational seaplane pilots in Canada to bring awareness on specific safety concerns. Overall, this analysis provided a comprehensive understanding of the factors contributing to seaplane occurrences, pilot decision-making during different flight phases, and the preferred methods of safety promotion. It revealed issues such as the reliance on technology, misuse of radios, proficiency and

currency challenges and interactions with boats, which could not be determined through the database analysis.

Engaging with experts and operators in the transport sector proved several significant advantages. One primary benefit is the acquisition of in-depth insights, providing detailed, context-specific information that cannot be gleaned from databases alone. This allows for the development of practical solutions tailored to real-world scenarios, ensuring that safety measures are both feasible and effective. By supplementing existing data with qualitative insights, the overall quality and comprehensiveness of the analysis are enhanced. This approach also increases the relevance of safety strategies, aligning them closely with current industry practices and challenges. Furthermore, involving industry stakeholders in the process helps build trust and collaboration, leading to a higher likelihood of successful implementation of safety measures. In this thesis, the appropriate sampling of the participants was ensured, including their number and characteristics (e.g., experience, qualifications, age).

However, there are also notable disadvantages to consider. The process of interviewing and consulting with experts can be time-consuming and resource-intensive, potentially delaying the overall project timeline. Information obtained from experts may be influenced by personal biases and experiences, introducing subjectivity into the analysis. Additionally, expert opinions can vary widely, making it challenging to derive a consensus or standardised approach. Finally, identifying and gaining access to the most knowledgeable and relevant experts can be difficult, potentially limiting the scope and effectiveness of the engagement.

In summary, the qualitative methods used in the case studies of this thesis complemented the quantitative analyses by providing deeper insights into human factors, regulatory challenges, and industry-specific concerns. They were tailored to address the gaps identified in the quantitative data and to meet the specific needs and preferences of the stakeholders involved, ensuring a holistic and practical understanding of accident causation patterns in the transport sector.

9.2.3. Implications of using mixed methods of analysis

Overall, despite the data limitations explained in the previous section, this section proved that significant results have been obtained by adopting a hybrid methodology. By using mixing methods of analysis and combining data sources, all categories of ideal factors presented at the beginning of this chapter could be addressed in this thesis, achieving a holistic understanding of transport safety.

Another rationale for using mixed methods of analysis is that, due to the rarity of accident occurrence, collecting a sufficient sample might require multiple years of accident data to be collated. During that

period, the conditions, technologies and behaviours of vehicles which led to these occurrences change, and therefore, the representativeness of the training data to future predictions becomes less strong (Guikema, 2020). For example, new technologies such as AIS, changes in Bridge Resource Management and training, or implementation of new risk control measures such as pilotage or traffic lanes would change the risk profile of that waterway. For these reasons, by using mixed methods of analysis, a holistic understanding of accident causation factors can be achieved even with a smaller set of accident/incident data.

The following section addresses further implications of this thesis, related to different pillars of the SMS, and what should be addressed following this comprehensive data analysis, providing a comprehensive framework for safety data analysis.

9.3. Proposed framework for safety data analysis

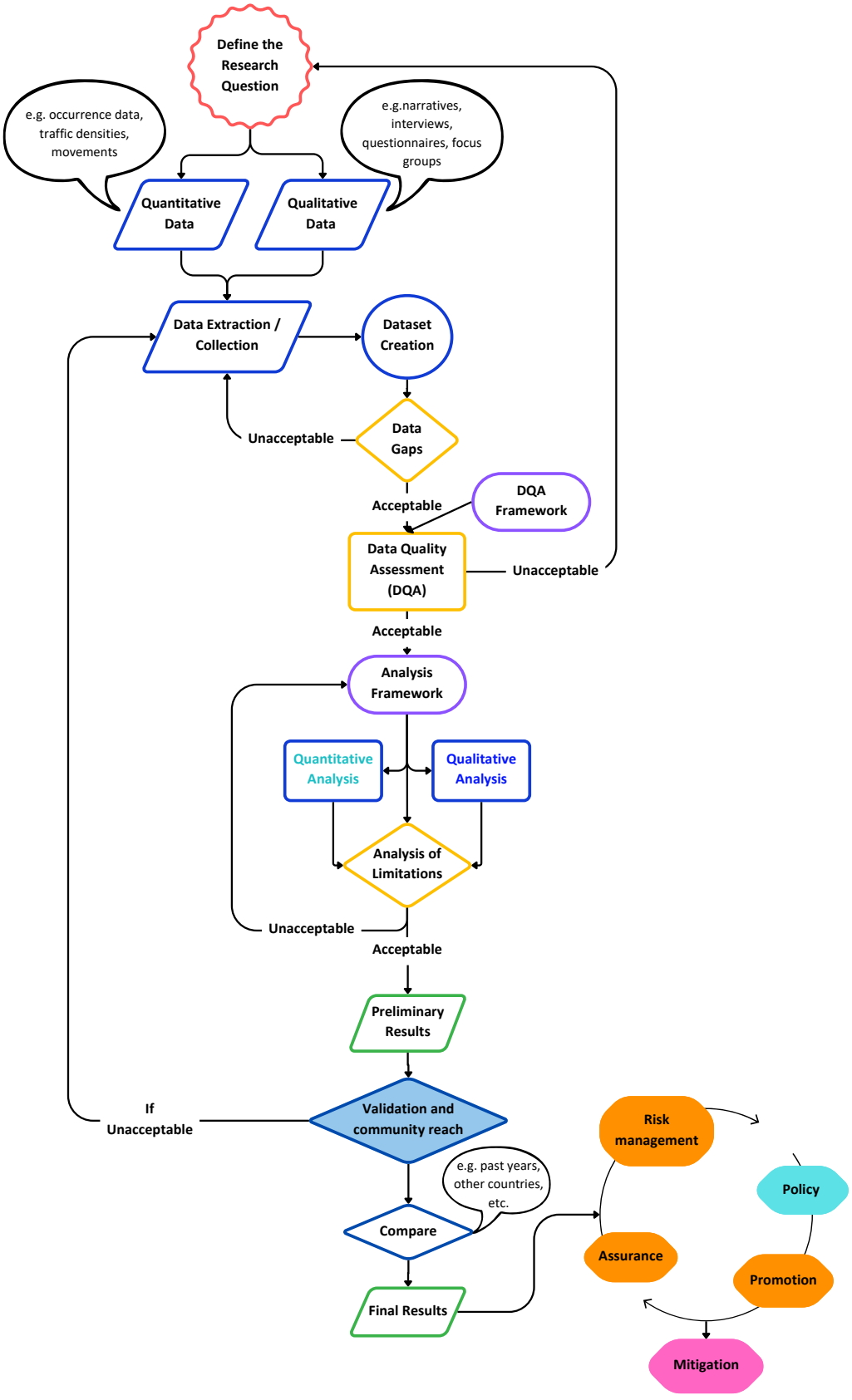
This section provides a comprehensive framework for safety data analysis needed to achieve a holistic understanding of accident causation patterns, while addressing all pillars of the SMS. This is represented if Figure 9.3 and based on the research presented in this thesis.

This framework emphasised some key factors in safety data analysis:

- The consideration of both quantitative and qualitative data sources, emphasising on the use of mixed methods of analysis.
- The importance to implement a robust data quality framework, which has been provided in Section 5.6 of this thesis.
- The necessary modifications of methods of analysis used (analysis framework) tailored for the specific limitations of the data.
- The need to redefine the research question or data analysis methods if the quality checks are unacceptable.
- The essentiality to validate the preliminary set of results and engage with the relevant communities of operators and other field experts.
- The significance of comparing the results with previous years, other countries or fields, which can modify the impact of the results.
- Ensuring the management of safety by addressing all pillars of the SMS to achieve mitigation of unwanted occurrences.

This framework expands on the one proposed in the methodology of this thesis (Section 5.4) to make it practical for regulators and transport organisations, by addressing all aspects of the SMS.

Figure 9.3. Proposed framework for safety data analysis for achieving a holistic understanding of accident causation patterns, while addressing all pillars of the SMS.



9.3.1. Integration of the proposed framework into SMS

The implementation of SMS in niche transport operations presented unique challenges due to limited regulation, lack of oversight, and data scarcity, inconsistent data collection and a lack of structured safety frameworks, requiring tailored approaches that differ from those used in mainstream transport sectors. Without mandatory reporting and established risk management procedures, hazard identification and accident prevention become reactive rather than proactive, limiting opportunities for improvement. Moreover, while structured SMS frameworks are widely implemented in larger, well-regulated systems, smaller-scale or emerging transport operations often lack the necessary resources or industry-wide standardisation to ensure effective safety oversight. This study highlighted the need for alternative, mixed approaches to address gaps in safety management. In thesis, a versatile framework that addresses the mentioned challenges has been developed, contributing to a more inclusive and adaptable SMS model that can be applied across diverse and evolving transport environments.

While the methodology of this thesis proved to be robust, it was enhanced to account for all pillars of the SMS and be applicable for use in the industry. This proposed framework for safety data analysis aims to achieve a holistic understanding of accident causation patterns, recognising that an exclusive focus on risk management alone is insufficient. Addressing safety policy, assurance, and promotion, in addition to risk management, is crucial for developing effective mitigation strategies that enhance overall transport safety. The focus of this thesis was on risk management, however the following summarise the importance of addressing the other SMS pillars.

Policy

Developing and enforcing a comprehensive safety policy is critical for establishing the groundwork for a robust safety culture. A well-defined safety policy outlines the commitment of the organisation to safety, sets clear expectations and provides a framework for all safety-related activities. It ensures that safety objectives are aligned with operational goals and regulatory requirements, promoting consistency and accountability across all levels of the organisation. By prioritising safety policy, organisations can proactively address potential risks, enhance compliance, and foster an environment where safety is an integral part of daily operations. This can lead to improved quantity and quality of safety data.

One key example of the importance of updating safety policy has been revealed in Chapter 8, where there was a consensus amongst participants around the need to update the TP 12668E Instructor Guide Seaplane Rating from May 1996. Through mixed-methods analysis, it was found that the current

guide is outdated and does not adequately address the evolving challenges in seaplane operations. Stakeholders expressed a preference for scenario-based training with clear guidelines. While the data alone does not directly indicate the need for an update, combining it with feedback from industry professionals reveals significant gaps in the guidance material. Updating this guide could reduce the number of seaplane occurrences by addressing these gaps and ensuring the training is relevant to current operational challenges.

Promotion

Promoting safety within the organisation and the broader community is vital for fostering a proactive safety culture. Safety promotion activities ensure that safety information is disseminated effectively, and that there is continuous engagement with all stakeholders. This can be achieved through regular safety communications, workshops and interactive sessions where safety issues are discussed, and best practices are shared. It is important to determine the best methods of safety promotion for the targeted audience, and combine different methods for a bigger reach. This is evident from the preferences of the participants of the seaplane interviews, focus groups and questionnaires, who chose different methods of safety promotion.

An important insight from community interactions is the strong demand for in-person engagement. In Chapter 8, the general aviation seaplane community expressed feelings of being under-supported, citing a lack of safety outreach specific for their community, outdated publications and insufficient engagement from regulatory bodies such as Transport Canada. As part of this thesis, a newsletter has been submitted to COPA to increase the reach even further and promote safety specifically for private, recreational seaplane pilots. Additionally, continuous feedback and discussions are recommended in practice for effective learning and developing best practices. These interactions facilitate knowledge sharing, and address safety concerns directly while fostering a collaborative, informal environment, ultimately leading to enhanced safety practices and solutions.

Assurance

Safety assurance involves the systematic monitoring and evaluation of safety performance to ensure that safety policies and procedures are effectively implemented and continuously improved. Regular audits, inspections and safety performance reviews can help identify areas for improvement, validate compliance with safety standards and verify that corrective actions are taken to address identified issues. However, the fact that the seaplane case study presented in Chapter 8 was so successful is due to the fact that the participants were assured of confidentiality and the encounters were informal, which proved very efficient in getting honest responses and identifying areas of concern that could be

missed by formal methods of safety assurance. Overall, assurance activities provide valuable feedback for refining safety management practices and ensuring that they remain effective in mitigating risks. As a result, organisations are encouraged to prioritise safety assurance in a non-punitive way, to maintain high safety standards and continuously enhance their safety management systems.

9.3.2. Summary of safety recommendations and proposed action plan

This chapter demonstrated the versatility of the novel frameworks for data quality assessment and safety data analysis, by integrating them into a conceptual framework applicable for the diverse needs of different sectors of the transportation industry.

The developed safety management and accident analysis framework extends beyond traditional data analysis methodologies which are widely used in the literature by integrating mixed-methods approaches to ensure a comprehensive understanding of accident causation patterns. Existing literature highlights the importance of combining quantitative and qualitative data in safety research, as seen in transport studies addressing human factors, operational risks and systemic vulnerabilities. This framework builds on previous research that emphasises holistic safety assessment by incorporating structured data quality checks, risk evaluation and stakeholder engagement, bridging gaps in conventional safety management practices.

A key strength of this framework is its adaptability across different transport modes. While developed for maritime and aviation safety, the underlying principles (identification of research question, data integration, data quality checks, mixed-method analysis, result validation and comparison, and safety management system alignment) can be applied to other transport modes such as road and rail. For instance, similar methodologies could enhance safety analysis for autonomous vehicles, railway infrastructure management or aviation ground operations.

Generalisation to other sectors where safety data is available is feasible due to the modular structure of the proposed framework, which accommodates sector-specific variables while maintaining a core analytical approach. Previous studies on transport safety frameworks (e.g., those examining regulatory gaps and data standardisation) align with this framework's emphasis on refining safety policies, ensuring robust risk assessments, and promoting proactive safety cultures. Future research should explore its application in diverse environments, testing its effectiveness in different regulatory landscapes and operational contexts.

To sum up, this robust framework is tailored to account for a holistic safety analysis using available data sources of varying quality and using mixed methods of analysis. Because of its adaptability, this framework is recommended for regulators and other organisations, and it can be used to address both

the big picture of transport safety, or the safety of smaller, underrepresented communities. This will ensure that the regulations reflect the needs of these smaller communities in different transportation sectors. Overall, this comprehensive framework can be used for a thorough analysis of areas that lack quantity or quality of available data, which is of utmost importance given the various data limitations uncovered in this thesis.

10. Conclusions - main contributions, impact and future work

Transport systems are integral to daily life and global commerce, and their safety is paramount in preventing devastating consequences, including loss of life, environmental harm, and economic loss. While there are various methods to measure and assess safety, they often only assess a part of the complicated picture of safety, e.g., quantitative safety measures ignoring narratives of accidents which contain much detail on causal factors. By acknowledging the transport system as a socio-technical system with complex interactions between human, technical and environmental factors, this thesis advocates for a more comprehensive approach to safety analysis. This perspective ensures that safety measures address the root causes of accidents and incidents, leading to more effective prevention strategies.

In this thesis, a pragmatic approach has been employed to address the real-world problems of the maritime and aviation sectors, through practical solutions and the prioritisation of the usefulness and applicability of the proposed framework. Additionally, through an epistemological approach, it was possible to assess safety beyond database capabilities and examine factors related to transport operators, such as decision-making, safety protocols and risk perception. Furthermore, this approach allowed for incorporating the different perspectives of stakeholders to fully understand the contributory factors to both safe and unsafe practices.

Therefore, hybrid methods of analysis (quantitative/qualitative and reactive/proactive/predictive) have been used to better understand accident causation factors, the reporting methods and limitations of accident data sets. By studying transport safety in two sectors (maritime and aviation), this thesis provided a holistic understanding of accident causation patterns by developing a robust, adaptable framework of analysis which addressed data limitations. This has been achieved through combining not only data sources, but also quantitative and qualitative methods of analysis. The data sources that have been combined in this thesis include accident/incident databases, investigation reports, vehicle tracking systems, voluntary reporting schemes, interviews with operators and other safety professionals, focus groups and questionnaires.

10.1. Review of the met aim and objectives of the thesis

This thesis has met the aim to develop a robust, versatile framework to improve transport safety management that can be applied to different transport sectors, as outlined in the previous chapter. To achieve this aim, the six research objectives have been met and are discussed below.

The *role of data and its collection in Safety Management Systems (SMS) in transport* has been reviewed through a case study in Section 2.5. This has also introduced transport data limitations, which have been further addressed throughout the thesis to account for limitations related to different types of data sources.

The second objective of *assessing the strengths, weaknesses and limitations of current methods of safety data analysis* has been achieved through lengthy reviews of available literature. This has also been achieved through employing multiple methods of analysis, for which the limitations have been addressed. Overall, multiple, mixed quantitative and qualitative methods of analysis have been employed to diminish the limitations of the results of any one method and achieve a realistic understanding of safety concerns for each case study included in this thesis.

The third objective focused on *establishing appropriate indicators of data quality using different data quality dimensions, to propose a framework for the quality assessment of accident data*. Such framework has been proposed in Section 5.6 and then applied to all case studies. This helped understand the limitations of the data sources to then decide which methods of further data collection are needed.

The above have been considered during the *development and implementation of a methodology for a holistic understanding of accident causation patterns using data analysis*. This has been accomplished through four case studies, by integrating multiple data sources and mixed methods of quantitative and qualitative analysis.

Based on the findings, *limitations of current databases have been identified and additional information requirements assess*. These included shifting the focus on a qualitative-oriented approach to fill the gaps identified through data analysis. By engaging with different stakeholders in the transport industry, as well as other professionals, two main goals have been achieved:

- Assess what contributed to the data limitations identified, and
- Determine the impact of factors that could not be analysed using the available data sources.

Lastly, a *framework which uses multiple sources of safety data and methods of analysis has been developed* to improve safety in transport operations through SMS, which is generic for different data sources and even transport sectors.

10.1.1. Summary of limitations encountered

This section summarises the limitations encountered throughout this PhD research. These affected the scope, choice of data sources and analysis depth. These limitations primarily stemmed from data

constraints, methodological challenges, and the inherent complexity of studying transport safety in socio-technical environments. While efforts were made to mitigate these issues, they should be acknowledged when interpreting the findings and considering future research directions.

One of the most significant challenges was the lack of comprehensive and standardised data. Accident and incident databases often had incomplete, inconsistent, or missing information, particularly concerning human factors and environmental conditions. Many occurrences lacked detailed narratives, limiting the ability to perform an in-depth causation analysis. Additionally, underreporting was a recurring issue, especially for minor incidents, meaning that many contributing factors remained undocumented. This challenge was particularly evident in private and recreational seaplane operations, where reporting requirements are less stringent than for commercial aviation.

Differences in taxonomy and classification systems across various datasets also complicated data integration. In some cases, accident categories or causal factors were labelled differently across sources, requiring standardisation efforts that introduced potential interpretation biases. Furthermore, data accessibility was a challenge, as some relevant databases were restricted, preventing a fully exhaustive analysis.

The use of mixed methods, combining quantitative and qualitative analysis, helped mitigate some data limitations but also introduced methodological challenges. Quantitative analysis was constrained by the lack of exposure data, such as total flight hours or seaplane movements, making it difficult to calculate accurate accident rates. The absence of such baseline data meant that trends could only be analysed in relative rather than absolute terms.

Qualitative methods, including interviews, focus groups, and questionnaires, provided valuable insights but introduced subjectivity and potential response biases. Participants' recollections of incidents may have been influenced by personal experiences, and their willingness to share information could have been affected by concerns over confidentiality. Additionally, the sample size for interviews and focus groups, while sufficient for thematic analysis, may not fully represent the diversity of perspectives within the seaplane pilot community.

The findings of this study are primarily focused on specific case studies in the maritime and aviation industries. Even though the framework proposed in this thesis can be applied to other data sources and even other sectors, the findings presented in this thesis may not be fully generalisable. Differences in regulations, environmental conditions and operational practices could result in varying safety challenges in different sectors and geographic areas. However, where possible, comparisons with international literature were made to highlight broader trends and transferable lessons.

Transport safety, particularly in environments where aviation and maritime operations intersect, is inherently complex. No dataset or methodology can fully capture the multifaceted interactions between human, technical and environmental factors. The dynamic nature of operations, evolving regulatory frameworks and external influences such as climate conditions or economic factors all play a role in safety outcomes. As such, while this research provides valuable insights into accident causation patterns and risk factors, it should be viewed as one piece of a broader safety analysis framework, where the last parts of the framework related to SMS (safety risk management, assurance, promotion and policy) should be fully explored separately in order to support the mitigation of future accidents and incidents.

Despite these challenges, this study successfully identified key safety concerns, provided insights into accident patterns and highlighted areas for improvement in transport safety management. The limitations identified emphasise the need for more comprehensive data collection, improved reporting mechanisms and standardised classification systems to enable more accurate and generalisable safety research. Future studies should address these gaps by incorporating longitudinal data, larger and more diverse sample sizes, and enhanced exposure metrics to refine accident risk assessments further.

10.2. Main contributions

The research presented in this thesis offers several significant contributions to the field of transport safety, particularly in the ways to assess and address accident causation patterns within the transport industry. These contributions are:

1) Development of a novel, holistic and versatile safety data analysis framework.

2) Development of a novel, robust data quality assessment framework.

3) Demonstrated the benefits of using mixed methods of analysis, as well as combined data sources.

4) Determined particular insights into maritime and aviation safety, through assessing the following:

- factors underlying safety in UK ports.
- the impact of autonomous vessels on maritime safety.
- piracy occurrences in West Africa and the Gulf of Guinea.
- factors underlying safety of private, recreational seaplane operations in Canada.

5) Offered practical recommendations for each pillar of the SMS.

Overall, this thesis makes substantial contributions to the field of transport safety by providing innovative methodologies, practical recommendations and a comprehensive framework for safety data analysis and mitigation of unwanted occurrences. These contributions are expected to enhance the understanding of accident causation patterns and support the development of more effective safety management practices across the transport industry. Thereby, this approach is recommended for all regulators as it is highly adaptable for particular needs and suitable for different types and sizes of data, while offering a holistic understanding of safety concerns.

10.3. Research impact

The primary application of this research is to assist in reducing the number of transport accidents, by learning from both what works and what doesn't and by having insights from different industries and countries. The research used maritime and aviation data towards the development of a framework for holistic understanding of accident causation patterns using mixed methods of analysis. Despite the focus being on only two transport sectors in this thesis, the proposed framework is adaptable for other transport modes and industries. This has a high impact by improving the understanding of the bigger picture for safety, as the proposed framework is suitable for any organisation. Indeed, it has the ability to enhance perceptions of safety management and allow a continuous improvement of safety management systems.

The case studies utilised in this thesis offer valuable insights into how SMS and accident analysis frameworks can be adapted for broader application across different transport modes. By examining safety management in less-regulated areas such as private seaplane operations, occupational risks in maritime transport and the impact of emerging technologies, this study highlights common challenges that extend beyond the specific sectors analysed. Many transport domains, such as urban air mobility, autonomous road transport and offshore energy operations, share similar issues related to regulatory gaps, data underreporting and the difficulty of implementing standardised SMS frameworks.

The methodology applied in this thesis, including mixed-methods analysis, stakeholder engagement and scenario-based risk assessment, can be transferred to other transport sectors even where data availability is limited. By integrating qualitative insights with quantitative safety data and by performing various quality checks, the proposed framework ensures a comprehensive assessment of safety risks, even in non-traditional transport environments. This adaptability makes it relevant not only for maritime and aviation, but also for other transport modes, emerging transport technologies,

or even other sectors where accidents are present and traditional safety approaches may not yet be fully established.

Overall, using mixed methods of analysis proved useful in this thesis, particularly in the last case study which allowed more interaction with the GA seaplane community and relevant stakeholders. The feedback received during the interviews, focus groups, questionnaire and via email was positive. The following quotes from the feedback received, highlights the strengths of the proposed framework and provides reassurance of the impact and quality of the research undertaken during this PhD:

- "I learned a lot from this. Glad I came to this. I will do some things different from now on!" – in-person focus group participant
- “This made me realise I became complacent […] you get complacent after flying for a long time.” – in-person focus group participant
- “Thank you […] for taking the time to host the meeting this morning. It was better than I expected and I was in awe of the years of experience in the room. I hope everyone found it beneficial.” – about the in-person focus group
- “I will forward this information to over 20-50 pilots in my region” – referring to the booklet and presentation
- “An absolute pleasure meeting you both today” – interviewed participant
- “I want to congratulate you and your team for an excellent presentation and round table. From my perspective, we need to have more opportunities for newer floatplane pilots so that they can mitigate.”
- “Terrific presentation by all today. We definitely need more of this kind of get together.”
- “Thanks for including me at that very worthwhile floatplane pilot exchange. This is TC at its best.”

10.4. Recommendations and future work

While this thesis has successfully developed and applied a robust, adaptable framework for transport safety analysis within the maritime and aviation sectors, future research should explore its application to other transport modes such as road and rail. Each sector has unique challenges and operational characteristics that could benefit from tailored safety analysis methodologies. By applying the framework to diverse transport modes, researchers can validate its versatility and further refine it to address sector-specific safety issues.

Despite the comprehensive data analysis conducted in this thesis, significant data gaps and quality issues were identified. Future work should aim to address these gaps by developing standardised data collection and reporting protocols across different transport sectors. Collaborating with industry

stakeholders to create centralised, high-quality databases will improve the reliability of safety analyses. Additionally, efforts should be made to encourage transparent and comprehensive reporting of safety incidents, including near-misses and minor occurrences.

Particular data gaps are related to human factors, which play a critical role in transport safety. Future research should delve deeper into the human elements of safety, such as decision-making processes, risk perception and the influence of organisational culture. Conducting qualitative studies, such as interviews and focus groups with operators and safety professionals rather than relying on investigation reports, will provide valuable insights into the human factors that contribute to accidents and incidents. Understanding these factors can lead to targeted interventions and training programs to enhance safety.

With higher quality databases, future research should focus on integrating advanced technologies such as artificial intelligence (AI), and big data analytics into the safety analysis framework because of the rapid advancement of technology which presents both opportunities and challenges for transport safety. This can enhance the predictive capabilities of the framework, identify emerging safety trends in real time and provide more accurate risk assessments. Additionally, the use of AI can automate the data analysis process, making it more efficient and capable of handling larger datasets.

Future research should also include ways to establish continuous monitoring systems that collect real-time data on transport operations. Real-time data can facilitate proactive safety management by allowing immediate identification and mitigation of emerging risks. Implementing such systems will require collaboration with industry partners and investment in advanced monitoring technologies.

Furthermore, the findings of this thesis highlight the importance of comprehensive safety policies and robust regulatory frameworks. Future work should explore the policy implications of the proposed safety analysis framework and provide recommendations for regulatory bodies. This includes advocating for the adoption of standardised safety management systems across different transport sectors and promoting policies that encourage data sharing and transparency. For this, the engagement with policymakers and industry regulators is.

This thesis proved the benefits of engaging with stakeholders and interacting with the broader community for effective safety management. Future research should focus on developing strategies to enhance stakeholder engagement and collaboration. This includes creating platforms for regular communication, feedback and knowledge sharing among stakeholders, to foster a culture of collaboration towards improving overall safety.

Because transport safety is a global concern, future research can benefit from international collaboration and comparative studies. Despite possible differences in factors underlying safety in different countries (e.g., differences in environmental conditions, infrastructure or safety culture), cross-country analyses would help identify best practices and share successful safety interventions. In this way, researchers can identify common challenges and innovative solutions that can then be adapted and applied locally. Furthermore, international collaboration could also facilitate the development of global safety standards and protocols.

In conclusion, the future work outlined above aims to build on the foundation established in this thesis by expanding the application of the safety analysis framework, integrating advanced technologies, addressing data quality issues and exploring the human factors of safety. By pursuing these research directions, the transport industry can continue to improve safety management practices, reduce accidents and enhance the overall safety of transport operations across various sectors.

References

Accou, B. & Carpinelli, F., (2022). Systematically investigating human and organisational factors in complex socio-technical systems by using the "SAfety FRactal ANalysis" method. Applied Ergonomics, Volume 100, 103662, ISSN 0003-6870. https://doi.org/10.1016/j.apergo.2021.103662.

Abdulla, A.M., (2011). Regulating vessel traffic service (VTS) to mitigate maritime accidents at port approaches. Masters' dissertation. https://core.ac.uk/download/pdf/217233287.pdf

Agrawal, R., Imieliński, T., Swami, A., (1993). Mining association rules between sets of items in large databases. ACM SIGMOD Record, 22, 207-216. http://doi.org/10.1145/170036.170072

Ahvenjärvi, S., (2016). The Human Element and Autonomous Ships. TransNav. https://www.transnav.eu/Article_The_Human_Element_and_Autonomous_Ahvenjärvi,39,675.html

Air Charter Service, (2018). From intercontinental travel to modern workhorse: the changing role of the seaplane. https://www.aircharterserviceusa.com/about-us/news-features/blog/from-intercontinental-travel-to-modern-workhorse-the-changing-role-of-the-seaplane

Aircraft Owners and Pilots Association (AOPA), (2023). Seaplane Accident Analysis Report 2008 – 2022. https://www.aopa.org/training-and-safety/air-safety-institute/accident-analysis/seaplane-accident-report

Allianz Global Corporate & Specialty, (2017). Safety and Shipping Review 2017, An annual review of trends and developments in shipping losses and safety. Munich, Germany, 44 pp.

Allianz, (2023). Safety and Shipping 1912-2012. https://www.allianz.com/content/dam/onemarketing/azcom/Allianz_com/migration/media/press/document/other/agcs_safety_shipping_1912-2012.pdf

Almajali, D.A., Dahalin, Z.M., (2011). Applying the triangulation approach in IT–business strategic alignment and sustainable competitive advantage. IBIMA Business Review, 2011, 1–13. doi:10.5171/2011.214481

American Association of Port Authorities, (2020).

Anderson, J.L., (1995). Piracy and World History: An Economic Perspective on Maritime Predation. Journal of World History, 6(2), 175-199. https://www.jstor.org/stable/20078637

Anderson, P., (2003). Managing Safety at Sea. PhD Thesis. Middlesex University. http://eprints.mdx.ac.uk/2657/

Andrade, J.F., Kalakou, S., Lopes da Costa, R., (2022). Exploratory analysis of seaplane operations in Greece: insights of a survey and SWOT analysis. European Planning Studies, 31(4), 679–699. https://doi.org/10.1080/09654313.2022.2057187

Antao, P., Sun, S., Teixeira, A.P., Soares, C.G., (2023). Quantitative assessment of ship collision risk influencing factors from worldwide accident and fleet data. Reliability Engineering & System Safety, 234, 18. http://doi.org/10.1016/j.ress.2023.109166

Arend, R.J., (2020). Strategic decision-making under ambiguity: a new problem space and a proposed optimization approach. Business research (Göttingen), 13 (3), 1231–1251. doi:10.1007/s40685-020-00129-7

Arnaldo Valdés, R.M., Gómez Comendador, V.F., Perez Sanz, L., Rodriguez Sanz, A., (2018). Prediction of aircraft safety incidents using Bayesian inference and hierarchical structures. Safety Science, 104, 216-230. https://doi.org/10.1016/j.ssci.2018.01.008

Association of British Ports (ABP), (2019). Safety. http://www.abports.co.uk/About_ABP/Safety/

Austal, Marinelink, (2023). Smart Artificial Intelligence. https://marinelink.austal.com/marinelink-smart

Australian Journal of Rural Health, (2019). Role of General Aviation in Remote Healthcare.

Badawi, E., Halawa, A., (2003). Maritime Communication: The Problem of Cross Cultural and Multilingual Crews. Presented at 4th IAMU General Assembly. http://iamu-edu.org/wp-content/uploads/2014/06/badawi-halawa.pdf

Baker, C., McCafferty, D.B., (2005). Accident database review of human element concerns: what do the results mean for classification? Proceedings of the Human Factors in Ship Design, Safety and Operation held in London, February 23-24, 2005.

Balmat, J.F., Lafont, F., Maifret, R., Pessel, N., (2009). Maritime risk assessment (MARISA), a fuzzy approach to define an individual ship risk factor. Ocean Engineering, 36(15-16), 1278-1286. https://doi.org/10.1016/j.oceaneng.2009.07.003

Baxter, G., Sommerville, I., (2011). Socio-technical systems: From design methods to systems engineering. Interacting with Computers, 23(1), 4-17.

Becker, H.S., (1996). Tricks of the Trade: How to Think About Your Research While You're Doing It. University of Chicago Press.

Bellamy, E., (2023). NAA Comparison report. UK Civil Aviation Authority. https://www.caa.co.uk/our-work/publications/documents/content/cap2516/

Bengtsson, M., (2016). How to plan and perform a qualitative study using content analysis. https://www.sciencedirect.com/science/article/pii/S2352900816000029

Berg, H.P., (2013). Human factors and safety culture in maritime safety. Int. J Mar. Navigat. Saf. Sea Transp., 7(3). http://www.transnav.eu

Berrones-Sanz, L.D., (2021). A methodological experience in the training of road safety promoters in Mexico.

Bhaskar, R., (1975). A Realist Theory of Science. Leeds Books.

Bhattacharya, S., (2009). The Impact of the ISM Code on Management and Occupational Health Safety in the Maritime Industry. PhD Thesis. Cardiff University. http://www.sciencedirect.com/science/article/pii/S0308597X11001497

Bimco, Clia, Ics, Intercargo, Intermanager, Intertanko, Iumi, Ocimf, Council, World Shipping., (2023). The guidelines on cyber security onboard ships. https://www.bimco.org/about-us-and-our-members/publications/the-guidelines-on-cyber-security-onboard-ships

Bird, F.E., Germain, G.L., (1985). Practical Loss Control Leadership. International Loss Control Institute.

Birkett, H., (2022). What Is Safety Culture? What is safety culture? | Chamber of Shipping. November 10. https://www.ukchamberofshipping.com/latest/what-safety-culture/

Böcker, L., Olsson, L.E., Uteng, T.P., Friman, M., (2022). Pandemic impacts on public transport safety and stress perceptions in Nordic cities.

Bolbot, V. et al., (2025). A systems-theoretic approach using association rule mining and predictive Bayesian trend analysis to identify patterns in maritime accident causes. ScienceDirect.

Brackstone, G., (1999). Managing data quality in a statistical agency. Survey methodology, 25(2), 139-150.

Braun, V., Clarke, V., (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3, 77-101. https://www.tandfonline.com/doi/abs/10.1191/1478088706qp063oa

Brin, S., Page, L., (1998). The anatomy of a large-scale hypertextual Web search engine. Computer Networks and ISDN Systems, 30, 107-117. http://doi.org/10.1016/S0169-7552(98)00110-X

British Ports Association (BPA), (2022). The British ports industry. British Ports Association. November 10. https://www.britishports.org.uk/

Brown, P., Smith, R., Jones, A., (2016). Fall incidents on cargo ships: A case study analysis. Marine Technology Journal, 51(3), 45-58.

Brown, R., Lee, S., (2018). The impact of crew fatigue on maritime accidents. Journal of Marine Science and Engineering, 6(4), 120-135.

Brownfield, M., Charpentier, R., (2006). Geology and Total Petroleum Systems of the Gulf of Guinea Province of West Africa.

Bryman, A., (2016). Social Research Methods. Stockholm. https://www.academia.edu/38228560/Alan_Bryman_Social_Research_Methods_4th_Edition_Oxford_University_Press_2012_pdf

Bueger, C., (2015). What is maritime security? Mar. Policy, 53, 159–164.

Busari, M., (2025). Data Analytics for Predictive Traffic Law Enforcement and Accident Prevention. ResearchGate.

Bye, R.J., Aalberg, A.L., (2018). Maritime navigation accidents and risk indicators: An exploratory statistical analysis using AIS data and accident reports. Reliability Engineering & System Safety, 176, 174-186. http://doi.org/10.1016/j.ress.2018.03.033

CAAC: Civil Aviation Administration of China., (2018). CAAC

Cai, L., Zhu, Y., (2015). The Challenges of Data Quality and Data Quality Assessment in the Big Data Era. Data Science Journal, 14. http://doi.org/10.5334/dsj-2015-002

Cakir, E., Fiskin, R., Sevgili, C., (2021). Investigation of tugboat accidents severity: An application of association rule mining algorithms. Reliability Engineering & System Safety, 209, 16. http://doi.org/10.1016/j.ress.2021.107470

Caldwell, J.A., Caldwell, J.L., Brown, D.L., Smith, J.K., (2009). The effects of 37 hours of continuous wakefulness on the physiological and cognitive performance of aviators. Military Medicine, 174(1), 37-45.

Cambridge University Press., (2020). Safety. Cambridge Advanced Learner's Dictionary & Thesaurus (4th ed., p. 234). https://dictionary.cambridge.org/dictionary/english/safety

Canadian Owners and Pilots Association (COPA)., (2024). Canada’s voice for General Aviation. https://copanational.org/about

Cao, Y., Wang, X., Wang, Y., Fan, S., Wang, H., Yang, Z., et al., (2023). Analysis of factors affecting the severity of marine accidents using a data-driven Bayesian network. Ocean Engineering, 269. http://doi.org/10.1016/j.oceaneng.2022.113563

Cao, Y., Wang, X., Yang, Z., Wang, J., Wang, H., Liu, Z., (2023). Research in marine accidents: A bibliometric analysis, systematic review and future directions. Ocean Engineering, 284. http://doi.org/10.1016/j.oceaneng.2023.115048

Cao, Y., et al. (2022)., Challenges and Advances in Predictive Safety Implementation for Transport Systems. IEEE Xplore.

Carter, T., Williams, J.G., (2019). Crew and passenger deaths from vessel accidents in United Kingdom passenger ships since 1900. International Maritime Health, 70(1), 39-48. doi:10.5603/IMH.2019.0001

CASA: Civil Aviation Safety Authority., (2019). CASA

CAST/ICAO Common Taxonomy Team (CAST/ICAO CTT)., (n.d.). Glossary of Terms. https://www.intlaviationstandards.org/apex/f?p=240:1:1749143038023::NO::P1_X:Glossary

CAST/ICAO Common Taxonomy Team (CICTT)., (2011). Definitions and Usage Notes - Aviation Occurrence Categories. https://www.icao.int/SAM/Documents/2017-SSP-BOL/CICTT%20Occurrence%20Category.pdf

CAST/ICAO Common Taxonomy Team (CICTT)., (2013). Definitions and Usage Notes – Phase of Flight. https://www.intlaviationstandards.org/Documents/PhaseofFlightDefinitions.pdf

CAST/ICAO Common Taxonomy Team (CICTT)., (2014). Definitions and Usage Notes – Hazard. https://www.intlaviationstandards.org/Documents/HazardDefinitions.pdf

Celik, M., Selcuk, C., (2009). Analytical HFACS for Investigating Human Errors in Shipping Accidents. Accident Analysis & Prevention, 41(1), 66-75. https://doi.org/10.1016/j.aap.2008.09.004

Cevik, I., Elfvengren, K., Dahanayake, A., (2022). Fatigue Risk Assessment of Cabin Crew for Aviation Transport Safety.

Chang, Y., Park, H., (2016). The impact of vessel speed reduction on port accidents. Accident Analysis & Prevention, 123, 422-432. https://doi.org/10.1016/j.aap.2016.03.003

Chauvin, C., Lardjane, S., Morel, G., Clostermann, J.P., Langard, B., (2013). Human and organisational factors in maritime accidents: Analysis of collisions at sea using the HFACS. Accident Analysis & Prevention, 59, 26-37. https://doi.org/10.1016/j.aap.2013.05.006

Chen, T., Chung, H., Jang, K., & Xu, P., (2025). Is there an emotional dimension to road safety? A spatial analysis for traffic crashes considering streetscape perception and built environment. Analytic Methods in Accident Research.

Cheong, H., Lyons, A., Houghton, R., Majumdar, A., (2023). Secondary Qualitative Research Methodology Using Online Data within the Context of Social Sciences. International Journal of Qualitative Methods, 22. https://doi.org/10.1177/16094069231180160

Cho, D.-O., (2007). The effects of the M/V Sea Prince accident on maritime safety management in Korea. Marine Policy, 31, 730-735. http://doi.org/10.1016/j.marpol.2007.01.005

Chung, C.J., Nam, Y., Stefanone, M.A., (2012). Exploring online news credibility: The relative influence of traditional and technological factors. Journal of Computer-Mediated Communication, 17(2), 171-186. https://doi.org/10.1111/j.1083-6101.2011.01565.

Civil Aviation Authority (CAA) of New Zealand., (2020). Aviation Safety Report – 1 January to 31 December 2019. Intelligence, Safety and Risk Analysis Unit. https://www.aviation.govt.nz/assets/safety/reports/Aviation-Safety-Report-1Jan-2019-to-31-Dec-2019-v2.pdf

Civil Aviation Authority (CAA)., (2018). CAA

Civil Aviation Safety Authority (CASA)., (2019). Annual Report.

Clegg, C.W., (2000). Sociotechnical principles for system design. Applied Ergonomics, 31(5),463-477.

Clinton, V., Oster, J.S., Strong, C., Kurt, Z., (2013). Analyzing aviation safety: Problems, challenges, opportunities. Research in Transportation Economics, 43(1), 148-164. https://doi.org/10.1016/j.retrec.2012.12.001

Cohen, S., (1980). Aftereffects of stress on human performance and social behavior: A review of research and theory. Psychological Bulletin, 88(1), 82-108.

Compare, L., Riccardi, M., Mascherona, R., & Zio, E., (2025). Structural causal modeling and STPA for the risk analysis of a rail system powered by H_2 fuel. Reliability Engineering & System Safety.

Correa-Jullian, C., Ramos, M., & et al., (2024). Exploring Human-Autonomy Teams in Automated Driving System Operations. IEEE Transactions on Human-Machine Systems.

Crawford, J., (2018). Operaciones con Buques no Tripulados, ¿Fin de los Accidentes en el Mar? https://revistamarina.cl/articulo/operaciones-con-buques-no-tripulados-fin-de-los-accidentes-en-el-mar

Creswell, J.W., (2014). Research Design: Qualitative, Quantitative, and Mixed Methods Approaches (4th ed.). SAGE Publications.

Creswell, J.W., Plano Clark, V.L., (2014). Designing and Conducting Mixed Methods Research (4th ed.). SAGE Publications.

Creswell, J.W., Plano Clark, V.L., (2018). Designing and Conducting Mixed Methods Research (Third edition.). SAGE.

Crossan, F., (2003). Research philosophy: towards an understanding. Nurse Researcher, 11(1), 46-55.

Cusumano, E., Ruzza, S., (2020). Piracy and the Privatisation of Maritime Security. Cham, Springer International Publishing AG.

Darbra, R.M., Casal, J., (2004). Historical analysis of accidents in seaports. Safety Science, 42(2), 85-98. https://doi.org/10.1016/S0925-7535(03)00002-X

Dawson, K., Harrison, R., Holmes, J., (2017). Preventing slips, trips, and falls on fishing vessels. Occupational Medicine, 67(1), 33-40.

Daxecker, U., Prins, B., (2013). Insurgents of the Sea: Institutional and Economic Opportunities for Maritime Piracy. The Journal of Conflict Resolution, 57(6), 940-965. 10.1177/0022002712453709

de Voogt, A., Campos, A., Lu, Y., (2023). Amphibious Airplane Accidents: An Exploratory Analysis. Applied Sciences, 13(22), 12224. https://doi.org/10.3390/app132212224

de Vos, J., Hekkenberg, R.G., Valdez Banda, O.A., (2021). The Impact of Autonomous Ships on Safety at Sea: A Statistical Analysis. Reliability Engineering & System Safety. https://doi.org/10.1016/j.ress.2021.107558

Denton, G.L., Harris, J.R., (2022). Maritime Piracy, Military Capacity, and Institutions in the Gulf of Guinea. Terrorism and Political Violence, 34(1), 1-27.10.1080/09546553.2019.1659783

Denzin, N.K., Lincoln, Y.S., (Eds.). (2011). The SAGE Handbook of Qualitative Research (4th ed.). SAGE Publications.

Department for Transport (DfT), Maritime and Coastguard Agency., (2022). Maritime Safety Action Plan. publishing.service.gov.uk.

Department for Transport (DfT)., (2016). Port Marine Safety Code; For all UK Harbour Authorities and other marine facilities, berths and terminals -- UPDATED November 2016. United Kingdom.

Department for Transport (DfT)., (2016). Port Marine Safety Code; For all UK Harbour Authorities and other marine facilities, berths and terminals -- UPDATED November 2016. United Kingdom. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/918935/port-marine-safety-code.pdf

Department for Transport (DfT)., (2016). A Guide To Good Practice On Port Marine Operations; Prepared In Conjunction With The Port Marine Safety Code. United Kingdom.

Department for Transport (DfT)., (2016a). Guidance: Port Marine Safety Code. United Kingdom. https://www.gov.uk/government/publications/port-marine-safety-code

Department for Transport (DfT)., (2017). MGN 564: marine casualty and marine incident reporting. Marine Accident Investigation Branch.

Desai, R.M., Shambaugh, G.E., (2021). Measuring the global impact of destructive and illegal fishing on maritime piracy: A spatial analysis. PloS One, 16(2), e0246835.10.1371/journal.pone.0246835

Dillon, R., Tinsley, C., (2008). How near misses influence decision making under risk: a missed opportunity for learning. Management Science.

Dinges, D.F., (1995). An overview of sleepiness and accidents. Journal of Sleep Research, 4(S2), 4-14.

Du, W.-B., Zhang, M.-Y., Zhang, Y., Cao, X.-B., Zhang, J., (2018). Delay causality network in air transport systems. Transportation Research Part E: Logistics and Transportation Review, 118, 466-476. http://doi.org/10.1016/j.tre.2018.08.014

Du, L., Goerlandt, F., Kujala, P., (2020). Review and analysis of methods for assessing maritime waterway risk based on non-accident critical events detected from AIS data. Reliability Engineering and System Safety, 200. doi:10.1016/j.ress.2020.106933

Dupuy, M.-D., (2012). A framework for the analysis of separation-related incidents in aviation. PhD Thesis, Imperial College London.

Ehrlinger, L., Wöß, W., (2022). A survey of data quality measurement and monitoring tools. Frontiers in Big Data, 5, 850611. https://doi.org/10.3389/fdata.2022.850611

Ek, A., (2014). Relationships Between Safety Culture Aspects – A Work Process to Enable Interpretation. Marine Policy, 44, 179-186.

Elliott, J., (2016). Safety I and safety II: the past and future of safety management. https://www-tandfonline-com.iclibezp1.cc.ic.ac.uk/doi/full/10.1080/00140139.2015.1093290

EMSA, (2022). Annual Overview of Marine Casualties and Incidents 2022. Lisbon: European Maritime Safety Agency.

Endsley, M.R., (1995). Toward a theory of situational awareness in dynamic systems. Human Factors, 37(1), 32-64.

Erlingsson, C., Brysiewicz, P., (2017). A hands-on guide to doing content analysis. African Journal of Emergency Medicine, 7(3), 93-99.10.1016/j.afjem.2017.08.001

Esmaeeli, H., Mazaheri, A., & Mohammadi Ghohaki, T., (2025). Evaluating Autonomous Vehicle Safety Countermeasures in Freeways Under Sun Glare. MDPI.

EU Maritime Security Factsheet., (2021). The Gulf of Guinea. https://www.eeas.europa.eu/eeas/eu-maritime-security-factsheet-gulf-guinea_en

EU Naval Force., (2022). Operation ATALANTA. https://eunavfor.eu/

European Aviation Safety Agency (EASA)., (2018). Annual Safety Review 2018. Cologne, Germany. https://www.easa.europa.eu/document-library/general-publications/annual-safety-review-2018

European Commission., (2023). MUNIN: Research in maritime autonomous systems project results and technology potentials. http://www.unmanned-ship.org/munin/wp-content/uploads/2016/02/MUNIN-final-brochure.pdf

European Maritime Safety Agency (EMSA)., (2015). Annual Overview of Marine Casualties and Incidents 2015. Lisbon, Portugal.

European Maritime Safety Agency (EMSA)., (2016). Data Definition Standard. Attribute properties. All Taxonomy References.

European Maritime Safety Agency (EMSA)., (2017). Annual Overview of Marine Casualties and Incidents 2017. http://emsa.europa.eu/publications/technical-reports-studies-and-plans/item/3156-annual-overview-of-marine-casualties-and-incidents-2017.html

European Maritime Safety Agency (EMSA)., (2018). Annual Overview of Marine Casualties and Incidents 2018.

European Maritime Safety Agency (EMSA)., (2021). Annual Overview of Marine Casualties and Incidents 2020.

European Maritime Safety Agency (EMSA)., (2023). Accident Investigation. https://www.emsa.europa.eu/we-do/safety/

European Union Aviation Safety Agency (EASA)., (2020). Annual Safety Review.

European Union Aviation Safety Agency (EASA)., (2021). GA Safety Statistics & Main Safety Issues. https://www.easa.europa.eu/community/content/ga-safety-statistics-main-safety-issues

European Union Aviation Safety Agency (EASA)., (2024). https://www.easa.europa.eu/en/domains/safety-management/safety-promotion

European Union., (2014). Regulation (EU) No 376/2014. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R0376

FAA., (2023). https://www.faa.gov/

FAA: Federal Aviation Administration., (2020). FAA

Fan, C., Montewka, J., Zhang, D., (2022). A risk comparison framework for autonomous ships navigation. Reliability Engineering & System Safety, 226, 108709. http://doi.org/10.1016/j.ress.2022.108709

Fan, C., Wrobel, K., Montewka, J., Gil, M., Wan, C., Zhang, D., (2020). A framework to identify factors influencing navigational risk for Maritime Autonomous Surface Ships. Ocean Engineering. https://doi.org/10.1016/j.oceaneng.2020.107188

Fan, S., Blanco-Davis, E., Yang, Z., Zhang, J., Yan, X., (2020). Incorporation of human factors into maritime accident analysis using a data-driven Bayesian network. Reliability Engineering & System Safety, 203. http://doi.org/10.1016/j.ress.2020.107070

Fan, S., Yang, Z., Blanco-Davis, E., Zhang, J., Yan, X., (2020). Analysis of maritime transport accidents using Bayesian networks. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 234, 439-454. http://doi.org/10.1177/1748006X19900850

Fan, S., Zhang, J., Blanco-Davis, E., Yang, Z., Yan, X., (2020). Maritime accident prevention strategy formulation from a human factor perspective using Bayesian Networks and TOPSIS. Ocean Engineering, 210, 107544. http://doi.org/10.1016/j.oceaneng.2020.107544

Fan, S.Q., Yang, Z.L., (2024). Accident data-driven human fatigue analysis in maritime transport using machine learning. Reliability Engineering & System Safety, 241, 10. http://doi.org/10.1016/j.ress.2023.109675

Fan, H., Jia, H., He, X., Lyu, J., (2024). Navigating uncertainty: A dynamic Bayesian network-based risk assessment framework for maritime trade routes, Reliability Engineering & System Safety, 250, 110311. ISSN 0951-8320. https://doi.org/10.1016/j.ress.2024.110311

Fang, S., Liu, Z., Wang, X., Cao, Y., Yang, Z., (2024). Dynamic analysis of emergency evacuation in a rolling passenger ship using a two-layer social force model. Expert Systems with Applications, 247, 123310. http://doi.org/10.1016/j.eswa.2024.123310

Fatima, H. (2025). AI-Driven Urban Mobility Solutions: Enhancing Smart Traffic Management and Urban Infrastructure Optimization. ResearchGate.

Fattah, M.M.A., (2017). Piracy in Gulf of Guinea Causes, Efforts and Solutions. Head of Training Department, Regional Maritime Security Institute, AASTMT.

Federal Aviation Administration (FAA)., (2018). General Aviation and Part 135 Activity Survey.

Feng, Y., Wang, H., Xia, G., Cao, W., Li, T., Wang, X., et al., (2024). A machine learning-based data-driven method for risk analysis of marine accidents. Journal of Marine Engineering & Technology, 1-12. http://doi.org/10.1080/20464177.2024.2368914

Feng, Y., Wang, X., Chen, Q., Yang, Z., Wang, J., Li, H., et al., (2024). Prediction of the severity of marine accidents using improved machine learning. Transportation Research Part E: Logistics and Transportation Review, 188, 103647. http://doi.org/10.1016/j.tre.2024.103647

Fielding, N.G., (2012). Triangulation and mixed methods designs: Data integration with new research technologies. Journal of Mixed Methods Research, 6, 124-136. doi:10.1177/1558689812437101

Fletcher, N., Colquhoun, W.P., Knauth, P., DeVoll, D., Plett, R., (1988). Work at sea: a study of sleep, and of circadian rhythms in physiological and psychological functions, in watchkeepers on merchant vessels. International Archives of Occupational and Environmental Health. https://link.springer.com/article/10.1007/BF00381607

Flight Safety Foundation., (2019). General Aviation Safety Improvements.

Forth Ports., (2016). Port Marine Safety Code: PMSC Risk Assessment. Forth Ports Limited. https://forthports.co.uk/marine/pmsc/

Fox, C., Levitin, A., Redman, T., (1994). The notion of data and its quality dimensions. Information Processing & Management, 30(1), 9-19. https://doi.org/10.1016/0306-4573(94)90020-5

Fransas, A., (2012). Maritime Safety and Security: Literature Review. Kymenlaakso University of Applied Sciences, Series B Research and Reports. No 77. http://www.merikotka.fi/julkaisut/B77_raportti.pdf

Fu, S.S., Zhang, Y., Zhang, M.Y., Han, B., Wu, Z.D., (2023). An object-oriented Bayesian network model for the quantitative risk assessment of navigational accidents in ice-covered Arctic waters. Reliability Engineering & System Safety, 238, 13. http://doi.org/10.1016/j.ress.2023.109459

Gagliardi, J., et al., (2021). AI-Based Predictive Safety Models for Maritime Traffic Risk Management. ScienceDirect.

GAJSC., (2023). https://www.gajsc.org

Galieriková, A., (2019). The human factor and maritime safety. Transportation Research Procedia, 40, 1319-1326.

Ganesan, S., Dhasan, M., Dhayanithi, R., Gowthaman, B., (2017). Factors Influencing in Landing of Seaplanes. https://www.researchgate.net/publication/316914559_Factors_Influencing_in_Landing_of_Seaplanes

Gao, L. (2014). Research on risk analysis of seaplane in Sanya Port and countermeasures. Master of Science in Maritime Af-fairs. Maritime Safety & Environment Management. Dalian, China

General Aviation Manufacturers Association (GAMA)., (2016). 2016 General Aviation Statistical Data Book & 2017 Industry Outlook.

General Aviation Manufacturers Association (GAMA)., (2018). The Economic Impact of General Aviation in the United States.

General Aviation Manufacturers Association (GAMA)., (2019). 2019 Data Book. https://gama.aero/wp-content/uploads/GAMA_2019Databook_Final-2020-03-20.pdf

Glaser, B.G., Strauss, A.L., (1967). Discovery of grounded theory: Strategies for qualitative research. New York: Aldine De Gruyter.

Goblet, V., Fala, N., Marais, K., (2015). Identifying Phases of Flight in General Aviation Operations. 15th AIAA Aviation Technology, Integration, and Operations Conference. https://doi.org/10.2514/6.2015-2851

Godyaev, A.I., Merkulov, A.V., (2023). Support for decision-making in tasks of ensuring safety in rail transport, 97-101. doi:10.30932/9785002182794-2023-97-101

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.

Gonel, O., Cicek, I., (2022). Multicriteria emergency decision for responding to man overboard casualties: A proposed procedure developed using Binary Logistics Regression and General Linear Models. Ocean Engineering, 265. http://doi.org/10.1016/j.oceaneng.2022.112581

Gong, X., Li, J., (2018). The Belt and Road Initiative and its Impact on Global Trade. Journal of Maritime Affairs, 14(3), 345-362.

Government of Canada TSBoC., (2023). Marine transportation occurrence data from January 1995.

Govindasamy, A., (2019). What is the Real Difference Between an Accident and an Incident? https://www.conserve.com.au/blog/difference-between-accident-and-incident/. Accessed 15 May 2023.

Grabbe, N., Brettschneider, S., & Bengler, K., (2024). The Work Organization in Teleoperated Driving–A Human Reliability and Socio-Technical Systems Perspective. De Gruyter.

Grech, M.R., Horberry, T., Koester, T., (2008). Human factors in the maritime domain. CRC Press.

Gries, T., Redlin, M., (2019). Pirates-The Young and the Jobless: The Effect of Youth Bulges and Youth Labor Market Integration on Maritime Piracy. Defence and Peace Economics, 30(3), 309-323.10.1080/10242694.2017.1333797

Guba, E.G., Lincoln, Y.S., (1989). Fourth Generation Evaluation. SAGE Publications.

Guba, E.G., Lincoln, Y.S., (1994). Competing Paradigms in Qualitative Research. In N.K. Denzin, Y.S. Lincoln (Eds.), Handbook of Qualitative Research (pp. 105-117). Sage Publications.

Guillerm, R., Demmou, H., (2014). Safety management method in complex system engineering. 2014 IEEE International Systems Conference Proceedings, 129-135.

Gultepe, I., Sharman, R., Williams, P.D., et al., (2019). A Review of High Impact Weather for Aviation Meteorology. Pure Appl. Geophys., 176, 1869–1921. https://doi.org/10.1007/s00024-019-02168-6

Guo, G., Xu, Y., Wu, B., (2016). Overview of Current Progress and Development of Seaplane Safety Management. In Proceedings of the 2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT), 7581307. IEEE. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7581307

Guo, J., Chen, L., Li, L., Na, X., Vlacic, L., & Zhao, X., (2024). Exploring the Economic Feasibility of Advanced Air Mobility in the Early Stages. IEEE Transactions on Intelligent Transportation Systems.

Hänninen, M., (2014). Bayesian networks for maritime traffic accident prevention: Benefits and challenges. Accident Analysis & Prevention, 73, 305-318.

Hänninen, M., (2015). Bayesian network modelling of potential patterns in maritime safety performance. https://aaltodoc.aalto.fi/handle/123456789/15104

Hansen, H.L., Laursen, L.H., Frydenberg, M., (2016). Fatigue as a factor in maritime accidents: A review. International Maritime Health, 67(2), 106-116.

Hanzu-Pazara, R., Barsan, E., Arsenie, P., Chiotoroiu, L., Raicu, G., (2008). Reducing of maritime accidents caused by human factors using simulators in training process. Journal of Maritime Research, 5(1), 3-18.

Haque, A.M., (2025). Analysis of Connected and Automated Vehicles to Advance Multimodal Safety. University of Tennessee.

Hashimoto, A., Okushima, T., (1990). Evaluating marine traffic safety at channels. Accident Analysis & Prevention, 22(5), 421-442.

Hassan, N.A., (2024). Big Data and Machine Learning in Autonomous Vehicle Navigation: Challenges and Opportunities. SciencePress.

He, Y., (2020). Maritime Safety: A Study on the Impact of Crew Experience and Vessel Age on Accident Rates. Journal of Maritime Research, 15(2), 145-162.

Health and Safety Executive (HSE)., (2001). Marine risk assessment. United Kingdom. http://www.hse.gov.uk/research/otopdf/2001/oto01063.pdf

Heidegger, M., (1962). Being and Time. Harper & Row.

Heinrich, H., (1931). Industrial Accident Prevention. A Scientific Approach. McGraw-Hill Book Company, Inc. New York, NY.

Heinrich, H.W., Petersen, D., Roos, N., (1980). Industrial Accident Prevention: A Safety Management Approach. 5th Edition, McGraw Hill, New York.

Hendriks, C., & Gooyert, V., (2023). Towards sustainable port areas: Dynamics of industrial decarbonization and the role of port authorities.

Hetherington, C., Flin, R., Mearns, K., (2006). Safety in shipping: the human element. Journal of Safety Research, 37(4), 401-411. https://doi.org/10.1016/j.jsr.2006.04.007

Hockey, G.R.J., (1997). Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework. Biological Psychology, 45(1-2), 73-93.

Hollnagel, E., (2008). Risk + barriers = safety? Safety Science, 46(2), 221-229. http://www.sciencedirect.com/science/article/pii/S0925753507000896

Hollnagel, E., (2012). FRAM, the functional resonance analysis method: Modelling complex socio-technical systems. Ashgate Publishing, Ltd.

Hollnagel, E., (2014). Safety-I and Safety-II: The past and future of safety management. CRC Press.

Hollnagel, E., Woods, D.D., Leveson, N., (2006). Resilience engineering: Concepts and precepts. Ashgate Publishing, Ltd.

Hovden, J., (1996). Safety Management Systems. Safety Science, 24, 157-158.

HSE., (2019). Injuries at work in Great Britain.

Hu, J., (2019). Analyzing the causal relationships in Bayesian networks for risk assessment. Journal of Risk Analysis and Management, 34(2), 123-135.

Huang, Y., van Gelder, P.H.A.J.M., (2020). Collision risk measure for triggering evasive actions of maritime autonomous surface ships. Safety Science. https://doi.org/10.1016/j.ssci.2020.104708

Hubbard, D.W., (2009). The failure of risk management: why it's broken and how to fix it. Wiley.

Hussein, A., (2009). The use of triangulation in social sciences research: Can qualitative and quantitative methods be combined? Journal of Comparative Social Work, 1, 1-12.

Husserl, E., (1970). Logical Investigations. Humanities Press.

IAOPA., (2024). https://www.iaopa.eu/what-is-general-aviation

ICAO., (2015). Asia Pacific Regional Guidance on Requirements for the Design and Operations of Water Aerodromes for Seaplane Operations. https://www.icao.int/APAC/Documents/edocs/APAC%20Guidance%20on%20WA%20for%20Seaplane%20Operations.pdf

ICC International Maritime Bureau., (2022). Piracy and Armed Robbery against Ships Report for the Period 1 January - 31 December 2021.

ICC-Commercial Crimes Service., (2022). IMB Piracy Reporting Centre. https://www.icc-ccs.org/index.php/piracy-reporting-centre

Ifesinachi, K., Nwangwu, C., (2015). Implementation of the Yaounde Code of Conduct and Maritime Insecurity in the Gulf of Guinea. Research on Humanities and Social Sciences, 2224-5766. https://www.researchgate.net/publication/288965394_Implementation_of_the_Yaounde_Code_of_Conduct_and_Maritime_Insecurity_in_the_Gulf_of_Guinea

IMO., (2022). Introduction to IMO. https://www.imo.org/en/About/Pages/Default.aspx

International Chamber of Shipping (ICS)., (2019). Representing the Global Shipping Industry. www.ics-shipping.org

International Chamber of Shipping., (2020). Economic Impact of the Global Shipping Industry.

International Civil Aviation Organization (ICAO)., (2014). Annex 19. https://www.icao.int/nacc/documents/meetings/2014/sspsmsant/annex19.pdf

International Civil Aviation Organization (ICAO)., (2016). Annex 13. https://ia803400.us.archive.org/8/items/icao-an13-2016/an13-2016_text.pdf

International Civil Aviation Organization (ICAO)., (n.d.). ICAO

International Civil Aviation Organization (ICAO)., (2013). Safety Management Manual. Third Edition. Doc 9859 AN/474.

International Civil Aviation Organization (ICAO)., (2019). Global Standards Related to the Design, Certification and Operations of Water Aerodromes. Thirtieth Meeting of the Asia/Pacific Air Navigation Planning and Implementation Regional Group (APANPIRG/30). Bangkok, Thailand. https://www.icao.int/APAC/Meetings/2019%20APANPIRG30/WP%2020,%20AI%203.1%20-%20Indonesia_Water%20Aerodromes_2%20Oct%202019.pdf#search=registered%20seaplanes

International Ergonomics Association (IEA)., (2019). Maritime Safety. http://www.imo.org/en/OurWork/Safety/Pages/Default.aspx

International Journal of Aviation, Aeronautics, and Aerospace., (2020). Challenges and Prospects in General Aviation.

International Maritime Bureau., (2021). Piracy and Armed Robbery against ships report for the period 1 January – 31 December 2020.

International Maritime Organisation (IMO)., (2007). Formal safety assessment. MSC 83/INF 2.

International Maritime Organisation (IMO)., (2008). Guidance on near-miss reporting. MSC-MEPC.7/Circ.7. http://www.vta.ee/public/MSC-MEPC.7-Circ.7_-_Guidance_On_Near-Miss_Reporting.pdf

International Maritime Organisation (IMO)., (2014). Casualty-Related Matters Reports On Marine Casualties And Incidents. MSC-MEPC.3/Circ.4/Rev.1; United Nations – International Maritime Organization. London, United Kingdom. http://studylib.net/doc/18513036/msc-mepc.3-circ.4-rev.1-18-november-2014-casualty

International Maritime Organisation (IMO)., (2019). Introduction to IMO. http://www.imo.org/en/About/Pages/Default.aspx

International Maritime Organisation (IMO)., (2022). Member State Audit Scheme & Implementation Support. https://www.imo.org/en/OurWork/MSAS/Pages/Default.aspx

International Maritime Organisation (IMO)., (1972). Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs). https://www.imo.org/en/About/Conventions/Pages/COLREG.aspx

International Maritime Organization (IMO)., (2008). Guidance on near-miss reporting. International Maritime Organization. MSC-MEPC.7/Circ.7

International Maritime Organization (IMO)., (2019). Technological Advancements in Maritime Industry.

International Maritime Organization (IMO)., (2020). Environmental Regulations in Maritime Industry.

International Maritime Organization (IMO)., (2023). Autonomous Shipping. https://www.imo.org/en/MediaCentre/Press Briefings/pages/MASSRSE2021.aspx

Irwin, A., Sedlar, N., Hamlet, O., (2019). Flying solo: General aviation pilot risk perception and decision-making. doi:10.31234/osf.io/7buv4

Ismail, A., (2023). Green shipping corridors: A comprehensive framework for overcoming port challenges. World Maritime University.

Ison, D.C., (2024). A Quantitative Analysis of Seaplane Accidents from 1982-2021. International Journal of Aviation, Aeronautics, and Aerospace, 11(2). https://doi.org/10.58940/2374-6793.1895

Jensen, F.V., Nielsen, T.D., (2007). Bayesian Networks and Decision Graphs. Springer.

Jiang, M., Lu, J., (2020). The Analysis of Maritime Piracy Occurred in Southeast Asia by Using Bayesian Network. Transportation Research Part E: Logistics and Transportation Review, 139101965. 10.1016/j.tre.2020.101965

Jiménez, F., (2022). Technologies and Applications of Communications in Road Transport.

Johan, B., Lera, A., Skjong, R., (2018). Group Technology & Research: Remote-controlled and autonomous ships in maritime industry. https://www.dnv.com/maritime/publications/remote-controlled-autonomous-ships-paper-download.html

Johnson, P., Duberley, J., (2000). Understanding Management Research. Sage Publications.

Johnson, R.B., Onwuegbuzie, A.J., (2004). Mixed Methods Research: A Research Paradigm Whose Time Has Come. Educational Researcher, 33(7), 14-26.

Jones, P., (2020). Navigational challenges in rough seas: A study on the effects of adverse weather on maritime safety. Marine Technology Society Journal, 54(2), 78-92.

Jones, P.J., (1994). Biodiversity in the Gulf of Guinea: An Overview. Biodiversity and Conservation, 3(9), 772-784. 10.1007/BF00129657

Journal of Aviation Technology and Engineering., (2018). Advances in General Aviation Technologies.

Kalliola, J., Stenroos, J., & Edelman, H., (2025). Data Collection and Analytics Using Mobile Phones for Safe Landing and Takeoff Procedures of Last-Mile Delivery Drones. SSRN.

Kandel, R., Baroud, H., (2024). A data-driven risk assessment of Arctic maritime incidents: Using machine learning to predict incident types and identify risk factors. Reliability Engineering & System Safety, 243, 15. http://doi.org/10.1016/j.ress.2023.109779

Kanki, B.G., Helmreich, R.L., Anca, J.M., (Eds.). (2010). Crew resource management. Academic Press.

Kim, H., Gausdal, A.H., (2020). Maritime safety management systems and recent developments. Safety Science, 123, 104575.

Kim, T., Mallam, S.A., (2020). Delphi-AHP study on STCW leadership competence in the age of autonomous maritime operations. https://link.springer.com/content/pdf/10.1007/s13437-020-00203-1.pdf

Kim, D., & Gausdal, A., (2020). Human Error in Port Operations: A Socio-Technical Perspective. Maritime Policy & Management.

Klein, G., (2008). Naturalistic decision making. Human Factors, 50(3), 456-460.

Komianos, A., (2018). The Autonomous Shipping Era: Operational, Regulatory, and Quality Challenges. TransNav. https://www.transnav.eu/Article_The_Autonomous_Shipping_Era._Operational,_Komianos,46,818.html

Korb, K.B., Nicholson, A.E., (2010). Bayesian Artificial Intelligence. CRC Press.

Kristiansen, S., (2005). Maritime Transportation: Safety Management and Risk Analysis. Elsevier Publishing. Amsterdam, Netherlands.

Kroemer, K.H.E., Grandjean, E., (1997). Fitting the task to the human: A textbook of occupational ergonomics. CRC Press.

Kujala, P., Hänninen, M., Arola, T., Ylitalo, J., (2009). Analysis of the marine traffic safety in the Gulf of Finland. Reliability Engineering & System Safety, 124, 17-30. https://doi.org/10.1016/j.ress.2009.02.028

Kyriakidis, M., Majumdar, A., Ochieng, W., (2015). Data based framework to identify the most significant performance shaping factors in railway operations. Safety Science, 78, 60-76. https://doi.org/10.1016/j.ssci.2015.04.010.

Kyriakidis, M., Pak, K., Majumdar, A., (2015). Railway Accidents Caused by Human Error. A historic analysis of the UK railways (1945-2012). Transportation Research Record: Journal of the Transportation Research Board, 2476(1), 126-136.

Lahtinen, J., Valdez Banda, O.A., Kujala, P., Hirdaris, S., (2020). Remote piloting in an intelligent fairway: A paradigm for future pilotage. Safety Science. https://doi.org/10.1016/j.ssci.2020.104889.

Lam, C.Y., Tai, K., (2020). Network topological approach to modeling accident causations and characteristics: Analysis of railway incidents in Japan. Reliability Engineering & System Safety, 193. http://doi.org/10.1016/j.ress.2019.106626.

Lan, H., Ma, X., Ma, L., Qiao, W., (2023). Pattern investigation of total loss maritime accidents based on association rule mining. Reliability Engineering & System Safety, 229. http://doi.org/10.1016/j.ress.2022.108893.

Lan, H., Ma, X., Qiao, W., Deng, W., (2023). Determining the critical risk factors for predicting the severity of ship collision accidents using a data-driven approach. Reliability Engineering & System Safety, 230, 108934. http://doi.org/10.1016/j.ress.2022.108934.

Laranjeiro, N., Soydemir, S.N., Bernardino, J., (2015). A survey on data quality: Classifying poor data. In 2015 IEEE 21st pacific rim international symposium on dependable computing (prdc) (p. 179-188). https://doi.org/10.1109/PRDC.2015.41

Lecue, M., Darbra, R.M., (2019). Accidents in European ports involving chemical substances: Characteristics and trends. Safety Science, 115, 278-284. https://doi.org/10.1016/j.ssci.2019.02.015.

Leveson, N., (2004). A new accident model for engineering safer systems. Safety Science, 42(4), 237-270.

Leveson, N., (2011). Engineering a Safer World: Systems Thinking Applied to Safety. MIT Press.

Leveson, N.G., (2004). A new accident model for engineering safer systems. Safety Science, 42(4), 237-270.

Li, G., Weng, J., Hou, Z., (2021). Impact analysis of external factors on human errors using the ARBN method based on small-sample ship collision records. Ocean Engineering, 236. http://doi.org/10.1016/j.oceaneng.2021.109533.

Li, H., Zhou, K., Zhang, C., Bashir, M., Yang, Z., (2024). Dynamic evolution of maritime accidents: Comparative analysis through data-driven Bayesian Networks. Ocean Engineering, 303, 117736. http://doi.org/10.1016/j.oceaneng.2024.117736.

Li, H.H., Çelik, C., Bashir, M., Zou, L., Yang, Z.L., (2024). Incorporation of a global perspective into data-driven analysis of maritime collision accident risk. Reliability Engineering & System Safety, 249, 15. http://doi.org/10.1016/j.ress.2024.110187.

Li, H., Ren, X., Yang, Z., (2023). Data-driven Bayesian network for risk analysis of global maritime accidents. Reliability Engineering & System Safety, 230, 108938. ISSN 0951-8320. https://doi.org/10.1016/j.ress.2022.108938

Li, K.X., Yin, J., Fan, L., (2014). Ship safety index. Transportation Research Part A: Policy and Practice, 66, 75-87. https://doi.org/10.1016/j.tra.2014.04.016

Li, K.X., Yin, J., Bang, H.S., Yang, Z., Wang, J., (2014). Bayesian network with quantitative input for maritime risk analysis. Transportmetrica (Abingdon, Oxfordshire, UK), 10(2), 89-118. doi:10.1080/18128602.2012.675527

Li, L., (2014). The Relationship Between Ship Age and Safety: An Analysis of Marine Accident Data. Marine Policy, 50, 208-216.

Li, M., Mou, J., Liu, R., Chen, P., He, Y., Dong, Z., (2019). Relational Model of Accidents and Vessel Traffic using AIS Data and GIS: A Case Study of the Western Port of Shenzhen City. Journal of Marine Science and Engineering, 7, 163. 10.3390/jmse7060163

Li, X., Li, G., Loianno, G., (2022). Safety-Aware Human-Robot Collaborative Transportation and Manipulation with Multiple MAVs.

Li, Y., Guldenmund, F., (2018). Safety management systems: A broad overview of the literature. Safety Science, 103, 94-123.

Liang, M.H., Li, H.H., Liu, R.W., Lam, J.S.L., Yang, Z.L., (2024). PiracyAnalyzer: Spatial temporal patterns analysis of global piracy incidents. Reliability Engineering & System Safety, 243, 15. http://doi.org/10.1016/j.ress.2023.109877

Liu, D., Wang, X., Cai, Y., Liu, Z., Liu, Z., (2020). A novel framework of real time regional collision risk prediction based on the RNN approach. Journal of Marine Science and Engineering, 8(3), 224. doi:10.3390/jmse8030224

Liu, H., Liu, S., (2016). Application of Grey Relational Decision-Making on Determination of Ship Collision Risk Degree. Revista Tecnica De La Facultad De Ingenieria Universidad Del Zulia, 39, 359-365. 10.21311/001.39.3.45

Liwang, H., (2016). Piracy off West Africa from 2010 to 2014: An Analysis. WMU Journal of Maritime Affairs (JoMA), 16(3), 385-403. 10.1007/s13437-016-0121-9

Ljung, M., Lindberg, E., Andersson, R., (2014). The role of housekeeping in maritime safety: An analysis of incident reports. Safety Science, 63, 86-92.

Lloyds List., (2016). Lloyd's List Viewpoint: The Reporting Culture. Lloyds Risk Register. https://www.chirpmaritime.org/wp-content/uploads/2016/10/Lloyds-List-reporting.pdf

Loughney, S., Wang, J., Matellini, D.B., (2024). Investigation and analysis of ship to platform collision incidents on the UK continental shelf: highlighting trends between the enforcement of offshore regulations and ship collision risks. Journal of Marine Science and Technology. doi:10.1080/20464177.2024.2338586

Louhichi, S., Gzara, M., Ben Abdallah, H., (2014). A density based algorithm for discovering clusters with varied density. In 2014 World Congress on Computer Applications and Information Systems (WCCAIS). IEEE, pp. 1-6. doi:10.1109/WCCAIS.2014.6916622

Luo, M., Shin, S.-H., (2019). Half-century research developments in maritime accidents: Future directions. Accident Analysis & Prevention, 123, 448-460. http://doi.org/10.1016/j.aap.2016.04.010

Ma, X., Lan, H., Qiao, W., Han, B., He, H., (2022). On the causation correlation of maritime accidents based on data mining techniques. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability. http://doi.org/10.1177/1748006x221131717

Ma, Y., Liu, Q., Yang, L., (2023). Analysis of human factors affecting seafarers' cognitive load on maritime safety.

MacDonald, C., Brooks, C., McGowan, R., (2021). Survival from Canadian seaplane water accidents: 1995 to 2019. Aerosp Med Hum Perform, 92(10), 798-805.

MacDonald, C., Brooks, C., McGowan, R., (2023). Canadian ultralight accidents in water (1990 to 2020). Aerosp Med Hum Perform, 94(6), 437-443.

MacDonald, C., Brooks, C., McGowan, R., (2021). Analysis of seaplane accidents: The importance of survival equipment and training. Journal of Aerospace Medicine and Human Performance, 92(3), 150-157.

Macrae, C., (2009). Human factors at sea: common patterns of error in groundings and collisions. Maritime Policy & Management, 36(1), 21-38. https://doi.org/10.1080/03088830802652262

Maguire, M., Delahunt, B., (2017). Doing a Thematic Analysis: A Practical, Step-by-Step-Guide for Learning and Teaching Scholars. All Ireland Journal of Higher Education. https://ojs.aishe.org/index.php/aishe-j/article/viewFile/335/553

MAIB., (2018). Annual Report 2017. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/720443/MAIB_Annual_Report_2017.pdf

Major, C.H., Savin-Baden, M., Haynes, S., (2022). A Practical Guide to Qualitative Research. Routledge.

Major, C.H., (2013). Qualitative Research: The Essential Guide to Theory and Practice. London: Routledge.

Majumdar, A., Manole, I., Garcia Sinobas, A., (2024). How safe are the United Kingdom's ports? A statistical analysis using accident and AIS data. Journal of Navigation.

Majumdar, A., Manole, I., Nalty, R., (2022). Analysis of Port Accidents and Calibration of Heinrich's Pyramid. Transportation Research Record, 2676(2), 476-489. https://doi.org/10.1177/03611981211044447

Mallam, S.C., Nazir, S., Sharma, A., (2019). The human element in future Maritime Operations – perceived impact of autonomous shipping. Ergonomics, 63(3), 334-345. https://doi.org/10.1080/00140139.2019.1659995

Mamcarz, P., Drożdziel, P., Madleňáková, L., Sieradzki, A., Drożdziel, P., (2019). Level of occupational stress, personality and traffic incidents: Comparative study of public and freight transport drivers.

Manole, I., (2019). Analysis of factors underlying safety in the ports of the United Kingdom. Imperial College London, Meng dissertation.

Manole, I., Majumdar, A., (2023). Assessing the Impact of Autonomous Vessels on the Navigational Safety of Maritime Transport. Conference: 33rd European Safety and Reliability Conference. DOI: 10.3850/978-981-18-8071-1_P607-cd.

Mansoor, A.A., (2011). Regulating vessel traffic service (VTS) to mitigate maritime accidents at port approaches. Master of Science. World Maritime University.

Mansson, J.T., Lutzhoft, M., Brooks, B., (2017). Joint Activity in the Maritime Traffic System: Perceptions of Ship Masters, Maritime Pilots, Tug Masters, and Vessel Traffic Service Operators. Journal of Navigation, 70, 547-560. 10.1017/S0373463316000758

Marc, A., Verjee, N., Mogaka, S., (2015). The challenge of stability and security in West Africa. Washington, World Bank.

Marine Accident Investigation Branch (MAIB)., (2015). MAIB Annual Report 2014.

Marine Accident Investigation Branch (MAIB)., (2015). Casualty Definitions used by the UK MAIB – from 2012. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/448650/MAIBAnnual2014-Supporting_Documentation.pdf

Marine Accident Investigation Branch (MAIB)., (2016). MAIB Annual Report 2015.

Marine Accident Investigation Branch (MAIB)., (2017). MAIB Annual Report 2016.

Marine Accident Investigation Branch (MAIB)., (2018). MAIB Annual Report 2017.

Marine Accident Investigation Branch (MAIB). (2018b). Maritime Accidents and Serious Incidents. https://www.gov.uk/transport/maritime-accidents-and-serious-incidents.

Marine Accident Investigation Branch (MAIB). (2020b). About us: The MAIB investigates marine accidents involving UK vessels worldwide and all vessels in UK territorial waters. United Kingdom. https://www.gov.uk/government/organisations/marine-accident-investigation-branch/about#our-responsibilities.

Marine Accident Investigation Branch (MAIB). (2019). Grounding of general cargo vessel Priscilla. Accident Investigation Report 12/2019. https://www.gov.uk/maib-reports/grounding-of-general-cargo-vessel-priscilla.

Marine Accident Investigation Branch (MAIB). (2020). MAIB Annual Report 2019. https://www.gov.uk/government/publications/maib-annual-report-2019.

Marine Management Organisation (MMO). (2014). Mapping UK shipping density and routes from AIS. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/317770/1066.pdf.

Marine Management Organisation (MMO). (2017). Anonymised AIS Derived Track Lines and grids. https://data.gov.uk/search?filters%5Bpublisher%5D=Marine+Management+Organisation.

Maritime and Coastguard Agency (MCA). (2016). Port Marine Safety Code. Retrieved from https://www.gov.uk/government/publications/port-marine-safety-code.

Maritime Coastguard Agency (MCA). (2019). What the Maritime and Coastguard Agency does. https://www.gov.uk/government/organisations/maritime-and-coastguard-agency.

Maritime UK. (2024). About Us. https://www.maritimeuk.org/about/about-us/.

Maritime UK. (2024). Ports. https://www.maritimeuk.org/about/our-sector/ports/.

Maxwell, J. A., & Mittapalli, K. (2010). Realism as a Stance for Mixed Methods Research. In A. Tashakkori & C. Teddlie (Eds.), SAGE Handbook of Mixed Methods in Social & Behavioral Research (pp. 145-168). SAGE Publications.

McLachlan, M. (2017). Maritime Psychology. Research in Organizational & Health Behavior at Sea. Springer International, Switzerland.

Mehrabi, D., Hassan, M., Sham, M., Shahkat Ali, M. S. (2009). News media credibility of the internet and television. European Journal of Social Sciences, 11(1), 136–148.

Mirkovic, B., Timotic Petkovic, D., & Netjasov, F., (2024). A Data-Driven Approach to Resilience in Air Traffic Management: Case Study Barcelona Area Control Centre. Cognition, Technology & Work.

Mkansi, M., & Acheampong, E. A. (2012). Research Philosophy Debates and Classifications: Students' Dilemma: EJBRM. Electronic Journal of Business Research Methods, 10(2), 132-140.

Morcos, P. A. (2021). Transatlantic Approach to Address Growing Maritime Insecurity in the Gulf of Guinea. https://www.csis.org/analysis/transatlantic-approach-address-growing-maritime-insecurity-gulf-guinea.

Mou, J., Tak, C., & Ligteringen, H. (2010). Study on collision avoidance in busy waterways by using AIS data. Ocean Engineering, 37, 483-490. https://doi.org/10.1016/j.oceaneng.2010.01.012.

Munim, Z. H., Sorli, M. A., Kim, H., & Alon, I. (2024). Predicting maritime accident risk using Automated Machine Learning. Reliability Engineering & System Safety, 248, 19. http://doi.org/10.1016/j.ress.2024.110148.

Nadtochiy, Y. B., Ivashova, V., Batov, A. Y., Chernykh, I. N., & Surov, D. (2022). Teamwork organization in transport industry.

Nalty, R. (2017). Calibration of Heinrich's accident pyramid for UK maritime sector using MAIB data. MSc. Dissertation. Imperial College London.

Nanyonga, A., Wasswa, H., Joiner, K., & Wild, G., (2025). Explainable Supervised Learning Models for Aviation Predictions in Australia. Preprints.

Narri, V., Alanwar, A., Mårtensson, J., Norén, C., Dal Col, L., & Johansson, K. H. (2021). Set-Membership Estimation in Shared Situational Awareness for Automated Vehicles in Occluded Scenarios.

Nascimento, F. A. C., Majumdar, A., & Ochieng, W. (2014). Helicopter Accident Analysis. Journal of Navigation, 67, 145-161. https://doi.org/10.1017/S037346331300057X.

National Civil Aviation Agency (ANAC). (2020). https://www.gov.br/anac/pt-br.

National Safety Council. (2023). Deaths by Transportation Mode - Passenger deaths and death rates, United States, 2007-2022. https://injuryfacts.nsc.org/home-and-community/safety-topics/deaths-by-transportation-mode/.

NAV Canada. (n.d.). Who We Are. https://www.navcanada.ca/en/corporate/about-us.aspx.

Neapolitan, R. E. (2003). Learning Bayesian Networks. Pearson Prentice Hall.

Newnam, S., Goode, N., Salmon, P., & Stevenson, M. (2017). Reforming the road freight transportation system using systems thinking: An investigation of Coronial inquests in Australia. Accident Analysis & Prevention, 101, 28-36. https://doi.org/10.1016/j.aap.2017.01.016.

Niels, K., & Senn, S. (1995). Risk. John Adams, UCL Press, London, 1995. No. of Pages XII + 228. ISBN 1-85728-067-9 HB, 1-85728-068-7 PB. Statistics in Medicine, 14(15), 1727-1728. https://doi.org/10.1002/sim.4780141513.

Nincic, D. (2009). Maritime piracy in Africa: The humanitarian dimension. African Security Review, 18(3), 1-16. https://doi.org/10.1080/10246029.2009.9627538.

Norman, D. A. (1990). The design of everyday things. Doubleday.

Nourbakhshrezaei, A., Jadidi, M., & Sohn, G. (2023). Improving Cyclists' Safety Using Intelligent Situational Awareness System.

Nowotny, H., Scott, P., & Gibbons, M. (2001). Re-thinking Science: Knowledge and the Public in an Age of Uncertainty. Polity Press.

Office of Rail and Road (ORR). (2019). Annual Report of Health and Safety Performance on Britain's Railways 2018-19.

Office of Rail and Road (ORR). (2023). Annual Health and Safety Report 2022-23.

Oraith, H., Blanco-Davis, E., Yang, Z., & Matellini, B. (2021). An Evaluation of the Effects of Human Factors on Pilotage Operations Safety. Journal of Marine Science and Application, 20, 393-409. http://doi.org/10.1007/s11804-021-00222-1.

Östrom, L., & Wilhelmsen, C. (2012). Risk Assessment in the Marine Industry. Elsevier.

Özaydın, E., Fışkın, R., Uğurlu, Ö., & Wang, J. (2022). A hybrid model for marine accident analysis based on Bayesian Network (BN) and Association Rule Mining (ARM). Ocean Engineering, 247, 110705. http://doi.org/10.1016/j.oceaneng.2022.110705.

Pak, J. Y., Yeo, G. T., Oh, S. W., & Yang, Z. (2015). Port safety evaluation from a captain's perspective: The Korean experience. Safety Science, 72, 172-181. https://doi.org/10.1016/j.ssci.2014.09.007.

Pattison, J. (2014). Justa Piratica: The Ethics of Piracy. Review of International Studies, 40(4), 631-656. https://doi.org/10.1017/S0260210513000405.

Patton, M. Q. (2002). Qualitative Research & Evaluation Methods (3rd ed.). Sage Publications.

Pearl, J. (1985). Bayesian Networks: A Model of Self-Activated Memory for Evidential Reasoning. Proceedings of the 7th Conference of the Cognitive Science Society.

Perrow, C. (1984). Normal Accidents: Living with High-Risk Technologies. Basic Books.

Pipino, L. L., Lee, Y. W., & Wang, R. Y. (2002). Data quality assessment. Communications of the ACM, 45, 211-218. http://doi.org/10.1145/505248.506010.

Plummer, K. (2014). What is a phi coefficient?. https://www.slideshare.net/plummer48/what-is-a-phi-coefficient.

Port of London Authority. (2019). Ship movements. http://www.pla.co.uk/Port-Trade/Ship-movements/Ship-movements.

Port of London Authority. (2023). Ship movements. http://www.pla.co.uk/Port-Trade/Ship-movements/Ship-movements.

President Buhari Launches Deep Blue Project in Lagos. (2022). https://nimasa.gov.ng/president-buhari-launches-deep-blue-project-in-lagos/.

Preutenborbeck, M., Weiser, P., & Pöttker, M., (2025). Towards Understanding Human-Technology Migration: Internal Interaction in Automated Road Vehicles. OpenAccess CMS.

Price, J. C., & Forrest, J. (2016). Safety Management Systems.

Project Horizon. (2012). Project Horizon - a wake-up call. https://www.warsashacademy.co.uk/about/resources/final-horizon-report-final-as-printed.pdf.

Project Martha. (2016). Project Martha. https://www.warsashacademy.co.uk/about/resources/martha-final-report.pdf.

Psaraftis, H. N., & Kontovas, C. A. (2009). Ship emissions: Logistics and other tradeoffs. International Journal of Sustainable Transportation, 3(5-6), 353-372.

Psyllou, E. (2017). Aviation Safety: A Framework to Analyse Airspace Infringements Involving General Aviation Flights. PhD thesis. Imperial College London.

Psyllou, E., & Majumdar, A. (2020). The Analysis of Airspace Infringements Over Complex Airspace in Europe and the United States of America. Journal of Navigation, 73(5), 1036-1051. https://doi.org/10.1017/S0373463320000156.

Punt, E., Monstadt, J., & Witte, P., (2023). Navigating cyber resilience in seaports: Challenges of preparing for cyberattacks at the Port of Rotterdam. Emerald.

Putra, I.N., Octavian, A., & Susilo, A.K., (2024). An Assessment of Cyber Resilience in the Maritime Domain Using System Dynamics and Analytical Hierarchy Process (AHP). Transactions on Maritime Science.

Qian, Y., Wang, B., Xue, Y., Zeng, J., & Wang, N. (2015). A simulation of the cascading failure of a complex network model by considering the characteristics of road traffic conditions. Nonlinear Dynamics, 80, 413-420. http://doi.org/10.1007/s11071-014-1878-z.

Ramoni, M., & Sebastiani, P. (2000). Parameter Estimation in Bayesian Networks from Incomplete Databases. Intelligent Data Analysis, 2. http://doi.org/10.1016/S1088-467X(98)00018-3.

Rashed, S. (2016). The Concept of Human Reliability Assessment Tool CREAM and Its Suitability for Shipboard Operations Safety. Journal of Shipping and Ocean Engineering, 6(6). https://pdfs.semanticscholar.org/8f98/e780bff74c04bdc7a681e9080aedb5a95c7b.pdf.

Rasmussen, J. (1982). Human errors: Taxonomy for describing human malfunction in industrial installations. Journal of Occupational Accidents, 4, 311-333.

Rasmussen, J. (1997). Risk management in a dynamic society: A modelling problem. Safety Science, 27(2-3), 183-213.

Rawson, A., & Brito, M. (2022). A survey of the opportunities and challenges of supervised machine learning in maritime risk analysis. Transport Reviews. https://doi.org/10.1080/01441647.2022.2036864.

Rawson, A., & Riding, J. (2014). Improving Port Safety with GIS. In 9th International Harbour Masters Association (IHMA) Congress.

Reason, J. (1990). Human Error. Cambridge University Press, New York.

Reason, J. (1997). Managing the Risks of Organizational Accidents. Ashgate.

Reason, J. (2000). Human error: Models and management. BMJ, 320(7237), 768-770.

Red Ensign Group (REG). (2022). Who We Are. https://www.redensigngroup.org/about-us/about-the-red-ensign-group/.

Ritchie, J., & Lewis, J. (Eds.). (2003). Qualitative Research Practice: A Guide for Social Science Students and Researchers. SAGE Publications.

Royal National Lifeboat Institution (RNLI). (2024). RNLI Return of Service 2019-2023. https://data-rnli.opendata.arcgis.com/pages/applications.

Royal Navy. (2008). The Principles of Navigation: Admiralty Manual of Navigation Volume 1 (Part 1). Hampshire; Fleet Publications and Graphics Organisation.

Russ, A. (2018). The human element – the effects of fatigue on ship safety. https://safety4sea.com/the-human-element-the-effects-of-fatigue-on-ship-safety/.

Russell, S., & Norvig, P. (2010). Artificial Intelligence: A Modern Approach. Prentice Hall.

Safety Management International Collaboration Group (SM ICG). (2022). Aviation Safety Management Systems and State Safety Programme Gap Analysis. https://skybrary.aero/sites/default/files/bookshelf/32973.pdf.

Salas, E., & Cannon-Bowers, J. A. (2001). The science of training: A decade of progress. Annual Review of Psychology, 52(1), 471-499.

Salas, E., Sims, D. E., & Burke, C. S. (2005). Is there a “Big Five” in teamwork? Small Group Research, 36(5), 555-599.

Sanders, M., & McCormick, E. (1993). Human Factors in Engineering and Design. New York, McGraw-Hill. 704 pp.

Saunders, M., Lewis, P., & Thornhill, A. (2019). Research methods for business students (8th ed.). Pearson Education, London, England.

Saurin, T.A., Patriarca, R., Hegde, S., & Rayo, M., (2025). Digital Technologies and Resilient Performance in Socio-Technical Systems: A Human Factors and Ergonomics Perspective. Applied Ergonomics.

Savin-Baden, M., & Howell Major, C. (2013). Qualitative Research: The Essential Guide to Theory and Practice (1st ed.). Routledge. https://doi.org/10.4324/9781003377986.

Schensul, S. L., Schensul, J. J., & LeCompte, M. (Eds.). (1999). Essential ethnographic methods: Observations, interviews, and questionnaires. Walnut Creek: Rowman & Littlefield Publishers.

Schonknecht, R. (1983). Ships and Shipping of Tomorrow. 0870332996. ISBN13 9780906536018. England: Cornell Maritime Press.

Schröder-Hinrichs, J.-U., Hollnagel, E., Baldauf, M., Hofmann, S., & Kataria, A. (2013). Maritime Human Factors and IMO Policy. Maritime Policy & Management, 40(3), 243–260. https://doi.org/10.1080/03088839.2013.782974.

Seafarers. (2019). IMO issues updated guidelines on fatigue - SAFETY4SEA. https://safety4sea.com/imo-issues-updated-guidelines-on-fatigue/.

Seafarers. (2023). IMO issues updated guidelines on fatigue - SAFETY4SEA. https://safety4sea.com/imo-issues-updated-guidelines-on-fatigue/.

Seaplane Pilots Association. (1996). Seaplane compatibility issues: A report about seaplanes focusing on safety, noise, and jurisdiction. https://seaplanepilotsassociation.org/wp-content/uploads/SeaplaneCompatibilityIssuesFullReport.pdf.

Seaplane Pilots Association. (2001). Flying America's Waterways – Seaplanes Operations: A Brief Overview. https://seaplanepilotsassociation.org/wp-content/uploads/Flying-Americas-Waterways.pdf.

Shappell, S. A., & Wiegmann, D. A. (2000). The Human Factors Analysis and Classification System (HFACS). Human Factors and Aerospace Safety, 1(1), 59-86.

Shiwen, X., Xingyun, W., Yang, L., Lianyue, P., & Baoqiang, C. (2019). Safety experience training box.

Shuler, M. (2018). Fully-Autonomous Ferry Demonstrated in Northern Europe. https://gcaptain.com/another-fully-autonomous-ferry-demonstrated-in-northern-europe/.

Silver, N. (2012). The signal and the noise: why so many predictions fail – but some don’t. Penguin.

SKYbrary Aviation Safety. (2024). Seaplanes. https://skybrary.aero/articles/seaplanes.

Smith, D., Brown, J., & White, C. (2015). The impact of lighting on fall incidents in maritime settings. Journal of Occupational Safety and Ergonomics, 21(4), 367-375.

Smith, E. (2020). Pirates are Expanding in West Africa, Threatening Offshore Oil Storage. https://www.cnbc.com/2020/04/27/pirates-are-expanding-in-west-africa-threatening-offshore-oil-storage.html.

Smith, J., Thompson, L., & Garcia, M. (2019). Weather-related risks in maritime navigation: An analysis of sea state conditions. International Journal of Maritime Engineering, 161(3), 250-265.

Soares, J., Fernandes, R., Brito, D., Oliveira, H., Neuparth, T., Martins, I., et al. (2020). Environmental risk assessment of accidental marine spills: A new approach combining an online dynamic Hazardous and Noxious substances database with numerical dispersion, risk and population modelling. Science of the Total Environment, 715, 136801. http://doi.org/10.1016/j.scitotenv.2020.136801.

Stanton, N. A., Salmon, P. M., Walker, G. H., Baber, C., & Jenkins, D. P. (2013). Human factors methods: A practical guide for engineering and design. Ashgate Publishing, Ltd.

Statista. (2022). Number of airports in the United States.

Statista. (2023a). Maritime ports in the UK - statistics & facts. https://www.statista.com/topics/5532/maritime-ports-in-the-uk/.

Statista. (2023b). Revenue from the freight shipping industry in the United Kingdom (UK) from 2000 to 2022. https://www.statista.com/statistics/383535/revenue-from-freight-shipping-industry-in-the-united-kingdom-uk/.

Statista. (2022). Pirate Attacks. https://www.statista.com/topics/1290/pirate-attacks/.

Stoyanov, S. (2009). Critical Review of the Effectiveness of Multinational Ship Crews. Master's Thesis. Southampton Solent University. http://ssudl.solent.ac.uk/824/.

Sui, Z., Huang, Y., Wen, Y., Zhou, C., & Huang, X. (2021). Marine traffic profile for enhancing situational awareness based on complex network theory. Ocean Engineering, 241, 110049. http://doi.org/10.1016/j.oceaneng.2021.110049.

Sui, Z., Wen, Y., Huang, Y., Song, R., & Piera, M. A. (2023). Maritime accidents in the Yangtze River: A time series analysis for 2011-2020. Accident Analysis & Prevention, 180, 106901. http://doi.org/10.1016/j.aap.2022.106901.

Sui, Z., Wen, Y., Huang, Y., Zhou, C., Xiao, C., & Chen, H. (2020). Empirical analysis of complex network for marine traffic situation. Ocean Engineering, 214, 107848. http://doi.org/10.1016/j.oceaneng.2020.107848.

Sun, Y., Liu, M., & Zhang, Z. (2017). Predictive Maintenance in Aviation Using Data Analytics. Journal of Aerospace Engineering, 30(3), 04017019. https://doi.org/10.1061/(ASCE)AS.1943-5525.0000704.

Support for decision-making in tasks of ensuring safety in rail transport. (2023).

Swaine, S., & Crossley, W.A., (2025). A Framework for Flight Resource Optimization: Safety, Technology, Wellbeing, and Infrastructure for Northern Geography. AIAA SCITECH 2025 Forum.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. Cognitive Science, 12(2), 257-285.

Tam, K., & Jones, K. (2019). Cyber-risk assessment for autonomous ships. In Cybersecurity of Industrial Control Systems (279-299).

Tashakkori, A., & Teddlie, C. (Eds.). (2010). SAGE Handbook of Mixed Methods in Social & Behavioral Research (2nd ed.). SAGE Publications.

Taylor, W. C., Murphy, S. L., & Smith, P. M. (2018). Footwear and slip-related injuries in the maritime industry. International Journal of Industrial Ergonomics, 64, 100-110.

Thayer, L. (1981). Communication and Communication Systems. Wadsworth Publishing Company.

The Maritime Executive. (2022). EU Renews its Commitment to Anti-Piracy Patrols in Gulf of Guinea. https://www.maritime-executive.com/article/eu-renews-its-commitment-to-anti-piracy-patrols-in-gulf-of-guinea.

The World Bank. (2021). Africa. https://www.worldbank.org/en/region/afr/overview#1.

Thylén, N., (2025). Design of Automated Guided Vehicle Systems Considering the Human, Technical, and Work Organisational Subsystems. Chalmers Research.

Tirunagari, S. (2015). Data mining of causal relations from text: analysing maritime accident investigation reports. https://arxiv.org/abs/1507.02447.

Transport Canada (TC). (1996). Instructor Guide for Seaplane Rating. Ottawa, Ontario.

Transport Canada (TC). (2015). Advisory Circular (AC) No. SUR-002. https://tc.canada.ca/en/aviation/reference-centre/advisory-circulars/advisory-circular-ac-no-002#appendix_c.

Transport Canada (TC). (2019). General information on pilot licences and permits. Date modified: 2019-11-15. https://tc.canada.ca/en/aviation/licensing-pilots-personnel/flight-crew-licences-permits-ratings/general-information-pilot-licences-permits.

Transport Canada (TC). (2019b). Standard 421 - Flight Crew Permits, Licences and Ratings - Canadian Aviation Regulations (CARs). Date modified: 2019-11-04. https://tc.canada.ca/en/corporate-services/acts-regulations/list-regulations/canadian-aviation-regulations-sor-96-433/standards/standard-421-flight-crew-permits-licences-ratings-canadian-aviation-regulations-cars#421_19.

Transport Canada (TC). (2020). Civil Aviation Safety. https://www.tc.gc.ca/.

Transport Canada (TC). (2020b). Safety management systems in aviation. https://tc.canada.ca/en/aviation/general-operating-flight-rules/aviation-safety-management/safety-management-systems-aviation.

Transport Canada (TC). (2020c). General aviation safety campaign. Date modified: 2020-07-17. https://tc.canada.ca/en/campaigns/general-aviation-safety-campaign.

Transport Canada (TC). (2020d). Staying current and proficient as a pilot. Date modified: 2020-02-20. https://tc.canada.ca/en/aviation/licensing-pilots-personnel/staying-current-proficient-pilot.

Transport Canada (TC). (2020e). Canadian Aviation Regulations (CARs). https://tc.canada.ca/en/aviation/regulations/canadian-aviation-regulations.

Transport Canada (TC). (2023). Report an incident affecting airport or aerodrome safety. Date modified: 2023-06-08. https://tc.canada.ca/en/aviation/operating-airports-aerodromes/report-incident-affecting-airport-aerodrome-safety.

Transportation Safety Board of Canada (TSB). (1993). Aviation safety study SSA9301. https://www.tsb-bst.gc.ca/eng/rapports-reports/aviation/etudes-studies/SSA9301/SSA9301.html.

Transportation Safety Board of Canada (TSB). (1994). Aviation safety study SA9401. https://www.tsb-bst.gc.ca/eng/rapports-reports/aviation/etudes-studies/SA9401/SA9401.html.

Transportation Safety Board of Canada (TSB). (2022). https://www.tsb.gc.ca/eng/medias-media/communiques/autres-other/2022/annual-stats-2021-20220617.html.

Trist, E. (1981). The evolution of socio-technical systems. A conceptual framework and an action research program. In A. H. Van De Ven & W. F. Joyce (Eds.), Perspectives on organization design and behavior (pp. 19-75). Wiley-Interscience.

Tsou, M. (2018). Big data analytics of safety assessment for a port of entry: A case study in Keelung Harbour. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 233(4), 1260–1275. http://doi.org/10.1177/1475090218805245.

Tsou, M.-C., & Hsueh, C.-K. (2010). The study of ship collision avoidance route planning by ant colony algorithm. Journal of Marine Science and Technology, 18(5). http://doi.org/10.51400/2709-6998.1929.

Turbli. (2022). The Safest Transport Modes, Ranked by Statistics From 10 Years of Data. https://turbli.com/blog/the-safest-transport-modes-ranked-by-statistics-from-10-years-of-data/.

Uebersax, D. (2014). Assumptions and Limitations of Chi-Squared Tests.

UK Government. (2022). Improving Safety and Organisational Performance Through A Just Culture. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/286139/just_culture.pdf.

UK P&I Club. (2018). Managing Safety in Ports. https://www.ukpandi.com/fileadmin/uploads/uk-pi/LP%20Documents/Ports%20and%20Terminals/Ports_and_Terminals_May_2018.pdf.

UNCTAD. (2019). Maritime connectivity: countries vie for positions. https://unctad.org/news/maritime-connectivity-countries-vie-positions.

UNCTAD. (2020). Review of Maritime Transport 2020.

UNCTAD. (2021). Review of Maritime Transport.

UNCTAD. (2024). Liner shipping connectivity index, quarterly. Second quarter. https://unctadstat.unctad.org/EN/ReleaseCalendar.html.

UNCTAD. (2022). Review of Maritime Transport 2021. https://unctad.org/webflyer/review-maritime-transport-2021.

Underwood, P., & Waterson, P. (2013). Systematic accident analysis: examining the gap between research and practice. Accident Analysis and Prevention, 55, 154–64.

Ung, S. T. (2021). Navigation Risk estimation using a modified Bayesian Network modeling-a case study in Taiwan. Reliability Engineering & System Safety, 213, 13. http://doi.org/10.1016/j.ress.2021.107777.

United Nations. (2010). Legal Framework for the Repression of Piracy Under UNCLOS. https://www.un.org/depts/los/piracy/piracy_legal_framework.htm.

United Nations. (2022). West Africa: Extreme poverty rises nearly 3 per cent due to COVID-19. https://news.un.org/en/story/2022/01/1110192.

Valde, B. O., & Goerlandt, F. (2018). A STAMP-based approach for designing maritime safety management systems. Safety Science, 109, 109-129. http://doi.org/10.1016/j.ssci.2018.05.003.

Veiga, J. L. (2002). Safety culture in shipping. WMU Journal of Maritime Affairs, 1, 17–31.

Vidan, P., Slišković, M., & Očašić, N. (2016). Seaplane Traffic in the Republic of Croatia.

Vorozhbiian, M., Brusentsov, V., Ivashchenko, M., & Skrypnyk, O. (2023). Ergonomics as a safety factor in the railway industry.

Vu, V. D., Lützhöft, M., & Emad, G. R. (2019). Frequency of use – the First Step Toward Human-Centred Interfaces for Marine Navigation Systems. Journal of Navigation, 1-19. http://doi.org/10.1017/S0373463319000183.

Wallen, M. (1993). What makes a good safety management system. ITE Journal - Institute of Transportation Engineers, 63.

Wamugi, J.W., Park, Y., Kim, J., & Kim, D., (2024). Analyzing Domestic Ferry Navigation Accidents in Mombasa Channel Using AcciMap. Journal of Navigation and Port Research.

Wandenkolk, I., Classen, S., & Williams, A., (2025). Autonomous Ride-Sharing Services in the United States: A Scoping Review of Policies, Implementation, Performance and Market Penetration. Preprints.

Wang, H., Chen, N., Wu, B., & Soares, C. G. (2024). Human and organizational factors analysis of collision accidents between merchant ships and fishing vessels based on HFACS-BN model. Reliability Engineering & System Safety, 249, 18. http://doi.org/10.1016/j.ress.2024.110201.

Wang, H., Liu, Z., Wang, X., Graham, T., & Wang, J. (2021). An analysis of factors affecting the severity of marine accidents. Reliability Engineering & System Safety, 210. http://doi.org/10.1016/j.ress.2021.107513.

Wang, L., & Yang, Z. (2018). Bayesian network modelling and analysis of accident severity in waterborne transportation: A case study in China. Reliability Engineering & System Safety, 180, 277-289. http://doi.org/10.1016/j.ress.2018.07.021.

Wang, S., Yang, D., & Lu, J. (2018). A connectivity reliability-cost approach for path selection in the maritime transportation of China's crude oil imports. Maritime Policy & Management, 45, 567-584. http://doi.org/10.1080/03088839.2018.1445308.

Wang, S., Zheng, L., & Yu, D. (2017). The improved degree of urban road traffic network: A case study of Xiamen, China. Physica A: Statistical Mechanics and its Applications, 469, 256-264. http://doi.org/10.1016/j.physa.2016.11.090.

Wang, Z. C., & Yin, J. B. (2020). Risk assessment of inland waterborne transportation using data mining. Maritime Policy & Management, 47, 633-648. http://doi.org/10.1080/03088839.2020.1738582.

Wang, C., Quddus, M. A., & Ison, S. G. (2011). Predicting accident frequency at their severity levels and its application in site ranking using a two-stage mixed multivariate model. Accident Analysis & Prevention, 43, 1979-1990. https://doi.org/10.1016/j.aap.2011.05.016.

Wang, J., & Pillay, A. (2001). Technology and safety management in the maritime industry: A case study of a shipyard. Journal of Quality in Maintenance Engineering, 7(4), 248-261.

Wang, Q., Smythe, D., Cao, J., Hu, Z., Proctor, K. J., Owens, A. P., & Zhao, Y. (2023). Characterisation of Cognitive Load Using Machine Learning Classifiers of Electroencephalogram Data.

Wang, Y., Cha, Z., Liang, G., Zhang, X., Li, K., & Guan, G. (2023). Risk assessment of LNG bunkering vessel operation based on formal safety assessment method. Process Safety Progress, 43(2). https://doi.org/10.1002/prs.12561.

Waterson, P., Robertson, M. M., Cooke, N. J., Militello, L., Roth, E., & Stanton, N. A. (2015). Defining the methodological challenges and opportunities for an effective science of sociotechnical systems and safety. Ergonomics, 58(4), 565-599.

Weng, J., & Li, G. (2019). Exploring shipping accident contributory factors using association rules. Journal of Transportation Safety & Security, 11, 36-57. http://doi.org/10.1080/19439962.2017.1341440.

Weng, J., Yang, D., Qian, T., & Huang, Z. (2018). Combining zero-inflated negative binomial regression with MLRT techniques: An approach to evaluating shipping accident casualties. Ocean Engineering, 166, 135-144. http://doi.org/10.1016/j.oceaneng.2018.08.011.

Weng, J., & Zhou, Y. (2013). Analysis of Risk Factors and Safety Countermeasures of Collision between Seaplanes and Vessels Based on ISM Theory. In Proceedings of the 2nd International Conference on Transportation Information and Safety (ICTIS). https://ascelibrary.org/doi/pdf/10.1061/9780784413036.307.

West, M. (1993). Developing high quality data models (Tech. Rep. No. 3). European Process Industries STEP Technical Liaison Executive.

Weyer, J., (2024). Safe Transitions in Complex Systems: Methods of Investigating the Interplay Between Safety and Sustainability. Climate Change and Safety in High-Risk Industries.

Whyte, H., & Narvey, M. (2017). Team Models in Interfacility Transport-Building and Maintaining Competencies.

Wiegmann, D. A., & Shappell, S. A. (2003). A Human Error Approach to Aviation Accident Analysis: The Human Factors Analysis and Classification System. Ashgate.

Wilke, S., Majumdar, A., & Ochieng, W. Y. (2014). A framework for assessing the quality of aviation safety databases. Safety Science, 63, 133-145. http://doi.org/10.1016/j.ssci.2013.11.005.

Wilke, S., Majumdar, A., & Ochieng, W. (2014a). Airport surface operations: A holistic framework for operations modeling and risk management. Safety Science, 63, 18-33. https://doi.org/10.1016/j.ssci.2013.10.015.

Wilke, S., Majumdar, A., & Ochieng, W. Y. (2015). The impact of airport characteristics on airport surface accidents and incidents. National Safety Council, 53, 63-75. http://doi.org/10.1016/j.jsr.2015.03.006.

Williams, J. H., & Geller, E. S. (2013). Maintenance and repair-related falls in the maritime industry. Journal of Safety Research, 47, 77-84.

Wróbel, K., Gil, M., & Montewka, J. (2020). Identifying research directions of a remotely-controlled merchant ship by revisiting her system-theoretic safety control structure. Safety Science. http://doi.org/10.1016/j.ssci.2020.104797.

Wróbel, K., Montewka, J., & Kujala, P. (2017). Towards the assessment of potential impact of unmanned vessels on maritime transportation safety. Reliability Engineering & System Safety, 165, 155-169. http://doi.org/10.1016/j.ress.2017.03.029.

Wróbel, K., Montewka, J., & Kujala, P. (2018). Towards the development of a system-theoretic model for safety assessment of autonomous merchant vessels. Reliability Engineering & System Safety. http://doi.org/10.1016/j.ress.2018.05.019.

Wu, B., Yan, X., Wang, Y., & Guedes Soares, C. (2016). Selection of maritime safety control options for NUC ships using a hybrid group decision-making approach. Safety Science, 88, 108-122. http://doi.org/10.1016/j.ssci.2016.04.026.

Wu, C., & Huang, L. (2019). A new accident causation model based on information flow and its application in Tianjin Port fire and explosion accident. Reliability Engineering & System Safety, 182, 73-85.

Xiao, Q., Luo, F., & Li, Y. (2020). Risk Assessment of Seaplane Operation Safety Using Bayesian Network. Symmetry, 12(6), 888.

Xu, H., Rong, H., & Guedes Soares, C. (2019). Use of AIS data for guidance and control of path-following autonomous vessels. Ocean Engineering. http://doi.org/10.1016/j.oceaneng.2019.106635.

Xu, X. et al., (2025). Ship Collision Risk Assessment and Visualization Using Radar Sequential Images for Intelligent Maritime Supervision. IEEE Xplore.

Yang, Y., Liu, Y., Zhou, M., & Li, F. (2015). Robustness assessment of urban rail transit based on complex network theory: A case study of the Beijing Subway. Safety Science, 79, 149-162. http://doi.org/10.1016/j.ssci.2015.06.006.

Yang, T., Cui, Z., Alshehri, A., Wang, M., Gao, K., & Yu, K. (2023). Distributed Maritime Transport Communication System With Reliability and Safety Based on Blockchain and Edge Computing.

Yang, Y., Yang, L., Li, G., & Zhang, Z. (2024). Harnessing the power of Machine learning for AIS Data-Driven maritime Research: A comprehensive review. Transportation Research Part E: Logistics and Transportation Review, 183, 103426. http://doi.org/10.1016/j.tre.2024.103426.

Yang, Z., Manole, I., Cao, Y., Majumdar, A., Feng, Y., Xin, X., Wang, X., & Wang, H. (2024). Investigation of the risk influential factors of maritime accidents: A novel topology and robustness analytical framework. Journal of Reliability Engineering & System Safety.

Yang, Z., Wang, J., & Li, K. (2013). Maritime safety analysis in retrospect. Maritime Policy & Management, 40, 261–277. http://doi.org/10.1080/03088839.2013.782952.

Yara. (2023). Yara Birkeland. https://www.yara.com/news-and-media/media-library/press-kits/yara-birkeland-press-kit/.

Yildiz, S., Uğurlu, Ö., Wang, J., & Loughney, S. (2021). Application of the HFACS-PV approach for identification of human and organizational factors (HOFs) influencing marine accidents. Reliability Engineering & System Safety, 208, 107395. http://doi.org/10.1016/j.ress.2020.107395.

Yip, T. L. (2008). Port traffic risks—a study of accidents in Hong Kong waters. Transportation Research Part E: Logistics and Transportation Review, 44(5), 921-931.

Yu, Y. R., Liu, K. Z., Fu, S. S., & Chen, J. H. (2024). Framework for process risk analysis of maritime accidents based on resilience theory: A case study of grounding accidents in Arctic waters. Reliability Engineering & System Safety, 249, 17. http://doi.org/10.1016/j.ress.2024.110202.

Yu, Z., Liu, L., Xu, L., & Chen, K. (2022). Fatigue detection for public transport drivers under the normalization of epidemic prevention.

Zhang, P., Wang, T., & Yan, J. (2022). PageRank centrality and algorithms for weighted, directed networks. Physica A: Statistical Mechanics and its Applications, 586. http://doi.org/10.1016/j.physa.2021.126438.

Zhang, J., Thai, V. V., & Jiang, L. (2018). Application of Bayesian Network to risk assessment of collision involving liquefied natural gas carriers. Reliability Engineering & System Safety, 169, 515-530.

Zhang, L., Teo, E., & Goh, Y. M. (2013). Applying the domino model to identify factors influencing unsafe behaviors in construction workers. Journal of Construction Engineering and Management, 139(1), 18-27.

Zhang, Q., Geerlings, H., Makhloufi, A., & Chen, S. (2018). Who Governs and What Is Governed in Port Governance: A Review Study. Transport Policy, 64, 51-60. http://doi.org/10.1016/j.tranpol.2018.01.019.

Zhang, Y., Sun, X., Chen, J. & Cheng C., (2021). Spatial patterns and characteristics of global maritime accidents. Reliability Engineering & System Safety, Volume 206, 107310, ISSN 0951-8320, https://doi.org/10.1016/j.ress.2020.107310.

Zheng, H. (2020). A comparative study of marine accident investigation agencies. https://oacis.repo.nii.ac.jp/records/2027.

Zhou, K. W., Xing, W. B., Wang, J. B., Li, H. H., & Yang, Z. L. (2024). A data-driven risk model for maritime casualty analysis: A global perspective. Reliability Engineering & System Safety, 244, 25. http://doi.org/10.1016/j.ress.2023.109925.

Zhou, Y., Kundu, T., Goh, M., & Sheu, J.-B. (2021). Multimodal transportation network centrality analysis for Belt and Road Initiative. Transportation Research Part E: Logistics and Transportation Review, 149. http://doi.org/10.1016/j.tre.2021.102292.

Zhou, W., et al., (2021). Machine Learning for Predictive Safety in Intelligent Transport Systems. ScienceDirect.

Zhou, W., Wang, Q., & Li, X. (2017). Environmental factors contributing to slips and falls on ships. Marine Safety and Security, 49(3), 58-72.

Ziakkas, D., & Henneberry, D., (2025). The Challenges of Integrating AI in Aviation Incident-Accident Investigations: A Human-Centric Approach. OpenAccess CMS.

Ziarati, R., & Ziarati, M. (2007). Review of accidents with special references to vessels with automated systems–A forward-looking perspective of the IMO policy. TransNav: International Journal on Marine Navigation and Safety of Sea Transportation, 1(4), 375-380.

Appendix

Appendix A. UK Port Marine Safety Code measures (DfT, 2016).

1. **Duty holder**: Formally identify and designate the duty holder, whose members are individually and collectively accountable for compliance with the Code, and their performance in ensuring safe marine operations in the harbour and its approaches.
2. **Designated Person**: A 'designated person' must be appointed to provide independent assurance about the operation of the marine safety management system. The designated person must have direct access to the duty holder.
3. **Legislation**: The duty holder must review and be aware of their existing powers based on local and national legislation, seeking additional powers if required in order to promote safe navigation.
4. **Duties and Powers**: Comply with the duties and powers under existing legislation, as appropriate.
5. **Risk Assessment**: Ensure that marine risks are formally assessed and are eliminated or reduced to the lowest possible level, so far as is reasonably practicable, in accordance with good practice.
6. **Marine Safety Management System**: Operate an effective MSMS which has been developed after consultation, is based on formal risk assessment and refers to an appropriate approach to incident investigation.
7. **Review and Audit**: Monitor, review and audit the risk assessment and MSMS on a regular basis – the independent designated person has a key role in providing assurance for the duty holder.
8. **Competence**: Use competent people (who are trained, qualified and experienced) in positions of responsibility for managing marine and navigation safety.
9. **Plan**: Publish a safety plan showing how the standards in the Code will be met and produce a report assessing performance against that plan at least every 3 years.
10. **Aids to Navigation**: Comply with directions from the General Lighthouse Authorities and supply information & returns as required.

Appendix B. Risk assessment guidance for the aviation industry in Canada (Transportation Safety Board Canada, 2021).

Risk assessment

The following questions are used in the occurrence classification to assess the probability of adverse consequences arising in similar occurrences in the future:

- Is there a history of occurrences like this one or is this an isolated occurrence?
- Are there any apparent links to TSB Watchlist issues?
- Are there any apparent links to outstanding TSB recommendations, safety concerns or emerging issues being monitored by the mode?
- How much equipment, systems or infrastructure might have similar issues?
- How many operating or maintenance personnel are following or are subject to the practices or procedures in question?
- How frequently are the procedures, practices, and equipment in question used?
- Are there underlying organizational, management, or regulatory issues that constitute systemic hazards posing a threat to public safety?

In assessing the severity of the consequences of the occurrence, consideration is given to the following:

- Did the occurrence involve commercial or private transportation?
- How many lives were at risk? Were the persons at risk fare-paying passengers, transportation employees, bystanders, or the general public?
- What might be the extent of other property damage? Is there direct property loss to the operator, damage to adjacent infrastructure, or third-party collateral damage?
- Will there be an environmental impact? Has there been a dangerous commodity spill or disruption of natural habitat?
- What might the impact on carriers and on their and others' commercial operations be? Has the occurrence affected their viability? Has the occurrence disrupted infrastructure? Have financial markets reacted?
- How are the public and media likely to interpret information about the occurrence? What might the political implications be, locally, nationally, or internationally?

Sometimes, even if there is little doubt that an unsafe condition with unacceptable risk exists, the potential for further practical safety action is limited. Consequently, an assessment will be made not only of the risks but of the potential for discovering new and meaningful safety lessons and for safety action being taken in a reasonable time in response.

To determine the value of the safety lessons that an investigation is likely to yield, the following questions should be considered:

- To what extent are the related safety hazards already well known or being attended to?
- Could this occurrence shed new light on an old problem?
- Has the TSB already identified this issue as one warranting extra attention by means of a safety concern or a recommendation that is outstanding? Does the TSB consider this issue to be significant and/or one of the emerging issues of particular interest? Is it a Watchlist issue?

Appendix C. Linking Safety Approaches to Safety Management System (SMS) Pillars.

1. Safety Policy and Objectives: A robust safety policy establishes the organisation's commitment to safety and outlines its safety objectives. Integrating reactive, proactive, and predictive approaches ensures that the safety policy is comprehensive and addresses all aspects of safety management. The reactive approach provides a foundation based on past incidents, while proactive and predictive measures ensure continuous improvement and future risk mitigation.

2. Safety Risk Management: This pillar involves identifying, assessing, and mitigating safety risks. Proactive and predictive approaches are critical here. Proactive measures help identify and mitigate risks before they lead to occurrences, while predictive analytics provide advanced warning of potential issues, allowing for timely interventions.

3. Safety Assurance: Safety assurance involves continuous monitoring and assessment of the safety performance. Integrating predictive analytics into safety assurance processes can significantly enhance the organisation's ability to monitor safety trends and predict future risks. Proactive measures ensure that the organisation continuously improves its safety performance.

4. Safety Promotion: Promoting a strong safety culture within the organisation is essential for the success of any safety management system. Encouraging open reporting of incidents and near-misses, providing continuous education and training, and leveraging advanced analytical tools can help foster a culture of safety. Integrating all three safety approaches ensures that safety promotion efforts are comprehensive and effective.

Appendix D. Summary of reportable aviation occurrences in Canada (TC, 2023)

- **2 (1)** The owner, operator, pilot-in-command, any crew member of the aircraft and any person providing air traffic services that have direct knowledge of an occurrence must report the following aviation occurrences to the Board if they result directly from the operation of an aircraft:
  - **(a)** in the case of an accident
    - **(i)** a person is killed or sustains a serious injury as a result of
      - **(A)** being on board the aircraft,
      - **(B)** coming into direct contact with any part of the aircraft, including parts that have become detached from the aircraft, or
      - **(C)** being directly exposed to jet blast, rotor down wash or propeller wash,
    - **(ii)** the aircraft sustains structural failure or damage that adversely affects the aircraft's structural strength, performance or flight characteristics and would normally require major repair or replacement of any affected component, except for
      - **(A)** engine failure or damage, when the damage is limited to the engine, its cowlings or accessories, or
      - **(B)** damage limited to propellers, wing tips, antennae, tires, brakes, fairings or small dents or puncture holes in the aircraft's skin, or
    - **(iii)** the aircraft is missing or inaccessible; and
  - **(b)** in the case of an incident involving an aircraft having a maximum certificated take-off weight greater than 2 250 kg, or of an aircraft being operated under an air operator certificate issued under Part VII of the *Canadian Aviation Regulations*
    - **(i)** an engine fails or is shut down as a precautionary measure,
    - **(ii)** a power train transmission gearbox malfunction occurs,
    - **(iii)** smoke is detected or a fire occurs on board,
    - **(iv)** difficulties in controlling the aircraft are encountered owing to any aircraft system malfunction, weather phenomena, wake turbulence, uncontrolled vibrations or operations outside the flight envelope,
    - **(v)** the aircraft fails to remain within the intended landing or take-off area, lands with all or part of the landing gear retracted or drags a wing tip, an engine pod or any other part of the aircraft,
    - **(vi)** a crew member whose duties are directly related to the safe operation of the aircraft is unable to perform their duties as a result of a physical incapacitation which poses a threat to the safety of persons, property or the environment,
    - **(vii)** depressurization of the aircraft occurs that requires an emergency descent,

- **(viii)** a fuel shortage occurs that requires a diversion or requires approach and landing priority at the destination of the aircraft,
- **(ix)** the aircraft is refuelled with the incorrect type of fuel or contaminated fuel,
- **(x)** a collision, a risk of collision or a loss of separation occurs,
- **(xi)** a crew member declares an emergency or indicates an emergency that requires priority handling by air traffic services or the standing by of emergency response services,
- **(xii)** a slung load is released unintentionally or as a precautionary or emergency measure from the aircraft, or
- **(xiii)** any dangerous goods are released in or from the aircraft.

Information in report

(2) The report must contain the following information:

- **(a)** the type, model, nationality and registration marks of the aircraft;
- **(b)** the name of the owner, operator, pilot-in-command and, if applicable, hirer of the aircraft;
- **(c)** the last point of departure and the intended destination of the aircraft, including the date and time of the departure;
- **(d)** the date and time of the occurrence;
- **(e)** the name of the person providing air traffic services related to the occurrence;
- **(f)** the number of crew members, passengers and other persons involved in the occurrence and the number of those who were killed or sustained serious injuries as a result of the occurrence;
- **(g)** the location of the occurrence by reference to an easily defined geographical point, or by latitude and longitude;
- **(h)** a description of the occurrence and the extent of any resulting damage to the environment and to the aircraft and any other property;
- **(i)** a list of any dangerous goods carried on board or released from the aircraft, including the shipping name or UN number and consignor and consignee information;
- **(j)** if the aircraft is missing or inaccessible
  - **(i)** the last known position of the aircraft by reference to an easily defined geographical point, or by latitude and longitude, including the date and time that the aircraft was at that position, and
  - **(ii)** the actions taken or planned to locate or gain access to the aircraft;
- **(k)** a description of any action taken or planned to protect persons, property and the environment;
- **(l)** the name and title of the person making the report and the phone number and address at which they can be reached; and
- **(m)** any information specific to the occurrence that the Board requires.

Time limit

(3) The person making the report must send to the Board

- **(a)** as soon as possible and by the quickest means available, all the information required under subsection (2) that is available at the time of the occurrence; and
- **(b)** the remainder of that information as soon as it becomes available within 30 days after the occurrence.

Agreement

(4) The Board and any person mentioned in subsection (1) may enter into an agreement regarding a format and time frame for reporting aviation occurrences that are not likely to require immediate Board response.

Exemption

(5) If a person making a report has sent any information described in subsection (2) to the Board

- **(a)** the Board may exempt other persons from the requirement to send that information; and
- **(b)** if the person is a member of a company, any other person from that company is exempt from the requirement to send that information.

Definitions

(6) The following definitions apply in this section.

air traffic services has the same meaning as in subsection 101.01(1) of the *Canadian Aviation Regulations*.

collision means an impact, other than an impact associated with normal operating circumstances, between aircraft or between an aircraft and another object or terrain.

loss of separation means a situation in which the distance separating two aircraft is less than the minimum established in the *Canadian Domestic Air Traffic Control Separation Standards*, published by the Department of Transport, as amended from time to time.

operation means the activities for which an aircraft is used from the time any person boards the aircraft with the intention of flight until they disembark.

operator has the same meaning as in subsection 101.01(1) of the *Canadian Aviation Regulations*.

owner has the same meaning as in subsection 101.01(1) of the *Canadian Aviation Regulations*.

risk of collision means a situation in which an aircraft comes so close to being involved in a collision that a threat to the safety of any person, property or the environment exists.

- SOR/2018-258, s. 1(F)

Transportation Safety Board of Canada



Bureau de la sécurité des transports du Canada

Aviation occurrence reporting form

From

Name		Mailing address	
Organization			
Email address			
Telephone		Fax	

Aircraft

Registration		Manufacturer	
Nationality		Model	

Owner

Name or organization		E-mail address	
		Phone number	

Operator

Name or organization		E-mail address	
		Phone number	

Pilot-in-command

Name		E-Mail address	
Licence number		Phone number	

Flight details

Flight number		Departure	
Departure date		Intended destination	
Departure time		Actual destination	

Occurrence details

Occurrence date		Occurrence location	
Occurrence time			

Persons on board

Total #	
Flight crew #	
Cabin crew #	
Passengers #	

Injuries

	Fatal	Serious	Minor	None
Flight crew				
Cabin crew				
Passengers				

Dangerous goods on board or released from aircraft?	☐ Yes ☐ No	Description
Damage to aircraft, environment or property?	☐ Yes ☐ No	Description

Occurrence summary / Description of events

Post occurrence actions / Maintenance

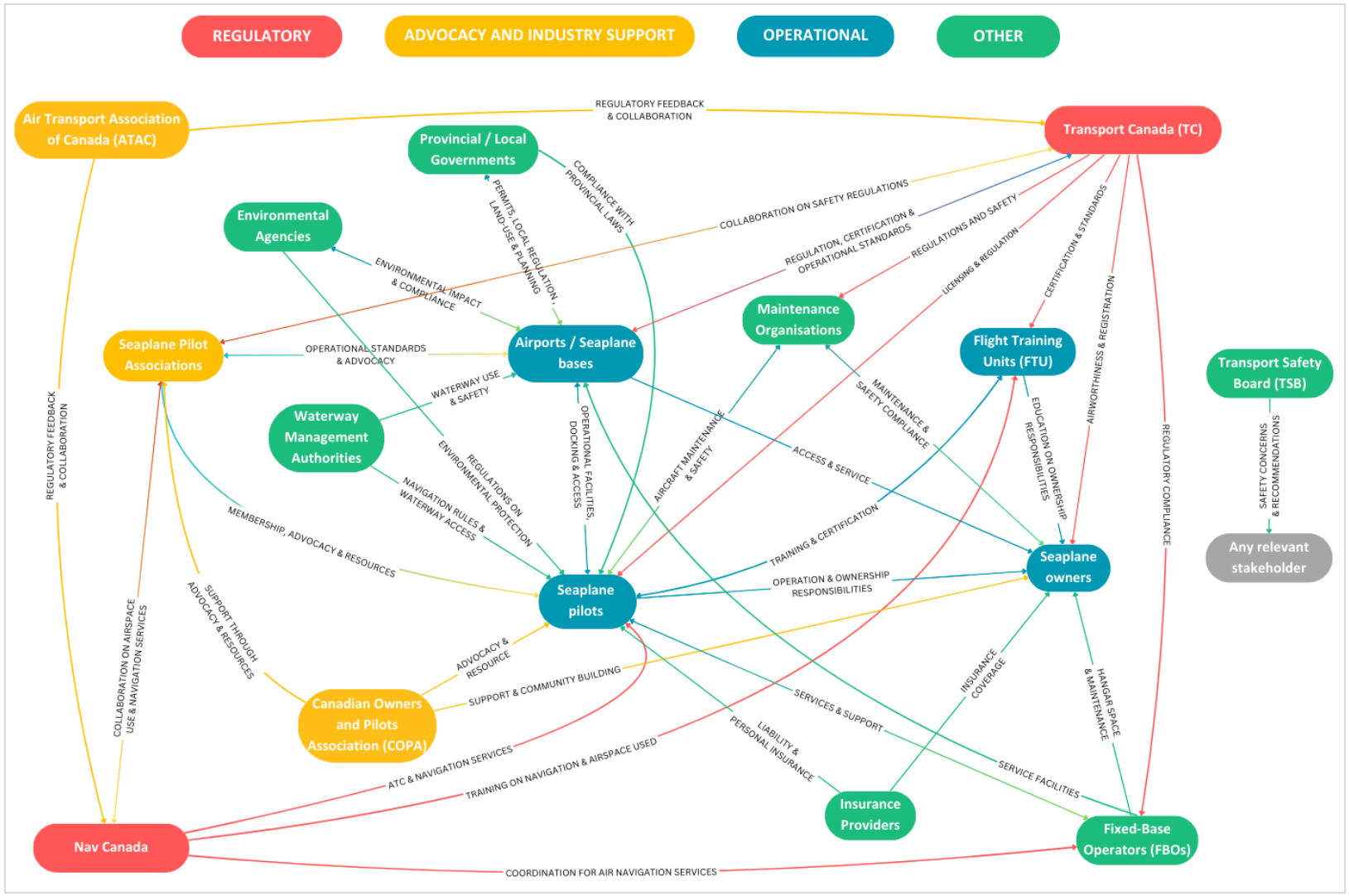


Email to the appropriate TSB regional office:

Pacific - airnotifications.vancouver@tsb-bst.gc.ca
Western - airnotifications.edmonton@tsb-bst.gc.ca
Central - airnotifications.winnipeg@tsb-bst.gc.ca
Ontario - airnotifications.toronto@tsb-bst.gc.ca
Quebec - airnotifications.montreal@tsb-bst.gc.ca
Atlantic - airnotifications.dartmouth@tsb-bst.gc.ca
International or Uncertain - airops@tsb-bst.gc.ca

Do you believe this report requires immediate attention by a TSB Investigator? ☐ Yes ☐ No

Appendix E. Stakeholders for recreational GA seaplanes in Canada.



Appendix F. Detailed description and use of different data sources

This table includes all data sources and types of analysis achieved during this PhD. Not all of them are included in this thesis.

No.	Data source	Location, Years & Data type	Description	Method of Analysis	Reason
1.	**Maritime**				
1.1	***Marine Accident Investigation Branch (MAIB)***	UK 5,078 ship casualties and occupational accidents from 2013 to 2022	Database of marine casualties and incidents in and around ports	Trend analysis	To determine accident trends and patterns.
				Contingency analysis	To detect potential associations and relationships that exist between two variables.
				Three-way associations	To detect potential associations and relationships that exist between three variables.
				Clustering analysis	To investigate accident relationships, especially across different severity levels, using K-means clustering.
				Prediction models (Binary logit model, Bayesian Networks, Complex Networks, Random Forests, Neural Networks)	To predict accidents based on associations of different accident causation factors, and more complex associations between factors.
				Narrative, content and thematic analysis	Interviews to assess factors not included in the accident database and the database accuracy.
		UK 74 accident reports of crew navigation errors from 2012 to 2020	Data fields extracted from accident reports to assess expected implications of introducing AVs	Trend, contingency and three-way associations analyses	Same reasoning as above
				Narrative analysis	To extract the desired information from the incident reports
				Content and thematic analysis	Interviews to assess factors not included in the accident reports and possible future implications of AVs.

1.2	***Automatic Identification System (AIS)***	UK Around 9 million vessel movements and 1.7 million gridded traffic densities, 2011-2017		Trend analysis and graphic representation	To find vessel traffic densities and study their impact of on accident causation at specific UK ports
				Binary logit model	To predict accident causation factors
				Content and thematic analysis	Interviews to assess the database accuracy.
1.3	***Royal National Lifeboat Institution (RNLI)***	UK Around 17,000 occ. 2008-2019	Extracted vessel-related occurrences	Trend analysis	To determine accident trends and patterns.
1.4	***IMO's Global Integrated Shipping Information System (GISIS)***	West Africa and the Gulf of Guinea 322 piracy related incident reports from 2017 to 2022	Data fields extracted from accident reports to analyse maritime piracy	Narrative analysis	To extract the desired information from the incident reports
				Trend analysis	To determine accident trends and patterns.
				Contingency analysis	To detect potential associations and relationships that exist between two variables.
				Three-way associations	To detect potential associations and relationships that exist between three variables.
				Clustering analysis	To investigate accident relationships, especially across different severity levels, using K-means clustering.
2.	**Aviation**				
2.1	***Seaplane database***	Canada 2,021 GA seaplane accidents from 1990 to 2022	Database of GA seaplane accidents and incidents, to analyse the reasons of an increase in seaplane accidents in the last studied years	Narrative analysis	To extract the desired information from the incident reports
				Trend analysis	To determine accident trends and patterns.
				Contingency analysis	To detect potential associations and relationships that exist between two variables.
				Three-way associations	To detect potential associations and relationships that exist between three variables.
				Prediction models	To predict accidents based on associations of different accident causation factors

				Content and thematic analysis	Interviews with pilots and flight training instructors to assess factors not included in the accident database.
2.2	***GA database – Landing***	Canada 283 GA accidents from 2019 to 2020 794 GA accidents from 2014 to 2018	Database of GA accidents, to analyse the impact of the unstable approach during approach and landing	Narrative analysis	To extract new data sets from the accident narratives
				Trend analysis	To determine accident trends and patterns.
				Contingency analysis	To detect potential associations and relationships that exist between two variables.
				Three-way associations	To detect potential associations and relationships that exist between three variables.
				Prediction models	To predict accidents based on associations of different accident causation factors
				Survey	To raise awareness on the unstable approach to landing, and find out the pilot's perspective on what leads to an unstable approach and how they approach the situation during flight.
				Thematic analysis	Interviews with pilots and flight training instructors to assess factors not included in the accident database.
2.3	***Aviation Accident Investigation Branch (AAIB)***	UK 303 GA related incident reports from 2016 to 2021	Data fields extracted from accident reports to analyse the impact of weather on GA accidents	Narrative analysis	To extract the desired information from the incident reports
				Trend analysis	To determine accident trends and patterns.
				Contingency analysis	To detect potential associations and relationships that exist between two variables.
				Three-way associations	To detect potential associations and relationships that exist between three variables.

Appendix G. The categories and data fields that would ideally be obtained from the Marine Accident Investigation Branch of the United Kingdom.

Category	No	Data Field
1. General Description	1	Case ID
	2	Date of occurrence
	3	Date of notification
	4	Time
	5	Categorisation
2. Accident Occurrence	6	Place on board
	7	Mode of occurrence
	8	Casualty Event
	9	Route – Direction
	10	Complexity of Route/ Manoeuvre
	11	Speed at Occurrence
3. Severity	12	Severity
	13	Physical Condition of Injury
	14	Details injured people
	15	Number injuries
	16	Number fatalities
	17	Number of Vessels Involved
	18	Economic Cost
4. Human performance	19	Human factor of crew
	20	Experience of Captain
	21	Training of Captain
	22	Mental Status of Captain
	23	Accident History of Captain
	24	Reaction of captain and crew - Narrative
5. Mechanical	25	Maintenance Status
	26	Mechanical Failure - Narrative
6. Environmental Conditions	27	Visibility
	28	Wind Force
	29	Sea State
	30	Light
	31	Current
	32	Temperature
	33	Weather
	34	Noise Pollution
	35	Air Pollution
7. Vessel Details	36	Identification
	37	Category
	38	Draught
	39	Width
	40	Tonnage
	41	System Technological Development
	42	Size
	43	Speed at Occurrence
	44	Age
	45	Accident history of Vessel
	46	Flag State
	47	Ship Manoeuvrability
8. Accident Details	48	Location
	49	Latitude
	50	Longitude
	51	Port of Accident
	52	People on Board – Population Density in Work Area
	53	Traffic Density
	54	Accident Description
9. Details Injured People	55	ID Injured Person
	56	Gender
	57	Rank
	58	Socio-demographic
	59	On duty?
	60	Part of Injury
	61	Mode of Injury
	62	Nationality
	63	Correct (precautionary) actions, PPE, etc.
10. Transit Details	64	Age
	65	Type of movement
	66	Commercial Voyage?
	67	Transit Length

Appendix H. The categories and data fields that would ideally be obtained from the AIS.

Category	No	Data Field	Category	No	Data Field
1. General Description	1	Transit ID	3. Trip Details	14	Type of movement
	2	Date Start of Trip		15	Latitude Start
	3	Date End of Trip		16	Longitude Start
	4	Time Start of Trip		17	Latitude Finish
	5	Time End of Trip		18	Longitude Finish
2. Vessel Details	6	Identification		19	Traffic Density- all Locations
	7	Category		20	Length of Trip
	8	Tonnage		21	Commercial Voyage?
	9	Draught		22	Hours in Operation
	10	Width		23	Average Speed during trip
	11	Size	4. Environmental Conditions	24	Visibility
	12	Age		25	Wind Force
	13	Flag State		26	Sea State
				27	Light
				28	Current
				29	Temperature
				30	Weather
				31	Noise Pollution
				32	Air Pollution

Appendix I: Results of the three-way association analysis for ship casualties in UK ports.

Table I indicates the relationships among different parameters, for ship casualties, along with their statistical significance (p-value), strength (phi-value), and qualitative strength of the relationship. It is just a subset of the full results which included over 8,000 associations of different strengths. Table I uses the parameters mentioned in Section 6.1.6, but excludes the following parameters: year, flag, season, hull material and size. Theis table includes only the strong relationships between three of the following nine parameters: accident type, severity, location, natural light, sea state, visibility, wind force, vessel type and year of build. The table also excludes marine incidents, military vessels and "other" categories.

Table I: Results for the three-way association analysis for ship casualties in UK ports, for 99% confidence level and strong associations.

Parameter 1	Parameter 2	Parameter 3	p-value	phi-value	Strength
Serious	Collision	Recreational vessel	3.36E-158	0.58	Strong
Serious	Collision	Service ship	3.36E-158	0.58	Strong
Serious	Collision	Passenger vessel	3.36E-158	0.58	Strong
Serious	Collision	Cargo vessel	3.36E-158	0.58	Strong
Serious	Contact	Recreational vessel	3.36E-158	0.58	Strong
Serious	Contact	Service ship	3.36E-158	0.58	Strong
Serious	Contact	Fishing vessel	3.36E-158	0.58	Strong
Serious	Contact	Passenger vessel	3.36E-158	0.58	Strong
Serious	Contact	Cargo vessel	3.36E-158	0.58	Strong
Serious	Fire/Explosion	Fishing vessel	3.36E-158	0.58	Strong
Less Serious	Contact	Fishing vessel	3.36E-158	0.58	Strong
Serious	Fire/Explosion	Recreational vessel	3.36E-158	0.58	Strong
Serious	Loss of control	Service ship	3.36E-158	0.58	Strong
Serious	Fire/Explosion	Passenger vessel	3.36E-158	0.58	Strong
Serious	Fire/Explosion	Cargo vessel	3.36E-158	0.58	Strong
Serious	Loss of control	Cargo vessel	3.36E-158	0.58	Strong
Serious	Loss of control	Passenger vessel	3.36E-158	0.58	Strong
Serious	Loss of control	Fishing vessel	3.36E-158	0.58	Strong
Serious	Loss of control	Recreational vessel	3.36E-158	0.58	Strong
Serious	Grounding/Stranding	Cargo vessel	3.36E-158	0.58	Strong
Serious	Grounding/Stranding	Passenger vessel	3.36E-158	0.58	Strong
Serious	Grounding/Stranding	Fishing vessel	3.36E-158	0.58	Strong
Serious	Grounding/Stranding	Service ship	3.36E-158	0.58	Strong
Serious	Grounding/Stranding	Recreational vessel	3.36E-158	0.58	Strong
Serious	Damage / loss of equipment	Cargo vessel	3.36E-158	0.58	Strong

Serious	Damage / loss of equipment	Passenger vessel	3.36E-158	0.58	Strong
Very serious	Collision	Recreational vessel	3.36E-158	0.58	Strong
Very serious	Collision	Service ship	3.36E-158	0.58	Strong
Very serious	Collision	Passenger vessel	3.36E-158	0.58	Strong
Very serious	Loss of control	Recreational vessel	3.36E-158	0.58	Strong
Serious	Damage / loss of equipment	Service ship	3.36E-158	0.58	Strong
Less Serious	Collision	Cargo vessel	3.36E-158	0.58	Strong
Less Serious	Collision	Passenger vessel	3.36E-158	0.58	Strong
Less Serious	Collision	Fishing vessel	3.36E-158	0.58	Strong
Less Serious	Collision	Service ship	3.36E-158	0.58	Strong
Less Serious	Collision	Recreational vessel	3.36E-158	0.58	Strong
Very serious	Grounding/Stranding	Fishing vessel	3.36E-158	0.58	Strong
Very serious	Fire/Explosion	Recreational vessel	3.36E-158	0.58	Strong
Very serious	Damage / loss of equipment	Service ship	3.36E-158	0.58	Strong
Very serious	Fire/Explosion	Cargo vessel	3.36E-158	0.58	Strong
Very serious	Fire/Explosion	Fishing vessel	3.36E-158	0.58	Strong
Less Serious	Damage / loss of equipment	Cargo vessel	3.36E-158	0.58	Strong
Less Serious	Damage / loss of equipment	Passenger vessel	3.36E-158	0.58	Strong
Less Serious	Damage / loss of equipment	Fishing vessel	3.36E-158	0.58	Strong
Less Serious	Damage / loss of equipment	Service ship	3.36E-158	0.58	Strong
Less Serious	Fire/Explosion	Cargo vessel	3.36E-158	0.58	Strong
Less Serious	Fire/Explosion	Passenger vessel	3.36E-158	0.58	Strong
Less Serious	Fire/Explosion	Fishing vessel	3.36E-158	0.58	Strong
Less Serious	Fire/Explosion	Service ship	3.36E-158	0.58	Strong
Less Serious	Fire/Explosion	Recreational vessel	3.36E-158	0.58	Strong
Less Serious	Contact	Cargo vessel	3.36E-158	0.58	Strong
Less Serious	Contact	Passenger vessel	3.36E-158	0.58	Strong
Less Serious	Contact	Service ship	3.36E-158	0.58	Strong
Less serious	Collision	Recreational vessel	3.36E-158	0.58	Strong
Less Serious	Grounding/Stranding	Recreational vessel	3.36E-158	0.58	Strong
Less Serious	Grounding/Stranding	Service ship	3.36E-158	0.58	Strong
Very Serious	Collision	Service ship	3.36E-158	0.58	Strong
Very Serious	Grounding/Stranding	Recreational vessel	3.36E-158	0.58	Strong
Very Serious	Fire/Explosion	Fishing vessel	3.36E-158	0.58	Strong
Very Serious	Fire/Explosion	Recreational vessel	3.36E-158	0.58	Strong
Very Serious	Collision	Passenger vessel	3.36E-158	0.58	Strong
Very Serious	Collision	Fishing vessel	3.36E-158	0.58	Strong

Very Serious	Collision	Recreational vessel	3.36E-158	0.58	Strong
Less Serious	Grounding/Stranding	Fishing vessel	3.36E-158	0.58	Strong
Less Serious	Loss of control	Cargo vessel	3.36E-158	0.58	Strong
Less Serious	Loss of control	Passenger vessel	3.36E-158	0.58	Strong
Less Serious	Loss of control	Fishing vessel	3.36E-158	0.58	Strong
Less Serious	Loss of control	Service ship	3.36E-158	0.58	Strong
Less Serious	Loss of control	Recreational vessel	3.36E-158	0.58	Strong
Less Serious	Grounding/Stranding	Cargo vessel	3.36E-158	0.58	Strong
Less Serious	Grounding/Stranding	Passenger vessel	3.36E-158	0.58	Strong
Less serious	Collision	Service ship	3.36E-158	0.58	Strong
Less serious	Collision	Fishing vessel	3.36E-158	0.58	Strong
Less serious	Collision	Passenger vessel	3.36E-158	0.58	Strong
Less serious	Loss of control	Service ship	3.36E-158	0.58	Strong
Less serious	Grounding/Stranding	Recreational vessel	3.36E-158	0.58	Strong
Less serious	Grounding/Stranding	Service ship	3.36E-158	0.58	Strong
Less serious	Grounding/Stranding	Fishing vessel	3.36E-158	0.58	Strong
Less serious	Grounding/Stranding	Passenger vessel	3.36E-158	0.58	Strong
Less serious	Grounding/Stranding	Cargo vessel	3.36E-158	0.58	Strong
Less serious	Loss of control	Recreational vessel	3.36E-158	0.58	Strong
Less serious	Loss of control	Fishing vessel	3.36E-158	0.58	Strong
Less serious	Loss of control	Passenger vessel	3.36E-158	0.58	Strong
Less serious	Loss of control	Cargo vessel	3.36E-158	0.58	Strong
Less serious	Collision	Cargo vessel	3.36E-158	0.58	Strong
Less serious	Fire/Explosion	Service ship	3.36E-158	0.58	Strong
Less serious	Contact	Recreational vessel	3.36E-158	0.58	Strong
Less serious	Contact	Service ship	3.36E-158	0.58	Strong
Less serious	Contact	Fishing vessel	3.36E-158	0.58	Strong
Less serious	Contact	Passenger vessel	3.36E-158	0.58	Strong
Less serious	Contact	Cargo vessel	3.36E-158	0.58	Strong
Less serious	Fire/Explosion	Recreational vessel	3.36E-158	0.58	Strong
Less serious	Fire/Explosion	Fishing vessel	3.36E-158	0.58	Strong
Less serious	Fire/Explosion	Passenger vessel	3.36E-158	0.58	Strong
Less serious	Fire/Explosion	Cargo vessel	3.36E-158	0.58	Strong
Less serious	Damage / loss of equipment	Recreational vessel	3.36E-158	0.58	Strong
Less serious	Damage / loss of equipment	Service ship	3.36E-158	0.58	Strong
Less serious	Damage / loss of equipment	Fishing vessel	3.36E-158	0.58	Strong
Less serious	Damage / loss of equipment	Passenger vessel	3.36E-158	0.58	Strong

Less serious	Damage / loss of equipment	Cargo vessel	3.36E-158	0.58	Strong
Less Serious	Contact	Recreational vessel	3.36E-158	0.58	Strong
Grounding/Stranding	England	Recreational vessel	8.96E-223	0.63	Strong
Grounding/Stranding	England	Service ship	8.96E-223	0.63	Strong
Grounding/Stranding	England	Fishing vessel	8.96E-223	0.63	Strong
Grounding/Stranding	England	Passenger vessel	8.96E-223	0.63	Strong
Grounding/Stranding	England	Cargo vessel	8.96E-223	0.63	Strong
Damage / loss of equipment	Scotland	Cargo vessel	8.96E-223	0.63	Strong
Damage / loss of equipment	Scotland	Passenger vessel	8.96E-223	0.63	Strong
Damage / loss of equipment	Scotland	Fishing vessel	8.96E-223	0.63	Strong
Damage / loss of equipment	Scotland	Service ship	8.96E-223	0.63	Strong
Damage / loss of equipment	Northern Ireland	Cargo vessel	8.96E-223	0.63	Strong
Damage / loss of equipment	Northern Ireland	Passenger vessel	8.96E-223	0.63	Strong
Damage / loss of equipment	Northern Ireland	Service ship	8.96E-223	0.63	Strong
Grounding/Stranding	Wales	Recreational vessel	8.96E-223	0.63	Strong
Damage / loss of equipment	Wales	Cargo vessel	8.96E-223	0.63	Strong
Loss of control	England	Service ship	8.96E-223	0.63	Strong
Grounding/Stranding	Wales	Service ship	8.96E-223	0.63	Strong
Grounding/Stranding	Wales	Fishing vessel	8.96E-223	0.63	Strong
Damage / loss of equipment	England	Cargo vessel	8.96E-223	0.63	Strong
Loss of control	Scotland	Passenger vessel	8.96E-223	0.63	Strong
Loss of control	Scotland	Fishing vessel	8.96E-223	0.63	Strong
Loss of control	Scotland	Service ship	8.96E-223	0.63	Strong
Loss of control	Scotland	Recreational vessel	8.96E-223	0.63	Strong
Loss of control	Northern Ireland	Cargo vessel	8.96E-223	0.63	Strong
Loss of control	Northern Ireland	Passenger vessel	8.96E-223	0.63	Strong
Loss of control	Northern Ireland	Fishing vessel	8.96E-223	0.63	Strong
Loss of control	Northern Ireland	Recreational vessel	8.96E-223	0.63	Strong
Loss of control	Wales	Cargo vessel	8.96E-223	0.63	Strong
Loss of control	Wales	Passenger vessel	8.96E-223	0.63	Strong
Loss of control	Wales	Fishing vessel	8.96E-223	0.63	Strong
Loss of control	Wales	Service ship	8.96E-223	0.63	Strong
Loss of control	Wales	Recreational vessel	8.96E-223	0.63	Strong
Loss of control	England	Cargo vessel	8.96E-223	0.63	Strong
Loss of control	England	Passenger vessel	8.96E-223	0.63	Strong
Loss of control	England	Fishing vessel	8.96E-223	0.63	Strong

Loss of control	England	Recreational vessel	8.96E-223	0.63	Strong
Grounding/Stranding	Scotland	Cargo vessel	8.96E-223	0.63	Strong
Grounding/Stranding	Scotland	Passenger vessel	8.96E-223	0.63	Strong
Grounding/Stranding	Scotland	Fishing vessel	8.96E-223	0.63	Strong
Grounding/Stranding	Scotland	Service ship	8.96E-223	0.63	Strong
Grounding/Stranding	Scotland	Recreational vessel	8.96E-223	0.63	Strong
Grounding/Stranding	Northern Ireland	Cargo vessel	8.96E-223	0.63	Strong
Grounding/Stranding	Northern Ireland	Passenger vessel	8.96E-223	0.63	Strong
Grounding/Stranding	Northern Ireland	Fishing vessel	8.96E-223	0.63	Strong
Grounding/Stranding	Northern Ireland	Service ship	8.96E-223	0.63	Strong
Grounding/Stranding	Northern Ireland	Recreational vessel	8.96E-223	0.63	Strong
Grounding/Stranding	Wales	Cargo vessel	8.96E-223	0.63	Strong
Damage / loss of equipment	Wales	Service ship	8.96E-223	0.63	Strong
Contact	Wales	Cargo vessel	8.96E-223	0.63	Strong
Damage / loss of equipment	England	Passenger vessel	8.96E-223	0.63	Strong
Contact	Wales	Fishing vessel	8.96E-223	0.63	Strong
Contact	Wales	Recreational vessel	8.96E-223	0.63	Strong
Contact	England	Cargo vessel	8.96E-223	0.63	Strong
Contact	England	Passenger vessel	8.96E-223	0.63	Strong
Contact	England	Fishing vessel	8.96E-223	0.63	Strong
Contact	England	Service ship	8.96E-223	0.63	Strong
Contact	England	Recreational vessel	8.96E-223	0.63	Strong
Collision	Scotland	Cargo vessel	8.96E-223	0.63	Strong
Collision	Scotland	Passenger vessel	8.96E-223	0.63	Strong
Collision	Scotland	Fishing vessel	8.96E-223	0.63	Strong
Collision	Scotland	Service ship	8.96E-223	0.63	Strong
Collision	Scotland	Recreational vessel	8.96E-223	0.63	Strong
Collision	Northern Ireland	Cargo vessel	8.96E-223	0.63	Strong
Collision	Northern Ireland	Passenger vessel	8.96E-223	0.63	Strong
Collision	Northern Ireland	Fishing vessel	8.96E-223	0.63	Strong
Collision	Northern Ireland	Service ship	8.96E-223	0.63	Strong
Collision	Northern Ireland	Recreational vessel	8.96E-223	0.63	Strong
Collision	Wales	Cargo vessel	8.96E-223	0.63	Strong
Collision	Wales	Passenger vessel	8.96E-223	0.63	Strong
Collision	Wales	Fishing vessel	8.96E-223	0.63	Strong
Collision	Wales	Service ship	8.96E-223	0.63	Strong
Collision	Wales	Recreational vessel	8.96E-223	0.63	Strong
Collision	England	Cargo vessel	8.96E-223	0.63	Strong

Collision	England	Passenger vessel	8.96E-223	0.63	Strong
Collision	England	Fishing vessel	8.96E-223	0.63	Strong
Collision	England	Service ship	8.96E-223	0.63	Strong
Collision	England	Recreational vessel	8.96E-223	0.63	Strong
Contact	Wales	Service ship	8.96E-223	0.63	Strong
Contact	Wales	Passenger vessel	8.96E-223	0.63	Strong
Damage / loss of equipment	England	Fishing vessel	8.96E-223	0.63	Strong
Contact	Northern Ireland	Service ship	8.96E-223	0.63	Strong
Damage / loss of equipment	England	Service ship	8.96E-223	0.63	Strong
Damage / loss of equipment	England	Recreational vessel	8.96E-223	0.63	Strong
Fire/Explosion	Scotland	Cargo vessel	8.96E-223	0.63	Strong
Fire/Explosion	Scotland	Passenger vessel	8.96E-223	0.63	Strong
Fire/Explosion	Scotland	Fishing vessel	8.96E-223	0.63	Strong
Fire/Explosion	Scotland	Service ship	8.96E-223	0.63	Strong
Fire/Explosion	Scotland	Recreational vessel	8.96E-223	0.63	Strong
Fire/Explosion	Northern Ireland	Cargo vessel	8.96E-223	0.63	Strong
Fire/Explosion	Northern Ireland	Passenger vessel	8.96E-223	0.63	Strong
Fire/Explosion	Northern Ireland	Service ship	8.96E-223	0.63	Strong
Fire/Explosion	Northern Ireland	Recreational vessel	8.96E-223	0.63	Strong
Fire/Explosion	Wales	Cargo vessel	8.96E-223	0.63	Strong
Fire/Explosion	Wales	Passenger vessel	8.96E-223	0.63	Strong
Fire/Explosion	Wales	Fishing vessel	8.96E-223	0.63	Strong
Fire/Explosion	Wales	Service ship	8.96E-223	0.63	Strong
Fire/Explosion	Wales	Recreational vessel	8.96E-223	0.63	Strong
Fire/Explosion	England	Cargo vessel	8.96E-223	0.63	Strong
Fire/Explosion	England	Passenger vessel	8.96E-223	0.63	Strong
Fire/Explosion	England	Fishing vessel	8.96E-223	0.63	Strong
Fire/Explosion	England	Service ship	8.96E-223	0.63	Strong
Fire/Explosion	England	Recreational vessel	8.96E-223	0.63	Strong
Contact	Scotland	Cargo vessel	8.96E-223	0.63	Strong
Contact	Scotland	Passenger vessel	8.96E-223	0.63	Strong
Contact	Scotland	Fishing vessel	8.96E-223	0.63	Strong
Contact	Scotland	Service ship	8.96E-223	0.63	Strong
Contact	Scotland	Recreational vessel	8.96E-223	0.63	Strong
Contact	Northern Ireland	Cargo vessel	8.96E-223	0.63	Strong
Contact	Northern Ireland	Passenger vessel	8.96E-223	0.63	Strong
Contact	Northern Ireland	Fishing vessel	8.96E-223	0.63	Strong
Loss of control	Scotland	Cargo vessel	8.96E-223	0.63	Strong

Appendix J. Investigation of the risk influential factors of maritime accidents: A novel topology and robustness analytical framework

This appendix includes a paper which is under final review, after being accepted with minor revisions by the Journal of "Reliability Engineering & System Safety".

Investigation of the risk influential factors of maritime accidents: A novel topology and robustness analytical framework

Yuhao Cao [a, b], Manole Iulia [b], Arnab Majumdar [b], Yinwei Feng [c], Xuri Xin [a], Xinjian Wang [c], Huanxin Wang [c], Zaili Yang [a, d, *]

[a] **Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Liverpool John Moores University, L3 3AF, United Kingdom**

[b] **Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, London, SW7 2AZ, United Kingdom**

[c] **Navigation College, Dalian Maritime University, Dalian 116026, PR China**

[d] **Transport Engineering College, Dalian Maritime University, Dalian 116026, PR China**

Abstract:

This study aims to develop a novel and fully data-driven approach to analyse the maritime accidents risk influential factors (RIFs) by integrating Association Rule Mining (ARM) and Complex Network (CN) modelling. Firstly, a comprehensive dataset comprising 21,206 maritime accident records from Marine Accident Investigation Branch and Transportation Safety Board are collected and processed to serve as the foundational data source supporting the development of the new approach. Secondly, a novel Combined Association Rule Mining method is proposed to extract the interconnections among RIFs, and the mined results are mapped into a CN framework. Finally, two importance ranking algorithms, namely the PageRank-Information-Entropy algorithm and edge betweenness centrality, are applied to identify the key RIFs and their information transmission paths. By simulating deliberate and random attacks within this network, a robustness analysis is conducted to further explore the evolution of RIFs. The findings reveal that ship-related factors demonstrate greater centrality and connectivity, exerting a more substantial influence on information propagation within the network structure. The robustness analysis has illustrated that strategic node and edge removals are effective in preventing risk propagation. It therefore makes contributions to the development of a theoretical basis for stakeholders to develop cost-effective preventive measures against specific RIFs, ultimately enhancing maritime safety.

Keywords: Maritime transportation, Maritime safety, Maritime accident, Association rule, Complex network

1. Introduction

With the greater integration of the global economy, shipping as the primary vehicle of maritime trade, bears the responsibility of transporting vast quantities of goods. The increasing volume of maritime trade has led to an increased frequency of ship voyages, thereby exposing the sector to a heightened risk of maritime accidents. According to the data from European Maritime Safety Agency (EMSA), the period spanning 2014 to 2021 witnessed a total of 21,173 reported maritime casualties and accidents, resulting in substantial human and property losses [1].

Despite extensive efforts made by various stakeholders in this domain, the state of maritime safety still remains critical due to many uncertainties [2, 3]. Maritime accidents, indeed, arise from a complex interplay of multiple Risk Influential Factors (RIFs), including but not limited to ship conditions [4], weather conditions [5], geographical factors [6], and navigational elements [7]. Typically, these factors exert mutual influence, creating chain reactions that ultimately lead to accidents. While maritime safety authorities and global shipping companies have dedicated considerable resources to enhance safety standards and service quality (e.g., increasing automation on board ships and coordinating with relevant regulatory bodies to strengthen regulations and emergency response), accidents still occur. Whenever an accident occurs, it necessitates a meticulous investigation process, involving the collection of facts and data, the analysis of gathered information, the determination of root causes, the prioritization of contributing factors, and the formulation of conclusions and recommendations [8]. The success of such accident investigation at large depends on the identification of the key RIFs of high interdependency and dynamics. Therefore, the primary aim of this paper is to develop a novel data-driven approach to enable effective assessment of key RIFs of maritime accidents, addressing today's fast-changing shipping operations of high uncertainty. It analyses maritime accident RIFs from a global systematic perspective with a focus on the interactive network features of the RIF and hence, differs with previous relevant analysis in the literature more from a local independent viewpoint. Furthermore, the novelty of

this approach lies in the systematic analysis of the accident reports to generate raw data, which in turn supports the development of the new approach in this paper.

The paper's structure is organised as follows: Section 2 critically assesses the literature on both maritime accident RIFs studies and data-driven approaches to accident analysis. In Section 3, research data is methodically presented, and a hybrid approach using association rule mining (ARM) and complex network (CN) modelling is also proposed. Based on the topological and robustness analysis from the analytical framework, the results are demonstrated in Section 4. Section 5 discusses the results and presents implications. Finally, the conclusions are presented in Section 6.

2. Literature review

2.1 Research on RIFs in maritime safety

As maritime safety research continues to evolve, the RIFs contributing to maritime accidents continue to be identified. Table 1 outlines an intensive literature review, where the representative research papers corresponding to different RIFs and along with their respective findings have been listed in.

Table 1 Relevant papers related to different RIFs.

RIFs	References	Findings
Ship type	[5, 9, 10]	Due to a lack resistant and resilient to hazardous situations, fishing vessels are generally recognised as more vulnerable. Furthermore, ships with carrying special and hazardous goods, are more susceptible to fires and explosions and leakage of cargoes in accidents, causing serious environmental pollution and loss of human lives.
Ship parameter	[4, 9, 11, 12]	Parameters such as the size of the ship, engine power and the gross tonnage (GT) show correlation and consistency with maritime accidents.
Accident type	[13-15]	In general, sinking is considered to be deemed as the type of accident that results in the most casualties. While the issue of cargo or fuel leakage due to collision, explosion or mechanical damage is equally critical.
Weather and climate	[16-18]	Severe wind and wave current conditions both increase the probability of maritime accidents, and also exacerbate the severity of accidents.

Channel condition	[6, 19]	Channel conditions such as navigational density channel width and depth increase the risk of collision and contact between ships, especially in port areas and inland waterways.

This state-of-the-art review highlights that the primary data sources for these papers are the accident investigation reports from worldwide maritime authorities, which typically contain detailed information such as: the condition of the vessels involved, environmental factors at the time of the accidents, and the consequences. Based on this content, researchers can summarise and extract relevant RIFs. However, a notable gap in the current research is the issue of insufficient data support. The limited quantity of accident statistics or reports fails to adequately illustrate the mechanisms behind maritime accidents from a generalised perspective. Also, the lack of information resulting from insufficient data complicates the definition and identification of RIFs, as certain RIFs might not be explicitly mentioned in the reports. This necessitates manual analysis, inherently introducing subjectivity and further uncertainty into the process. Meanwhile, a comparative analysis of Table 1 reveals a discernible limitation in the depth of analysis in the current research on maritime accident RIFs. This is principally reflected in the absence of a global analysis of the interactive and dynamic effects resulting from multiple objective RIFs. Therefore, this highlights the need to explore maritime accident RIFs from the dynamic and objective perspectives.

2.2 Research on modelling methods of maritime accident analysis

A wide range of methods have been applied in the literature for modelling accident analysis, including both traditional and emerging methods. These are reviewed below in turn.

2.2.1 Traditional methods.

Traditional maritime accident analysis methods typically explore the causes of accidents through a qualitative or subjective evaluation process, finding widespread applications. They include Human Factors Analysis and Classification System (HFACS), Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and fuzzy theory [2]. These methods have demonstrated their ability to incorporate expert knowledge, thereby producing results that align with "real-world" scenarios. The underlying

mechanisms and processes of these methods can normally be clearly identified. For instance, an innovative study demonstrated the adaptability of the modified HFACS for Passenger Vessel collisions (HFACS-PV) [20]. Wu et al. [21] proposed a fuzzy-TOPSIS framework to assess safety control measures under complex navigation conditions. Oraith et al. [22] analysed the human factors affecting pilot operations using AHP, and the hierarchical structure of the study was established mainly through the utilization of questionnaires and expert knowledge.

Despite the valuable contributions of such traditional methods, they continue to suffer from a notable limitation due to their reliance on expert judgment for certain structural elements or weighting factors. It is important to acknowledge that the variations in preferences among different experts may lead to disparate outcomes. This inherent drawback has the potential to impact the accuracy of assessments, wanting new solutions to be found.

2.2.2 Emerging methods

To improve objectivity, accuracy, and the capability to predict potential risks, data-driven approaches have emerged, attracting increasing attention [23]. Within contemporary maritime safety research, researchers have applied different approaches, such as regression analysis (e.g., linear regression and logic regression), cluster analysis (e.g., K-means), tree-structured algorithms (e.g., accident trees and decision trees), network-structured algorithms (e.g., Bayesian networks and CN) and mining algorithms (e.g., text mining and ARM) to comprehensively assess the risks during ship navigation [2]. To facilitate comparative analysis, Table 2 summarises different data-driven methods. It is worth noting that the strengths and weaknesses outlined in Table 2 pertain specifically to the performance of the target methods.

123 Table 2 Relevant papers based on different data-driven methods

References	Methods	Application	Advantage	Disadvantage
[9]	Ordered logistic regression (OLR)	Generate the RIFs related to maritime accident severity.	Applicable to ordered categorical dependent variables (e.g., severity). The model is highly interpretable and does not need to satisfy the linearity assumption.	Multiple covariance issues between RIFs and a high requirement of the data quality.
[24]	HFACS and Bayesian networks (BN)	A hybrid methodology to investigate the human and organizational factors of collision accidents between two types of ship.	Ability to incorporate the hierarchical framework with the quantitative analysis.	Model validation and sensitive to missing data.
[25]	Object-oriented Bayesian network (OOBN)	A quantitative risk assessment of navigational accidents in ice-covered Arctic waters	Ability to reflect relationships between RIFs and quantify their impact.	Additional decision-making methods are needed to evaluate the effectiveness.
[26]	Text mining	An algorithm capable of extracting keywords from accident reports.	Ability to extract information from unstructured data.	Computationally complex, data quality issues and explicability.
[27, 28]	ARM	A comparative analysis between two ARM algorithms.	Suitable for large-scale data and the ability to discover implicit relationships.	Hard to explain the results well if just reliant on the model parameters.
[29]	ARM	An algorithm to mine the critical factors of ship total loss accident.	Ideal for initial exploration of an area and the ability to discover implicit relationships.	Complexity is positively correlated with the amount and latitude of data.
[10]	BN	A data-driven BN model to analyse the RIFs of accident severity.	Strong predictability and explain ability.	Computationally complex for a large network, expert/manual intervention.
[30]	Least Absolute Shrinkage and Selection Operator (LASSO) and BN	A data-driven combined method to investigate the human fatigue.	Strong explain ability and easy to handle multiple data types.	Limited data and sensitive to missing data.
[31]	CN	A framework to evaluate marine traffic situation.	Ability to visualise and real complex relationships and couple with other models.	Lack of a basis for network establishment and systematic dynamic evaluation.
[32]	CN	A comprehensive framework to investigate the key factors in collision accidents.	Ability to model and visualise complex relationships.	Lack of systematic topological analysis and dynamic evaluation.

124

Research on maritime accidents can benefit to some extent from the analysis of accidents in other transport modes, including railways [33] and aviation [34]. These studies have adeptly incorporated complex networks (CN) to the research on transport safety by abstracting real accident causation and relationships into nodes and edges within networks. This abstraction allows for the application of CN theory to enhance the explanatory power of risk analysis.

In the maritime safety research domain, although Sui et al. [31] and Sui et al. [35] have explored the topological characteristics of maritime traffic situational awareness by employing CN, the process of establishing complex networks remains unclear for data quality and quantity, parameter setting and model validation. These drawbacks are inherent in the CN method. To address this concern, Lan et al. [32] utilised the rule mining capability of ARM to improve the evidence of the CN structure. ARM, a common data mining technique in unsupervised learning, exhibits capacities to uncover the relationships between data to extract valuable insights. Hence ARM can assist in identifying the contributing factors and exploring links within accident investigation, thereby mitigating certain limitations of CN as a foundational modelling approach [28]. However, the main objective of Lan et al. [32] was to predict the severity of accidents through the subsequent random forest approach. Consequently, the topological analysis of that study was primarily discussed from the perspective of node degree, making it challenging to fully capture a comprehensive global topology pattern and the evolution of robustness.

2.3 Research contributions

Both the systematic reviews pertaining to the RIFs of maritime accident and the modelling methods reveal a pressing need for a new analytical framework to address the issues such as lack of a data-driven approach to objectively conduct the topological and robustness analysis of maritime accident RIFs. Therefore, this paper aspires to enrich the field of maritime accident investigation by harnessing cutting-edge methodologies, manifesting across the following distinct dimensions:

1. An up-to-date and comprehensive database is established. Maritime accident data containing 21,206 maritime accidents from the MAIB and the TSB spanning the period between 2010 to 2023 is employed as the data source. A thorough data quality assessment is conducted to evaluate the reliability of the database.

2. This study represents the endeavour in synthesizing ARM's ability to uncover implicit relationships and CN's prowess in visualizing and analysing the intricate relationships involved in maritime accident research. A novel Combined Association Rule Mining (CARM) method is introduced to identify associations at the factor level. Alongside state-level associations, this study addresses the prevailing uncertainties surrounding the causal factors and evolution mechanisms of maritime accidents from both macro and micro perspectives.

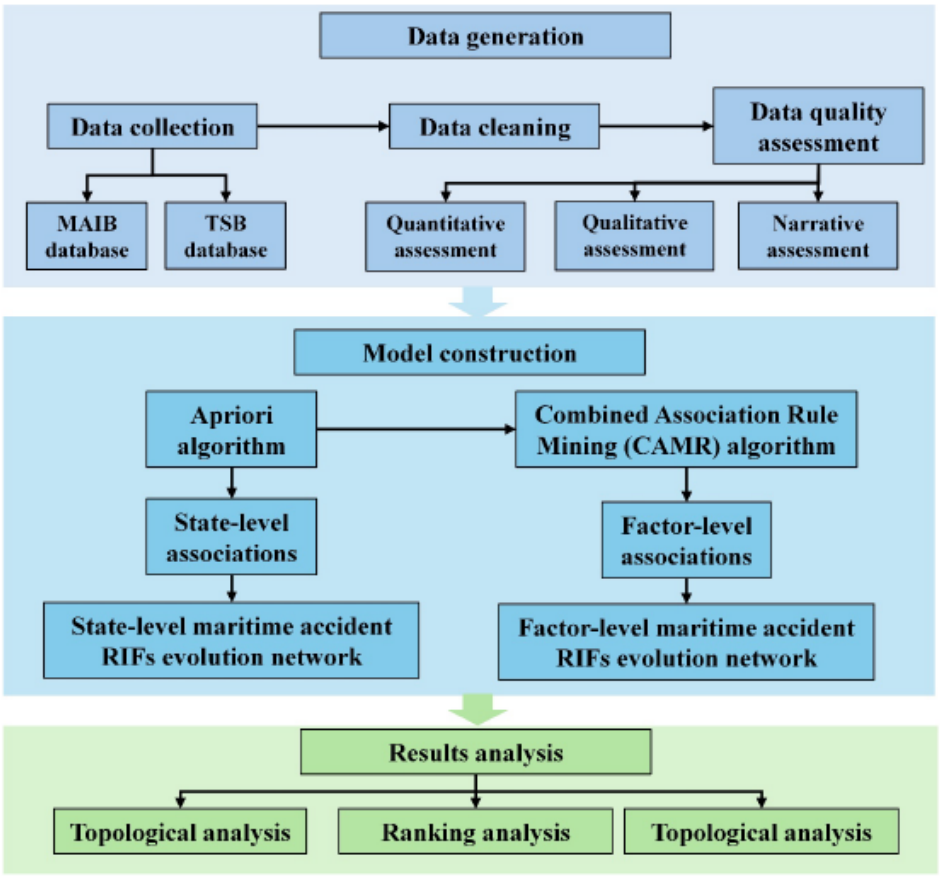
3. A comprehensive analytical framework encompassing model construction, topological analysis and robustness analysis is proposed. Six parameters are utilized to measure the topology within this framework. The innovative PageRank-Information-Entropy (PIE) algorithm and edge centrality metric are used to rank key nodes and edges, providing a theoretical basis of robustness analysis.

4. To facilitate a dynamic accident evolution assessment, the reachability matrix (RM) is developed as a novel criterion for evaluating the robustness. The Monte Carlo simulation algorithm and the importance ranking results are applied to implement both random and deliberate attacks on nodes and edges for the first time. A comparison of the decrease in robustness using PIE and existing methods demonstrates the effectiveness of the proposed framework in this study.

3. Methodology

Towards achieving a systematic exploration of maritime accident RIFs, the methodology of this paper involves database development, as well as ARM and CN modelling. The methodological framework of this study is shown in Figure 1.

177



178

179 Figure 1. The methodological framework

180

181 **3.1 Research data**

182 The data used in this paper are from two sources: the MAIB
183 (https://www.gov.uk/government/organisations/marine-accident-investigation-branch) and the
184 TSB (https://www.tsb.gc.ca/eng/stats/marine/data-6.html) official maritime accident statistics.
185 Both authorities specialise in the investigation of transport accidents and maintain
186 comprehensive datasets over an extended timeframe and encompassing a multitude of cases,
187 which provides a sufficient sample size for this paper. The reason of using both databases is to

avoid any data bias introduced by using only one database and ensure the comprehension of the new formed database in this paper. Moreover, the database used in this paper does not contain human factors, and in order to ensure the objectivity of the data, this paper will focus on the evolution of these objective factors during the accident process, which will provide an interesting view on accident prevention.

3.1.1 Classification of RIFs

In the original MAIB and TSB databases, each row represents an accident record, and each column represents a RIF. Both databases contain a substantial number of RIFs and data records, while there is still missing or poorly documented data despite the effort of merging the two sources to address it. Therefore, this paper seeks to identify and define RIFs in advance and establish a classification system for the various RIFs. Considering the feasibility of the database and desire to select the most comprehensive RIFs possible, referring to the relevant literature [10, 36, 37] and the actual accident report, this paper establishes a maritime accident RIFs classification criteria, as shown in Appendix 1.

The maritime accident RIFs classification criteria contain two types of factors: internal and external. The former predominantly revolve around the inherent attributes of ships and the nature of accidents. Since the classification criteria for ship type and accident type from the MAIB and TSB are generally consistent, in addition to applying the official classification criteria, this paper harmonizes related duplicated or synonymous items. Similarly, external factors primarily pertain to navigational conditions. Both the MAIB and TSB employ similar criteria and units for categorising natural light, sea state, wind and visibility, and therefore, the original categorisation is retained.

3.1.2 Data cleaning

The database released by the TSB contains all maritime accident data recorded by the Marine Safety Information System (MARSIS) from January 1995 to July 2023, with some exceptions and deletions due to protections of third party, personal and privileged information [38]. The database published by the MAIB contains maritime accident data recorded from

January 2013 to December 2021. To ensure the relevance and timeliness of the study outlined in this paper, as well as to avoid potential bias in the results stemming from data processing, the databases are processed as follows:

1. Data Selection: Accident data from 2010 onwards in the TSB database (due to the large amount of missing information in the previous data), and from 2013 onwards in the MAIB database, in total 21,206 accidents, are selected for analysis. This dataset includes 17,923 accidents from TSB and 3,283 accidents from MAIB. A visualisation of the distribution of the accident data is shown in Figure 2, with the red scatter points indicate the locations where the accidents occurred.

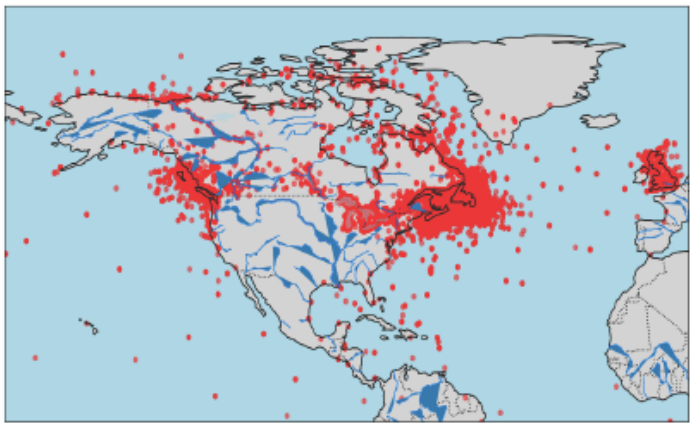


Figure 2. Distribution of maritime accidents recorded by MAIB and TSB.

2. RIFs Selection: To ensure the relevance of this study, 13 RIFs encompassing both internal and external factors are selected, based on the classification system established in Appendix 1.

3. Handling Missing Data: The original database contains missing items. To avoid bias arising from data processing methods, such as data deletion or imputation, the missing data was tackled through the ARM (see section 3.2 for a detailed description). Data cleaning is then

executed on the remaining data according to the classification system established in Appendix 1, to obtain the maritime accident database used for analysis.

3.1.3 Data quality assessment

An assessment of the data is essential in order to validate its reliability and quality. In this paper, we make use of the following data quality assessment (DQA) from the perspectives of quantitative [39-41], qualitative [39, 42, 43], and narrative assessments [42]. The specific dimensions of each assessment are shown in Section 4.1, and specific descriptions and formulas are given in Appendix 2.

3.2 Association rule mining (ARM)

ARM is a machine learning algorithm for mining potential relationships in the data. Common ARM algorithms include FP-Growth [44], Apriori [27, 45] and Eclat [29]. Although the different algorithms exhibit slight variations in terms of their runtime and mining patterns, they consistently produce identical outcomes. According to [46], the Apriori algorithm has demonstrated excellent performance in various simulations and hence will be chosen to mine association rules among RIFs in this paper.

Specifically, an association rule (AR) contains items A_i and B_j in this study, representing different states of the different RIFs, respectively. In the ARM method, there are three parameters that correspond to the patterns of the RIFs namely: support, confidence and lift, see equations (1) – (3) [29]. The Apriori algorithm is an iterative algorithm that searches for the frequent item sets by examining them layer by layer. The search process depends on the thresholds of minimum support and minimum confidence.

$Support(A_iB_j)$ signifies the probability of the co-occurrence of items A_i and B_j:

$$Support(A_iB_j) = \frac{N_{A_iB_j}}{N} \tag{1}$$

where:

A_iB_j represents the simultaneous occurrence of items A_i and B_j;

$N_{A_iB_j}$ represents the count of accidents where the items A_i and B_j co-occur;

N represents the total accidents count.

$Confidence(A_i \Longrightarrow B_j)$ is the conditional probability of item B_j occurring when item A_i is observed.

$$Confidence(A_i \Longrightarrow B_j) = \frac{Support(A_i B_j)}{Support(B_j)} \quad (2)$$

where $A_i \Longrightarrow B_j$ represents the AR between item A_i and item B_j.

$Lift(A_i \Longrightarrow B_j)$ is defined as the ratio of $Confidence(A_i \Longrightarrow B_j)$ to $Support(B_j)$. A lift value greater than one signifies a strong positive association, a strong negative association is indicated by a value less than one and when the value equals 1, there is no discernible association between the RIFs.

$$Lift(A_i \Longrightarrow B_j) = \frac{Confidence(A_i \Longrightarrow B_j)}{Support(B_j)} \quad (3)$$

However, as previously noted, the convectional ARM technique primarily delivers results at a micro-level, i.e., items in ARs are states of the different RIFs, and fails to capture associations at a higher, factor level. To overcome this limitation, this study introduces a novel algorithm, the Combined Association Rule Mining (CARM) method, which builds on traditional ARM principles. The pseudocode for CARM is detailed in Table 3. Unlike standard ARM outputs, CARM not only identifies but also elevates associations to the factor level. To quantify how antecedents influence consequences at this level, a new metric is proposed, the Joint Conviction (JC), which is defined as follows in

$$JC(A \Rightarrow B) = \sum_i \sum_j Conviction(A_i \Rightarrow B_j) \times \frac{Support(A_i \Rightarrow B_j)}{\sum_i \sum_j Support(A_i \Rightarrow B_j)} \quad (4)$$

where $Conviction(A_i \Rightarrow B_j) = 1 - Support(B_j)/1 - Confidence(A_i \Rightarrow B_j)$. Conviction measures the ratio between the frequency of occurrence of A_i when B_j does not occur and the frequency of independent occurrences of A_i and B_j when the rule is not applicable. It thus reflects the dependency of the consequent on the antecedent within an AR. A key attribute of conviction is its asymmetry concerning the support of the itemsets, implying that for the rules

279 "$A_i \Rightarrow B_j$" and "$B_j \Rightarrow A_i$", despite identical support and confidence, their conviction values can
280 differ significantly, thereby revealing deeper insights into rule evaluation.

281 In Equation (4), A and B represent different RIFs, while A_i and B_j denote distinct states
282 of these RIFs. The JC metric synthesizes these conviction values across all state pairs,
283 weighting them by their occurrence probabilities to provide a comprehensive measure of
284 influence at the factor level. This approach not only enhances interpretability by aggregating
285 different state convictions into a unified metric but also ensures robustness against the influence
286 of anomalous state pairs, offering a more stable measure of association.

287

288 Table 3 The pseudocode of CARM algorithm

Algorithm 1: Combined Association Rule Mining algorithm	
Input: Dataset, **DS**; Minimum support threshold, **min_sup**	
Output: CARs	
1	**Begin**
2	Calling Association Rule algorithm (Apriori)
3	**Return** association rules that satisfy **min_sup** and **lift > 1, AR**
4	Generate two matrices **C** and **S** with $Conviction(A_i \Rightarrow B_j)$ and $Support(A_i \Rightarrow B_j)$ as elements, respectively, based on the **AR**
5	Use Eq. (4) to perform scaling nodes operations are performed on C and S based on factors states to form new joint matrices, **JC**
6	Change the diagonal of **JC** to all Zeros, **CAR**
7	Transforming **CAR** matrix into association rule format
8	**Return** CARs
9	**End**

289

290 ## 3.3 Complex network

291 Based on the ARM and CARM methods, the ARs between the states of the RIFs and the
292 CARs between the RIFs are obtained. In this section, antecedents and consequents and the
293 relationships between them are extracted as nodes and edges in networks, respectively. The
294 established CN models can reveal the network structure by explaining topological
295 characteristics, identifying key nodes and edges within the network, and lead to a better
296 understanding of accident evolution mechanisms.

297 **3.3.1 Complex network development**

298 In this paper, a network can be expressed as $G = (N, E)$, where $N = \{n_1, n_2, \dots, n_p\}$
299 represents the sets of nodes (i.e., the states of RIFs or the RIFs), and $E = \{e_1, e_2, \dots, e_q\}$
300 represents the sets of edges. The network is considered as an adjacency matrix G. If there is a
301 total of p nodes, there are $p \times p$ elements in the matrix G, as shown in equation (5):

$$G = \begin{bmatrix} g_{11} & \cdots & g_{1p} \\ \vdots & \ddots & \vdots \\ g_{p1} & \cdots & g_{pp} \end{bmatrix} \quad (5)$$

302 where $g_{A_iB_j} = w_{A_iB_j} \times e_{A_iB_j}$, $w_{A_iB_j}$ represents the weight of the directed edge from node A_i to
303 node B_j, $e_{A_iB_j}$ represents the index of the AR between from node A_i to node B_j, as illustrated
304 in equation (6).

$$\begin{cases} e_{A_iB_j} = 1, If\ A_i \Rightarrow B_j\ exists \\ e_{A_iB_j} = 0, otherwise \end{cases} \quad (6)$$

305 The direction of the edges can in practice symbolize a chain reaction triggered by a change
306 in the state of one RIF caused by another RIF. The realisation of this reaction relies on abstract
307 information transfer along the edges. Thus, the direction in the network model will be in line
308 with the sequence of "antecedents" and "consequences" in the mined ARs and CARs. To
309 enhance the theoretical basis for modelling complex networks, this study also maps the ARM
310 and CARM results to the CN model through weights, i.e., $w_{A_iB_j} = Confidence\left(A_i \Rightarrow B_j\right)$ and
311 $w_{AB} = JC(A \Rightarrow B)$.

312 **3.3.2 Network topological characteristics**

313 In the field of accident investigation, the topological analysis of CN has proved effective
314 in identifying the key RIFs, and different values of parameters can effectively distinguish the
315 functions of different RIFs [32]. In this study, parameters comprising degree, strength,
316 centrality and the clustering coefficient are discussed in turn, to provide a comprehensive
317 analysis of the RIFs network.

1) The degree quantifies the number of edges connected to a node, which encompasses both incoming (i.e., in-degree) and outgoing (i.e., out-degree) links. Correspondingly, the algebraic sum of edge weights can be expressed by a parameter named strength, including both in-strength and out-strength. As the basic statistical parameters among the network structure, both degree and strength characterise the activity level of a RIF in the network [33]. In practice, nodes with high degree and strength values tend to raise a more pronounced influence on other factors through changes in their own properties during accident evolution.
2) Degree centrality (DC) serves as a direct index to measure the centrality, assisting in identifying critical RIFs in the network from the perspective of connectivity [47].
3) Node closeness centrality (NCC) reflects the proximity of a node to other nodes, facilitating the detection of RIFs with high information dissemination rates [32].
4) Node betweenness centrality (NBC) reflects the hubness and transitivity of a node, i.e., a series of changes that may be induced through a given condition. To compute NBC, it is necessary to compute node betweenness (NB) and subsequently normalise it.
5) Clustering coefficient (CC) quantifies the likelihood of neighbouring nodes being connected to each other, which thereby can be used to measure the level of clustering in a network [33]. In conventional road traffic networks, the CC is typically used to assess congestion and traffic mobility [48, 49]. While in the accident network established in this paper, the function of the CC is to discover small-world structures and community structures, thus measuring the closeness of the network and discovering those RIFs that are prone to interact with each other.

3.3.3 Importance ranking of RIFs

To achieve the dynamic analysis of the information transmission of RIFs during the occurrence of maritime accidents, this paper uses PageRank-Information-Entropy (PIE) algorithm and edge betweenness centrality (EBC) to further identify and rank the key nodes and edges comprehensively.

(1) PageRank-Information-Entropy (PIE) algorithm

PageRank algorithm is a classical ranking method considering the global link structure to assess the importance of nodes [50]. This contrasts with other topological approaches (e.g. DC, NCC, NBC) which are only based on local neighbourhood information. The algorithm initiates by assigning the initial PageRank values to each node in the network, reflecting their initial importance or centrality within the network. Subsequently, the PageRank algorithm iteratively refines these values until they converge to stable values [51]. The PageRank value is calculated as shown in equation (7):

$$PR_i = \beta \sum_{j \in N} \frac{e_{ji}}{d_j^{out}} PR_j + \frac{1-\beta}{p} \tag{7}$$

where $\beta \in [0, 1)$ represents a damping factor to ensure the randomness in traversing nodes. e_{ji} represents the edge from node j to node i. d_j^{out} represents the out-degree of node j. PR_i represents the PageRank value of node i. p represents the number of nodes.

However, the traditional PageRank algorithm assesses the importance of nodes in a single dimension, and this algorithm will have certain limitations in the face of the complex and dynamically changing network environment. Therefore, based on the traditional PageRank algorithm and inspired by the mutual information theory (a concept of calculating the information interaction between nodes), this study proposes an innovative node importance ranking method, i.e., the PIE algorithm. The pseudocode for the PIE algorithm is detailed in Table 4.

Specifically, the PIE algorithm treats the PageRank value as the initial information retained by each node. A PageRank information matrix (PIM) is built to achieve the weighted assignment of information:

$$PIM = (\gamma_{ij})_{p \times p} \tag{8}$$

$$\gamma_{ij} = PR_i \times \frac{w_{ij}}{\sum_{k \in N} w_{ik}} \tag{9}$$

where k denotes a node connecting with node i.

Based on the PIM, the PageRank mutual information (PMI) between any two connected nodes can be calculated:

$$PMI_{ij} = \ln\left(\frac{\sum_{k\in N}\gamma_{ij}}{\sum_{k\in N}\gamma_{kj}}\right) \tag{10}$$

The PIE of each node can be then calculated as:

$$PIE_i = \sum_k PMI_{ik} - \sum_k PMI_{ki} \tag{11}$$

Therefore, the improved PIE algorithm introduces a multidimensional understanding of RIFs importance from different computational levels. The PIE algorithm combines the mutual information between nodes on the basis of calculating the PageRank value, which means that it not only takes into account the number and quality of edges, but also integrates the strength and direction of information transfer between nodes. This not only helps to identify nodes that are traditionally "important", but also nodes that play a key role in information transfer, network influence and structural stability.

Table 4 The pseudocode for the PIE algorithm

Algorithm 2 PageRank-Information-Entropy algorithm

Require: A network $G = (N, E)$; a damping factor β; max iterations $maxiter$; convergence threshold $epsilon$.
Ensure: PageRank-Information-Entropy of each node PIE

Initialize the PageRank value for each node $PR_i = 1/p$
for iteration from 1 to $maxiter$ **do**
  $pre\_PR = PR$
  for each node i **do**
    $sum = 0$
    for each node j **do**
      if $e_{ij} = 1$
        $sum \mathrel{+}= pre\_PR_j/d_j^{out}$
    end for
    $PR_i = (1-\beta)/p + \beta \times sum$
  end for
  $error = 0$
  for each node i **do**
    $error \mathrel{+}= abs(PR_i - pre\_PR_i)$
  end for
  if $error < epsilon$
    break
end for
Calculate the PageRank mutual information:

$PIM = (\gamma_{ij})_{p\times p}$; $\gamma_{ij} = PR_i \times \frac{w_{ij}}{\sum_{k\in N} w_{ik}}$
Initialize the PageRank mutual information between each pair of nodes $PMI_{ij} = 0$
for each node i **do**
  for each node j **do**
    if $i \neq j$ and there is a shortest path from node i to node j
      $PMI_{ij} = \ln(\sum_{k\in N} \gamma_{ij} / \sum_{k\in N} \gamma_{kj})$
  end for
end for
Initialize the PageRank information entropy of each node PIE_i
for each node i **do**
  $PIE_i = \sum_k PMI_{ik} - \sum_k PMI_{ki}$
end for
return PIE

(2) Edge betweenness centrality (EBC)

Correspondingly, key edges within the network bear increased responsibilities and act as connecting nodes. Therefore, the objective of edge identification is to reveal the paths in the network that are most critical for abstract information, resources or flows. Cutting off these key edges could halt the ongoing evolution of accidents. Existing methods for ranking edges have their own focus, such as edge information centrality for evaluating the efficiency of communication networks, edge flow centrality for traffic network path identification and edge clustering coefficients for community detection. For the abstracted maritime accident evolution network, EBC can be used to identify bridges or bottleneck paths, which is in line with the aim of this paper [52]. In general, calculating the EBC involves considering the frequency of occurrence of a particular edge in the information transfer process (i.e., the number of times a particular edge lies on the shortest path between any two nodes) and this requires the computation of the edge betweenness (EB) first, followed by normalisation to obtain the EBC, as illustrated in equations (12) - (13):

$$EB_{e_v} = \sum_{\substack{i,j,v\in N \\ e_v\in E \\ i\neq j\neq v}} \frac{\sigma_{ij}(e_v)}{\sigma_{ij}} \tag{12}$$

$$EBC_v = \frac{EB_v}{(p-1)(p-2)} \tag{13}$$

where $\sigma_{ij}(e_v)$ represents the number of the shortest paths between node i to node j through edge e_v. σ_{ij} represents the total number of the shortest paths between node i to node.

3.3.4 Robustness

Network robustness refers to the ability to retain functionality even when a portion of nodes or edges fail [52]. In the maritime accident RIFs network, a complete connecting path represents a complete chain of accident causation, leading to the occurrence of an accident. At this point, network robustness distinguishes itself from previous applications, and this concept will here represent the ability of the accident evolution network to resist external corrections, which is a negative effect on mitigating accidents in reality. If the failure of a specific RIF in the network can effectively block the accident causal chain, then the likelihood of an accident occurring should gradually decrease as the robustness diminishes. Therefore, in this paper, the reachability matrix (RM) is developed as a criterion for evaluating the robustness and defined as follows:

$$RM = \begin{bmatrix} rm_{11} & \cdots & rm_{1p} \\ \vdots & \ddots & \vdots \\ rm_{p1} & \cdots & rm_{pp} \end{bmatrix} \tag{14}$$

$$rm_{ij} = \begin{cases} 1, RIF\ i\ can\ reach\ RIF\ j \\ 0, RIF\ i\ cannot\ reach\ RIF\ j \end{cases} \tag{15}$$

Subsequently, the RM calculates the reachability and the network robustness, as shown in equations (16)-(17):

$$Reachability = (ones)_{1\times p} \cdot RM \cdot (ones)_{p\times 1} \tag{16}$$

$$Robustness = \frac{Reachability_{after}}{Reachability_{before}} \tag{17}$$

where $(ones)_{1\times p}$ represents a 1-row p-column matrix with all elements equal to 1, $(ones)_{p\times 1}$ represents a p-row 1-column matrix with all elements equal to 1. In this study, the failures in nodes and edges are simulated by random and deliberate attacks. Both random and deliberate attacks will be conducted on the nodes and edges within the network to test the changes of the network robustness [53]. Therefore, in equation (17), $Reachability_{after}$ represents the reachability after attacks, and $Reachability_{before}$ represents the reachability before attacks.

415 During random attacks, the Monte Carlo simulation algorithm is used to randomly
416 generate failed nodes and edges, respectively. The number of such failed nodes and edges is
417 gradually increased from one to all nodes and edges, thereby spanning the entire network. The
418 experiment is repeated 100 times to obtain the complex network robustness changes. While
419 during deliberate attacks, the nodes and edges of both networks are attacked based on the
420 importance ranking results of nodes and edges obtained from Section 3.3.3, respectively. Then,
421 the attacked nodes or edges are removed from the network at each iteration, and the robustness
422 of the network is calculated. Particularly, the results from another two commonly used node
423 ranking methods (i.e., the traditional PageRank algorithm and the Weight LeaderRank
424 algorithm), together with the Monte Carlo random simulation are compared to validate the
425 effectiveness of the PIE algorithm.

426 Distinguishing from realistic networks, such as transport networks or grid networks, this
427 is an innovational attempt to measure the performance in maritime accident evolution networks
428 by the reachability between nodes. In this study, the existence of a connection between two
429 nodes indicates that the occurrence of one RIF causes another RIF, and a complete reachability
430 path of RIFs represents a complete accident causation chain. As the attack strategy is
431 implemented (i.e., simulating the measures to be taken in practice), some connections may be
432 severed or some nodes may be removed, both of which result in poorer network reachability,
433 which in turn reduces robustness. Therefore, the robustness dynamics in this study demonstrate
434 the changes in the network performance before and after the attacks, thus revealing the impact
435 of RIFs in the evolution of maritime accidents at the network science level.

436 # 4. Results

437 ## 4.1 Data assessment results

438 The maritime accident RIFs database used in this paper contains a total of 21,206
439 accidents. Specifically, the database records 13 RIFs with a total of 221,412 items. To assess
440 the feasibility of the database, the results obtained through the DQA are presented in Table 5.
441

442 Table 5 The DQA results of research data.

Classifications	Dimension	Results
Quantitative assessment	Accessibility	61%
	Consistency	93.8%
	Completeness	79.8%
	Relevance	87.9%
Qualitative assessment	Accuracy	67.9%
	Credentials	The source of the data comes from official accident investigation agencies (MAIB and TSB) and can therefore be considered reliable.
	Timeliness	12.47days
	Interpretability	Both the MAIB and the TSB provide corresponding explanatory documents, and the standards they use are internationally recognized and universal.
Narrative assessment	Narrative	Detailed

443

444 Overall, all quantitative assessments results exceed 50%, and both qualitative and
445 narrative assessments yield commendable results, thereby validating the overall reliability and
446 suitability of the database.

447 Specifically, the values of consistency and relevance reach the values of 93.8% and 87.9%
448 in the quantitative assessment, a testament to the alignment between the RIFs selected for this
449 study and those found in the original TSB and MAIB databases. In addition, the completeness
450 value is 79.8% since there are 44,627 missing items and 221,412 known items in the entire
451 database. As an acceptable result, this score ensures that this study is not biased due to the large
452 amount of missing data. However, the accessibility value of the database is relatively low,
453 primarily due to the selective extraction of the information from the original MAIB and TSB
454 databases.

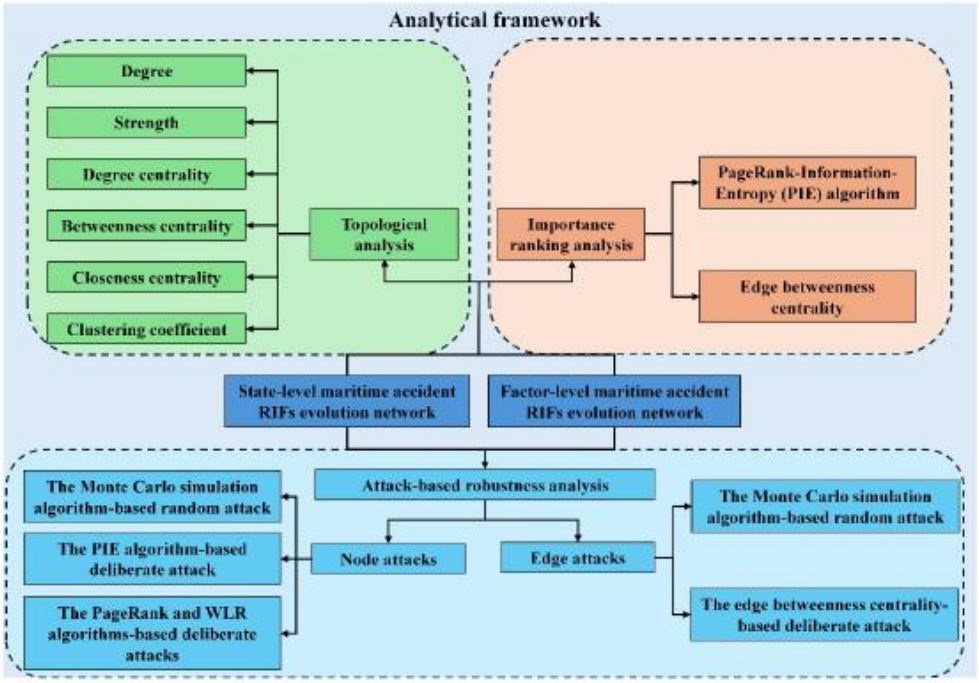
455 This extraction also affects the accuracy of qualitative analysis to some extent. Some RIFs
456 are obtained by integrating a range of variables at different levels. For example, "ship type" in
457 the original MAIB database has four sub-levels of categorisation, while this study integrates
458 them into a single RIF. Furthermore, since the databases are sourced from the MAIB and the
459 TSB, which are the official investigating organisations for maritime accidents in the UK and
460 Canada respectively. The widely applied investigation system has been modified over decades
461 and recognised by the academic community, carrying credentials and interpretability. Moreover,

462 the maritime accident investigation reports are published or recorded on average 12.47 days
463 after the accident. This also validates the timeliness and accuracy of these accident reports.

464 In addition, a 10% data sample is randomly selected for narrative assessment. It is found
465 that 76.8% of the sample contains more than 50 words of narrative description of the relevant
466 accident. The completeness of the data within the sample stands as 81.2%, which is similar to
467 the overall completeness value, further reinforcing its reliability.

468 In light of these findings, the maritime accident database established in this study can be
469 considered reliable and feasible for the in-depth analysis. The analytical framework of this
470 study is shown in Figure 3.

471



472

473 Figure 3. The analytical framework

474

4.2 Association rule results

After completing the DQA, the Apriori algorithm and the CARM algorithm are used to explore the association relationships among the states of RIFs and the RIFs. It is important to note that the results of both algorithms are influenced by the parameter settings. Optimal thresholds for support and confidence are crucial to strike a balance between capturing meaningful associations and avoiding noise. After several trials and with reference to a similar study [32], the minimum support and confidence thresholds are set to 0.1 and 0.3, respectively. The maximum restriction length is set to two, ensuring that each node represents only one RIF.

The association rules are programmed in Python. By calling "Apriori" package and running "CARM algorithm" and inputting the database, 115 ARs and 75 CARs are mined. The distribution of these ARs is visualized in Figure 4, with the horizontal coordinate representing the support, the vertical coordinate representing the confidence, and the size of the scatter point indicating the lift. In addition, the top ten ARs and CARs ranked by the confidence and the JC values are shown in Table 6 and Table 7, where the terms of "Antecedents" and "Consequents" represent the conditions and results in equation (1) - (3).

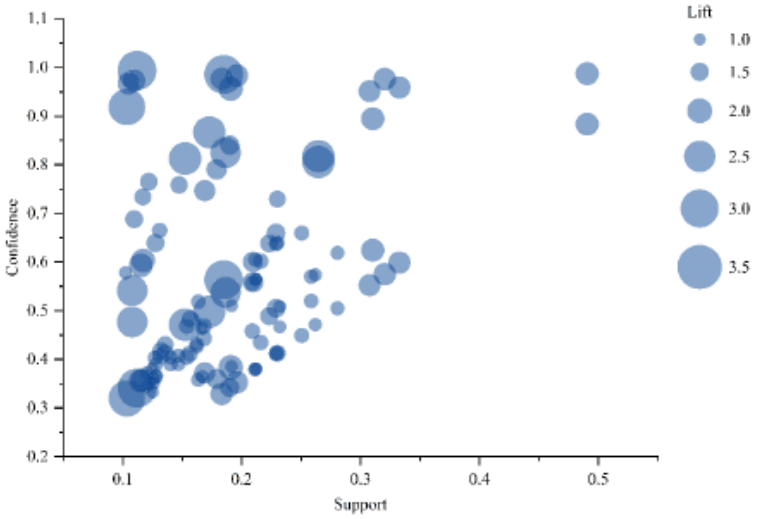


Figure 4. The distribution of ARs.

492

493 Table 6 Top 10 ARs at state level ranked by confidence.

Rank	Antecedents	Consequents	Support	Confidence	Lift
1	SL3	GT2	0.1119	0.9937	3.0286
2	GT0	SL0	0.4906	0.9875	1.7778
3	SL2	GT2	0.1848	0.9859	3.0048
4	H2	SL0	0.1959	0.9834	1.7705
5	SL2	H0	0.1831	0.9766	1.7530
6	GT2	H0	0.3203	0.9761	1.7522
7	SL3	H0	0.1095	0.9732	1.7469
8	SL1	H0	0.1048	0.9673	1.7364
9	ST0	SL0	0.3325	0.9591	1.7266
10	H2	GT0	0.1907	0.9569	1.9260

494 Table 7 Top 10 CARs at factor level ranked by JC.

Rank	Antecedent	Consequent	JC
1	SL	GT	0.9231
2	L	SL	0.8400
3	ST	GT	0.8319
4	GT	SL	0.7960
5	ST	H	0.7778
6	SL	H	0.7683
7	GT	H	0.7551
8	L	A	0.7466
9	ST	SL	0.7280
10	H	GT	0.7175

495

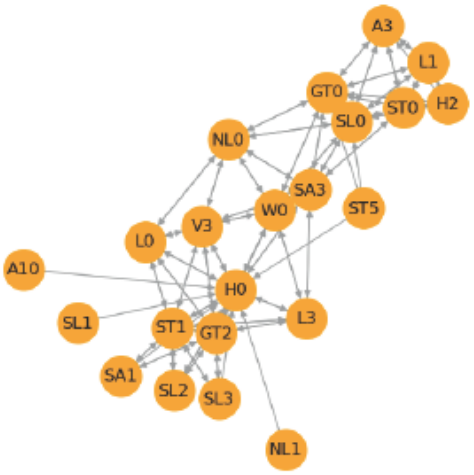
496 Figure 4 reveals that the ARs are centrally distributed within the support range of 0.1-0.25
497 and the confidence range of 0.3-0.65. By analysing the data in Table 6, it can be found that the
498 top ten ARs are all related to the internal factors. Specifically, one AR is related to "ship type",
499 five ARs are associated with "gross tonnage", six ARs pertains to "hull materials", and eight
500 ARs are connected to "length". This suggests a strong correlation between the ship's inherent

501 characteristics with the occurrence of the accident. Particularly, both SL3 (length > 200m) and
502 GT2 (gross tonnage > 3000t) exhibit confidence exceeding 0.99. This observation aligns with
503 the reality that larger and longer ships generally have greater cargo carrying capacity,
504 confirming the realism of these AR results [10]. Moreover, the CARs between L (location) and
505 SL (length) and L (location) and A (accident type) likewise indicate practical accident scenarios.
506 For example, narrow inland waterways or congested port waters will pose a greater threat to
507 the safe navigation of longer ships. The probability of contact, grounding and collision
508 accidents is higher in these waters.

509 **4.3 Complex network development**

510 Based on the ARM and CARM results, two directed weighted complex networks are built:
511 Figure 5 illustrates the established complex network at state level consisting of 22 nodes and
512 115 edges; and Figure 6 illustrates the established complex network at factor level consisting
513 of 10 nodes and 75 edges. The details of each node can be found in Appendix 1.

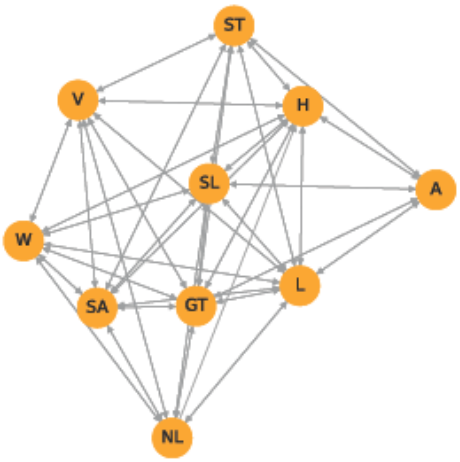
514 Figures 5 and 6 position nodes primarily based on their node degree, with nodes having
515 higher node degree located at the centre of the network. An overall analysis of the complex
516 networks exposes the interconnectivity of the maritime accident RIFs. There exists the
517 information dissemination, energy exchange, interaction or other forms of connectivity among
518 these RIFs. These abstract behaviours can in practice be responded to as a change in the state
519 of one factor triggered by another. The information transfer efficiency of network in Figure 5
520 is 0.484, significantly surpassing the transfer efficiency of a stochastic network of similar size,
521 which is approximately 0.26. This suggests that information in the network is more readily
522 available, and nodes are more likely to swiftly influence each other quickly. Such a well-
523 connected and efficiently propagated evolution network poses a great challenge in efforts to
524 reduce the accident rates.



525

526 Figure 5. The established CN at state level based on ARs.

527



528

529 Figure 6. The established CN at factor level based on ARs.

530

4.4 Topological analysis

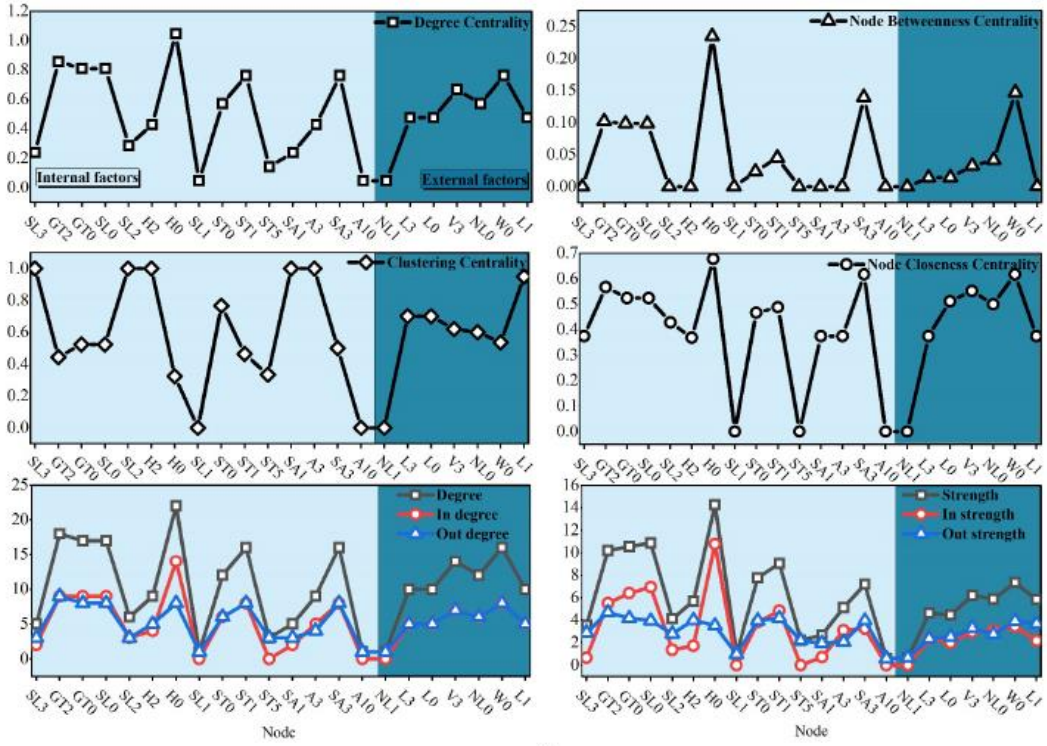
Based on the established networks, this study further investigates six topological parameters for both state-level network and factor-level network, as visualised in Figures 7 and 8 respectively. Topological analysis offers insights from a static network science theoretical perspective.

Specifically, the node degree and node strength indicate the diversity of interactions between nodes. Although there are twice as many nodes for internal factors than for external factors, the mean values of node degree for internal and external factors are similar, at 10.43 and 10.47 in Figure 7, and at 15.17 and 14.75 in Figure 8, respectively. This suggests that the two types of factors have a comparable degree of connectivity and interaction in both networks. Notably, the node with the largest degree and strength is H0 (hull materials with steel), followed by GT2 (gross tonnage > 3000t), GT0 (gross tonnage < 500t) and SL0 (length < 50m) in Figure 7. Similarly, in Figure 8, GT (gross tonnage), L (location), H (hull materials) are nodes with the largest degree and SL (length), GT and H have the largest strength. Conversely, the nodes with the smallest node degree are SL1 (50m < length < 100m), A10 (non-accidental events) and NL1 (nightlight), all of which are 1 and all have an in-degree value of 0. This suggests that these nodes will only pass interaction information to other nodes without receiving information from other nodes. Both figures theoretically indicate that SL, GT, L and H are four RIFs which interact with most of nodes, and practically reveal that the reliable RIFs including a ship's inherent properties are the basis for its safe navigation.

Furthermore, from the perspective of centrality metrics, H0 (hull materials with steel) has the highest DC, NCC and NBC in Figure 7. In Figure 8, the nodes with highest DC, NCC and NBC are GT (gross tonnage) and L (location). Taking H0 as an example, as the central node of the whole network at state level, not only has the highest degree of proximity to other nodes, but also services as a bridge that connects multiple nodes. Therefore, from the theoretical point of view, a change in the state of H0 significantly influences the efficiency of information transfer within the network, potentially affecting the stability of the network and accelerating

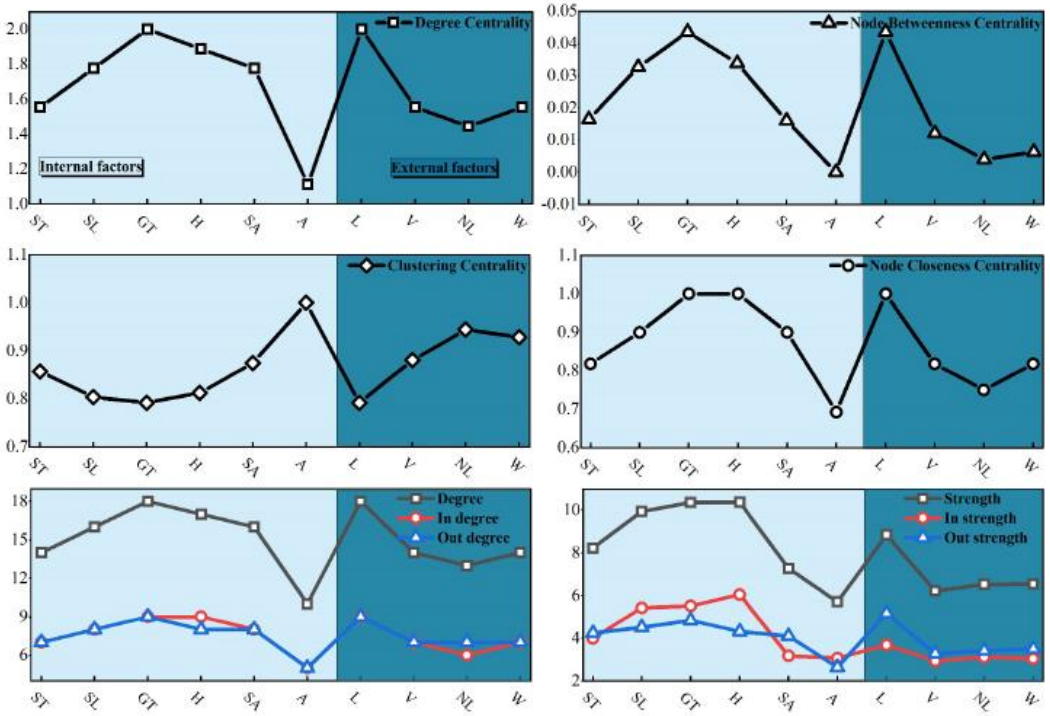
the transfer of information about the risk of accidents. From a practical perspective, such changes can make it more difficult for the ship to respond to emergencies, potentially leading to maritime accidents. Hence, regardless of the ship's scenario or characteristics, any alteration in the state of the steel hull (e.g., damage) can impact the ship's stability and manoeuvrability.

The CC is a value between 0 and 1 and indicates how closely the nodes in the network are connected to each other's neighbours. In Figures 7 and 8, SL3 (length > 200m), SL2 (100m < length < 200m), H2 (hull materials with GRP), SA1 (10years < ship age < 20years), A3 (hull/machinery damage) and A (accident type) have a CC of 1, which indicates that the neighbouring nodes of these nodes are equally interconnected. The network in this study is structured as a functional network, and the high CC indicates that the nodes belong to the same functional module or community and have similar attributes. This concept can be verified from a practical standpoint. For example, GRP, also known as fibre reinforced plastics, is commonly used in the construction of small and medium-sized ships, such as sailboats and yachts. Although this material reduces the cost and weight of the ship and improves the manoeuvrability, it is still less reliable and stronger than steel. As the ship ages, GRP hull structure becomes increasingly susceptible to deterioration, consequently elevating the likelihood of hull/machinery damage.


Degree Centrality
Internal factors
External factors
Node Betweenness Centrality
Clustering Centrality
Node Closeness Centrality
Degree
In degree
Out degree
Strength
In strength
Out strength
Node
Node

575

576 Figure 7. Topological analysis at state level


Degree Centrality
Internal factors
External factors
Node Betweenness Centrality
Clustering Centrality
Node Closeness Centrality
Degree
In degree
Out degree
Strength
In strength
Out strength
Node
Node

577

578 Figure 8. Topological analysis at factor level

579

580 ## 4.5 Ranking analysis

581 To stop the evolution of risk and to prevent accidents quickly and effectively, key nodes
582 and edges in the network need to be analysed.

583 ### 4.5.1 The identification of key nodes

584 The importance of each node is calculated based on the PIE algorithm as shown in Tables
585 8 and 9. Notably, in addition to L (location), the top five nodes in both tables are all internal
586 factors, highlighting the pivotal role that the ship factors play in maritime accident RIFs
587 network. In addition, W0 (clear weather), V3 (good visibility) and NL0 (daylight) are the top
588 ten external factors in Table 8. This suggests that environmental factors also have a substantial
589 influence on the occurrence of maritime accidents. Indeed, in the public's perception, bad
590 weather is dangerous for ship navigation and it inevitably leads to heightened alertness among
591 crews. Conversely, in good weather conditions, as demonstrated by W0 (clear weather), V3
592 (good visibility) and NL0 (daylight), it is still crucial to strengthen the safety management and
593 enhance the vigilance of the crew, which can effectively delay the risk evolution and reduce
594 the accident rate.

595

596 Table 8 Nodes importance ranking at state level based on PIE values.

Rank	Nodes	PIE value	Rank	Nodes	PIE value
1	H0	34.8426	12	A3	-2.2148
2	SL0	27.3330	13	H2	-3.2483
3	GT0	26.5579	14	ST5	-4.8115
4	GT2	25.4225	15	L3	-6.2813
5	ST1	20.5494	16	L0	-8.7096
6	ST0	14.2072	17	SL2	-14.7766
7	W0	11.6229	18	SL1	-19.4954
8	SA3	10.5691	19	NL1	-26.2393
9	V3	5.1661	20	A10	-28.7740
10	NL0	3.2614	21	SL3	-30.0016
11	L1	0.3546	22	SA1	-35.3343

597

598 Table 9 Nodes importance ranking at factor level based on PIE values.

Rank	Nodes	PIE value
1	GT	5.6694
2	H	5.4458
3	SL	4.8041

4	L	2.2828
5	ST	1.0992
6	SA	-1.5149
7	NL	-3.5242
8	W	-3.5247
9	V	-4.5039
10	A	-6.2336

599
600

601 **4.5.2 The identification of key edges**

602 This study ranks the risk evolution paths (i.e., edges) in the network based on EBC. The
603 top ten edges of both levels are shown in Tables 10 and 11. At state level, Table 10 indicates
604 that the most important edges are: H0 (hull materials with steel) to SA3 (ship age > 30 years),
605 W0 (clear weather) to GT2 (gross tonnage > 3000t) and H0 (hull materials with steel) to W0
606 (clear weather) and so on. While at factor level, the top five edges in terms of importance are
607 all related to A (accident type), which reveals the impact of different RIFs on different types of
608 accidents. It is worth noting that in complex network structures, although edges do not account
609 for real causal relationships between nodes, it can be assumed that they interact with each other
610 by conveying abstract information. For example, it is hard to explain which specific
611 interactions between the edges W0 (clear weather) and GT2 (gross tonnage > 3000t) will have
612 in the event of a maritime accident. However, it is possible to mitigate the transfer of
613 information when W0 and GT2 co-occur. In other words, taking precautions may reduce the
614 likelihood of accidents from occurring to some extent.

615 In addition, edges with higher EBC take more tasks as intermediaries in the network,
616 which suggests that most information transmission flows through these edges. When these
617 edges are blocked, the structure of the network changes significantly. Therefore, when certain
618 factors cannot be directly prevented or controlled, the goal of preventing accidents can still be
619 achieved by blocking the corresponding edges.

620

621 Table 10 Edges importance ranking at state level based on EBC.

Rank	Edges	EBC	Rank	Edges	EBC
1	('H0', 'SA3')	0.0757	6	('NL1', 'H0')	0.0390

2	('W0', 'GT2')	0.0510	7	('A10', 'H0')	0.0390
3	('H0', 'W0')	0.0466	8	('W0', 'SL0')	0.0376
4	('SA3', 'ST0')	0.0413	9	('W0', 'GT0')	0.0376
5	('SL1', 'H0')	0.0390	10	('GT0', 'W0')	0.0358

Table 11 Edges importance ranking at factor level based on EBC.

Rank	Edges	EBC	Rank	Edges	EBC
1	('A', 'GT')	0.0226	6	('SL', 'NL')	0.0205
2	('A', 'L')	0.0226	7	('A', 'SL')	0.0198
3	('GT', 'A')	0.0217	8	('ST', 'V')	0.0196
4	('H', 'A')	0.0217	9	('V', 'ST')	0.0192
5	('L', 'A')	0.0217	10	('SL', 'A')	0.0190

4.6 Robustness analysis

Since maritime accidents occur as the result of a combination of multiple RIFs, which can be abstractly represented in the network structure as the successful transmission of information along a complete link, which in turn triggers a maritime accident. Therefore, disrupting the maritime accident RIFs network and reducing the stability of the network can stop the evolution of accidents to some extent. In this study, nodes and edges will be attacked respectively.

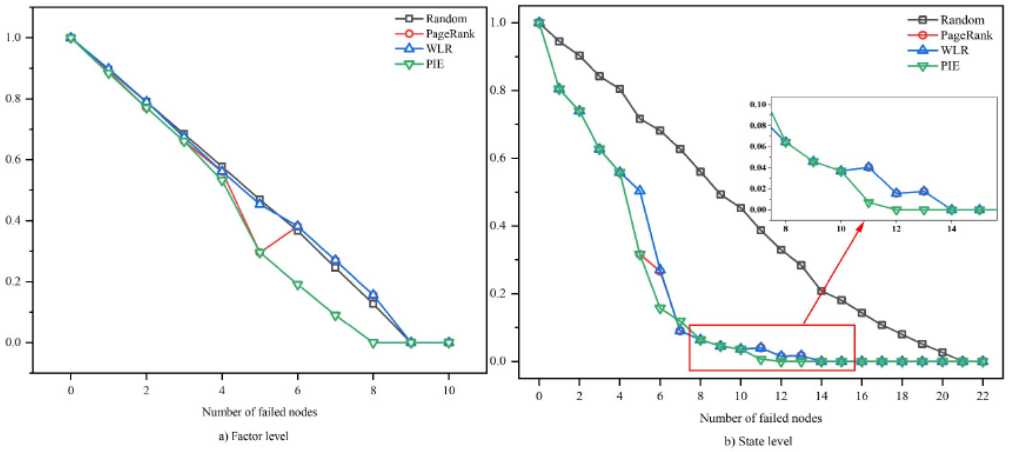
4.6.1 Node attacks

In this study, two strategies, random attack with Monte Carlo simulation and deliberate attacks sorted by node importance are adopted to attack two networks. To validate the effectiveness of the proposed PIE algorithm, more deliberate attacks are conducted based on the ranking results from another two classical methods, i.e., the PageRank algorithm and the WLR algorithm. The changes of both networks' robustness are recorded, as shown in Figure 9.

From Figure 9, it is evident that the network robustness gradually decreases with the increase of the number of failed nodes, regardless of the random attack or deliberate attack. A comparison of the two strategies reveals that deliberate attacks result in faster and more severe damage to the network than random attacks. Specifically, in deliberate attacks, the robustness of both networks drops faster to 0 according to the results of the PIE algorithm for the attack. It demonstrates that the importance ranking result based on the PIE algorithm is more reasonable and effective as accidents can be stopped by controlling fewer nodes in response to

644 this result. For example, at state level, once the number of failed nodes exceeds 12, the
645 robustness of the entire network drops to 0 based on the PIE algorithm, while both deliberate
646 attacks based on the PageRank algorithm and the WLR algorithm require 14 failed nodes and
647 the random attack requires 21 nodes. In practice, the result based on the PIE algorithm implies
648 that when more than 12 nodes with higher importance are controlled, the ship will be in a
649 relatively safe state, with a low probability of a maritime accident. Therefore, this highlights
650 the effectiveness of targeted prevention and control of key RIFs in preventing maritime
651 accidents from occurring.
652

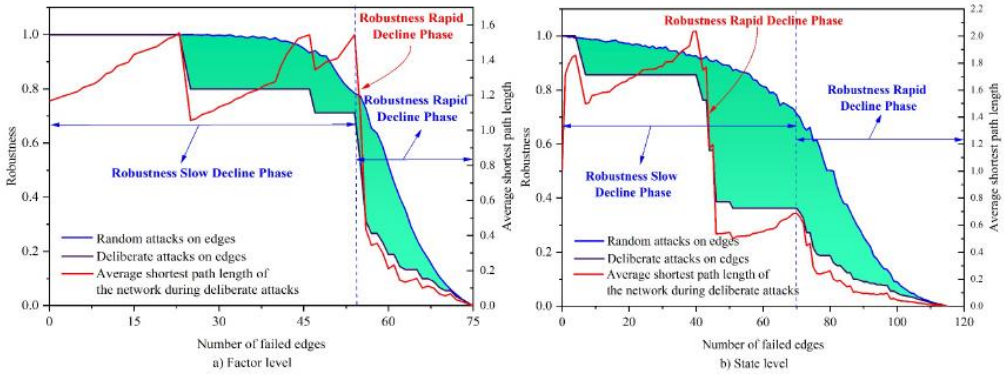
653



654

655 Figure 9. Robustness of network nodes failure.

656



657

658 Figure 10. Robustness of network edges failure.

659

660 **4.6.2 Edge attacks**

661 Similar to node attacks, this paper also attacks the edges and records the robustness
662 changes for both networks (see Figure 10). It is re-emphasised here that the concept of network
663 robustness here represents the ability of the maritime accident evolution network to resist
664 external corrections, and that high robustness has a negative impact on mitigating accidents.
665 From Figure 10, at state level, when the number of failed edges reaches 45, the network
666 robustness decreases by 8.72% for random attacks and 60.59% for deliberate attacks. At this
667 point, the network still maintains high robustness with random attacks. The network robustness
668 significantly decreases only when more than 70 edges are randomly attacked. At factor level,
669 although the rapid declines of robustness under random attack and deliberate attack appear with
670 a same number of failed edges, the robustness level of deliberate attack is always lower than
671 the random attack's when more than 20 edges failed. Therefore, the deliberate attack damages
672 both networks faster than the random attack. Figure 10 also highlights that although deliberate
673 attacks can rapidly reduce network robustness, the latter can only be made 0 when all edges
674 are attacked since it is based on network reachability as an indicator, and reachability is greater
675 than 0 as long as there are edges in the network.

676 In addition, the changes in network robustness with deliberate attacks exhibit a stepwise
677 decrease indicating that the network robustness remains stable within a certain range of failed
678 edges. Only when the number of failed edges exceeds that range, does network robustness
679 decrease dramatically. To investigate the change of network structure when the network
680 robustness remains constant, this study calculates the change of the average shortest path length
681 (AL) of the network during deliberate attacks (as shown in the red line in Figure 10). Figure
682 10 indicates that the change in AL of the network and the change in the network robustness are
683 synchronised. However, when the network robustness remains constant, the AL of the network
684 starts to increase, since deliberate attacks on edges are based on the order of the magnitude of
685 the EBC which is calculated based on the number of shortest paths through the edge. Therefore,

686 edge failure directly changes the shortest path length between nodes, while the reachability
687 between nodes in the network does not necessarily change immediately.

688 Although deliberate attacks on edges don't break the network directly, they can impede the
689 interaction among RIFs. Consequently, edge attacks can reduce the probability of maritime
690 accidents, especially when node attacks are challenging to implement directly. For example, at
691 state level, one of the interaction paths is as follows: NL1 (nightlight) → H0 (hull materials
692 with steel) → W0 (fog weather) → GT0 (gross tonnage <500t) →A3 (hull/machinery damage).
693 In general, it is very difficult to take direct action on individual nodes to make them fail, since
694 both weather conditions and ship parameters are objective. However, it is possible to stop the
695 accident chain from evolving by taking practical measures to cut off W0 (fog weather) → GT0
696 (gross tonnage < 500t). More specifically, small ships with a gross tonnage of less than 500t
697 may face limited visibility, limited navigation or limited signal transmission in foggy weather,
698 and most small ships are not equipped with radar or Automatic identification System (AIS).
699 This in turn can make it difficult to identify other ships, obstacles, or buoys. This may increase
700 the risk of collision with other ships, docks, dykes, etc., leading to ship damage. Therefore, if
701 ship operators and crews can take appropriate measures, such as using navigational equipment
702 to help the ship navigate, slow down or pause, this will effectively stop the evolution of
703 maritime accidents.
704

705 5. Discussion and implications

706 The findings from this study underscore the complexity and interconnectivity of risk
707 factors in maritime safety, as evidenced by the small-world characteristics of the maritime
708 accident RIFs networks, cross-checking with findings from other studies [32, 54]. Notably, the
709 state level network's average path length of 2.06 steps and a high aggregation coefficient
710 suggest a tightly-knit structure that is prone to a chain reaction leading to accidents. These
711 properties underscore the critical need for reliability engineering strategies that address
712 systemic vulnerabilities rather than isolated factors.

.01

713 In particular, this study highlights certain ship-related factors—such as hull materials,
714 gross tonnage, and ship length—that significantly contribute to the occurrence of accidents and
715 the network's robustness. For instance, nodes representing specific ship sizes (e.g., GT2: gross
716 tonnage > 3000t, GT0: gross tonnage < 500t) and hull materials (H0: hull materials with steel)
717 are pivotal. This insight mandates enhanced preventive measures for shipowners and builders,
718 including rigorous maintenance and inspection routines, to prevent the onset of chain reactions
719 that can lead to structural and mechanical failures.

720 Through comparative analysis, these findings are also consistent with several similar
721 studies in the maritime safety domain. For example, both [36] and [10] considered ship
722 parameters (e.g., GT) as one of the most critical RIFs. In particular, all of these studies
723 highlighted the importance of monitoring the safety of small ships (e.g., small fishing vessels),
724 as these are less resistant to the overall development of an accident and the risks can rapidly
725 evolve into an accident. These scenarios include, but are not limited to high winds and waves,
726 collisions or an emergency situation. This finding can be reflected in the importance of GT0
727 and SL0 in this study. Furthermore, small, GRP-constructed ships also should be considered
728 with high risk for the occurrence of hull or machinery failure, demonstrated by association
729 rules between GT0, SL0, H2 and A3. Therefore, regulatory authorities should promote relevant
730 policies, improve the regulations of practice for small ships, assist ships to install safety
731 navigational aids and reinforce hull structure, and enhance the training and safety awareness of
732 crews.

733 Furthermore, the analysis reveals that certain nodes, including those indicating ship age
734 (SA3: ship age > 30 years) and environmental conditions (W0: clear weather), act as central
735 hubs in the network. These findings imply that controlling these hubs could significantly
736 diminish the network's ability to propagate risk. For aging ships, stringent operational
737 restrictions and frequent inspections should be implemented to curtail their use in high-risk
738 conditions, thereby mitigating potential accidents due to equipment failure or decreased
739 performance. However, the influence of favourable weather conditions on accident occurrence

)2

seems to present a paradoxical risk factor. Despite the intuitive belief that poor weather increases accident risk, the analysis shows a higher incidence of accidents in clear weather conditions, possibly due to reduced vigilance. This unexpected trend highlights the necessity for continuous safety practices and awareness, regardless of favourable environmental conditions. Shipping companies and regulatory authorities should emphasize the maintenance of high safety standards and situational awareness through all weather conditions, enhancing training programs to cover a variety of environmental scenarios.

In summary, the comprehensive analytical framework employed in this study has proven effective. The CARM algorithm facilitates the extraction of association rules at the factor level, while the innovative PIE algorithm identifies key nodes concerning information transfer, network influence, and structural stability. The robustness analysis of the dynamic accident evolution network reveals mechanisms for controlling accident development, and comparisons with existing methods validate this study's methodology. Overall, the network analysis of maritime accidents not only demonstrates the interdependencies among risk factors but also informs the development of targeted interventions. By concentrating on high-impact nodes and employing a holistic approach to risk management, the maritime industry can more successfully interrupt potential pathways leading to accidents, thereby enhancing overall system safety and reliability.

6. Conclusion

The increasing volume of maritime trade has unfortunately been accompanied by a heightened risk of maritime accidents. Hence understanding the RIFs in reported maritime casualties and accidents should result in greatly improved maritime safety.

This study proposes an analytical framework to provide a comprehensive analysis of maritime accident RIFs and explore the evolutionary mechanism of maritime accidents. Based on the critical literature review, the contributions of this study in the terms of data, objectives, models and analysis are highlighted. Subsequently, 21,206 accident reports for the last 10 years are introduced to the quantitative framework integrating ARM and CN. By conducting the

.03

767 topological analysis, the maritime accident RIFs network has been recognised as an active,
768 high connectivity and functional community network with rapid information transmission.
769 Meanwhile, as a dynamic evolution process, targeted control and prevention have been proven
770 effective in mitigating accidents. Finally, building upon the discussions and implications, the
771 risk control measures are developed.

772 In future, the limitations of this current study can be improved. Although the regional data
773 contributes to a targeted assessment, the patterns of global shipping network need to be further
774 studied. Applying a larger scale global maritime accident data and including human factors will
775 improve its universal acceptance. Furthermore, the investigation of the directed network is the
776 first step in understanding the role of RIFs in maritime accidents. Finally, more detailed and
777 accurate modelling can be undertaken by considering the engagement of the weights and
778 community structure. Nevertheless, the framework proposed in this paper will prove invaluable
779 to maritime regulators in order to improve safety and the authors recommend its incorporation
780 into safety management systems.

781

782 Acknowledgment

783 This research was funded by a European Research Council project under the European Union's
784 Horizon 2020 research and innovation programme (TRUST CoG 2019 864724). The authors
785 also gratefully acknowledge support from the National Natural Science Foundation of China
786 (Grant No. 52101399), the Bolian Research Funds of Dalian Maritime University (Grant No.
787 3132023617) and the China Scholarship Council (Grant No. 202308060322).

788

789 References

790 [1] EMSA. Annual Overview of Marine Casualties and Incidents 2022. Lisbon: European
791 Maritime Safety Agency; 2022.
792 [2] Cao Y, Wang X, Yang Z, Wang J, Wang H, Liu Z. Research in marine accidents: A
793 bibliometric analysis, systematic review and future directions. Ocean Engineering. 2023;284.
794 http://doi.org/10.1016/j.oceaneng.2023.115048

[3] Fang S, Liu Z, Wang X, Cao Y, Yang Z. Dynamic analysis of emergency evacuation in a rolling passenger ship using a two-layer social force model. Expert Systems with Applications. 2024;247:123310. http://doi.org/10.1016/j.eswa.2024.123310

[4] Antao P, Sun S, Teixeira AP, Soares CG. Quantitative assessment of ship collision risk influencing factors from worldwide accident and fleet data. Reliability Engineering & System Safety. 2023;234:18. http://doi.org/10.1016/j.ress.2023.109166

[5] Li HH, Çelik C, Bashir M, Zou L, Yang ZL. Incorporation of a global perspective into data-driven analysis of maritime collision accident risk. Reliability Engineering & System Safety. 2024;249:15. http://doi.org/10.1016/j.ress.2024.110187

[6] Liang MH, Li HH, Liu RW, Lam JSL, Yang ZL. PiracyAnalyzer: Spatial temporal patterns analysis of global piracy incidents. Reliability Engineering & System Safety. 2024;243:15. http://doi.org/10.1016/j.ress.2023.109877

[7] Yu YR, Liu KZ, Fu SS, Chen JH. Framework for process risk analysis of maritime accidents based on resilience theory: A case study of grounding accidents in Arctic waters. Reliability Engineering & System Safety. 2024;249:17. http://doi.org/10.1016/j.ress.2024.110202

[8] Bye RJ, Aalberg AL. Maritime navigation accidents and risk indicators: An exploratory statistical analysis using AIS data and accident reports. Reliability Engineering & System Safety. 2018;176:174-86. http://doi.org/10.1016/j.ress.2018.03.033

[9] Wang H, Liu Z, Wang X, Graham T, Wang J. An analysis of factors affecting the severity of marine accidents. Reliability Engineering & System Safety. 2021;210. http://doi.org/10.1016/j.ress.2021.107513

[10] Cao Y, Wang X, Wang Y, Fan S, Wang H, Yang Z, et al. Analysis of factors affecting the severity of marine accidents using a data-driven Bayesian network. Ocean Engineering. 2023;269. http://doi.org/10.1016/j.oceaneng.2022.113563

[11] Kandel R, Baroud H. A data-driven risk assessment of Arctic maritime incidents: Using machine learning to predict incident types and identify risk factors. Reliability Engineering & System Safety. 2024;243:15. http://doi.org/10.1016/j.ress.2023.109779

[12] Munim ZH, Sorli MA, Kim H, Alon I. Predicting maritime accident risk using Automated Machine Learning. Reliability Engineering & System Safety. 2024;248:19. http://doi.org/10.1016/j.ress.2024.110148

[13] Fan S, Yang Z, Blanco-Davis E, Zhang J, Yan X. Analysis of maritime transport accidents using Bayesian networks. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability. 2020;234:439-54. http://doi.org/10.1177/1748006X19900850

[14] Weng J, Yang D, Qian T, Huang Z. Combining zero-inflated negative binomial regression with MLRT techniques: An approach to evaluating shipping accident casualties. Ocean Engineering. 2018;166:135-44. http://doi.org/10.1016/j.oceaneng.2018.08.011

[15] Ung ST. Navigation Risk estimation using a modified Bayesian Network modeling-a case study in Taiwan. Reliability Engineering & System Safety. 2021;213:13. http://doi.org/10.1016/j.ress.2021.107777

[16] Cho D-O. The effects of the M/V Sea Prince accident on maritime safety management in Korea. Marine Policy. 2007;31:730-5. http://doi.org/10.1016/j.marpol.2007.01.005

[17] Soares J, Fernandes R, Brito D, Oliveira H, Neuparth T, Martins I, et al. Environmental risk assessment of accidental marine spills: A new approach combining an online dynamic Hazardous and Noxious substances database with numerical dispersion, risk and population modelling. Sci Total Environ. 2020;715:136801. http://doi.org/10.1016/j.scitotenv.2020.136801
[18] Gonel O, Cicek I. Multicriteria emergency decision for responding to man overboard casualties: A proposed procedure developed using Binary Logistics Regression and General Linear Models. Ocean Engineering. 2022;265. http://doi.org/10.1016/j.oceaneng.2022.112581
[19] Zhou KW, Xing WB, Wang JB, Li HH, Yang ZL. A data-driven risk model for maritime casualty analysis: A global perspective. Reliability Engineering & System Safety. 2024;244:25. http://doi.org/10.1016/j.ress.2023.109925
[20] Yildiz S, Uğurlu Ö, Wang J, Loughney S. Application of the HFACS-PV approach for identification of human and organizational factors (HOFs) influencing marine accidents. Reliability Engineering & System Safety. 2021;208:107395. http://doi.org/10.1016/j.ress.2020.107395
[21] Wu B, Yan X, Wang Y, Guedes Soares C. Selection of maritime safety control options for NUC ships using a hybrid group decision-making approach. Safety Science. 2016;88:108-22. http://doi.org/10.1016/j.ssci.2016.04.026
[22] Oraith H, Blanco-Davis E, Yang Z, Matellini B. An Evaluation of the Effects of Human Factors on Pilotage Operations Safety. J Marine Sci Appl. 2021;20:393-409. http://doi.org/10.1007/s11804-021-00222-1
[23] Luo M, Shin S-H. Half-century research developments in maritime accidents: Future directions. Accident Analysis & Prevention. 2019;123:448-60. http://doi.org/10.1016/j.aap.2016.04.010
[24] Wang H, Chen N, Wu B, Soares CG. Human and organizational factors analysis of collision accidents between merchant ships and fishing vessels based on HFACS-BN model. Reliability Engineering & System Safety. 2024;249:18. http://doi.org/10.1016/j.ress.2024.110201
[25] Fu SS, Zhang Y, Zhang MY, Han B, Wu ZD. An object-oriented Bayesian network model for the quantitative risk assessment of navigational accidents in ice-covered Arctic waters. Reliability Engineering & System Safety. 2023;238:13. http://doi.org/10.1016/j.ress.2023.109459
[26] Ma X, Lan H, Qiao W, Han B, He H. On the causation correlation of maritime accidents based on data mining techniques. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability. 2022. http://doi.org/10.1177/1748006x221131717
[27] Cakir E, Fiskin R, Sevgili C. Investigation of tugboat accidents severity: An application of association rule mining algorithms. Reliability Engineering & System Safety. 2021;209:16. http://doi.org/10.1016/j.ress.2021.107470
[28] Weng J, Li G. Exploring shipping accident contributory factors using association rules. Journal of Transportation Safety & Security. 2019;11:36-57. http://doi.org/10.1080/19439962.2017.1341440
[29] Lan H, Ma X, Ma L, Qiao W. Pattern investigation of total loss maritime accidents based on association rule mining. Reliability Engineering & System Safety. 2023;229. http://doi.org/10.1016/j.ress.2022.108893

[30] Fan SQ, Yang ZL. Accident data-driven human fatigue analysis in maritime transport using machine learning. Reliability Engineering & System Safety. 2024;241:10. http://doi.org/10.1016/j.ress.2023.109675

[31] Sui Z, Huang Y, Wen Y, Zhou C, Huang X. Marine traffic profile for enhancing situational awareness based on complex network theory. Ocean Engineering. 2021;241. http://doi.org/10.1016/j.oceaneng.2021.110049

[32] Lan H, Ma X, Qiao W, Deng W. Determining the critical risk factors for predicting the severity of ship collision accidents using a data-driven approach. Reliability Engineering & System Safety. 2023;230:108934. http://doi.org/10.1016/j.ress.2022.108934

[33] Lam CY, Tai K. Network topological approach to modeling accident causations and characteristics: Analysis of railway incidents in Japan. Reliability Engineering & System Safety. 2020;193. http://doi.org/10.1016/j.ress.2019.106626

[34] Du W-B, Zhang M-Y, Zhang Y, Cao X-B, Zhang J. Delay causality network in air transport systems. Transportation Research Part E: Logistics and Transportation Review. 2018;118:466-76. http://doi.org/10.1016/j.tre.2018.08.014

[35] Sui Z, Wen Y, Huang Y, Zhou C, Xiao C, Chen H. Empirical analysis of complex network for marine traffic situation. Ocean Engineering. 2020;214. http://doi.org/10.1016/j.oceaneng.2020.107848

[36] Fan S, Blanco-Davis E, Yang Z, Zhang J, Yan X. Incorporation of human factors into maritime accident analysis using a data-driven Bayesian network. Reliability Engineering & System Safety. 2020;203. http://doi.org/10.1016/j.ress.2020.107070

[37] Li G, Weng J, Hou Z. Impact analysis of external factors on human errors using the ARBN method based on small-sample ship collision records. Ocean Engineering. 2021;236. http://doi.org/10.1016/j.oceaneng.2021.109533

[38] Government of Canada TSBoC. Marine transportation occurrence data from January 1995. 2023.

[39] Pipino LL, Lee YW, Wang RY. Data quality assessment. Communications of the ACM. 2002;45:211-8. http://doi.org/10.1145/505248.506010

[40] Cai L, Zhu Y. The Challenges of Data Quality and Data Quality Assessment in the Big Data Era. Data Science Journal. 2015;14. http://doi.org/10.5334/dsj-2015-002

[41] Majumdar A, Manole I, Nalty R. Analysis of Port Accidents and Calibration of Heinrich's Pyramid. Transp Res Record. 2022;2676:476-89. http://doi.org/10.1177/03611981211044447

[42] Majumdar A, Manole I. Transport Environmental Impacts and Safety: Data Quality Assessment (DQA). Centre for Transport Studies, Department of Civil and Environmental Engineering, lmperial College London; 2023.

[43] Wilke S, Majumdar A, Ochieng WY. A framework for assessing the quality of aviation safety databases. Safety Science. 2014;63:133-45. http://doi.org/10.1016/j.ssci.2013.11.005

[44] Wang ZC, Yin JB. Risk assessment of inland waterborne transportation using data mining. Maritime Policy & Management. 2020;47:633-48. http://doi.org/10.1080/03088839.2020.1738582

916 [45] Özaydın E, Fışkın R, Uğurlu Ö, Wang J. A hybrid model for marine accident analysis
917 based on Bayesian Network (BN) and Association Rule Mining (ARM). Ocean Engineering.
918 2022;247:110705. http://doi.org/10.1016/j.oceaneng.2022.110705
919 [46] Agrawal R, Imieliński T, Swami A. Mining association rules between sets of items in large
920 databases. ACM SIGMOD Record. 1993;22:207-16. http://doi.org/10.1145/170036.170072
921 [47] Zhou Y, Kundu T, Goh M, Sheu J-B. Multimodal transportation network centrality analysis
922 for Belt and Road Initiative. Transportation Research Part E: Logistics and Transportation
923 Review. 2021;149. http://doi.org/10.1016/j.tre.2021.102292
924 [48] Qian Y, Wang B, Xue Y, Zeng J, Wang N. A simulation of the cascading failure of a
925 complex network model by considering the characteristics of road traffic conditions. Nonlinear
926 Dynamics. 2015;80:413-20. http://doi.org/10.1007/s11071-014-1878-z
927 [49] Wang S, Zheng L, Yu D. The improved degree of urban road traffic network: A case study
928 of Xiamen, China. Physica A: Statistical Mechanics and its Applications. 2017;469:256-64.
929 http://doi.org/10.1016/j.physa.2016.11.090
930 [50] Zhang P, Wang T, Yan J. PageRank centrality and algorithms for weighted, directed
931 networks. Physica A: Statistical Mechanics and its Applications. 2022;586.
932 http://doi.org/10.1016/j.physa.2021.126438
933 [51] Brin S, Page L. The anatomy of a large-scale hypertextual Web search engine. Computer
934 Networks and ISDN Systems. 1998;30:107-17. http://doi.org/10.1016/S0169-7552(98)00110-X
935 [52] Yang Y, Liu Y, Zhou M, Li F, Sun C. Robustness assessment of urban rail transit based on
936 complex network theory: A case study of the Beijing Subway. Safety Science. 2015;79:149-62.
937 http://doi.org/10.1016/j.ssci.2015.06.006
938 [53] Wang S, Yang D, Lu J. A connectivity reliability-cost approach for path selection in the
939 maritime transportation of China's crude oil imports. Maritime Policy & Management.
940 2018;45:567-84. http://doi.org/10.1080/03088839.2018.1445308
941 [54] Sui Z, Wen Y, Huang Y, Song R, Piera MA. Maritime accidents in the Yangtze River: A
942 time series analysis for 2011-2020. Accid Anal Prev. 2023;180:106901.
943 http://doi.org/10.1016/j.aap.2022.106901
944 [55] Wang L, Yang Z. Bayesian network modelling and analysis of accident severity in
945 waterborne transportation: A case study in China. Reliability Engineering & System Safety.
946 2018;180:277-89. http://doi.org/10.1016/j.ress.2018.07.021
947 [56] Fan C, Montewka J, Zhang D. A risk comparison framework for autonomous ships
948 navigation. Reliability Engineering & System Safety. 2022;226:108709.
949 http://doi.org/10.1016/j.ress.2022.108709
950 [57] Feng Y, Wang X, Chen Q, Yang Z, Wang J, Li H, et al. Prediction of the severity of marine
951 accidents using improved machine learning. Transportation Research Part E: Logistics and
952 Transportation Review. 2024;188:103647. http://doi.org/10.1016/j.tre.2024.103647
953 [58] Feng Y, Wang H, Xia G, Cao W, Li T, Wang X, et al. A machine learning-based data-driven
954 method for risk analysis of marine accidents. Journal of Marine Engineering & Technology.
955 2024:1-12. http://doi.org/10.1080/20464177.2024.2368914

[59] Li H, Zhou K, Zhang C, Bashir M, Yang Z. Dynamic evolution of maritime accidents: Comparative analysis through data-driven Bayesian Networks. Ocean Engineering. 2024;303:117736. http://doi.org/10.1016/j.oceaneng.2024.117736

[60] Fan S, Zhang J, Blanco-Davis E, Yang Z, Yan X. Maritime accident prevention strategy formulation from a human factor perspective using Bayesian Networks and TOPSIS. Ocean Engineering. 2020;210:107544. http://doi.org/10.1016/j.oceaneng.2020.107544

Appendix 1

Maritime accident RIFs classification criteria

	Variables	Index	Statements	Indexes	References
External factors	Month	M	1-12	M1-M12	NA
	Location	L	Port	L0	[57, 58]
			Open sea	L1	
			Coastal water	L2	
			Inland water	L3	
	Nature light	NL	Daylight	NL0	[59] TSBM16P0 362
			Nightlight	NL1	
			Twilight	NL2	
	Sea state	SS	0 Calm glassy (0 m)	SS0	MAIB 26-2017 MAIB 22-2017
			1 Calm rippled (0 – 0.1 m)	SS1	
			2 Smooth (0.1 – 0.5 m)	SS2	
			3 Slight (0.5 – 1.25 m)	SS3	
			4 Moderate (1.25 – 2.5 m)	SS4	
			5 Rough (2.5 – 4 m)	SS5	
			6 Very rough (4.0 – 6.0 m)	SS6	
			7 High (6.0 – 9.0 m)	SS7	
			8 Very High (9.0 – 14.0 m)	SS8	
			9 Phenomenal (over 14 meters)	SS9	
			Ice covered	SS10	
	Wind force	WF	0 Calm (0-1 knot or 0-1 m/s)	WF0	MAIB 26-2017 MAIB 22-2017 MAIB 20-2017
			1 Light air (1-3 knot or 1-2 m/s)	WF1	
			2 Light Breeze (4-6 knot or 2-3 m/s)	WF2	
			3 Gentle Breeze (7-10 knot or 4-5 m/s)	WF3	
			4 Moderate Breeze (11-16 knot or 6-8 m/s)	WF4	
			5 Fresh Breeze (17-21 knot or 9-11 m/s)	WF5	
			6 Strong Breeze (22-27 knot or 11-14 m/s)	WF6	
			7 Near Gale (28-33 knot or 14-17 m/s)	WF7	
			8 Gale (34-40 knot or 17-21 m/s)	WF8	
			9 Strong Gale (41-47 knot or 21-24 m/s)	WF9	
			10 Storm (48-55 knot or 25-28 m/s)	WF10	
			11 Violent Storm (56-63 knot or 29-32 m/s)	WF11	
			12 Hurricane (+64 knot or +33 m/s)	WF12	
	Visibility	V	Very poor - Vis < 0.5 nm	V0	MAIB 26-2017
			Poor - 0.5 <=Vis < 2.0 nm	V1	

			Moderate - 2.0 <=Vis < 5.0 nm	V2	MAIB 22-2017
			Good - 5.0 <= Vis < 25.0 nm	V3	
			Very good - Vis >= 25.0 nm	V4	
	Weather	W	Clear	W0	
			Fog	W1	MAIB 26-2017
			Overcast	W2	
			Rain	W3	MAIB 22-2017
			Snow	W4	
			Thunder/storm/lightning	W5	
Internal factors	Accident type	A	Capsizing / Listing	A0	[59, 60]
			Collision	A1	
			Contact	A2	
			Hull/machinery damage	A3	
			Fire / Explosion	A4	
			Floating object	A5	
			Flooding / Foundering	A6	
			Grounding / Stranding	A7	
			Cargo/shift/loss/released	A8	
			Loss of control	A9	
			Non-accidental events	A10	
	Ship type	ST	Fishing ships	ST0	[10, 36]
			Cargo ships	ST1	
			Navy ships	ST2	
			Passenger ships	ST3	
			Recreational ships	ST4	
			Service ships	ST5	
			Other ships	ST6	
	Length	SL	0-50m	SL0	[5, 59]
			50-100m	SL1	
			100m-200m	SL2	
			200m+	SL3	
	Gross tonnage	GT	0-500t	GT0	[10, 57]
			500-3000t	GT1	
			3000t+	GT2	
	Ship age	SA	0-10 years	SA0	[10, 57]
			10-20 years	SA1	
			20-30 years	SA2	
			30 years+	SA3	
	Hull materials	H	Steel	H0	[5, 59]
			Wood	H1	
			GRP (Glass Fiber Reinforced plastics)	H2	
			Aluminium alloy	H3	
			Composite materials	H4	
			Ferro cement	H5	
			Other materials	H6	

Appendix 2

Data quality assessment system

Categories	Dimension	Description	Formula
Quantitative assessment	Accessibility	Accessibility reflects the ease of access to the data. Assessing the accessibility of data quantifies the number of data without further modification. Data are considered to have good accessibility when the value of accessibility is greater than 50%.	$Accessibility = \frac{1 \times N_{explicit} + 0.8 \times N_{implicit} + 0.2 \times N_{inferred}}{N_{variables}} \times 100\%$ Where $N_{explicit}$ represents the number of variables that already exist in the database, $N_{implicit}$ represents the number of variables that are newly created, $N_{inferred}$ represents the number of the variables that are modified for this study, $N_{variables}$ represents the number of the total variables.
	Consistency	Consistency is concerned with the continuity of data collection, recording and updating. Assessing data consistency helps to estimate that accident data remains consistent in concept, value domain and format as it is prior to processing.	$Consistency = \frac{1 \times N_{consistent} + 0.8 \times N_{recoded} + 0.2 \times N_{newly\ coded}}{N'_{variables}} \times 100\%$ Where $N_{consistent}$ represents the variables that are provided in the same manner within each dataset, $N_{recoded}$ represents the number of variables that are recoded, $N_{newly\ coded}$ represents the number of variables that are newly coded. $N'_{variables}$ represents the number of variables that are used in this study.
	Completeness	In the maritime accident database, due to the presence of missing variables, assessing data completeness helps to investigate the usability of the data and to test whether this data can support the breadth and depth of this study.	$Completeness = 1 - \bar{P}_{missing}$ Where $\bar{P}_{missing}$ represents the arithmetic average of missing values percentage.
	Relevance	Relevance reflects the degree to which the data are relevant to the objective of this study. Assessing the relevance helps to determine the applicability of the data to the current study and to quantify the extent to which the data are helpful.	$Relevance = \frac{1}{N_{categories}} \sum_{i=1}^{N_{categories}} \frac{N_{relevant,i}}{N_{request,i}}$ Where $N_{categories}$ represents the number of categories in which the required (ideal) datasets are grouped, $N_{relevant,i}$ represents the number of relevant datasets in category i, $N_{request,i}$ represents the number of requested datasets in category i.
Qualitative assessment	Accuracy	The accuracy of data reflects the extent to which it is accurate, true and free from error.	$Accuracy = \frac{N_{accuracy}}{N_{variables}} \times 100\%$

411

			Where $N_{accuracy}$ represents the number of variables that are accurate.
	Credentials	Credentials reflect the extent to which data is obtained from reliable data sources. The credentials of maritime accident data typically depends on the investigating agency.	NA
	Interpretability	Assessing the interpretability of data requires that the data are clearly presented in terms of language, notation, units and definitions, which helps to ensure that the database can be used effectively.	NA
	Timeliness	Timeliness reflects the extent to which data is up to date. Assessing the timeliness of data usually requires consideration of the time gap between the moment an accident occurs and the moment it is recorded.	$Timeliness = \frac{\sum_{i=1}^{N_{record}}(T_{report,i} - T_{occurrence,i})}{N_{record}}$ Where N_{record} represents the number of accident statistics that are recorded in the database, $T_{report,i}$ represents the time of accident i reported, $T_{occurrence,i}$ represents the time of accident i occurred.
Narrative assessment	Narrative	In this study, 10% of the accident data will be selected as a sample for narrative assessment. This sample will be used to calculate narratives of more than 50 words and to check whether they provide information about the variables identified in the dataset (1 if yes, 0 if no).	$Narrative = \frac{1}{N_{variables}} \sum_{j=1}^{N_{variables}} \frac{N_{record,j}}{N_{record}} \times 100\%$ Where $N_{record,j}$ represents the number of accident statistics where variable j exists.

Appendix K. Detailed results of the application of the Bayesian Networks model on maritime occurrences.

This appendix starts with the definition of parameters, variables and prior probabilities in Table K. Then, tables of sensitivity analysis and figures showing the effects of each parameter on occurrence severity or accident type are presented.

Table K is based on based on Table 6.1-E which showed the parameters and variables used for 3-way associations. One parameter (visibility) has been regrouped into two variables instead of three, for a higher count of each variable, to improve the accuracy of the BN. The crossed parameters have not been considered in this model as their associations with the severity or contact/collision accident types were not strong.

Table K. Prior probabilities for the different factors considered in the BN, based on Table 6.1-E.

Parameter	**Variables**	**Prior probability**
~~Season~~	~~Winter~~	-
	~~Spring~~	-
	~~Summer~~	-
	~~Autumn~~	-
Vessel type	Cargo vessel	35.9%
	Fishing vessel	6.83%
	Passenger vessel	22%
	Recreational vessel	7.02%
	Service ship	28.15%
	Military vessel	0.16%
Vessel size	Small (<8m)	30.4%
	Medium (8m-40m)	36.9%
	Large (>40m)	32.7%
~~Year~~	~~2013 - 2017~~	-
	~~2018 - 2022~~	-
Severity	Very serious	16.2%
	Serious	17%
	Less serious	36.5%
	Marine incident	30.3%
Accident type	Contact/Collision	40.4%
	Non-contact/collision	59.6%
~~Location~~	~~England~~	-
	~~Northern Ireland~~	-
	~~Scotland~~	-
	~~Wales~~	-
~~Natural light~~	~~Daylight~~	-
	~~Night~~	-
	~~Twilight~~	-
Sea state	Calm/Smooth [0]	73.6%

	Slight/Moderate [1]	24.1%
	Rough to Very high [2]	2.36%
Visibility	Good	89.8%
	Poor	10.2%
Wind force	No/Light wind [0]	43.2%
	Moderate wind [1]	53.4%
	High wind [2]	3.4%
Flag	UK	59.3%
	Non-UK	40.7%
Year of build / Vessel age	Very old (<1980)	10.1%
	Old (1980-2000)	49.2%
	New (>2000)	40.7%
~~Hull material~~	~~Steel~~	-
	~~Other~~	-

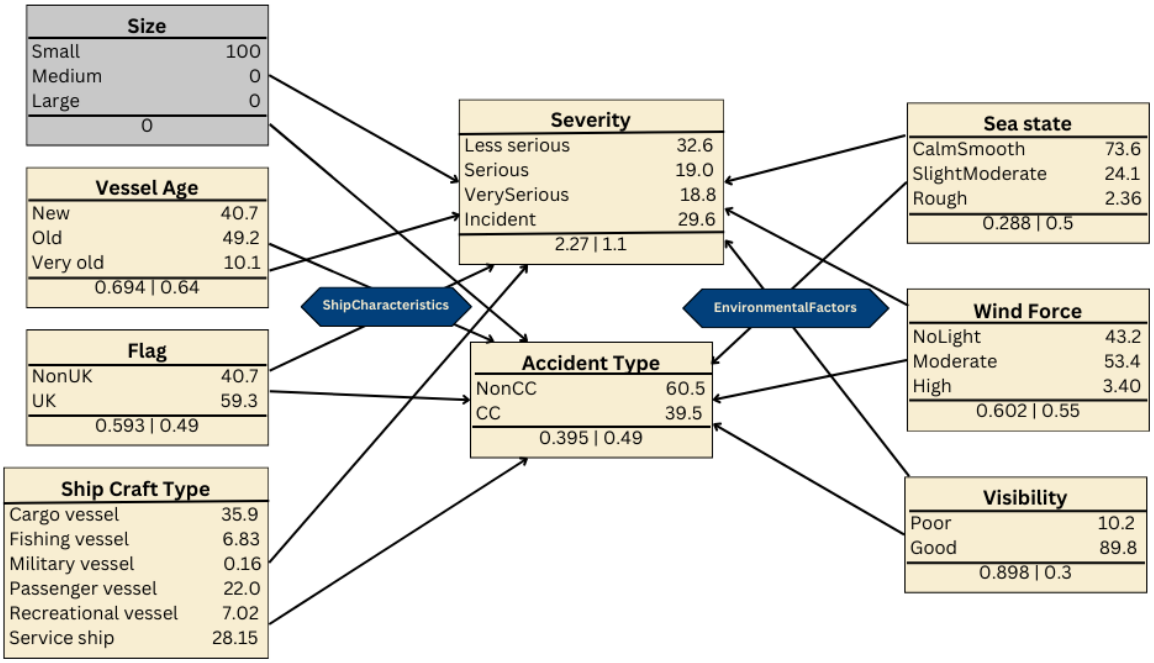
Tables of sensitivity analysis (including change rates between posterior probabilities) and figures showing the effects of some of the parameter on occurrence severity or accident type. A summary of all results is offered in Section 6.1.8.2 of the main body of this thesis.

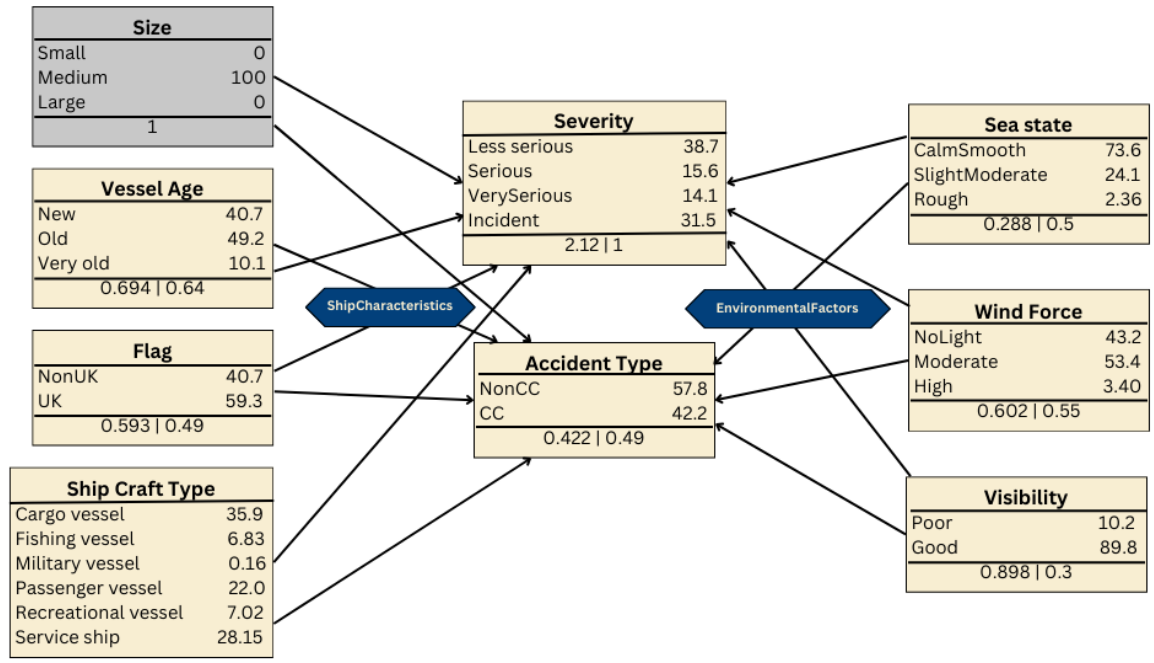
- ***Vessel size***

Table of sensitivity analysis for vessel size.

Nodes	Classification	Prior probability	Small size	Middle size	Change rate
Accident type	Non-C/C	59.6	60.5	57.8	-0.0446
	Contact/Collision	40.4	39.5	42.2	0.0683
Severity	Marine incident	30.3	29.6	31.5	0.0641
	Less serious	36.5	32.6	38.7	0.1871
	Serious	17	19	15.6	-0.1789
	Very serious	16.2	18.8	14.1	-0.25

Figures showing the effects of vessel size on accident type and severity, for small and medium-sized vessels.





Summary of results:

The figures and accompanying table provide a detailed analysis of how different factors influence maritime accidents, specifically focusing on vessel size, accident type, and severity.

Vessel Size and Accident type

The analysis indicates that larger vessels have a higher probability of being involved in contact or collision incidents. This is evident from the change in the contact and collision occurrence probability, which increases from 39.5% to 42.2% when transitioning from small to middle-sized vessels. This trend suggests that as vessel size increases, so does the likelihood of such accidents, and could be caused by their reduced manoeuvrability.

Vessel Size and Severity

The severity of accidents also appears to be influenced by vessel size. Small vessels are more prone to serious and very serious accidents compared to middle-sized vessels. The probability of serious accidents decreases from 19% to 15.6%, and very serious accidents from 18.8% to 14.1% when moving from small to middle-sized vessels. This suggests that, while smaller vessels may be involved in more severe occurrences, middle-sized vessels might benefit from better stability and resilience, leading to less severe outcomes.

Sensitivity Analysis

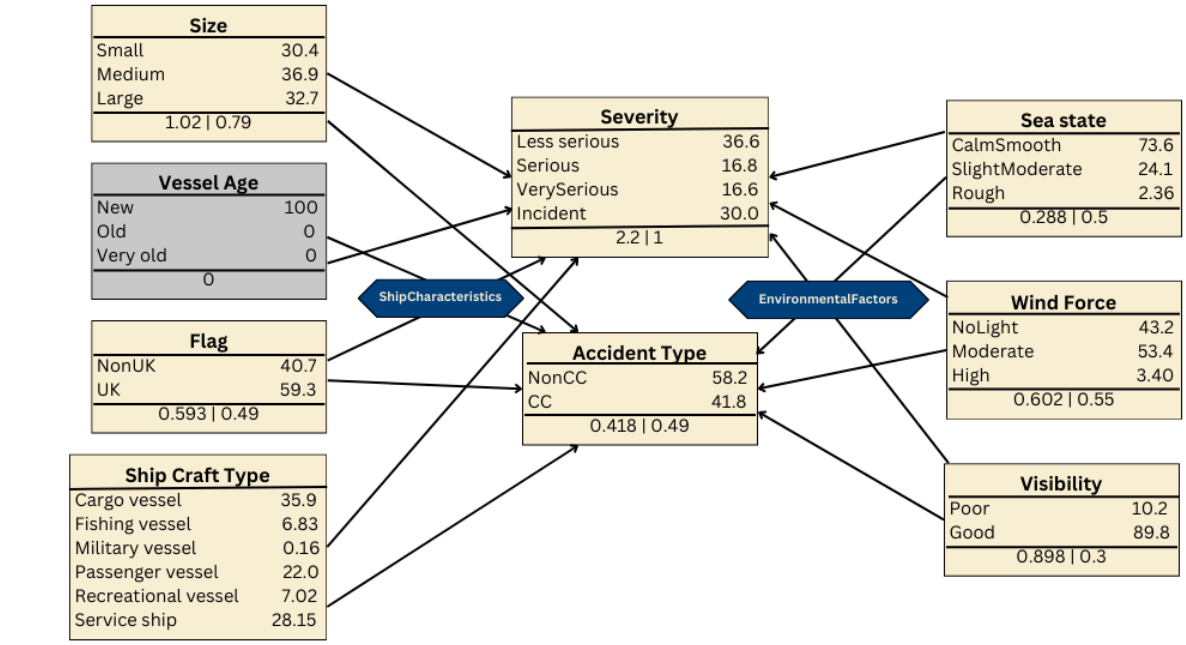
The figures illustrate the sensitivity analysis for small and medium-sized vessels. For small vessels, the probability of contact and collision is notably higher, and the severity of these incidents is also greater. When the vessel size is changed to medium, there is a significant impact on both the type and severity of accidents. The occurrence probability for contact and collision increases by 2.7%, while the probability of very serious accidents decreases by 4.7%.

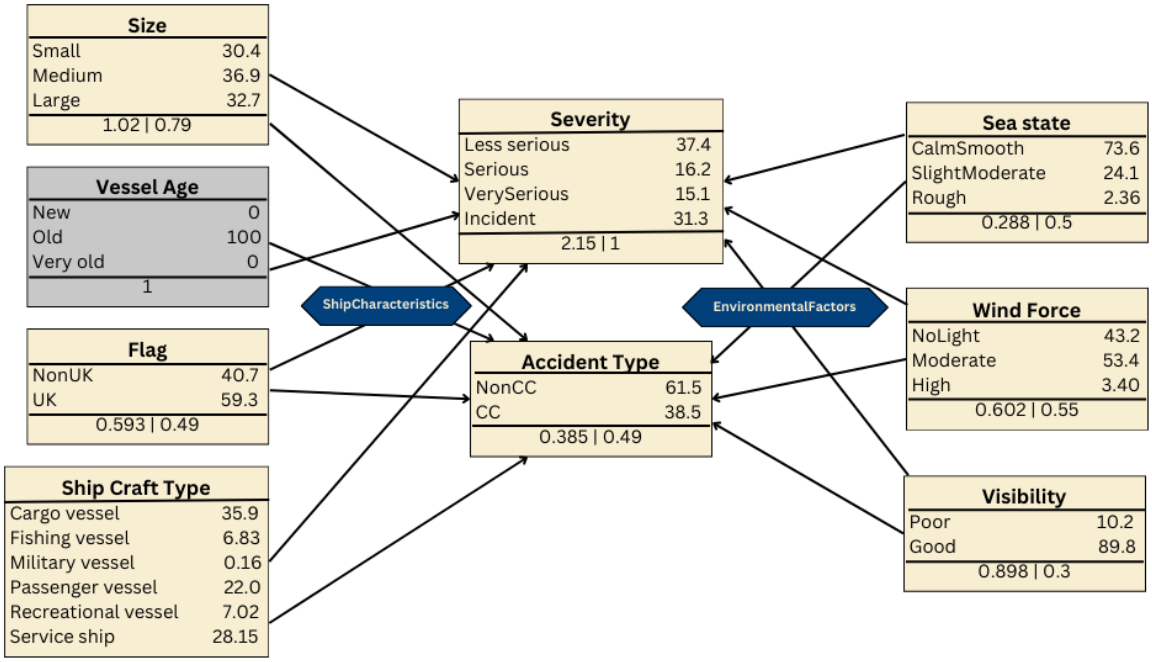
- ***Vessel age***

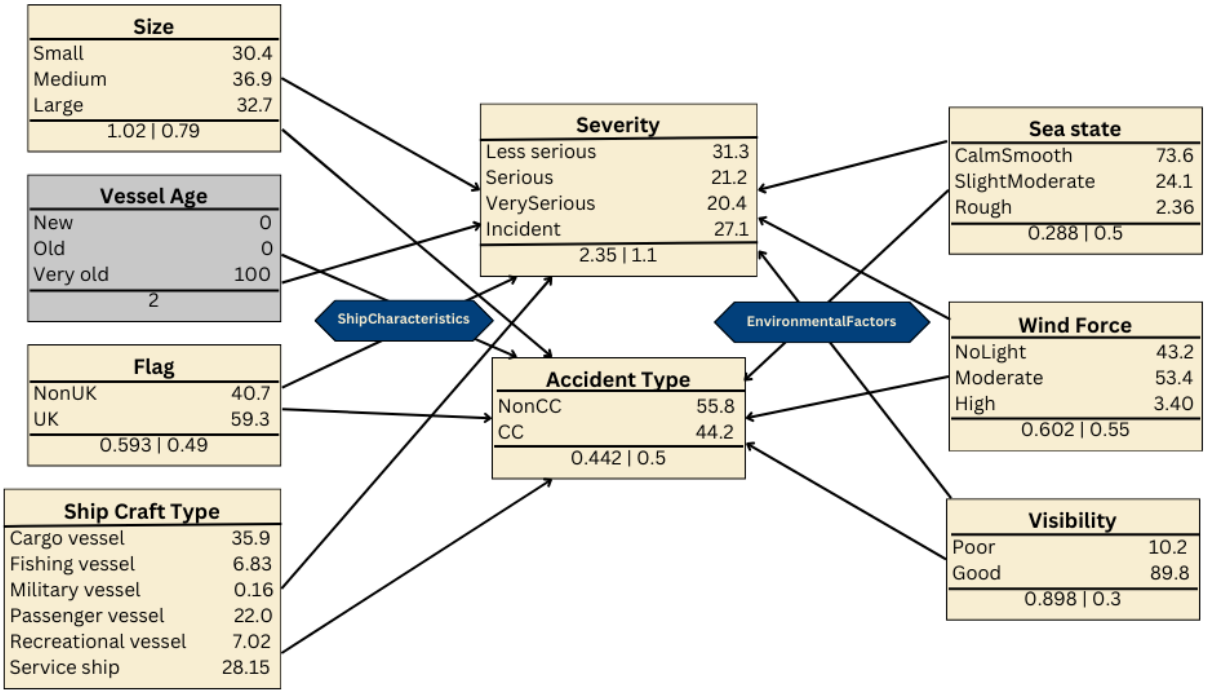
Table of sensitivity analysis for vessel age.

Nodes	Classification	New	Middle	Old	Change rate
Accident type	Non-C/C	41.8	38.5	44.2	0.1480
	Contact/Collision	58.2	61.5	55.8	-0.0926
Severity	Marine incident	30	31.3	27.1	-0.1341
	Less serious	36.6	37.4	31.3	-0.1631
	Serious	16.8	16.2	21.2	0.3086
	Very serious	16.6	15.1	20.4	0.3509

Figures showing the effects of vessel age on accident type and severity, for new, old and very old vessels, as defined in the table of variables used.


Size
Small 30.4
Medium 36.9
Large 32.7
1.02 | 0.79
Vessel Age
New 100
Old 0
Very old 0
0
Flag
NonUK 40.7
UK 59.3
0.593 | 0.49
Ship Craft Type
Cargo vessel 35.9
Fishing vessel 6.83
Military vessel 0.16
Passenger vessel 22.0
Recreational vessel 7.02
Service ship 28.15
ShipCharacteristics
Severity
Less serious 36.6
Serious 16.8
VerySerious 16.6
Incident 30.0
2.2 | 1
Accident Type
NonCC 58.2
CC 41.8
0.418 | 0.49
EnvironmentalFactors
Sea state
CalmSmooth 73.6
SlightModerate 24.1
Rough 2.36
0.288 | 0.5
Wind Force
NoLight 43.2
Moderate 53.4
High 3.40
0.602 | 0.55
Visibility
Poor 10.2
Good 89.8
0.898 | 0.3


Size
Small 30.4
Medium 36.9
Large 32.7
1.02 | 0.79
Vessel Age
New 0
Old 100
Very old 0
1
Flag
NonUK 40.7
UK 59.3
0.593 | 0.49
Ship Craft Type
Cargo vessel 35.9
Fishing vessel 6.83
Military vessel 0.16
Passenger vessel 22.0
Recreational vessel 7.02
Service ship 28.15
ShipCharacteristics
Severity
Less serious 37.4
Serious 16.2
VerySerious 15.1
Incident 31.3
2.15 | 1
Accident Type
NonCC 61.5
CC 38.5
0.385 | 0.49
EnvironmentalFactors
Sea state
CalmSmooth 73.6
SlightModerate 24.1
Rough 2.36
0.288 | 0.5
Wind Force
NoLight 43.2
Moderate 53.4
High 3.40
0.602 | 0.55
Visibility
Poor 10.2
Good 89.8
0.898 | 0.3



Summary of results:

The figures and accompanying table provide a detailed analysis of how different factors influence maritime accidents, specifically focusing on vessel age, accident type, and severity.

Vessel age and Accident type

The analysis shows a notable correlation between vessel age and the likelihood of accidents. Specifically, older vessels have a higher probability of being involved in contact or collision incidents. The table indicates that as vessels age, the probability of contact or collision increases from 38.5% to 44.2% when moving from middle-aged to old vessels. This is likely due to the accumulation of structural flaws and under-maintenance as vessels age (Li, 2014).

Vessel age and Severity

Older vessels are also more prone to severe accidents. The probability of very serious accidents increases significantly from 15.1% to 20.4% when comparing middle-aged vessels to old vessels. This increase in severity can be attributed to the deterioration of the vessel's condition over time and the potential for more critical failures (He, 2020).

Sensitivity analysis

The figures demonstrate the sensitivity analysis for different vessel age categories. The results indicate that new vessels are less likely to be involved in contact or collision incidents compared to older vessels. This is likely because ship owners and/or operators tend to invest more in the maintenance

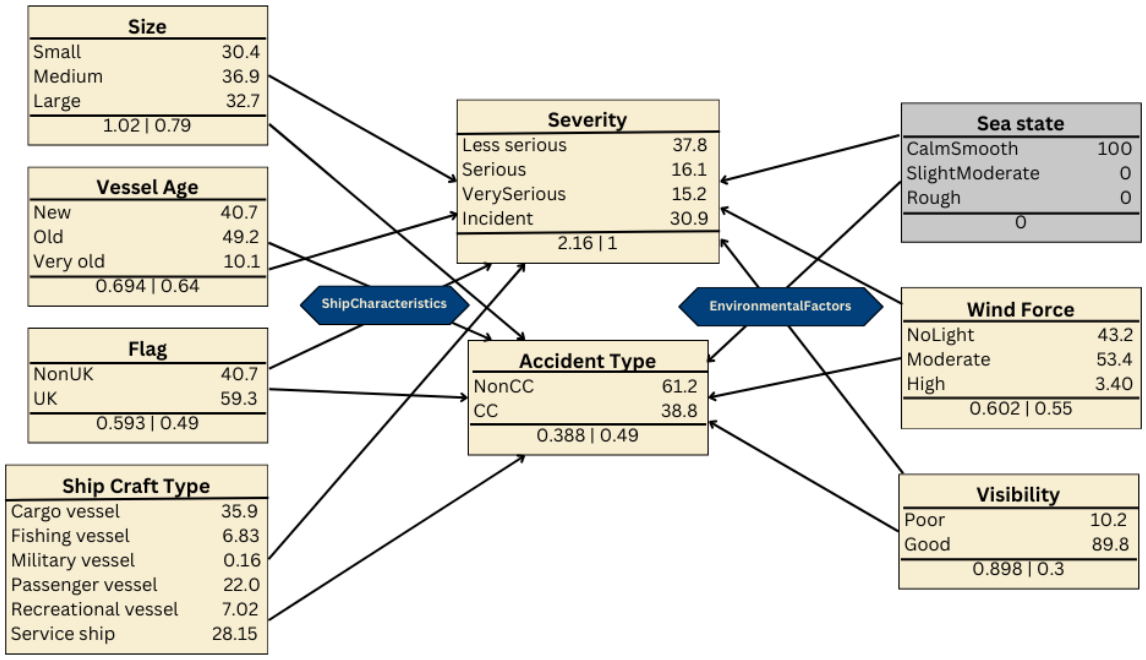
of newer vessels. Conversely, older vessels, which could suffer from deterioration and under-maintenance, show a higher likelihood of severe accidents.

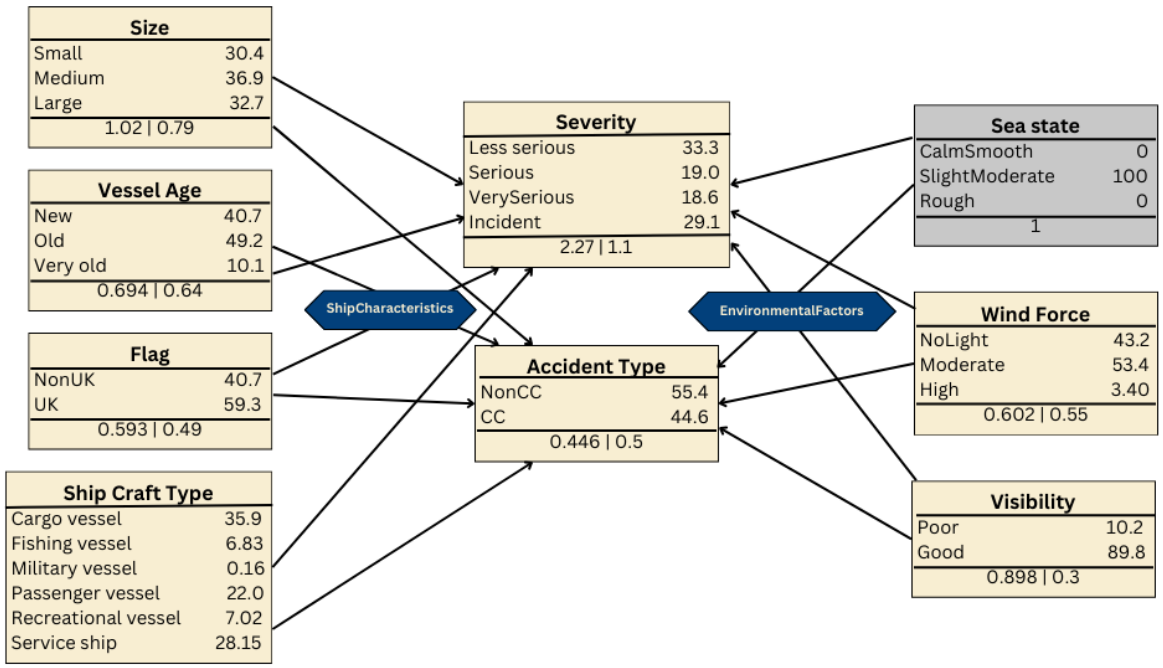
- ***Sea state***

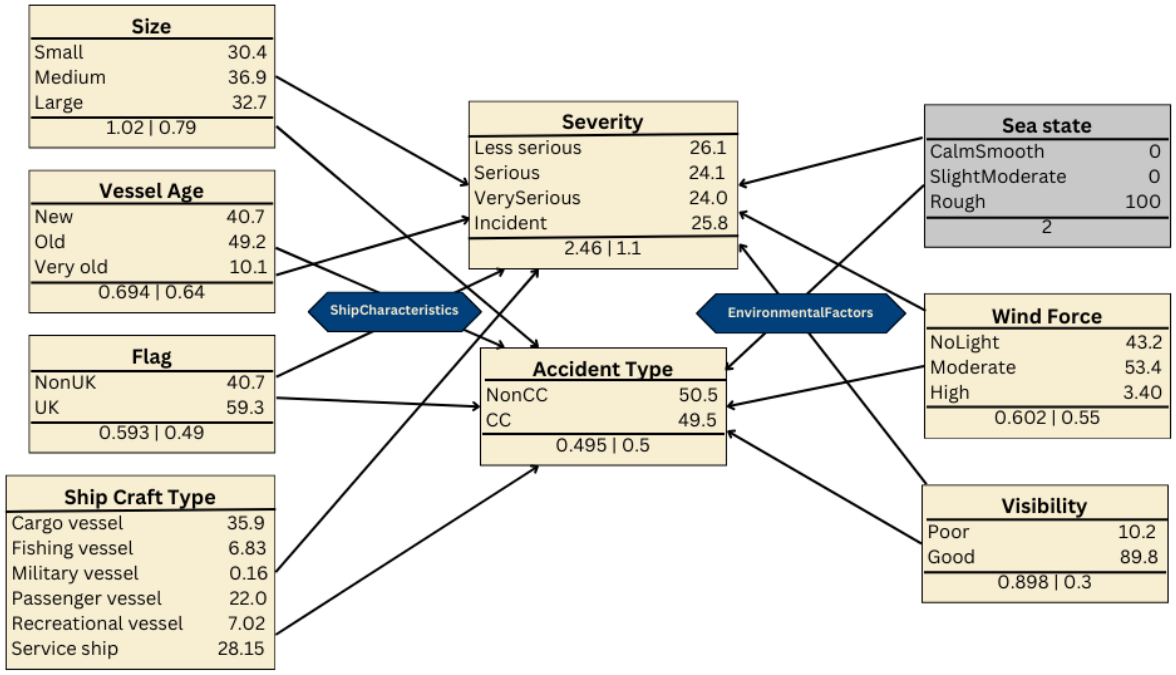
Table of sensitivity analysis for sea state.

Nodes	Classification	Calm	Rough	Change rate
Accident type	Non-C/C	38.8	49.5	0.2758
	Contact/Collision	61.2	50.5	-0.1748
Severity	Marine incident	30.9	25.8	-0.1651
	Less serious	37.8	26.1	-0.3095
	Serious	16.1	24.1	0.4969
	Very serious	15.2	24	0.5789

Figures showing the effects of sea state on accident type and severity, for calm/smooth (0), slight/moderate (1) and rough to very high (2) sea state, as defined in the table of variables used.







Summary of results:

The figures and accompanying table provide a detailed analysis of how different factors influence maritime accidents, specifically focusing on sea state, accident type, and severity.

Sensitivity analysis

The figures depict the BN's conditional probabilities for various nodes, showing how the severity and type of accidents fluctuate with changing sea states. In conclusion, rough sea conditions exacerbate

the severity and frequency of maritime accidents, necessitating rigorous safety protocols and weather management systems to protect maritime operations.

From the results shown in the table, it is evident that as the sea state worsens, the severity of accidents becomes more serious, and more collisions and contacts occur. The sensitivity analysis only compares the calm sea state and the rough sea state. From the table, the occurrence posterior probabilities of serious and very serious accidents have increased from 16.1% to 24.1%, and 15.2% to 24%, respectively. The occurrence probability of contacts and collisions also has a sharp increase of 10.7% with a large changing rate (27.58%).

- ***Other results:***

Similar figures and tables of results have been obtained for other parameters, and the conclusions are summarised in Section 6.1.8.2 of the main body of this thesis.

Appendix L. Questions used for the interviews and questionnaire about autonomous vessels.

* *Please answer the questions (if relevant) for people's safety on-board of a ship and on-land, separately*.

1. Personal details
   a) General (name, age, gender – these will be kept anonymous and not used in any way)
   b) Professional (studies, certifications, official position / profession)
   c) Experience in the maritime sector (e.g., fields of practice)

2. Safety Management System (SMS) and Safety Risk Management
   a) Do you have a SMS in place for the port operations? If yes, what is this based upon? e.g., International Maritime Organization (IMO / European Maritime Safety Agency (EMSA) recommendations? Are there others?
   b) How are hazards and various possible risks that can impact the safety of ships / people on-board of a ship or on land identified?
   c) How do you assess and mitigate those risks?

3. Safety policy and objectives
   a) What is the management's commitment and what are its responsibilities regarding safety assurance in a port.
   b) How are responsibilities shared in maintaining port safety?
   c) How does the appointment of key safety personnel work?
   d) How is the response method planned and coordinated in different emergency situations?
   e) Safety Management System (SMS) documentation
   f) What is the relationship with safety regulators? Are these authorities perceived as active or passive?

4. Safety assurance
   a) Safety performance monitoring and measurement – how is it done?
   b) The management of change – how does it work?
   c) How do you maintain a continuous improvement of the SMS?
   d) How to proceed with learning from previous experience and mistakes? Are there changes at a local or national level? And are these following a serious accident only, or also a minor incident / near-misses?
   e) How are accidents reported in your organisation?
   f) Do you feel that people are encouraged to actively report near-misses, or do they report only what is mandatory?
   g) What measures are you taking to encourage people to report marine casualties and near-misses?
   h) Do you feel that people are not willing to report because they fear punishment?
   i) Do you send out questionnaires (or something else) for people's opinion on what can be improved?
   j) In your opinion, how effective is safety reporting in your organisation?

k) What is the level of “follow up” after reporting? e.g., is there a learning culture in your organisation?

5. Safety culture and promotion
   a) What is your opinion on the safety culture of your organisation? What are the strengths and which areas could be improved? How will the safety culture will be improved with the introduction of autonomous vessels?
   b) Is there an effective and on-going employee training program? How much diversity of training scenarios is there? Will these training program will be changed with the autonomous cargo vessels?
   c) Do you have safety forums or follow-ups of safety recommendations in your organisation?
   d) How does the requirement for auditing in your organisation impact the safety and resource allocations?
   e) Does hierarchy affect the safety of operations in your organisation? How? Do you think employees at lower levels in the hierarchy are afraid of punishment if they report something that went wrong?
   f) Do you think that safety could be enhanced more if more funds were allocated to safety? Are the financial resources seen as limited for safety, when comparing to other departments?
   g) How are safety measures implemented and communicated to the people in your organisation?

6. Incident data collection
   a) How is accident data collected? (i.e. online platform, forms, anonymous or not)
   b) What are the accident severity categories used in port you work at? Are they in line with IMO or EMSA recommendations? *(as IMO combines less serious casualties and near-misses in one category)*
   c) Are there any way people can report minor injuries and near-misses anonymously?
   d) Do you have safety databases at a port level? Do you have to report accidents to national / international databases? If so, do you communicate all the reports you receive?
   e) Is the incident database publicly available or can access be requested?
   f) How do you use the data from your accident database to prevent future reoccurrences? Is there a team responsible for analysing the data?
   g) How often do you revise safety regulations/practices based on accident data?

7. Equipment
   a) Are all employees required to always wear protective personal equipment (PPE)?
   b) Are there cases when employees do not comply with the PPE requirement measures?
   c) What does the PPE comprise of?
   d) Is PPE used properly?
   e) Where is the PPE stored?
   f) Is PPE always available, free of charge, for all employees? e.g., if their helmet breaks, can they immediately get a new one free of charge?

g) Do you have equipment such as exit lights, emergency lights, fire extinguishers, safety posters in all areas?

8. Autonomous Vessels

a) What does the concept of “autonomous cargo vessel” mean to you?
b) Do you see cargo vessels without crew feasible in the XXI century? (with less or no crew)
c) The main cause of ship accidents is due to "human errors". Do you think that this type of unmanned vessels would help reduce the number of maritime accidents? If yes, how would it help to reduce the number of accidents?
d) During docking / undocking manoeuvres, accidents caused by equipment and / or main engine failure continue to be seen. The fact that in an autonomous ship there is no crew, the situation could be aggravated or, instead, be improved since it will be able to predict this failure in advance and thus, anticipate the situation and be able to save it sooner?
e) If the ship does not have manoeuvres, an automatic mooring system will have to be invented for when the ship is in port. Do you see it feasible? Do you believe that the figure of the "mooring" of the port will disappear.
f) In your opinion, how would the figure of the Pilot change with automation? Would Pilots “give orders” to a computer / console?
g) The viability of fully autonomous vessels on a global scale will depend on their ability to face challenges, such as moorings, high traffic routes and emergency situations with no crew on board. What are some of the biggest concerns and disadvantages of autonomous vessels, and also the main advantages of unmanned cargo vessels?
h) Do you know ports working on the development and innovation of new technologies? Are you participating at a national or international level in any projects about autonomous vessels?
i) As technologies have developed in the past, we have always seen a number of benefits that come with them. In the case of automation in the maritime industry, the greatest benefits are likely to be found in improving safety, a cleaner environment, and a reduction of human error accidents. What will be the role of international regulations in this area?
j) What we see in the first tests are relatively small boats being built for specific trips and conditions. In your opinion, when will this trend apply for large ships sailing the high seas?
k) Do you think the safety communications will be affected by autonomous vessels, as everything will be done remote control?

Appendix M. Conference paper submitted to the Transport Research Board annual meeting.

TRB Annual Meeting

Analysis of Maritime Piracy in West Africa and the Gulf of Guinea

--Manuscript Draft--

Full Title:	Analysis of Maritime Piracy in West Africa and the Gulf of Guinea
Abstract:	Piracy in the Gulf of Guinea (GoG) is a major threat to maritime transport and has recently seen a sharp increase in its incidence and severity. This paper analyses the factors underlying piracy related incidents in this region. It reveals that the reporting schemes implemented provide most essential data, but they are inconsistent and underreport. A set of 322 piracy related incident reports in the GoG were extracted from the IMO's Global Integrated Shipping Information System between 2017 and 2022. Statistical analysis suggests that severe incidents, such as hijackings and kidnappings, are most likely occur in international waters during daytime and are usually orchestrated attacks carried out by organized gangs, especially off the coasts of the countries. Less serious attacks, such as theft and burglary, are more common in port areas at night. The impact of seasonal weather indicates that severe incidents typically occur during the dry season under calm climatic conditions. These results can potentially be used to develop predictive models and better understand the conditions in which pirates operate, thereby helping shipping companies and navies boost their defensive strategies and technologies to counter piracy.
Manuscript Classifications:	Data and Data Science; Statistical Methods AED60; Analysis; Safety; Marine; Marine Safety and Human Factors AW040; Accident; Data; Incident; Maritime; Safety
Manuscript Number:	TRBAM-23-02606
Article Type:	Presentation and Publication
Order of Authors:	Iulia Manole, PhD
	Arnab Majumdar
	Marc Oueiss
Additional Information:	
Question	**Response**
The total word count limit is 7500 words including tables. Each table equals 250 words and must be included in your count. Papers exceeding the word limit may be rejected. My word count is:	7498
Is your submission in response to a Call for Papers? (This is not required and will not affect your likelihood of publication.)	No

Powered by Editorial Manager® and ProduXion Manager® from Aries Systems Corporation

INTRODUCTION

Maritime transport accounts for more than 80% of the volume of international trade and the past decade has witnessed an unprecedented boom with major fleet(*1*). Hence, the safety of the ships, both in term of the cargo carried and the wellbeing of the crew, has become of paramount importance. However, such maritime trade remains exposed to one of its oldest and enduring threats, that of piracy. According to Article 101 of the United Nations Convention on the Law of the Sea(*2*), piracy consists of any of the following acts:

"(a)any illegal acts of violence or detention, or any act of depredation, committed for private ends by the crew or the passengers of a private ship or a private aircraft, and directed-

(i)on the high seas, against another ship or aircraft, or against persons or property on board such ship or aircraft.

(ii)against a ship, aircraft, persons, or property in a place outside the jurisdiction of any State.

(b)any act of voluntary participation in the operation of a ship or of an aircraft with knowledge of facts making it a pirate ship or aircraft.

(c)any act of inciting or of intentionally facilitating an act described in subparagraph (a) or (b)."

History highlights that the main factors underlying piracy are episodic wars and unstable and fluctuating economies. These factors, which are often linked by a causal relationship, generally cause a surge in unemployment and instability of the labor markets, triggering a rise in the black-market demand for goods stolen and provided by pirates. As ships laid idle and less profitable opportunities were available for sea merchants, piracy offered a suitable alternative that would match their skills and expertise and offered an escape from starvation and bankruptcy(*3*).

In certain regions of the world, these conditions are prevalent, e.g.Western Africa and the Gulf of Guinea has experienced a sharp rise in piracy during the past 30years, characterized by increasing violence against crew members. Piracy accounted for more than 95% of kidnappings at sea in 2020(*4*) and poses a serious danger to maritime transport on the Atlantic seaboard of Africa. The importance of piracy can be seen by the International Maritime Organization(IMO) which collects the data on such incidents in considerable detail.

The aim of this paper is to provide an overview of the piracy threat in west Africa using the IMP's database and study the complex relationships that exist between the different parameters and characteristics of piracy-related incidents. This paper develops a methodology to analyze the underlying factors driving piracy and assess their impact based upon data from the IMO and subsequently analyses the key trends in order to provide feasible recommendations.

CURRENT GLOBAL CONTEXT OF PIRACY

To better understand piracy in West Africa, it is necessary to consider piracy globally.There are several piracy hotspots that are considered as high-risk areas(HRAs) where sailing in such waters is characterized by a high probability of pirate attacks.To compensate for the risk taken, the crew is given a risk premium and higher wages.While some waters have always been infested with piracy, some new hotspots have emerged these past decades.

South-east Asia is one of the most active piracy hotspots in the world, accounting for 42% of all pirate attacks in 2021(*4*).Another piracy hotspot is the horn of Africa and the Gulf of Aden, with major economic losses and damages to global trade, including kidnappings, of greater than 3 billion$(*5*).In response to this, several military operations were instigated, and naval assets deployed to the area. This has been effective as piracy related incidents dramatically dropped from 358 attacks between 2010 and 2015,to 8 from 2016 to 2021(*5*).Currently,operation ATALANTA is ongoing in the Gulf of Aden and attacks have reached record lows as the new hotspot of piracy in Africa has shifted to the continent's western seaboard(*6*). Piracy in West Africa and the Gulf of Guinea has been increasing at alarming rates and will be explored in greater depth in this paper.

The International Maritime Bureau(IMB) is a specialized branch of the International Chamber of Commerce(ICC) that aims to protect crews and fight piracy and commercial fraud. Based in London,the IMB possesses a piracy reporting center(PRC) in Kuala Lumpur that is alerted when a ship subjected to a

pirate attack reports the incident. The PRC is an independent and non-governmental entity that provides a 24-hour free service for shipmasters to report any piracy, armed robbery, or stowaway incidents(*7*).

Under the definitions of Piracy or Armed Robbery,(*8*)reports incidents as follows:

1. **Boarded**:Perpetrators successfully gaining access onto the vessel in an illegal manner
2. **Hijacked**:Perpetrators successfully gaining access onto and taking over the control of the vessel in an illegal fashion.
3. **Fired Upon**:Perpetrators discharging weapons towards ship while attempting to gain access onto the vessel.
4. **Attempted**:An illegal act of perpetrators attempting to approach a vessel with possible intention to board but remain unsuccessful due to the timely actions of the crew.

The International Maritime Organization(IMO) is the specialized entity of the United Nations for shipping regulation and maritime transit, with the fundamental objective of the development and upholding of a comprehensive framework for maritime shipping.The IMO also oversees maritime safety, legal concerns, environmental impact, and maritime security concerns, such as piracy.The IMO entails of a council and an assembly, as well as five main committees (Maritime Safety, Marine Environment Protection,Legal, Technical Co-operation and Facilitation committees)that will carry out the work and implement the motions passed(*9*).

WEST AFRICAN PIRACY

West Africa and the Gulf of Guinea

Piracy has become an increasingly problematic phenomenon in the western seaboard of Africa as a HRA has been declared over the waters of 18 sovereign states stretching from Senegal in the north to Angola in the South.This vast area, known as the Gulf of Guinea(GoG), spans over approximately 6,000 km of coastline(**Figure 1**) and is characterized by rich and diverse fish stocks(*10*).

The GoG experiences high daily volumes of maritime transit as it is the main supply and shipping hub for western Africa.On any day, more than 1,500 fishing vessels,tankers and cargo ships navigate these waters(*11*). Furthermore, eight countries of the GoG are oil exporting nations and possess offshore oil fields and rigs(**Figure 2**). Foreign oil companies and their expatriate employees present a lucrative prospect for pirates as they can demand greater ransoms from their kidnapping(*12*).

Under Review



Figure 1 Map of the GoG (*13*)

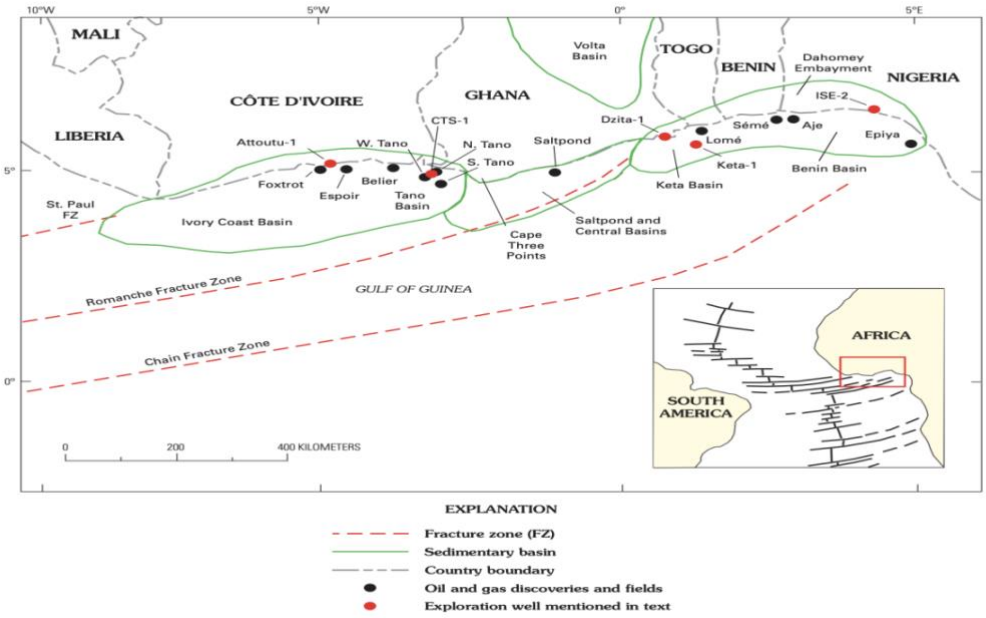


Figure 2 Major geomorphological features of the GoG (*14*)

Economic growth of the GoG

The GoG is home to dynamic and fast-growing economies.Western Africa houses more than 420 million inhabitants as of 2022,with Nigeria accounting for 49%of this number.Moreover, the population is young with a median age of 18.6years and is growing at a rate of 3.6%in 2022(*15*). The economies in this region are growing, with Nigeria set for a GDP growth of 2.7%in 2022 while neighboring countries are poised for greater growth rates.The expansion of the regional economies implies an increase in the volume of trade activity,especially imports(**Figure 3**). This increase in maritime shipping activity relates to the spike in piracy as more targets are available.

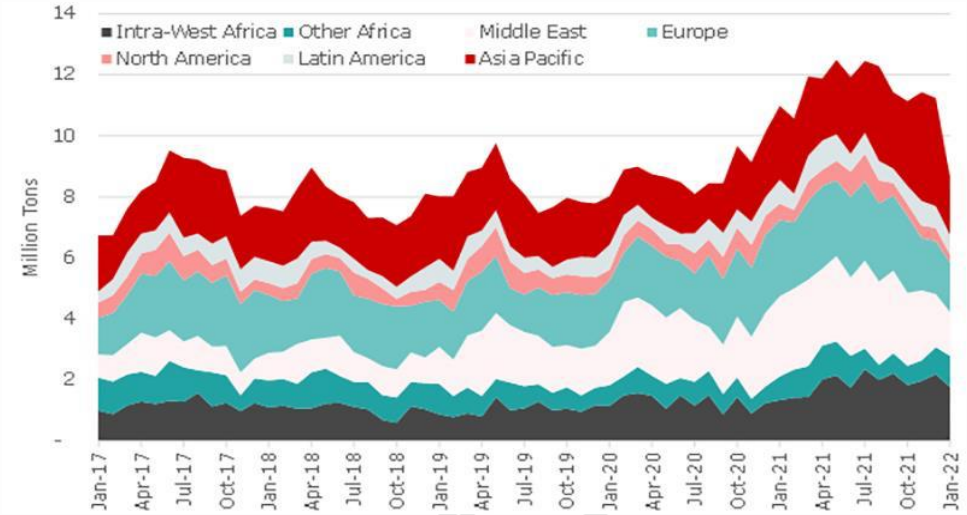


Figure 3 West African dry bulk imports by source (*1*)

Another key factor that should be highlighted is the poverty rate as well as political instability and corruption that is widespread in this area.About 3%of the population of West Africa lives under 1.90$per day,which is a 3%rise compared to 2020's level(*16*) Furthermore, the region has witnessed its fair share of instability over the past few decades as several countries experienced civil wars,extensive corruption, civil unrest,coups and the rise of terrorism(*17*).

Overview of piracy in the region

The waters of the GoG have been a haven for illicit activities such as piracy.The global data retrieved by(*7*) indicates a sharp rise in the number of crew members kidnapping can be observed,despite the overall drop in number of incidents over the past few years. Indeed, western Africa is subjected to the largest count of crew kidnappings and accounts for ~97%of kidnappings at sea.Whereas knives are more popular amongst pirates in other hotspots,guns are the weapon of choice for west African pirates.This highlights the criticality of GoG piracy as attackers with guns are more difficult to apprehend or neutralize.The 2021 spatial distribution of piracy related incidents in the GoG is illustrated in **Figure 4**.



Figure 4 Spatial distribution of pirate related incidents in the GoG in 2021 (*7*)

Regional response to piracy

Yaoundé code of conduct(YCoC)

The Yaoundé Code of Conduct is comprehensive maritime security framework drawn up and signed by 18 states in 2013,has for primary objective to promote cooperation between all concerned parties to tackle piracy and armed robbery at sea in the GoG(*18*).The architecture of the maritime safety framework proposed by the YCoC is shown in **Figure 5** and **Figure 6**.

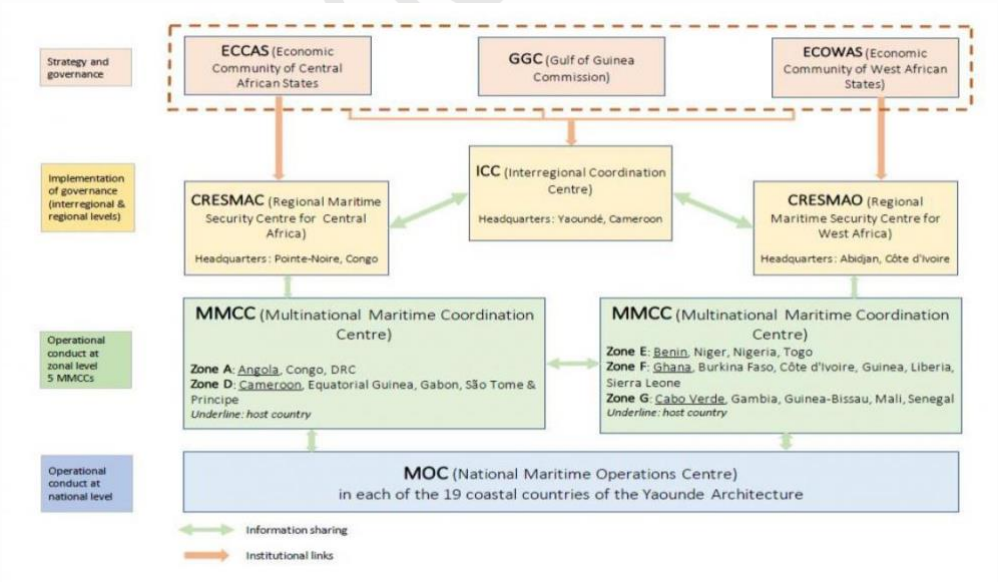


Figure 5 Maritime safety and security architecture of the YCoC (*11*)

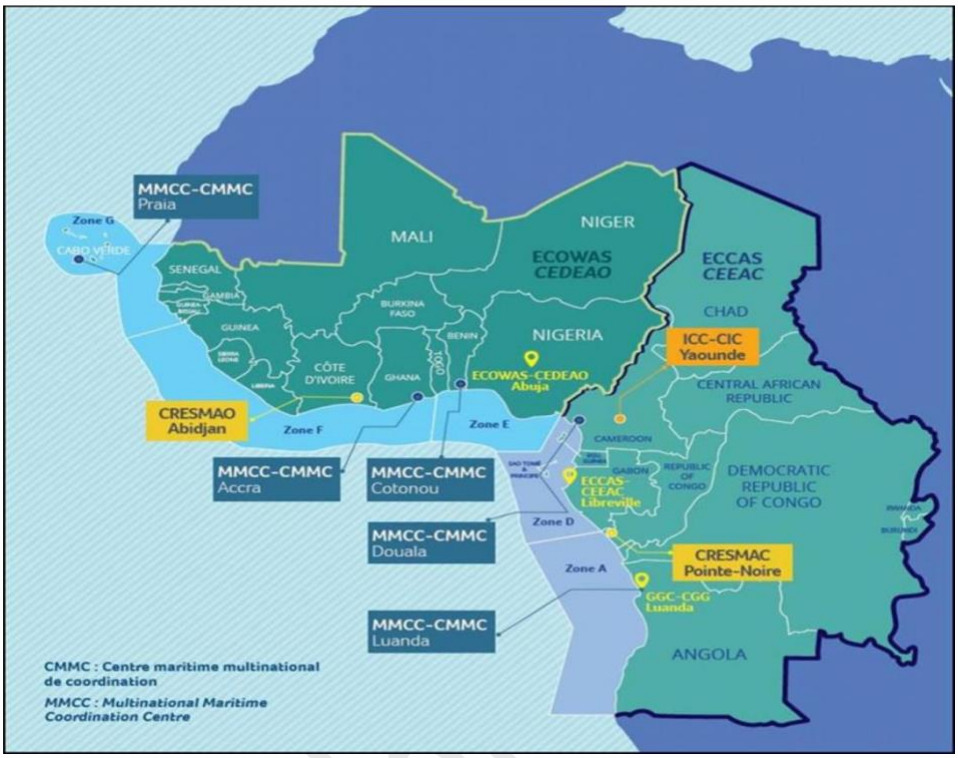


Figure 6 Map of the different components of the YCoC (*11*)

Military response

A military response has been to retaliate against piracy in the GoG. Indeed,Nigeria in 2021 launched an initiative to secure its territorial waters in the GoG through a combination of efforts and military assets on sea,air and land. This"Deep Blue project"is the first of integrated inter-arm maritime protection policy adopted in the region(*19*).

Foreign countries such as the US,Russia, China, and several European nations have also contributed to the fight against piracy in the region by offering grants and equipment to regional navies, conducting counter-piracy exercises with them and by deploying naval assets to the region(*20*).

Main factors driving piracy in the region

Illegal Fishing

A key factor behind west African piracy is destructive and IIU(Illegal, unregulated,and unreported) fishing practices.(*21*) developed a model that asserted the existence of a link between destructive and IIU fishing with the incidence of piracy.Destructive fishing refers to the displacement of small-scale fisheries by foreign,industrial fishing fleets that service the global seafood market.(*22*) confirmed this by noting that an increase in industrial fishing,that accounts for IIU activity,is directly related to an increase in pirate attack occurrences.It is though worth noting that a rise in artisanal and subsistence fish catch value is accompanied by a decline in maritime attacks.

Given that fisheries are a prominent sector of the local economies of western Africa,attack numbers should in theory drop when artisanal fishing is on the rise.Individuals living on coastal areas and partaking in artisanal fishing activities contribute to the local economy,make a living,and provide for their families.Hence, they are less likely to engage in illegal activities such as piracy and endanger themselves and their families.Consequently, increased industrial fishing implies that less fish is available for local fishermen since most of the fish caught on the large industrial fishing boats becomes the property of foreign corporations and is bound for international markets.This will then induce a considerable drop in the income of local population, especially fishermen and local seafood markets.These alienated fishermen then turn to crime and engage in pirate operations for survival.As they already own boats and know how to navigate the local waters extremely well, the lack of fish ensures that piracy becomes a lucrative opportunity,and the benefits start to outweigh the risks.

Youth bulges and lack of opportunities

Another underlying factor in the rise of piracy in the GoG is youth bulges and the lack of opportunities for the youth labor market.(*23*) examined the impact of youth bulges and insufficient absorption of the labor market on the emergence of piracy and concluded that such youth bulges have a significant effect on pirate activity in the GoG as a 1%increase in the young population is associated with a 16.8%increase in the probability of occurrence of a pirate incident.On average,a larger proportion of young people in a country amplifies the opportunities and motives for piracy.

The effect of youth bulges depends on the characteristics of the labor market. The harder it is for young population to find job opportunities and be integrated in the labor market,the stronger the impact of youth bulge(*23*).This situation can be clearly observed in west African countries that are subjected to a sharp rise in their young population.Indeed, most countries in the GoG had,in 2021,a median age of about 18years, with a constant global annual population growth of about 2%(*5*). Furthermore, they have fragile economies and labor markets unable to satisfy the demand, especially for young adults(*24*).

Political factors and military capacity

Piracy in the region can also be politically driven.The Movement for the Emancipation of the Niger Delta ("MEND") is an organization that claims to be fighting as a protest to the damage caused by oil production in the Niger delta,and advocates for a fairer distribution of Nigeria's oil resources amongst the local population. Furthermore,the pollution caused by oil extraction has decimated the local fisheries and farmland.Hence, MEND partisans have decided to take matters into their own hand and combat what they perceive as an injustice through pirate activity(*25*).

Political instability and state fragility also instrumental in the emergence of piracy.(*22*) argued that the polity term is positive when determining the likelihood and counts of hijackings and pirate attacks.This suggests that anocracies are more likely to experience pirate attacks than democratic and autocratic regimes.This argument is also bought forward by(*23*) as they suggest that a sound political system has a bearing on piracy reduction.

LITERATURE REVIEW

Previous studies

(*26*) thoroughly describes the main factors behind piracy,offers an assessment of the current efforts to tackle this issue and proposes potential solutions to exterminate piracy in the region. Although that research was mostly based on qualitative principles, a basic analysis of descriptive statistics was also achieved to support his arguments by studying piracy incidents in the region from 2010 to 2016.(*26*) also proposed potential causes that drive piracy in the GoG that agree with those presented in the previous section of this paper. Finally,(*26*) offered key recommendations that would help solve the piracy problem in the region instead of just mitigating the incident as it is occurring.These solutions span from enhanced inter-state and inter-agencies cooperation to build a stronger capacity for monitoring and acting against the pirates,as well as agreements that should facilitate the investigation,pursuit, capture and prosecution of

pirates all over the GoG. Furthermore, promoting collaboration and cooperation between regional navies as well as with foreign counterparts would be instrumental to tackle piracy.(*26*) stressed the prominence of military presence as a deterrent to potential pirate activity.

(*27*) focused their research on investigating the trends and analyzing patterns in pirate attacks in the GoG from 2010 to 2014.Three main phases were identified for each incident: phase1 which consists of planning and preparations, phase2 which is the approach towards the target and phase3 which englobes boarding and post-boarding actions. Overall,the analysis indicated that incidents occurring at night are most likely theft or burglary and take place close to the shore in areas of high ship density.On the other hand,more complex attacks such as kidnappings and hijackings transpire during the day far from the shoreline.The effectiveness of pre-emptive measures during the different phases of the attack was also scrutinized. It was found that detecting the attack during phase2 will render the highest chances of effectively defending against and ward off the predators.On the other hand,the ship and crew are the most vulnerable if pirates have successfully boarded the vessel. **Figure7** and **Figure8** depict the probabilities computed by(*27*) to quantify the potential risks of attacks as well as his main findings when it comes to the unfolding of the events with respect to different parameters.

	Ship approached	Pirates detected	Ship boarded	P_{path}	Consequences				
					Frequency			Average number	
					Stores stolen	Cargo stolen	Ship hijacked	Killed*	Kidnapped
Tankers:	No, P= 0.9998			0.9998					
	Yes, P= 0.0002	No, P=0.4	No, P=0	0				0.04	
			Yes, P=1	0.0001	0.8	0.3	0.3	0.09	0
		Yes, P=0.6	No, P=0.8	0.0001				0.04	
			Yes, P=0.2	0.00002	0.3	0	0	0.3	0.8
Other ships:	No, P= 0.9999			0.9999					
	Yes, P= 0.0001	No, P=0.5	No, P=0	0				0.07	
			Yes, P=1	0.00004	0.7	0.04	0.1	0.3	2
		Yes, P=0.5	No, P=0.6	0.00003				0.07	
			Yes, P=0.4	0.00002	1	0	0	0.3	1

*) Including injured/10

Figure 7 Event tree for piracy attacks off Nigeria from 2010 to 2014 (*27*)

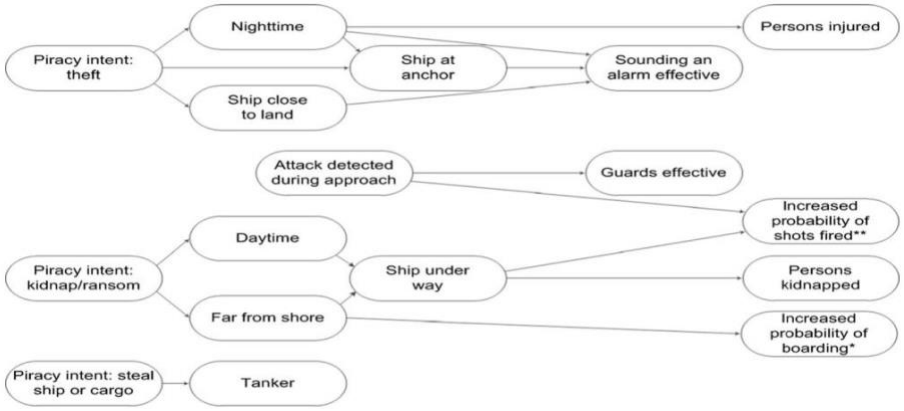


Figure 8 Summary of (*27*)'s main findings

Literature gap

A thorough literature review has indicated that research on maritime piracy in West Africa proactively investigated a wide variety of aspects.While some focus more on the underlying factors,such as(*21*), other papers are more oriented towards proposing solutions to this issue such as(*26*). The only attempt at better understanding the conditions under which attacks occur in West Africa was initiated by(*27*),who through the use of descriptive statistics, scratched the surface of this very interesting topic.

Deeper statistical analysis has been used by(*28*) to quantify the different parameters affecting the pirates'decision to attack.That study was focused on piracy in South-eastern Asia,which is characterized by different trends,politics, and modus operandi than in West Africa. Nonetheless,it is interesting to understand their logic and apply it to different areas of interest. (*28*)effectively deployed a Bayesian Network(BN) to analyze their dataset that was constructed with GSIS data on south-eastern Asia, spanning from 2010 to 2019.As **Figure9** suggests,the BN model developed indicated that several factors can affect the success of an attack.

This study provides similar action by using statistical tools to determine the impact different factors have on piracy incidence in the GoG.This methodology is unique compared to previous studies on maritime piracy in West Africa as the main objective of this paper is to harness the power of available data and observe key trends and associations relevant for a deeper understanding of the mechanisms of piracy in the Gulf of Guinea.

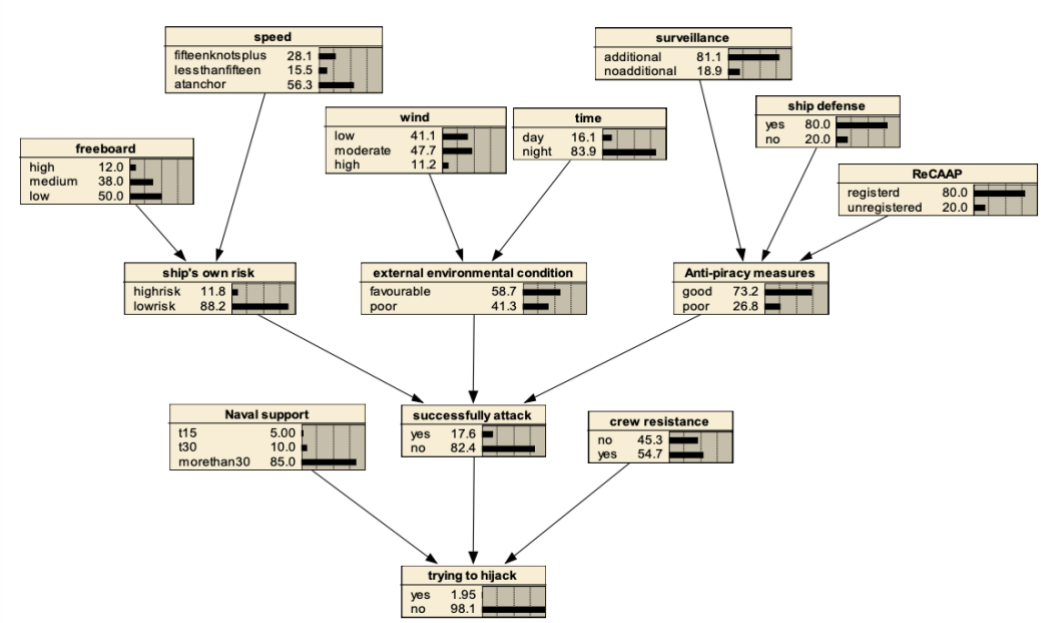


Figure 9 Expanded BN model with influence of each node (*28*)

METHODOLOGY

The methodology followed in this paper is illustrated in **Figure 10**. Firstly,a dataset is created after determining the desired parameters and the most appropriate data source. Secondly,the dataset's quality is assessed to check its suitability for the analysis.Then, the incidents are separated into different severity groups, according to their threat level.These are assessed individually to determine patterns and trends amongst the various accident types.Finally, accident reports are analyzed and contingency analysis is carried out to test possible associations between various pairs of parameters.

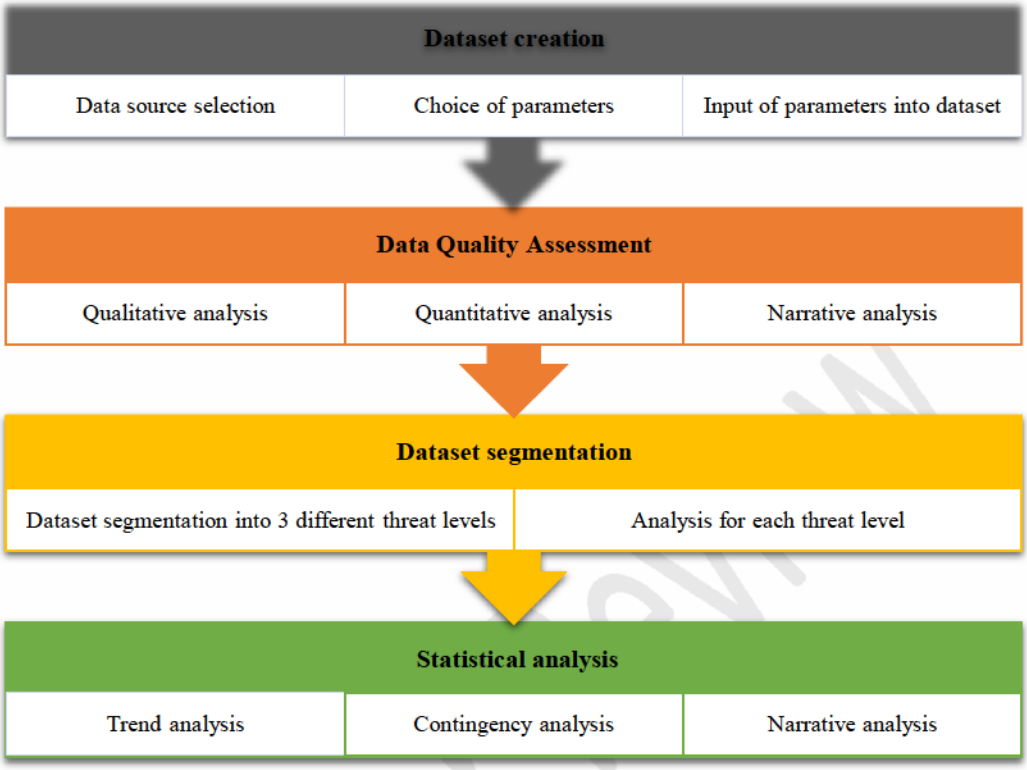


Figure 10 Methodology flowchart

RESULTS

Dataset creation

Incident reports in the GoG were extracted from the IMO's Global Integrated Shipping Information System(GISIS).A dataset of 322 piracy related incidents was created by accessing each report from 2017 to2022 and extracting the desired information, presented in **Figure11**. The incidents were also categorized with respect to the effect of the crew.This severity marker is labelled as threat level in the dataset and is based on the definition provided by the IMB as depicted below(*7*):

- Level I:accidents which have direct impact on crew:crew taken hostage,injured,kidnapped,killed, missing, threatened;hijacking where the command of the ship is taken over by those boarding; accidents where the crew retreats into the citadel;
- Level II:vessel being fired upon,security team firing against approaching threat, robbers/pirates identified with weapons whether boarding or otherwise;
- Level III:other incidents.

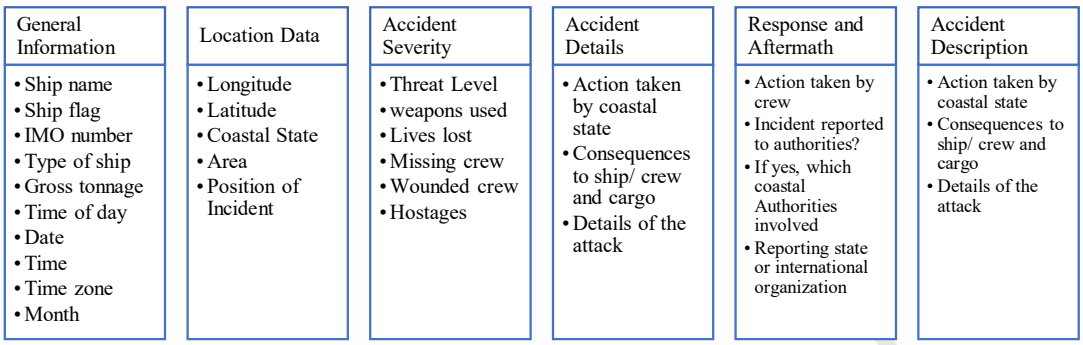


Figure 11 Accident characteristics compiled in dataset

The parameters were reformatted for the purpose of the analysis (**Table 1**). For example,the month of the accidents were divided into the four seasons:winter, spring, summer,and autumn as well as.The four seasons were used in this case to help visualize any trend or fluctuation of the pirate activity with respect to global market as well as local seasonality.To better understand the impact of weather and climatic conditions in between seasons,parameters for the dry season (fall and winter)and for the rainy season (spring and summer)were added to the analysis.

The types of ships were segmented using the system highlighted in **Figure 12**.The ships were categorized into 3 groups:cargo ships and carriers,oil and gas related ships and tankers,and other miscellaneous ships.This helps identify the preferences of the pirates when choosing their targets. Moreover,the geographical area where the accidents occurred was segmented into three zones.ZoneA represents the northernmost past of the area,zoneB is the center and zoneC is the southernmost edge (**Figure13**).

TABLE 1 Formatting of the parameters for the statistical analysis

Parameter	Number of groups	Separation rule	Groups	Characteristic tested
Date (season)	4	Manual	Winter (January to March)-Spring (April to June)-Summer (July to September)- Autumn (October to December)	Season
Time (period of day)	4	Manual	Night (12 am-6am)-Morning (6 am-12pm)-Afternoon (12pm-6pm)-Evening (6pm-12 am)	Period of day
Location of ship	3	Categorical	Port Areas/ Not port areas	Port Area
			Territorial Waters/ Not territorial waters	Territorial waters
			International Waters/ Not international waters	International waters
Status of ship	2	Categorical	Steaming/Not steaming	Steaming
			At anchor/ Not at anchor	At anchor

Under Review

Threat level	3	Manual	Level 1	Most severe attacks
			Level 2	Serious attacks
			Level 3	Less serious incidents
Weapons used	2	Yes/No	Weapons involved in incidents/ No weapons involved or stated	Weapons involved in attack
People involved in attack	3	Categorical	1-4 people involved	Small group
			5-10 people involved	Medium group
			10+ people involved	Large group
Hostages/ Kidnapped	2	Yes/No	Taken hostage or kidnapped/ Crew safe	Crew abducted or taken hostage
Injuries	2	Yes/No	Crew injured/ Crew unharmed	Injuries
Fatalities	2	Yes/No	Casualties/ Crew safe	Fatalities
Gross tonnage	3	Manual	Small GT:0-20000/ Medium GT: 20000-70000/ Large GT: >70000	Gross Tonnage
Ship type	3	Categorical	Cargo/ Not Cargo	Cargo ships and carriers
			Oil & Gas or tanker/ Not Oil & Gas or tanker	Oil & Gas related ships or tankers
			Other	Other ships
Geographical Zone	3	Manual	Zone A, Zone B, Zone C (view on map)	Coastal states
Season Type	2	Manual	Dry or Rain season	Monsoon season?

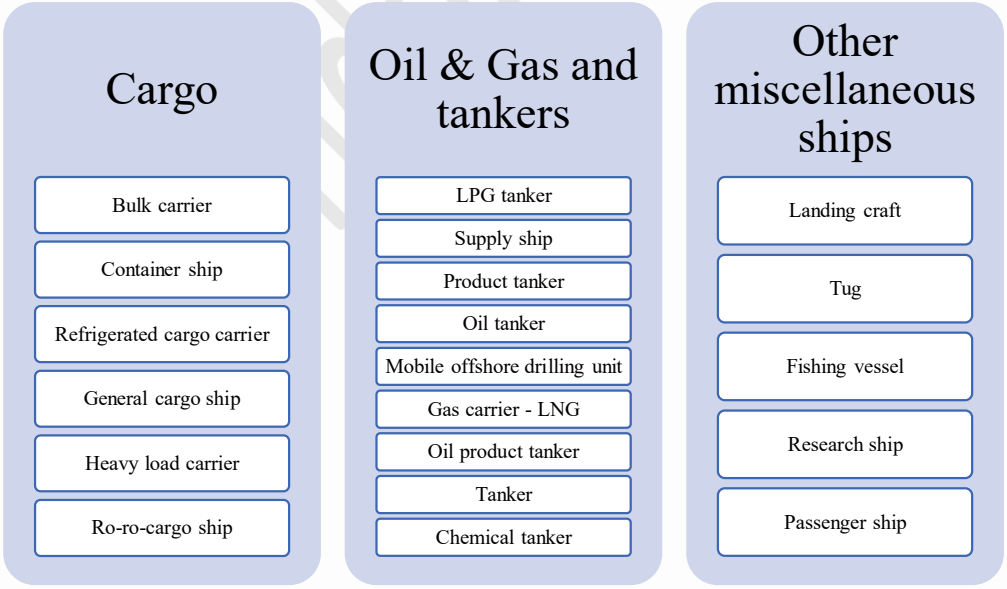


Figure 12 Segmentation into ship types

Under Review

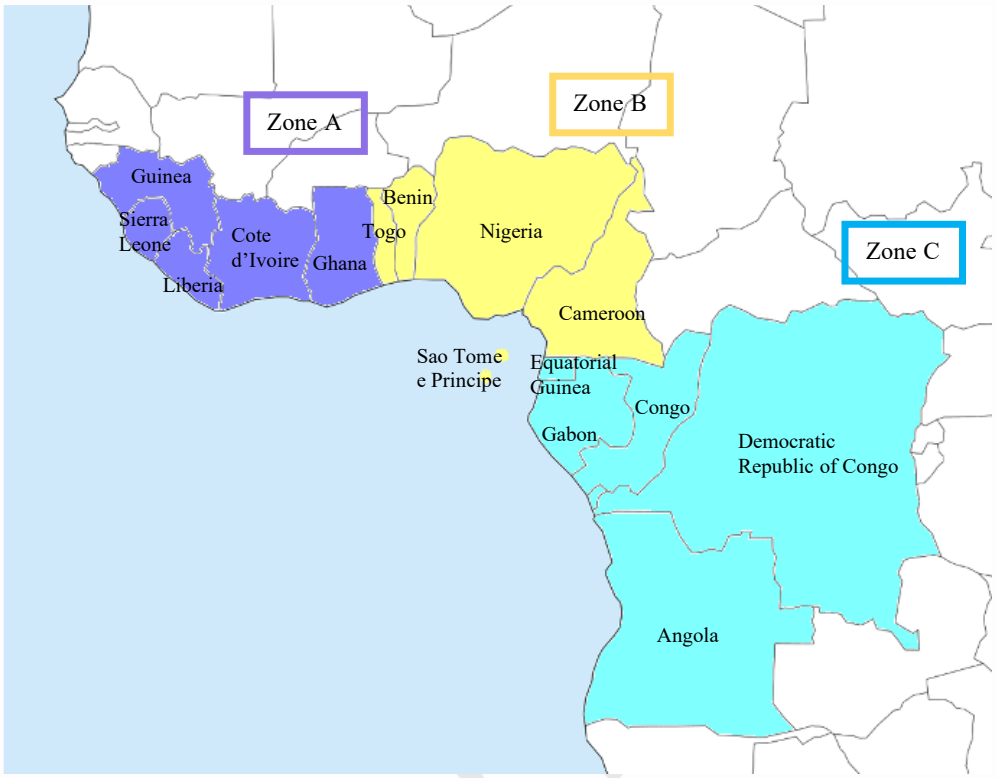


Figure 13 Segmentation of area of study

Although the IMO's databank is official and reliable when it comes to all maritime related activities, it lacks precise information about the companies to whom the ships belong,as well as the equipment and defense mechanisms fitted on each ship.Most shipping companies do not make their data available to the public(*27*).A data gap can be observed when it comes to the perpetrators involved in the attack,such as socio-demographic information that could help to visualize the profile of pirates in the region and better understand their motives.Furthermore, no detailed information is available on the military interventions that occurred as a response to the attacks. However,this kind of information is very sensible and thus classified.

Data quality assessment

A Data Quality Assessment(DQA) was conducted to ensure the suitability of the data for the ensuing analysis, following the methodology of (*29*).**Figure14** represents the full breakdown of the data quality assessment and the scores obtained.All scores are superior to 50%,which renders the dataset valid.

Quantitative analysis	Qualitative analysis	Narrative analysis
•Accessibility: 63.52% •Completenes: 91.31% •Consistency: 93.94% •Relevance: 100%	•Accuracy: High (data is consistent with narratives) •Interpretability: It is assumed that the reporter (IMO) and the analyst have similar understanding and interpretation of data fields. •Timeliness: No information available, but assumed to be short gap of time •Credentials: Data is obtained from a reliable and credible source (IMO)	•Level of detail of narrative: 81.89% (Detailed: likely to provide majority of requested information) •Narrative length (> 50 words): 63.33% •Outcome to ship and crew: 100% •Weapons mentioned: 57% •If used, type of weapon stated: 82%

Figure 14 Data Quality Assessment results

Dataset Segmentation

The threat level of attacks is based on a definition of the IMB regarding the severity of attacks.Level1 attacks are the most severe and encompass any incident that resulted in harm to the crew.This englobes hijackings, hostage situations, kidnappings, injuries,and casualties. Level2 attacks are less serious but involve weapons and any attempt to board the ship and/or harm the crew,even if it had to be aborted. Finally,Level3 incidents are the less severe and encompass any accident that doesn't fit in the two categories previously described,such as mainly robberies and theft. Most incidents are not serious. Nonetheless, it is crucial to highlight that amount of Level3 attacks is approximately equal to the sum of more severe attacks(Level1 and Level2) which intend harm to the crew.**Figure15** highlights the aggressivity of pirates in the GoG and their willingness to commit violence.

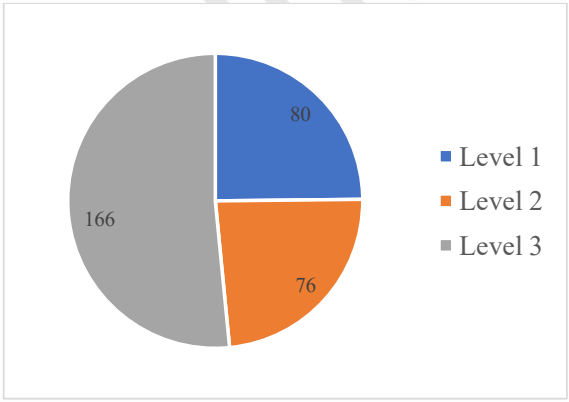


Figure 15 Number of incidents according to their severity (2017-2022)

Statistical analysis

This section of the paper depicts the main observations and takeaways obtained from the dataset as well as the results of the statistical analysis that was conducted. Firstly,data and parameters of interest were visualized through tables, plots,and charts in order to facilitate the observation process and retain some key insights. Subsequently,a contingency analysis was carried out on IBM's SPSS26 in order to test the association between a pair of parameters.

Ship state and location

As depicted in **Figure16**, attacks most frequently occur international waters,followed by port areas and lastly territorial waters.When considering Level 1&2 attacks,most incidents took place when the ship was in international waters(62%), followed by territorial waters(23%). The relationship between attack location and threat level will be discussed further in the following part of this paper.

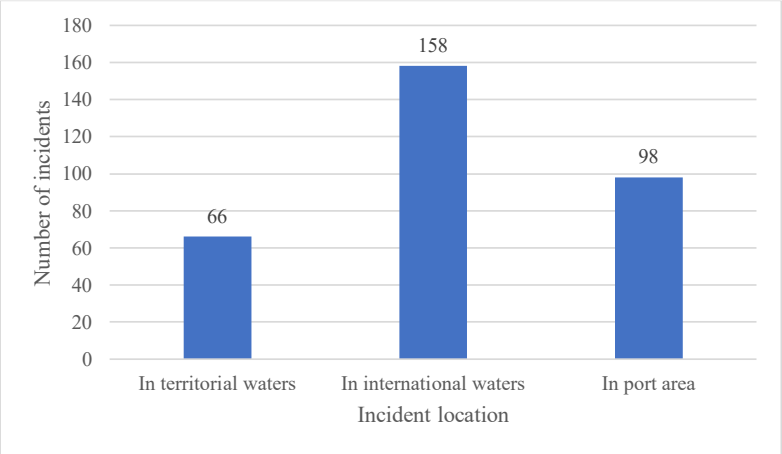


Figure 16 Plot of the distribution of location of incidents

The dataset indicates that most attacks in international and territorial waters occurred while the vessel was steaming whereas the ship was at anchor in incidents reported in port areas. Incidents when the ship is at berth were disregarded as they do not fall under the umbrella of piracy. Furthermore,incidents with higher severity levels are more likely to occur when the ship is steaming.This can be tied back to the fact that ships are more likely to be steaming while out at sea and at anchor in ports.

Weapons and people involved

In most attacks, weapons are not involved(67%). The IMO reports do not distinguish between the absence of weapons and lack of reporting of the presence of weapons.This is the case for numerous Level1-2 attacks with hostage situations,but no reported weapons. Thus, the number of attacks involving weapons is underreported. Overall, weapons were involved in 32% reported incidents.Regarding incidents that involved firearms, most attacks occur in international waters(68%) followed by territorial waters(20%). Attacks with smaller groups(1-4 persons) are typically less serious,whereas severe attacks tend to involve larger groups, however most incidents have not reported the number of perpetrators involved.

Attack time

Most attacks occur at night (51.24%), especially in port areas where about 82% of incidents take place between midnight and 6am.On the other hand, attacks at sea(especially international waters) are more frequent during the day(**Figure17)**. Similar observations can be made for the state of the ship.Incidents

involving ships at anchor are mostly at night, whereas attacks on steaming vessels are more common during daytime.

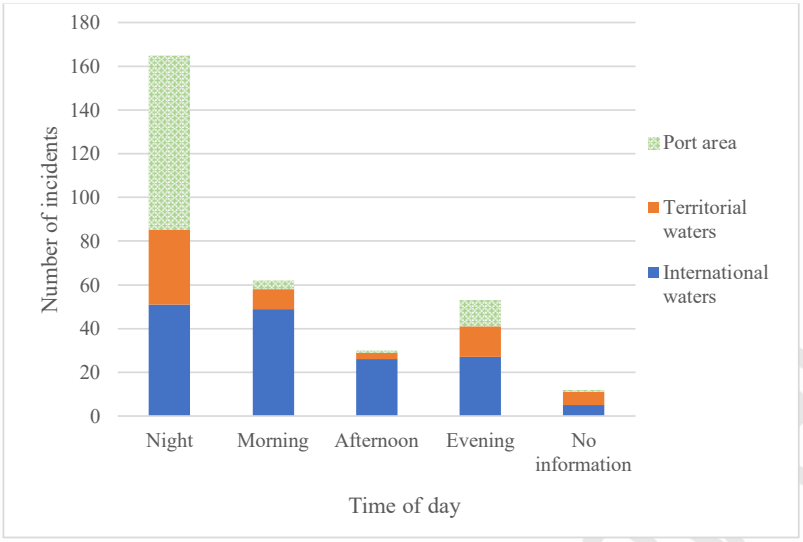


Figure 17 Plot of the distribution of attacks with respect to period of day and location

Attack season

As **Figure18** indicates, most attacks occur in dry season(winter and fall).Over the period analyzed,the peaks of attacks were from December to March.The dry season has from 2017 to 2022 witnessed double the number of incidents compared to the rainy season.A similar situation can be observed for the attack location.It can be observed that attacks in international and territorial waters are more frequent during the dry season.On the other hand, attacks occurring in the rainy season are more frequently located in port areas.

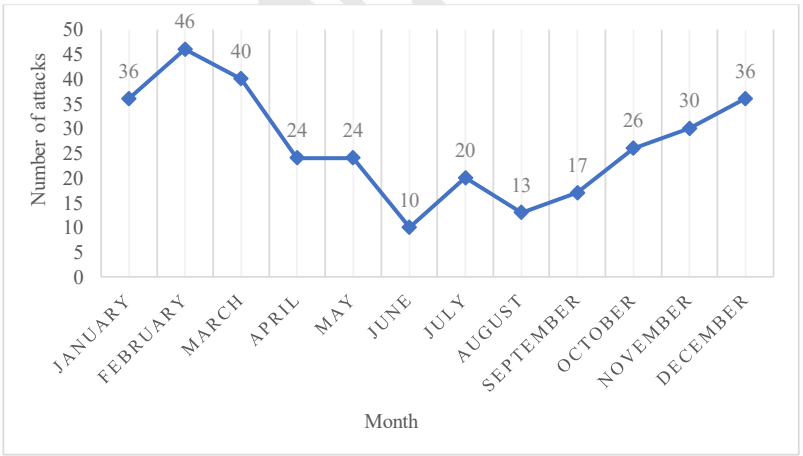


Figure 18 Temporal distribution of attacks by month (2017-2022)

Contingency analysis

The dataset comprises of four distinct types of variables: continuous (e.g.number of hostages, gross tonnage, casualties,etc.),text (narratives), dates and categorical (e.g.location of ship, state of ship, etc.).The several categorical and continuous variables that were gathered to assemble the dataset can be examined in greater depth to detect any potential associations and relationships that exist between the variables.This is achieved using Pearson's chi-squared test,which compares the actual observed counts of events against the expected counts if all variables were independent.The observed frequency refers to the actual observed counts of accidents whereas the expected frequency depicts the count that would be expected if no relationship or association existed between the variables.For the test assumptions to be valid, less than 20%of the data fields should have expected frequencies below five.For this analysis, the null hypothesis is rejected with a 95% confidence level(*30*).

Then, the correlation coefficient Phi is used to determine the strength of these associations,with the following Phi ranges:

- 1.0 to -0.5 & 0.5 to 1.0 –Strong relationship;
- 0.5 to -0.3 & 0.3 to 0.5 -Moderate relationship;
- 0.3 to -0.1 & 0.1 to 0.3 -Weak relationship;
- 0.1 to 0.1 -None or very weak relationship.

Contingency- Threat level

A relationship of moderate strength has been observed between threat level and attack location.The data and statistical analysis suggest that severe attacks (threat Levels1&2) are more likely to occur in territorial and especially international waters.The lack and difficulty of policing and patrolling the seas,especially international waters, incentivizes pirates to conduct more threatening attacks.Severe attacks typically involve guns and other kinds of firearms and often result in the kidnapping of the crew.It would be more practical to carry out these attacks and operate firearms at sea rather than closer to shore due to the absence of witnesses and security. However,less severe attacks, such as petty theft, are more common in ports.This is understandable as it is easier to access the ship unnoticed when it is at port, since some crewmembers may be out, being easier to board that ship. Furthermore, individuals approaching the ship in ports would seem less suspicious than in open sea due to the high volume of transit of ships of all sizes.

A moderate strength relationship exists between threat level and period of the day.While Level3 incidents are more likely to occur at night (12:00am to 6:00am), Level 1 and 2 attacks are more probable during the day or evening (6:00am to 12:00am).As stated earlier, severe attacks usually involve weapons and are more likely to occur in international waters.It is safer to sail during daytime as visibility is a key safety factor.The same argument is also valid for the use of weapons, which is a trademark of serious attacks. On the other hand, Level 3 attacks are more likely at night, in ports.Pirates can access the ships and steal more easily at night as they benefit the cover of darkness. Furthermore, the crew is more likely to be out or sleeping at night, increasing the probability of pirates going undetected. Finally,traffic and the presence of witnesses and bystanders is less likely at such late hours.

A weak positive association exists between the number of people involved in the attack and accident severity.The data suggests that more people are likely to be involved in severe attacks, whereas Level3 attacks are typically carried out by smaller groups. Indeed, Level1 attacks frequently entail kidnappings and hostage situations, which would require more people to ensure a smooth coordination and successful execution.

A moderate positive relationship exists between threat level and the status of the ship when attacked, which can be tied back to the associations between severity and attack location as well as time.

Finally,a weak positive relationship links the severity of the attack and the season at which it occurred.In this situation,the season refers to the dry and rainy season as no substantial relationship was found when testing for each three months season separately.As described previously, the dry season has a calmer weather that facilitates seafaring.On the other hand, the monsoon season has a very turbulent climate which would make any seaborn operations very challenging and dangerous. Since relationships

between threat level and attack location were formerly discovered, this validates the hypothesis of the existence of a link between season and threat level. Indeed, serious attacks are more likely to occur in the dry season.Similarly, sever attacks usually take place in territorial and international waters. Hence, the existence of a relationship between the season and severe attacks is expected.As for less serious attacks, since they mostly occur in port areas, climate is not such an important factor and therefore are not sensitive to seasonality.

Contingency- Attack location

A relationship of moderate strength correlates attack location and time.As a matter of fact, attacks in territorial and international waters are more likely to occur during the day whereas incidents in port areas are common at night.This relates to the concept of visibility and how it can affect the pirate's behavior and dictate the modus operandi used in the incidents. Sailing in the open seas is difficult at night due to poor visibility, especially for pirates who lack the proper equipment.As for attacks in port areas, they are more likely to occur at night under the cover of darkness.The poor visibility plays in the pirates' advantage in this case as it will prevent crew and bystanders from noticing them and alert security.

As Level1 and Level2 attacks are more likely to occur in territorial and international waters,this validates the hypothesis that weapons usage in pirate attacks is more likely to occur at sea instead of port areas.This association between the attack location and the weapons used can be explained by multiple factors.First, policing and security is weaker at sea, especially in international waters, compared to onshore and in port areas.Hence, carrying and using a firearm can go unnoticed while at sea.Indeed, firing their guns towards the bridge is a technique used by the pirates to scare the crew and force the ship to stop.Besides, since most serious entail hostages that can be released for ransoms, firearms are a common deterrent and intimidation tool used to manipulate the crew and force them to submit. Since it is conventional to hire private armed guards to protect the ships,pirates also look at weapons as a self-defense instrument.

Contingency- Ship state

A relationship of moderate strength can be observed between the status at time of incident and type of the ship, which can be tied back to the severity level of the incident. Indeed, tankers and oil and gas related ships are more likely to be attacked while at anchor.Actually, pirates often tend to attack during STS operations with the aim of stealing the oil to resell it on the black market.

On the other hand,attacks on cargo ships and other miscellaneous vessels are more likely to occur while steaming. Indeed, stealing cargo from these ships can be cumbersome and difficult to sell on black market as they are not essential goods in high demand. Hence,pirates might favor kidnappings and hostage situations for cargo and miscellaneous ships as the crew is the most valuable asset onboard.

Narrative analysis

The analysis of the narratives and detailed accounts of each incident suggest that the presence of armed guards onboard is a successful pre-emptive and protection method.The detailed accounts of some Level2 incidents indicate that the actions and presence of armed guards onboard of the ship have effectively pushed the pirates into aborting the attack. From firing warning shots to engaging the pirates in combat and returning fire,the armed guards have successfully prevented the situation from escalating any further on several occasions.The guards foiled any attempt of the pirates to board the ship and harm the crew. This observation highlights the effectiveness of PMSCs in the fight against piracy and raises the question about the scale of their implementation,which will be debated in greater depth in the subsequent section of this report. Finally,the narratives also indicate that boarding was rarely successful when the master of the ship undertook evasive maneuvers, which highlights the effectiveness of this tactic against pirate threat.

A summary of the key findings obtained from the observations and statistical analysis of the dataset is depicted in **Figure19**:

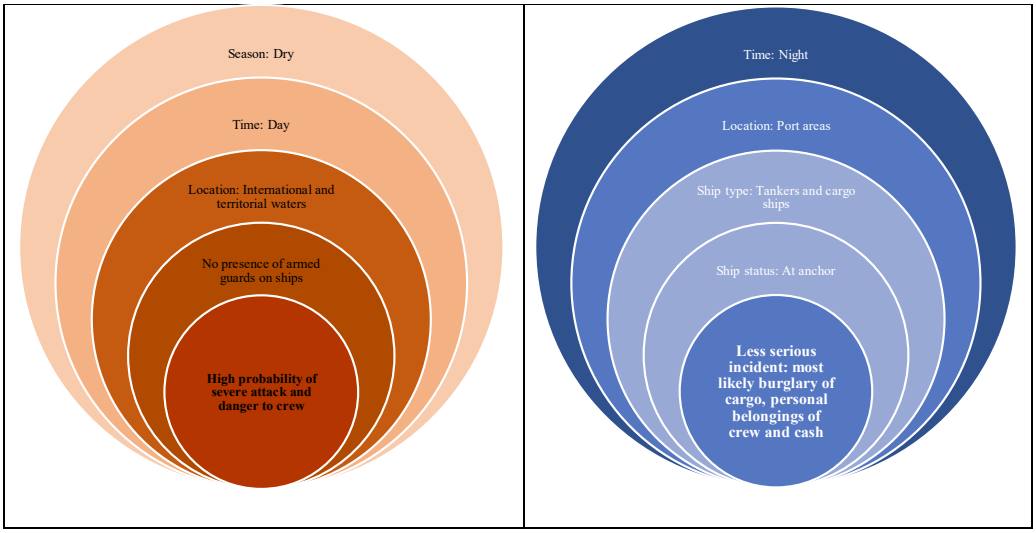


Figure 19 Summary of the main links found between the parameters and their relationship in a real-life scenario

DISCUSSION

Results summary

This research investigated the main traits of piracy in Western Africa.To do so, a dataset was constructed by compiling relevant data from reports provided by the IMO.This study has focused on a period spanning from 2017 to 2022 where 322 incidents were reported.This paper is the first statistical analysis of west African piracy over this timespan.A full breakdown of the main results is available in **Figure20**:

Under Rev

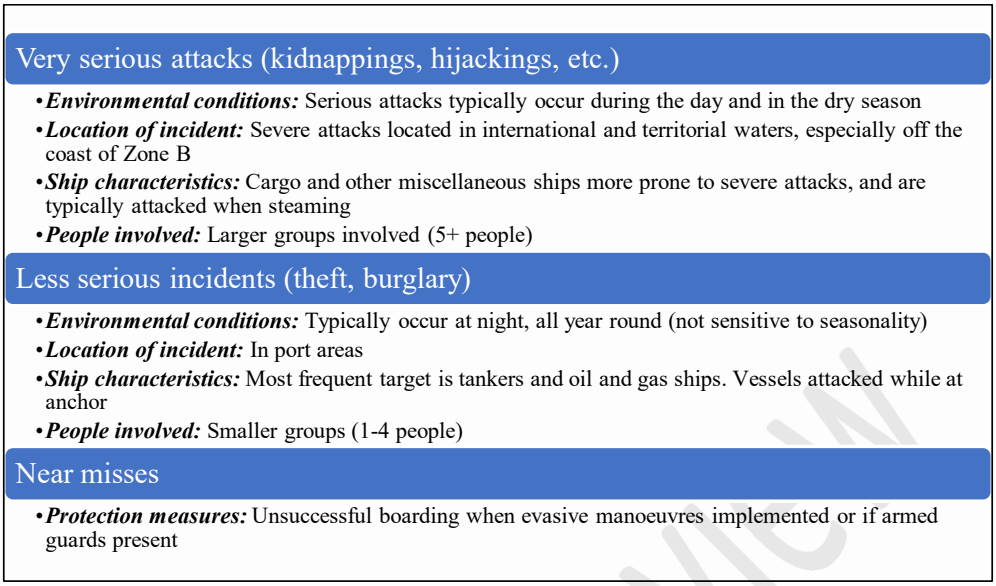


Figure 20 Summary of the main findings of this study

Implications

This paper has found concurring results to previous literature.The influence of time and location of incident on its severity validates the observations made by(*27*).As well,the discovered impact of climate and time agrees with(*28*).

This study has shown that ship properties and the implementation of protection measures play a role in determining the incident occurrence likelihood and its outcome.Another interesting observation is that large groups carry out more severe attacks. This draws a parallel to(*26*), where it is argued that west African piracy is exhibiting the signs of organized crime.**Figure21** depicts the summary of the most effective protective measures according to the narrative analysis.

Under Review

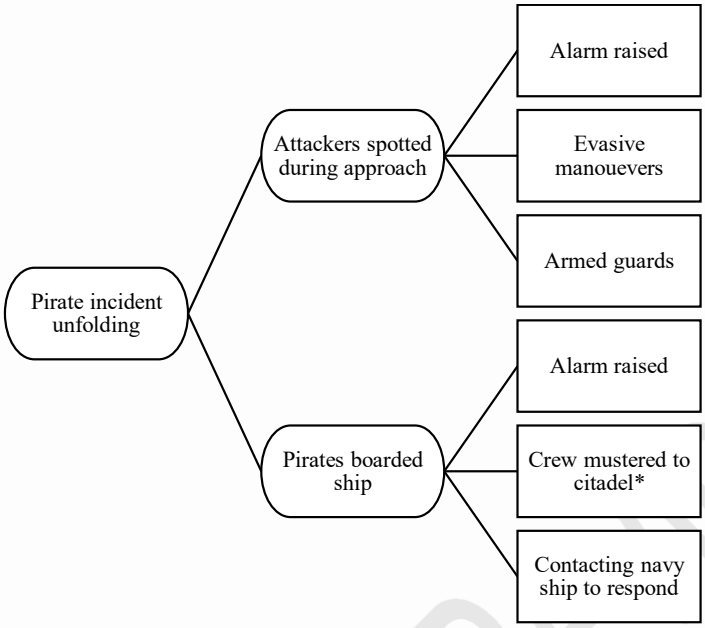


Figure 21 Effective protective measures in different scenarios, based on analysis of narratives

Limitations and dataset issues

Several limitations should be considered as they obstruct the accuracy and reliability of the data and results obtained.The IMO reports used to assemble the dataset exhibited numerous gaps and were not able to discern between the absence of weapons and lack of reporting. Besides, the narratives provided showed inconsistency in length and detail level.Furthermore, another limitation to this analysis is the sole reliance on the IMO to compile the dataset.Other reliable sources such as shipping companies and governmental agencies, private maritime security companies and militaries keep their records classified given the sensitive nature of the information. Lastly,the IMO data fails to mention the protective infrastructure that is fitted on each ship as it can play a big part in understanding their effectiveness on preventing boardings. Evasive maneuvers,SSAS and citadels were mentioned but other measures such as fortification of deck, pressurized water cannons or motion sensors were not stated in the reports.

Another issue that affects the integrity of the data is underreporting of incidents.The IMB estimated underreporting worldwide to be as high as 48% in 2018 and 62% in 2017,which is problematic as the absence of data impedes the accuracy of the analysis.This issue was also brought forward by(*27*), arguing that incidents with severe consequences were underreported since they might entail classified information or the people responsible for reporting are no longer onboard or alive. Incidents with low to no consequences are also underreported as they can seem normal and not worth the bother of going through the reporting process.(*27*) claimed that the investigation of news reports in 2012 and 2013 suggests that more than 7%of severe incidents were not reported(2 in 31).

Overview

The scrutinization of the narratives suggests that incidents where armed guards were present on the ship had no boarding or harm done to the crew.This is a testament to the effectiveness of PMSCs as a first layer of defense against piracy.The superior firepower has, in all studied cases, dissuaded the pirates from pursuing their attack. Nonetheless, this topic is sensible as it entails legal and ethical challenges.The

Under Review

legislations on Private Maritime Security Companies (PSMCs) and presence of weapons onboard of ships is variable from one port authority to the other. This is problematic for long voyages, which can discourage ships from hiring PSMCs and expose them to a greater risk.

The use of PSMCs also raises serious ethical questions.As(*31*) argued, pirates are morally innocent as they commit crimes to end their starvation. Armed guards would in that case be an unjust form of warfare. Furthermore,the use of PSMCs could lead to accidents and endanger the guards,crew, non-liable pirates, and bystanders.Finally,the lack of proper mental state and psychological background check on PSMCs could put crew members at risk(*32*). Indeed,emotionally unstable guards could use their weapons to harm other onboard of the ship.

Another takeaway from this analysis is the ineffectiveness of citadels as kidnappings occurred on 14 occasions after mustering to the citadel.It is important to highlight that the citadel acts as a last line of defense when pirates already boarded. Although the fortification level of the citadel was not specified, it is fair to assume that it can't hold indefinitely against automatic weapons and explosives. Hence, new technologies could reinforce the citadels, enabling them to last longer. Indeed,technology plays a big role in the fight against piracy.For instance, motion sensors and CCTVs with night vision and thermal imaging can be fitted across the ship and AI systems can be used to detect any potential threat approaching the ship.Machine learning can be implemented to teach the system to identify the presence of weapons and detect their thermal signature, then triggering an alarm.This time-saving technology could allow the ship to start evasive maneuvers early-on and remove human error in the surveillance of the ship. Another interesting prospect is the use of autonomous or remotely controlled system taking over the commands of the ship in the event of a hijacking.

Finally,all the aforementioned methods would effectively mitigate piracy incidents as they are unfolding. Nonetheless,to eradicate piracy in the region, it is crucial to tackle this problem at its roots. Indeed, mitigating and offering sustainable solutions to the factors driving piracy in the region would have a great impact in dissuading potential pirates in favor of living a normal life. **Figure22** highlights the main recommendations that could in theory reduce piracy incidence in the GoG as well as improve the regional economies, empower local populations, and ascertain the sovereignty of west African nations. These suggestions,based on the results of this research,corroborate the arguments of previous literature. Although they are hypothetical and their implementation is constrained by great limitations,the combination of these resolutions can potentially contribute to reducing the number of people who will resort to piracy as a way to survive and provide for their families.

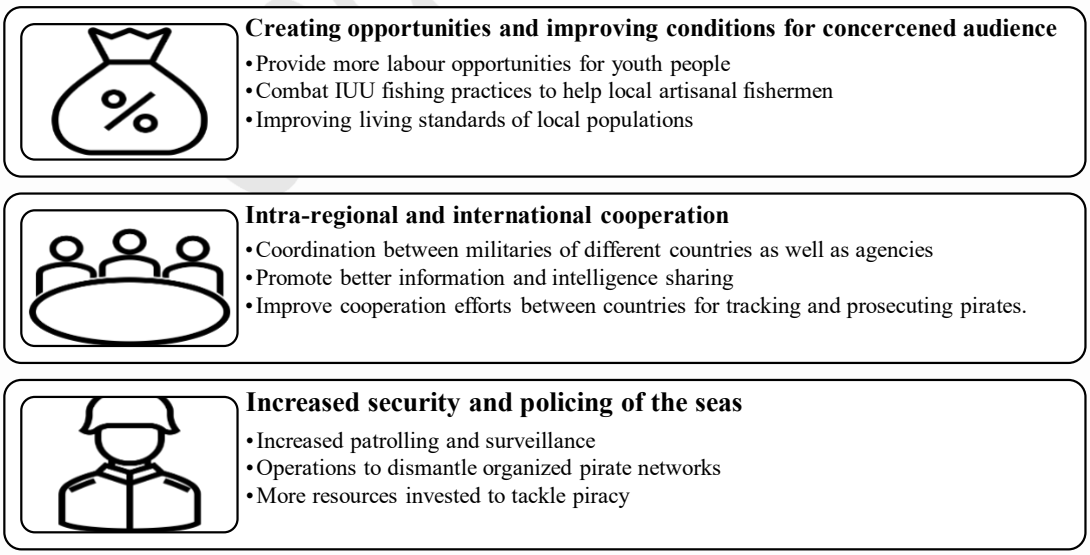


Figure 22 Efficiency of protective measures in different scenarios, based on analysis of narratives

This study's main objective is to understand the parameters and factors behind pirate attacks in the GoG, with the aim of providing tangible solutions to improve the safety of the waters of Western Africa.The data analysis has suggested the existence of links between different parameters that, if brought together, can create an environment prone to pirate attacks.Although piracy is a random and unpredictable hazard, the insight delivered from the data can serve as a first step in implementing predictive models and that can assess the likelihood of a pirate attack given the current conditions and parameters. This research acts as a foundation for others to build on, by expanding the analysis, increasing the size, and addressing the gaps of the dataset, as well as considering new relevant parameters, such as data regarding the tactics, weapons and equipment used by the pirates.This information can provide great insight and help shipping companies,PMSCs and militaries better understand the modus operandi of pirates,which will allow them to boost their defenses and reduce likelihood of boardings.

CONCLUSION

Since the dawn of naval exploration, piracy has been an enduring threat to the safety of seafarers. Although rare and endemic to some areas nowadays, piracy still has drastic ramifications for both cargo and crew. While other hazards can be forecasted, maritime piracy is dynamic and virtually unpredictable. This research has aimed to provide an overview and analysis of the piratical threat in the waters of the GoG. Reports spanning from 2017 to 2022 were compiled to generate a dataset that was subsequently analyzed.The occasional lack of detail in some of the narratives as well as gaps in the reporting of data concerning the presence of weapons and people involved acted as a clear obstruction to the completion of this investigation. A contingency analysis was conducted (**Figure23**), proving the existence of correlations between several parameters of interest. The existence of an association between different parameters is of paramount importance as it indicates the conditions under which pirates like to operate. The results suggest that severe incidents are most likely daytime attacks in international waters, while the ship is steaming, carried out by large armed groups during the dry season. Moreover, less serious incidents involve smaller groups and occur in port areas at night when the ship is at anchor. The high proportion of severe attacks highlights the brutality of pirates in the GoG, thus stressing the urgency of fighting this heinous crime. This ground-breaking research helps better understand and visualize the factors and conditions of each incident occurring in the GoG. This can play a substantial role in potentially predicting the probability of incidents, assessing the risk level of the area,and reducing the number of tragic losses suffered at the hands of pirates.

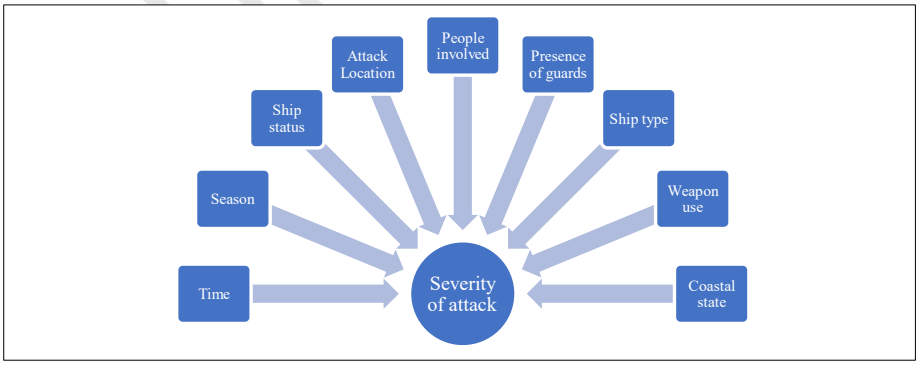


Figure 23 Diagram highlighting the different factors influencing the probability and severity of an attack

REFERENCES

1. UNCTAD.Review of Maritime Transport 2021,2022.https://unctad.org/webflyer/review-maritime-transport-2021[Accessed01/06/2022].
2. United Nations.Legal Framework for the Repression of Piracy Under UNCLOS,2010.https://www.un.org/depts/los/piracy/piracy_legal_framework.htm[Accessed01/06/2022].
3. Anderson,J.L. Piracy and World History:An Economic Perspective on Maritime Predation, 1995.Journal of World History.6(2),175-199.https://www.jstor.org/stable/20078637.
4. ICC International Maritime Bureau.Piracy and Armed Robbery against ships report for the period 1January-31December2020,2021.
5. Statista.Pirate Attacks, 2022.Available from:https://www.statista.com/topics/1290/pirate-attacks/[Accessed22/03/2022].
6. EU Naval Force.Operation ATALANTA,2022.https://eunavfor.eu/[Accessed03/04/2022].
7. ICC International Maritime Bureau.Piracy and Armed Robbery against ships report for the period 1January-31December2021,2022.
8. ICC-Commercial Crimes Service.IMB Piracy Reporting Centre,2022.https://www.icc-ccs.org/index.php/piracy-reporting-centre[Accessed15/04/2022].
9. IMO.Introduction to IMO,2022.https://www.imo.org/en/About/Pages/Default.aspx[Accessed11/03/2022].
10. Jones,P.J.Biodiversity in the Gulf of Guinea: an overview,1994.Biodiversity and Conservation.3(9),772-784.10.1007/BF00129657.
11. EU Maritime Security Factsheet:The Gulf of Guinea,2021https://www.eeas.europa.eu/eeas/eu-maritime-security-factsheet-gulf-guinea_en[Accessed13/03/2022].
12. Smith,E.Pirates are expanding in West Africa, threatening offshore oil storage,2020.https://www.cnbc.com/2020/04/27/pirates-are-expanding-in-west-africa-threatening-offshore-oil-storage.html[Accessed17/04/2022].
13. Morcos,P.A.Transatlantic Approach to Address Growing Maritime Insecurity in the Gulf of Guinea,2021.https://www.csis.org/analysis/transatlantic-approach-address-growing-maritime-insecurity-gulf-guinea[Accessed08/05/2022].
14. Brownfield,M.,Charpentier,R.Geology and Total Petroleum Systems of the Gulf of Guinea Province of West Africa,2006.
15. The World Bank in Africa,2021.https://www.worldbank.org/en/region/afr/overview#1[Accessed02/03/2022].
16. United Nations.West Africa:Extreme poverty rises nearly 3 per cent due to COVID-19,2022.https://news.un.org/en/story/2022/01/1110192[Accessed23/03/2022].
17. Marc,A.,Verjee,N.,Mogaka,S.The challenge of stability and security in West Africa,2015.Washington,World Bank.
18. Ifesinachi,K.,Nwangwu,C.Implementation of the Yaounde Code of Conduct and Maritime Insecurity in the Gulf of Guinea,2015.Research on Humanities and Social Sciences.(2224-5766),https://www.researchgate.net/publication/288965394_Implementation_of_the_Yaounde_Code_of_Conduct_and_Maritime_Insecurity_in_the_Gulf_of_Guinea.
19. President Buhari Launches Deep Blue Project in Lagos,2022.https://nimasa.gov.ng/president-buhari-launches-deep-blue-project-in-lagos/[Accessed15/05/2022].
20. The Maritime Executive.EU Renews its Commitment to Anti-Piracy Patrols in Gulf of Guinea,2022.https://www.maritime-executive.com/article/eu-renews-its-commitment-to-anti-piracy-patrols-in-gulf-of-guinea[Accessed11/05/2022].
21. Desai,R.M.,Shambaugh,G.E.Measuring the global impact of destructive and illegal fishing on maritime piracy: A spatial analysis,2021.PloS One.16(2),e0246835.10.1371/journal.pone.0246835.
22. Denton,G.L.,Harris,J.R.Maritime Piracy,Military Capacity,and Institutions in the Gulf of Guinea,2022.Terrorism and Political Violence.34(1),1-27.10.1080/09546553.2019.1659783.

23. Gries,T.,Redlin,M.Pirates-The Young and the Jobless:The Effect of Youth Bulges and Youth Labor Market Integration on Maritime Piracy,2019.Defence and Peace Economics.30(3),309-323.10.1080/10242694.2017.1333797.
24. Daxecker,U.,Prins,B.Insurgents of the Sea:Institutional and Economic Opportunities for Maritime Piracy,2013.The Journal of Conflict Resolution.57(6),940-965.10.1177/0022002712453709.
25. Nincic,D.Maritime piracy in Africa: The humanitarian dimension,2009.African Security Review.18(3),1-16.10.1080/10246029.2009.9627538.
26. Fattah,M.M.A.Piracy in Gulf of Guinea causes, efforts and solutions,2017.Head of Training Department,Regional Maritime Security Institute,AASTMT.
27. Liwång,H.Piracy off West Africa from 2010 to 2014:an analysis,2016.WMU Journal of Maritime Affairs(JoMA).16(3),385-403.10.1007/s13437-016-0121-9.
28. Jiang,M.,Lu,J.The analysis of maritime piracy occurred in Southeast Asia by using Bayesian network,2020.Transportation Research.Part E,Logistics and Transportation Review.139101965.10.1016/j.tre.2020.101965.
29. Psyllou,E.,Majumdar,A.The Analysis of Airspace Infringements Over Complex Airspace in Europe and the United States of America.Journal of Navigation,Vol.73,No.5,2020,pp.1036–1051.https://doi.org/10.1017/S0373463320000156.
30. Wilke,S.,Majumdar,A.andOchieng,W.Y.The impact of airport characteristics on airport surface accidents and incidents,2015.National Safety Council.53,63-75.Available from:https://doi.org/10.1016/j.jsr.2015.03.006[Accessed04/05/2012].
31. Pattison,J.Justa piratica:the ethics of piracy,2014.Review of International Studies.40(4),631-656.10.1017/S0260210513000405.
32. Cusumano,E.,Ruzza,S.Piracy and the Privatisation of Maritime Security,2020.Cham,Springer International Publishing AG.

Appendix N. Results of the three-way association analysis for private, recreational GA seaplane occurrences in Canada.

Table N indicates relationships among different parameters along with their statistical significance (p-value), strength (phi-value), and qualitative strength of the relationship. It is just a subset of the full results which included over 3,000 associations of different strengths. Table N uses the parameters mentioned in Section 7.5.3, but it excludes the following parameters: month, time, aircraft category, amateur built, province/state and year. It includes only the moderate and strong relationships between three of the following four parameters: landing gear, aircraft damage level, phase of flight and initiating occurrence category.

Table N. Results for the three-way association analysis for private, recreational GA seaplane occurrences in Canada, for 99% confidence level and moderate or strong associations.

Parameter 1	Parameter 2	Parameter 3	p-value	phi-value	Strength
Float	Substantial	Landing	2.76E-10	0.3367	Moderate
Amphibious	Substantial	Approach	2.76E-10	0.3367	Moderate
Amphibious	Destroyed	Landing	2.76E-10	0.3367	Moderate
Amphibious	Destroyed	Climb	2.76E-10	0.3367	Moderate
Amphibious	Destroyed	Cruise	2.76E-10	0.3367	Moderate
Amphibious	Destroyed	Other Phase	2.76E-10	0.3367	Moderate
Amphibious	Destroyed	Approach	2.76E-10	0.3367	Moderate
Amphibious	Destroyed	Take-Off	2.76E-10	0.3367	Moderate
Amphibious	Other damage	Climb	2.76E-10	0.3367	Moderate
Amphibious	Other damage	Other Phase	2.76E-10	0.3367	Moderate
Other Gear	Substantial	Landing	2.76E-10	0.3367	Moderate
Other Gear	Substantial	Cruise	2.76E-10	0.3367	Moderate
Other Gear	Substantial	Other Phase	2.76E-10	0.3367	Moderate
Other Gear	Substantial	Take-Off	2.76E-10	0.3367	Moderate
Other Gear	Destroyed	Cruise	2.76E-10	0.3367	Moderate
Other Gear	Destroyed	Other Phase	2.76E-10	0.3367	Moderate
Float	Substantial	Climb	2.76E-10	0.3367	Moderate
Amphibious	Substantial	Take-Off	2.76E-10	0.3367	Moderate
Other Gear	Substantial	Climb	2.76E-10	0.3367	Moderate
Amphibious	Substantial	Other Phase	2.76E-10	0.3367	Moderate
Float	Destroyed	Cruise	2.76E-10	0.3367	Moderate
Amphibious	Substantial	Cruise	2.76E-10	0.3367	Moderate
Float	Substantial	Cruise	2.76E-10	0.3367	Moderate
Float	Substantial	Other Phase	2.76E-10	0.3367	Moderate
Float	Substantial	Approach	2.76E-10	0.3367	Moderate
Float	Destroyed	Landing	2.76E-10	0.3367	Moderate
Float	Destroyed	Climb	2.76E-10	0.3367	Moderate
Float	Substantial	Take-Off	2.76E-10	0.3367	Moderate
Float	Destroyed	Other Phase	2.76E-10	0.3367	Moderate
Float	Destroyed	Approach	2.76E-10	0.3367	Moderate
Float	Other damage	Cruise	2.76E-10	0.3367	Moderate
Float	Other damage	Other Phase	2.76E-10	0.3367	Moderate
Float	Other damage	Approach	2.76E-10	0.3367	Moderate
Amphibious	Substantial	Landing	2.76E-10	0.3367	Moderate
Amphibious	Substantial	Climb	2.76E-10	0.3367	Moderate
Amphibious	Destroyed	SCF-NP	3.84E-22	0.4733	Moderate
Amphibious	Destroyed	CTOL	3.84E-22	0.4733	Moderate
Amphibious	Destroyed	FUEL	3.84E-22	0.4733	Moderate
Amphibious	Destroyed	SCF-PP	3.84E-22	0.4733	Moderate
Amphibious	Destroyed	LOC-I	3.84E-22	0.4733	Moderate
Amphibious	Substantial	UNK	3.84E-22	0.4733	Moderate
Amphibious	Destroyed	Other Category	3.84E-22	0.4733	Moderate
Amphibious	Substantial	CTOL	3.84E-22	0.4733	Moderate
Amphibious	Substantial	ARC	3.84E-22	0.4733	Moderate
Amphibious	Other damage	Other Category	3.84E-22	0.4733	Moderate
Amphibious	Destroyed	ARC	3.84E-22	0.4733	Moderate
Other Gear	Substantial	FUEL	3.84E-22	0.4733	Moderate
Amphibious	Other damage	SCF-PP	3.84E-22	0.4733	Moderate
Amphibious	Other damage	FUEL	3.84E-22	0.4733	Moderate
Other Gear	Substantial	LOC-G	3.84E-22	0.4733	Moderate
Other Gear	Substantial	Other Category	3.84E-22	0.4733	Moderate
Other Gear	Substantial	SCF-NP	3.84E-22	0.4733	Moderate
Other Gear	Substantial	LOC-I	3.84E-22	0.4733	Moderate
Other Gear	Substantial	SCF-PP	3.84E-22	0.4733	Moderate
Other Gear	Substantial	ARC	3.84E-22	0.4733	Moderate
Other Gear	Substantial	UNK	3.84E-22	0.4733	Moderate
Other Gear	Destroyed	UNK	3.84E-22	0.4733	Moderate
Amphibious	Substantial	SCF-PP	3.84E-22	0.4733	Moderate

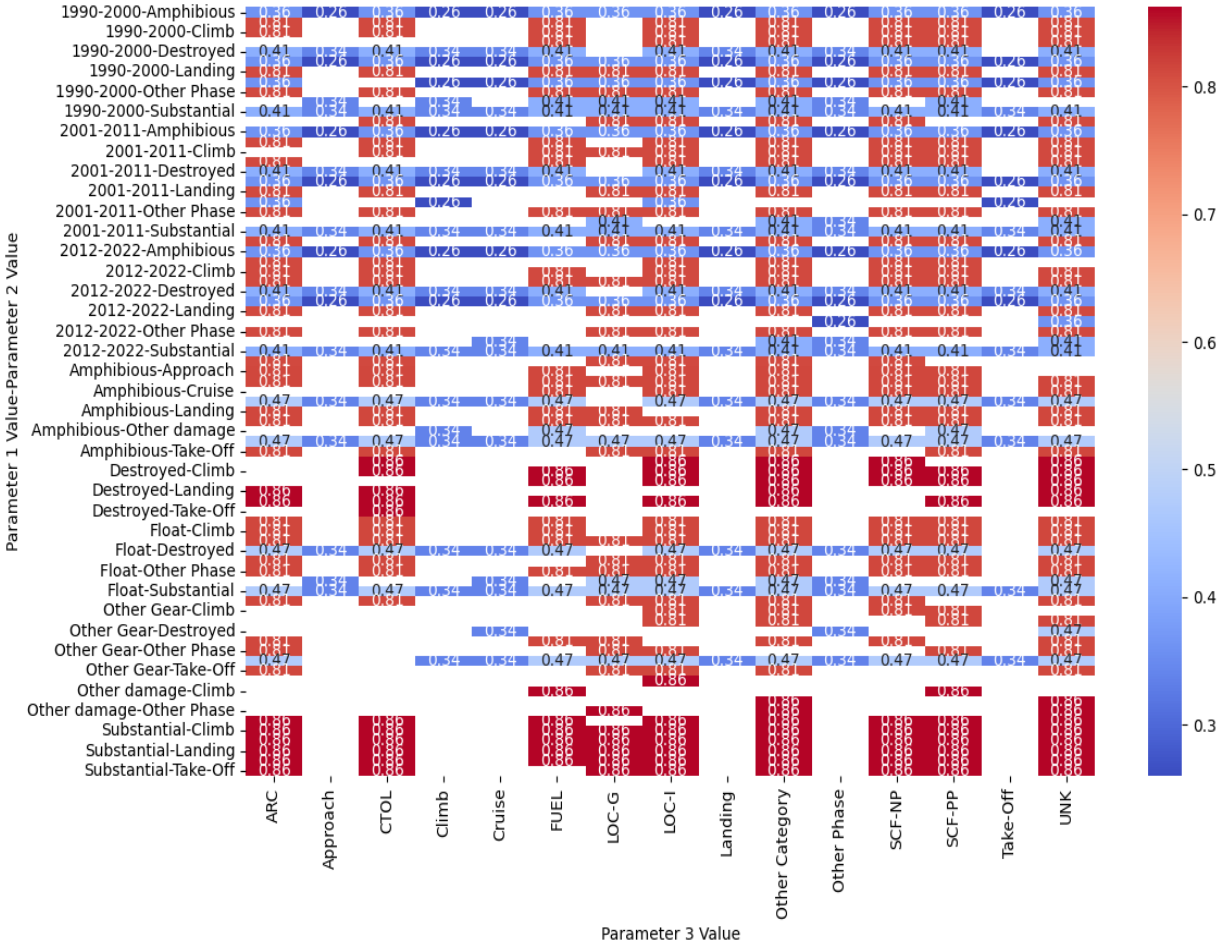
Parameter 1	Parameter 2	Parameter 3	p-value	phi-value	Strength
Amphibious	Substantial	FUEL	3.84E-22	0.4733	Moderate
Amphibious	Destroyed	UNK	3.84E-22	0.4733	Moderate
Amphibious	Substantial	LOC-I	3.84E-22	0.4733	Moderate
Float	Destroyed	LOC-I	3.84E-22	0.4733	Moderate
Amphibious	Substantial	SCF-NP	3.84E-22	0.4733	Moderate
Float	Substantial	LOC-G	3.84E-22	0.4733	Moderate
Float	Substantial	Other Category	3.84E-22	0.4733	Moderate
Float	Substantial	SCF-NP	3.84E-22	0.4733	Moderate
Float	Substantial	LOC-I	3.84E-22	0.4733	Moderate
Float	Substantial	SCF-PP	3.84E-22	0.4733	Moderate
Float	Substantial	FUEL	3.84E-22	0.4733	Moderate
Float	Substantial	ARC	3.84E-22	0.4733	Moderate
Float	Substantial	UNK	3.84E-22	0.4733	Moderate
Float	Destroyed	Other Category	3.84E-22	0.4733	Moderate
Float	Destroyed	SCF-NP	3.84E-22	0.4733	Moderate
Float	Substantial	CTOL	3.84E-22	0.4733	Moderate
Float	Destroyed	SCF-PP	3.84E-22	0.4733	Moderate
Float	Destroyed	FUEL	3.84E-22	0.4733	Moderate
Float	Destroyed	CTOL	3.84E-22	0.4733	Moderate
Float	Destroyed	ARC	3.84E-22	0.4733	Moderate
Float	Destroyed	UNK	3.84E-22	0.4733	Moderate
Float	Other damage	LOC-G	3.84E-22	0.4733	Moderate
Float	Other damage	Other Category	3.84E-22	0.4733	Moderate
Float	Other damage	LOC-I	3.84E-22	0.4733	Moderate
Float	Other damage	UNK	3.84E-22	0.4733	Moderate
Amphibious	Substantial	LOC-G	3.84E-22	0.4733	Moderate
Amphibious	Substantial	Other Category	3.84E-22	0.4733	Moderate
Destroyed	Cruise	SCF-NP	3.18E-91	0.8621	Strong
Destroyed	Cruise	LOC-I	3.18E-91	0.8621	Strong
Destroyed	Climb	SCF-NP	3.18E-91	0.8621	Strong
Destroyed	Cruise	Other Category	3.18E-91	0.8621	Strong
Destroyed	Climb	UNK	3.18E-91	0.8621	Strong
Destroyed	Climb	CTOL	3.18E-91	0.8621	Strong
Destroyed	Climb	FUEL	3.18E-91	0.8621	Strong
Destroyed	Climb	SCF-PP	3.18E-91	0.8621	Strong
Destroyed	Climb	LOC-I	3.18E-91	0.8621	Strong
Destroyed	Landing	Other Category	3.18E-91	0.8621	Strong
Destroyed	Climb	Other Category	3.18E-91	0.8621	Strong
Destroyed	Landing	UNK	3.18E-91	0.8621	Strong
Destroyed	Landing	ARC	3.18E-91	0.8621	Strong
Destroyed	Landing	CTOL	3.18E-91	0.8621	Strong
Substantial	Take-Off	UNK	3.18E-91	0.8621	Strong
Substantial	Take-Off	ARC	3.18E-91	0.8621	Strong
Substantial	Take-Off	CTOL	3.18E-91	0.8621	Strong
Substantial	Take-Off	SCF-PP	3.18E-91	0.8621	Strong
Destroyed	Cruise	FUEL	3.18E-91	0.8621	Strong
Substantial	Take-Off	LOC-I	3.18E-91	0.8621	Strong
Destroyed	Cruise	SCF-PP	3.18E-91	0.8621	Strong
Destroyed	Approach	UNK	3.18E-91	0.8621	Strong
Destroyed	Cruise	UNK	3.18E-91	0.8621	Strong
Destroyed	Other Phase	Other Category	3.18E-91	0.8621	Strong
Substantial	Take-Off	Other Category	3.18E-91	0.8621	Strong
Other damage	Other Phase	UNK	3.18E-91	0.8621	Strong
Other damage	Other Phase	Other Category	3.18E-91	0.8621	Strong
Other damage	Other Phase	LOC-G	3.18E-91	0.8621	Strong
Other damage	Cruise	UNK	3.18E-91	0.8621	Strong
Other damage	Cruise	Other Category	3.18E-91	0.8621	Strong
Other damage	Climb	FUEL	3.18E-91	0.8621	Strong
Other damage	Climb	SCF-PP	3.18E-91	0.8621	Strong
Destroyed	Take-Off	CTOL	3.18E-91	0.8621	Strong
Destroyed	Approach	CTOL	3.18E-91	0.8621	Strong
Destroyed	Approach	LOC-I	3.18E-91	0.8621	Strong
Destroyed	Approach	SCF-NP	3.18E-91	0.8621	Strong
Destroyed	Approach	Other Category	3.18E-91	0.8621	Strong
Destroyed	Other Phase	UNK	3.18E-91	0.8621	Strong
Destroyed	Other Phase	ARC	3.18E-91	0.8621	Strong
Destroyed	Other Phase	CTOL	3.18E-91	0.8621	Strong
Destroyed	Other Phase	FUEL	3.18E-91	0.8621	Strong
Destroyed	Other Phase	SCF-PP	3.18E-91	0.8621	Strong
Destroyed	Other Phase	LOC-I	3.18E-91	0.8621	Strong
Substantial	Take-Off	SCF-NP	3.18E-91	0.8621	Strong
Substantial	Climb	CTOL	3.18E-91	0.8621	Strong
Substantial	Take-Off	LOC-G	3.18E-91	0.8621	Strong
Substantial	Cruise	LOC-I	3.18E-91	0.8621	Strong
Substantial	Cruise	Other Category	3.18E-91	0.8621	Strong
Substantial	Cruise	LOC-G	3.18E-91	0.8621	Strong
Substantial	Climb	UNK	3.18E-91	0.8621	Strong
Substantial	Climb	ARC	3.18E-91	0.8621	Strong
Substantial	Climb	FUEL	3.18E-91	0.8621	Strong
Substantial	Climb	SCF-PP	3.18E-91	0.8621	Strong
Substantial	Climb	LOC-I	3.18E-91	0.8621	Strong
Substantial	Climb	SCF-NP	3.18E-91	0.8621	Strong
Substantial	Climb	Other Category	3.18E-91	0.8621	Strong
Substantial	Climb	LOC-G	3.18E-91	0.8621	Strong
Substantial	Landing	UNK	3.18E-91	0.8621	Strong

Parameter 1	Parameter 2	Parameter 3	p-value	phi-value	Strength
Substantial	Landing	ARC	3.18E-91	0.8621	Strong
Substantial	Landing	CTOL	3.18E-91	0.8621	Strong
Substantial	Landing	FUEL	3.18E-91	0.8621	Strong
Substantial	Landing	SCF-PP	3.18E-91	0.8621	Strong
Substantial	Landing	LOC-I	3.18E-91	0.8621	Strong
Substantial	Landing	SCF-NP	3.18E-91	0.8621	Strong
Substantial	Landing	Other Category	3.18E-91	0.8621	Strong
Substantial	Landing	LOC-G	3.18E-91	0.8621	Strong
Substantial	Cruise	SCF-NP	3.18E-91	0.8621	Strong
Substantial	Cruise	SCF-PP	3.18E-91	0.8621	Strong
Substantial	Approach	UNK	3.18E-91	0.8621	Strong
Substantial	Cruise	FUEL	3.18E-91	0.8621	Strong
Substantial	Approach	ARC	3.18E-91	0.8621	Strong
Substantial	Approach	CTOL	3.18E-91	0.8621	Strong
Substantial	Approach	FUEL	3.18E-91	0.8621	Strong
Substantial	Approach	SCF-PP	3.18E-91	0.8621	Strong
Substantial	Approach	LOC-I	3.18E-91	0.8621	Strong
Substantial	Approach	SCF-NP	3.18E-91	0.8621	Strong
Substantial	Approach	Other Category	3.18E-91	0.8621	Strong
Substantial	Other Phase	UNK	3.18E-91	0.8621	Strong
Substantial	Other Phase	ARC	3.18E-91	0.8621	Strong
Substantial	Other Phase	CTOL	3.18E-91	0.8621	Strong
Substantial	Other Phase	FUEL	3.18E-91	0.8621	Strong
Substantial	Other Phase	SCF-PP	3.18E-91	0.8621	Strong
Substantial	Other Phase	LOC-I	3.18E-91	0.8621	Strong
Substantial	Other Phase	SCF-NP	3.18E-91	0.8621	Strong
Substantial	Other Phase	Other Category	3.18E-91	0.8621	Strong
Substantial	Other Phase	LOC-G	3.18E-91	0.8621	Strong
Substantial	Cruise	UNK	3.18E-91	0.8621	Strong
Substantial	Cruise	ARC	3.18E-91	0.8621	Strong
Substantial	Cruise	CTOL	3.18E-91	0.8621	Strong
Other damage	Approach	LOC-I	3.18E-91	0.8621	Strong
Amphibious	Approach	Other Category	8.98E-74	0.8145	Strong
Amphibious	Other Phase	FUEL	8.98E-74	0.8145	Strong
Amphibious	Other Phase	CTOL	8.98E-74	0.8145	Strong
Amphibious	Other Phase	ARC	8.98E-74	0.8145	Strong
Amphibious	Other Phase	UNK	8.98E-74	0.8145	Strong
Amphibious	Approach	CTOL	8.98E-74	0.8145	Strong
Amphibious	Approach	SCF-NP	8.98E-74	0.8145	Strong
Amphibious	Approach	LOC-I	8.98E-74	0.8145	Strong
Amphibious	Approach	SCF-PP	8.98E-74	0.8145	Strong
Amphibious	Approach	FUEL	8.98E-74	0.8145	Strong
Amphibious	Approach	ARC	8.98E-74	0.8145	Strong
Amphibious	Other Phase	LOC-I	8.98E-74	0.8145	Strong
Amphibious	Other Phase	SCF-PP	8.98E-74	0.8145	Strong
Amphibious	Climb	CTOL	8.98E-74	0.8145	Strong
Amphibious	Other Phase	SCF-NP	8.98E-74	0.8145	Strong
Amphibious	Other Phase	Other Category	8.98E-74	0.8145	Strong
Amphibious	Other Phase	LOC-G	8.98E-74	0.8145	Strong
Amphibious	Cruise	UNK	8.98E-74	0.8145	Strong
Amphibious	Cruise	FUEL	8.98E-74	0.8145	Strong
Amphibious	Cruise	SCF-PP	8.98E-74	0.8145	Strong
Amphibious	Cruise	LOC-I	8.98E-74	0.8145	Strong
Amphibious	Cruise	SCF-NP	8.98E-74	0.8145	Strong
Amphibious	Cruise	Other Category	8.98E-74	0.8145	Strong
Amphibious	Climb	UNK	8.98E-74	0.8145	Strong
Amphibious	Climb	ARC	8.98E-74	0.8145	Strong
Amphibious	Take-Off	Other Category	8.98E-74	0.8145	Strong
Amphibious	Climb	SCF-PP	8.98E-74	0.8145	Strong
Amphibious	Take-Off	LOC-G	8.98E-74	0.8145	Strong
Other Gear	Climb	Other Category	8.98E-74	0.8145	Strong
Amphibious	Take-Off	LOC-I	8.98E-74	0.8145	Strong
Amphibious	Take-Off	SCF-PP	8.98E-74	0.8145	Strong
Amphibious	Climb	SCF-NP	8.98E-74	0.8145	Strong
Other Gear	Take-Off	UNK	8.98E-74	0.8145	Strong
Other Gear	Take-Off	ARC	8.98E-74	0.8145	Strong
Other Gear	Take-Off	LOC-I	8.98E-74	0.8145	Strong
Other Gear	Take-Off	Other Category	8.98E-74	0.8145	Strong
Other Gear	Take-Off	LOC-G	8.98E-74	0.8145	Strong
Other Gear	Other Phase	UNK	8.98E-74	0.8145	Strong
Other Gear	Other Phase	ARC	8.98E-74	0.8145	Strong
Other Gear	Other Phase	SCF-PP	8.98E-74	0.8145	Strong
Other Gear	Other Phase	LOC-I	8.98E-74	0.8145	Strong
Other Gear	Other Phase	LOC-G	8.98E-74	0.8145	Strong
Other Gear	Cruise	UNK	8.98E-74	0.8145	Strong
Other Gear	Cruise	SCF-PP	8.98E-74	0.8145	Strong
Other Gear	Cruise	LOC-I	8.98E-74	0.8145	Strong
Other Gear	Cruise	Other Category	8.98E-74	0.8145	Strong
Other Gear	Climb	SCF-PP	8.98E-74	0.8145	Strong
Other Gear	Climb	LOC-I	8.98E-74	0.8145	Strong
Other Gear	Climb	SCF-NP	8.98E-74	0.8145	Strong
Other Gear	Landing	UNK	8.98E-74	0.8145	Strong
Other Gear	Landing	ARC	8.98E-74	0.8145	Strong
Other Gear	Landing	FUEL	8.98E-74	0.8145	Strong
Other Gear	Landing	SCF-NP	8.98E-74	0.8145	Strong

Parameter 1	Parameter 2	Parameter 3	p-value	phi-value	Strength
Other Gear	Landing	Other Category	8.98E-74	0.8145	Strong
Other Gear	Landing	LOC-G	8.98E-74	0.8145	Strong
Amphibious	Take-Off	UNK	8.98E-74	0.8145	Strong
Amphibious	Take-Off	ARC	8.98E-74	0.8145	Strong
Amphibious	Take-Off	CTOL	8.98E-74	0.8145	Strong
Amphibious	Climb	LOC-I	8.98E-74	0.8145	Strong
Amphibious	Climb	FUEL	8.98E-74	0.8145	Strong
Amphibious	Climb	Other Category	8.98E-74	0.8145	Strong
Float	Other Phase	LOC-I	8.98E-74	0.8145	Strong
Float	Other Phase	Other Category	8.98E-74	0.8145	Strong
Float	Other Phase	LOC-G	8.98E-74	0.8145	Strong
Float	Cruise	UNK	8.98E-74	0.8145	Strong
Float	Cruise	ARC	8.98E-74	0.8145	Strong
Float	Cruise	CTOL	8.98E-74	0.8145	Strong
Float	Cruise	FUEL	8.98E-74	0.8145	Strong
Float	Cruise	SCF-PP	8.98E-74	0.8145	Strong
Float	Cruise	LOC-I	8.98E-74	0.8145	Strong
Float	Cruise	SCF-NP	8.98E-74	0.8145	Strong
Float	Cruise	Other Category	8.98E-74	0.8145	Strong
Float	Cruise	LOC-G	8.98E-74	0.8145	Strong
Float	Climb	UNK	8.98E-74	0.8145	Strong
Float	Climb	ARC	8.98E-74	0.8145	Strong
Float	Climb	CTOL	8.98E-74	0.8145	Strong
Float	Climb	FUEL	8.98E-74	0.8145	Strong
Float	Climb	SCF-PP	8.98E-74	0.8145	Strong
Float	Climb	LOC-I	8.98E-74	0.8145	Strong
Float	Climb	SCF-NP	8.98E-74	0.8145	Strong
Float	Climb	Other Category	8.98E-74	0.8145	Strong
Float	Landing	ARC	8.98E-74	0.8145	Strong
Float	Landing	CTOL	8.98E-74	0.8145	Strong
Float	Landing	SCF-PP	8.98E-74	0.8145	Strong
Float	Landing	LOC-I	8.98E-74	0.8145	Strong
Float	Landing	SCF-NP	8.98E-74	0.8145	Strong
Float	Landing	Other Category	8.98E-74	0.8145	Strong
Float	Landing	LOC-G	8.98E-74	0.8145	Strong
Amphibious	Climb	LOC-G	8.98E-74	0.8145	Strong
Float	Other Phase	SCF-NP	8.98E-74	0.8145	Strong
Float	Landing	UNK	8.98E-74	0.8145	Strong
Float	Other Phase	SCF-PP	8.98E-74	0.8145	Strong
Float	Take-Off	SCF-NP	8.98E-74	0.8145	Strong
Amphibious	Landing	UNK	8.98E-74	0.8145	Strong
Float	Other Phase	FUEL	8.98E-74	0.8145	Strong
Amphibious	Landing	ARC	8.98E-74	0.8145	Strong
Amphibious	Landing	CTOL	8.98E-74	0.8145	Strong
Amphibious	Landing	FUEL	8.98E-74	0.8145	Strong
Amphibious	Landing	SCF-NP	8.98E-74	0.8145	Strong
Amphibious	Landing	Other Category	8.98E-74	0.8145	Strong
Amphibious	Landing	LOC-G	8.98E-74	0.8145	Strong
Float	Take-Off	UNK	8.98E-74	0.8145	Strong
Float	Take-Off	ARC	8.98E-74	0.8145	Strong
Float	Take-Off	CTOL	8.98E-74	0.8145	Strong
Float	Take-Off	LOC-I	8.98E-74	0.8145	Strong
Amphibious	Landing	SCF-PP	8.98E-74	0.8145	Strong
Float	Take-Off	Other Category	8.98E-74	0.8145	Strong
Float	Approach	SCF-PP	8.98E-74	0.8145	Strong
Float	Take-Off	LOC-G	8.98E-74	0.8145	Strong
Float	Other Phase	CTOL	8.98E-74	0.8145	Strong
Float	Other Phase	UNK	8.98E-74	0.8145	Strong
Float	Approach	SCF-NP	8.98E-74	0.8145	Strong
Float	Approach	LOC-I	8.98E-74	0.8145	Strong
Float	Approach	Other Category	8.98E-74	0.8145	Strong
Float	Approach	FUEL	8.98E-74	0.8145	Strong
Float	Approach	CTOL	8.98E-74	0.8145	Strong
Float	Approach	ARC	8.98E-74	0.8145	Strong
Float	Approach	UNK	8.98E-74	0.8145	Strong
Float	Other Phase	ARC	8.98E-74	0.8145	Strong

Figure N shows the heat map for the associations between the parameters mentioned in Section 7.5.3, but it excludes the following parameters: month, time, aircraft category, amateur built and province/state. Therefore it includes either three of the following: year, landing gear, aircraft damage level, phase of flight and initiating occurrence category.

Figure N. Heat map for the three-way associations between year, landing gear, aircraft damage level, phase of flight and initiating occurrence category.



The main findings for associations with a 99% confidence level are:

- A seaplane is more likely to be destroyed for the following occurrences:
    - ARC, CTOL, LOC-I, SCF-NP and UNK occurrence categories for amphibious aircraft (moderate correlation)
    - Take-off, cruise, approach and landing phases of flight for amphibious aircraft (moderate correlation)
    - CTOL, SCF-NP and UNK on approach (strong correlation)
    - CTOL, LOC-I, SCF-NP and UNK on climb (strong correlation)
    - FUEL, LOC-I, SCF-NP and SCF-PP on cruise (strong correlation)
    - ARC, CTOL and UNK on landing (strong correlation)
    - CTOL on take-off (strong correlation)
    - ARC, CTOL, FUEL, SCF-NP and SCF-PP for float landing gear (moderate correlation)
    - Climb and landing phases of flight for float landing gear (moderate correlation)
- A seaplane is likely to have substantial damage for the following occurrences:
    - ARC, CTOL, LOC-G, LOC-I, SCF-NP and UNK occurrence categories for amphibious aircraft (moderate correlation)

    - Take-off, cruise, approach and landing phases of flight for amphibious aircraft (moderate correlation)
    - ARC, CTOL, FUEL, SCF-NP and SCF-PP for float landing gear (moderate correlation)
    - Climb, take-off and landing phases of flight for float landing gear (moderate correlation)
    - ARC, CTOL, FUEL, SCF-NP, SCF-PP and UNK on approach (strong correlation)
    - ARC, CTOL, LOC-G, LOC-I, SCF-NP and UNK on climb (strong correlation)
    - ARC, CTOL, FUEL, LOC-G, LOC-I, SCF-NP and SCF-PP on cruise (strong correlation)
    - ARC, CTOL, FUEL, LOC-G, LOC-I, SCF-NP, SCF-PP and UNK on landing (strong correlation)
    - ARC, CTOL, LOC-G, LOC-I, SCF-NP, SCF-PP and UNK on take-off (strong correlation)
- A seaplane is likely to have minor or no damage for the following occurrences:
    - LOC-G for float landing gear (moderate correlation)
- A seaplane is more likely to be involved in ARC in the following situations:
    - Amphibious aircraft on approach, climb, landing, take-off (moderate correlation)
    - Float seaplane on approach, climb, cruise, landing, take-off (moderate correlation)
- A seaplane is more likely to be involved in CTOL in the following situations:
    - Amphibious aircraft on approach, climb, landing, take-off (moderate correlation)
    - Float seaplane on approach, climb, cruise, landing, take-off (moderate correlation)
- A seaplane is more likely to be involved in FUEL in the following situations:
    - Amphibious aircraft on approach, climb, cruise, landing (moderate correlation)
    - Float seaplane on approach, climb, cruise (moderate correlation)
- A seaplane is more likely to be involved in LOC-G in the following situations:
    - Amphibious aircraft on climb, landing, take-off (moderate correlation)
    - Float seaplane on cruise, landing, take-off (moderate correlation)
- A seaplane is more likely to be involved in LOC-I in the following situations:
    - Amphibious aircraft on approach, climb, cruise, take-off (moderate correlation)
    - Float seaplane on approach, climb, cruise, landing, take-off (moderate correlation)
- A seaplane is more likely to be involved in SCF-NP in the following situations:
    - Amphibious aircraft on approach, climb, cruise, landing (moderate correlation)
    - Float seaplane on approach, climb, cruise, landing, take-off (moderate correlation)
- A seaplane is more likely to be involved in SCF-PP in the following situations:

    - Amphibious aircraft on approach, climb, cruise, landing, take-off (moderate correlation)
    - Float seaplane on approach, climb, cruise, landing (moderate correlation)
- A seaplane is more likely to be involved in UNK for:
    - Amphibious aircraft on climb, cruise, landing, take-off (moderate correlation)
    - Float seaplane on approach, climb, cruise, landing, take-off (moderate correlation)
- A moderate association was present for the likelihood of seaplanes occurrences during take-off to result in destroyed aircraft for 2012-2022, which was not obtained for previous years.

Appendix O. Documents approved by the Head of Department of Civil and Environmental Engineering and the Research Governance and Integrity Team (RGIT) of Imperial College London, for the study involving seaplane pilots in Canada.

This appendix includes the Participant Information Sheet and Consent Form for the interviewed participants as part of the study involving seaplane pilots in Canada. Similar documents have been approved for the questionnaire. These two documents have been shared with all participants, and voluntary consent has been obtained.

1) Participant Information Sheet

Participant Information Sheet

Safety In The Skies And Waters: Understanding Seaplane Pilot Decision Making In Critical Situations While Bringing Safety Awareness On Current Challenges - INTERVIEW

Principal investigator: Iulia Manole
Coinvestigator: Prof. Arnab Majumdar
Collaborator: Simon Garrett

- **Invitation paragraph**

We invite you, a valued member of the seaplane pilot community in Canada, to take part in a research study aimed at enhancing the safety of Seaplane General Aviation (GA). This will be in the form of an interview. Your insights and experiences are crucial to our understanding and improvement of safety measures within the community.
Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish.
The purpose of this study is to bring awareness on Seaplane General Aviation (GA) safety concerns in Canada that resulted from an in-depth analysis of Seaplane GA past accident and incident data, as well as to determine further details in areas previously overlooked by existing data, such as pilot concerns and decision making during pre-determined scenarios (answer "What would you do in this scenario?").
If you decide to take part, your contribution will consist of completing an online survey or interview divided into 3 parts:

- Part 1: General details - Share general information about yourself, including your age group, flying experience, and any relevant training.
- Part 2a: Scenarios - Engage with hypothetical scenarios to reveal your decision-making processes, by providing your own answers and flag any areas of concern.
- Part 2b: Review and reflect on statistics and trends from past GA seaplane accidents in Canada, which are linked to the scenarios in Part 2a.
- Part 3: Ending questions - Help us understand the factors influencing the reporting of minor incidents and near misses, since these can often signal that something is amiss and analysing these could help prevent more serious events. This will also help us understand how accurate the analysis of past accidents and incidents actually is.

Your participation is entirely voluntary, but immensely valuable. We encourage you to take the time you need to consider this invitation. Should you have any questions or need further information, please do not hesitate to contact us.
We appreciate your consideration of this invitation and hope you will decide to contribute to our shared goal of improving seaplane safety in Canada.

- **What is the purpose of the study?**

This study aims to enhance safety awareness within the Seaplane General Aviation (GA) community in Canada using the results from an in-depth analysis of Seaplane GA past accident and incident data, as well as to determine further details that had not been captured by the previously analysed databases, such as pilot concerns and decision making during pre-determined scenarios (answer "What would you do in this scenario?").
The interview covers a wide range of scenarios during take-off, climb, cruise, approach and landing, based on the most recurring accident types seen after analysing data between 1990 and 2022 of privately registered seaplanes in Canada. This format encourages pilots to think critically about their actions in different conditions, while bringing awareness on current safety issues. The interviewed participant will be able to answer freely and flag any points of concern. This study will significantly contribute to safety awareness and training improvements.
This study is conducted for a student research project, as part of the PhD research of the main investigator (Iulia Manole), under the supervision of Prof. Arnab Majumdar.

- **Why have I been invited?**

You have been invited as you are a GA Seaplane pilot, or you have other relevant experience in seaplane operations and safety.

- **Do I have to take part?**

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

- **What do I have to do?**

You will be invited to take part in an online interview.

- **What will happen to me if I take part?**

Within two months of receipt, you will be asked to take part in an online interview when you are available. This interview has been designed to take under 60 minutes.

- **What are the possible disadvantages and risks of taking part?**

There are no risks or disadvantages associated with taking part in this study.

- **What if something goes wrong?**

If you are harmed by taking part in this research project, there are no special compensation arrangements. If you are harmed due to someone's negligence, then you may have grounds for a legal action. Regardless of this, if you wish to complain, or have any concerns about any aspect of the way you have been treated during the course of this study then you should immediately inform the Investigator (Iulia Manole at iuliamanole97@gmail.com). If you are still not satisfied with the response, you may contact the Imperial College Research Governance Integrity Team (rgitcoordinator@imperial.ac.uk).

- **What will happen to the results of the research study?**

The results will be analysed and studied together with the findings from the analysis of past seaplane accidents/incidents. This will provide a comprehensive understanding of what is amiss, so that recommendations can be made on ways to improve seaplane safety. The aim is to publish the results this year, so that the findings are not outdated. You will not be identified in any publication as grouped study data will be used and not individual data.

- **Who has reviewed the study?**

This study was given favourable opinion by the Research Governance and Integrity Team (RGIT) and approval by Prof. Washington Ochieng, Head of Department of Civil and Environmental Engineering.

Contact for Further Information

A copy of the written information and signed Informed Consent form will be given to the participant to keep.
For further information, please contact Iulia Manole at iuliamanole97@gmail.com or +447936696372, or Prof. Arnab Majumdar at a.majumdar@imperial.ac.uk .
Thank you for taking part in this study!

Transparency Notice

How will we use information about you?

Imperial College London is the sponsor for this study and will act as the data Controller for this study. This means that we are responsible for looking after your information and using it appropriately Imperial College London will keep your personal data for:

- 10 years after the study has finished in relation to data subject consent forms.
- 10 years after the study has completed in relation to primary research data.

The study is expected to finish in July / 2024

For more information / confirmation regarding the end date please contact the study team, see '**WHERE CAN YOU FIND OUT MORE ABOUT HOW YOUR INFORMATION IS USED'** for contact information.
We will need to use information (including personal data and data created as part of the study) from you for this research project.
This information will include your email address. People within Imperial College London and study team (see section 'Sharing your information with others') will use this information to do the research or to check your records (see information to be collected) to make sure that the research is being done properly and the information held (such as contact details) is accurate.
If you wish to provide your email address, people who do not need to know who you are will not be able to see your contact details. Your data will have a unique study number instead.
We will keep all information about you safe and secure.
Once we have finished the study, we will keep some of the data so we can check the results. We will write our reports in a way that no-one can work out that you took part in the study.

LEGAL BASIS

As a university we use personal information to conduct research that will either be in the public interest, or the 'legitimate interests' of Imperial College whose interests are to conduct world leading research and innovation aiming to deliver transformative impact for society.
Our legal basis for using your information under the General Data Protection Regulation (GDPR) and the Data Protection Act 2018, is as follows:
• Imperial College London - "performance of a task carried out in the public interest";
Where special category personal information is involved (most commonly health data, biometric data and genetic data, racial and ethnic data etc.), Imperial College London relies on "scientific or historical research purposes or statistical purposes
We will conduct scientific research in compliance with the law and the recommendations and guidance published by the UK Information Commissioners Office (ICO). This will follow similar rules to health and social care research but may not meet the definition of the College's public interest task or requirement. In such cases we will be holding and using your data for what are called our "legitimate interests" where, as previously stated, the College aims to conduct world leading research and innovation aiming to deliver transformative impact for society. Scientific research should serve the public interest, which means that we have to demonstrate that our research has societal impact serving the interests of society as a whole.

INTERNATIONAL TRANSFERS

There may be a requirement to transfer information to countries outside the United Kingdom for example, to a research partner, either within the European Economic Area (EEA) or to other countries outside the EEA. Where this information contains your personal information, Imperial College London will ensure that it is transferred in accordance with data protection legislation. If the data is transferred to a country which is not subject to a UK adequacy decision in respect of its data protection standards, Imperial College London will enter into a data sharing agreement with the recipient organisation that incorporates UK approved standard contractual clauses or use another transfer mechanism that safeguards how your personal data is processed.

SHARING YOUR INFORMATION WITH OTHERS

We will only share your personal data with certain third parties for the purposes referred to in this participant information sheet and by relying on the legal basis for processing your data as set out above.

- Other Imperial College London employees (including staff involved directly with the research study or as part of defined secondary activities which may include support functions, internal audits, ensuring accuracy of contact details etc.), College agents, contractors and service providers (for example, suppliers of printing and mailing services, email communication services or web services, or suppliers who help us carry out any of the activities described above). Our third party service providers are required to enter into data processing

agreements with us. We only permit them to process your personal data for specified purposes and in accordance with our policies.

- the following Research Collaborators / Partners in the study:
  - Transport Canada – Only the survey data, not personal data (i.e., Participant Information Sheet), will be shared with Simon Garrett, Lead of the General Aviation Safety Program and Seaplane Working Group, for the purposes of further research and analysis to improve seaplane safety in Canada. Mr. Garrett is listed as a Collaborator on this project.

POTENTIAL USE OF STUDY DATA FOR FUTURE RESEARCH
When you agree to take part in a research study, the information collected either as part of the study or in preparation (such as contact details) may, with your consent, be provided to researchers running other research studies in this organisation and in other organisations. These organisations may be universities or organisations involved in research in this country or abroad. Your information will only be used by organisations and researchers to conduct research in accordance with all relevant legislation including the GDPR (UK GDPR and EU GDPR 2016/679), the Data Protection Act 2018.

This information will not identify you and will not be combined with other information in a way that could identify you, used against you or used to make decisions about you.

COMMERCIALISATION
Samples / data from the study may also be provided to organisations not named in this participant information sheet, e.g. commercial organisations or non-commercial organisations for the purposes of undertaking the current study, future research studies or commercial purposes such as development by a company of a new test, product, service or treatment. We will ensure your name and any identifying details will NOT be given to these third parties, instead you will be identified by a unique study number with any sample analysis having the potential to generate 'personal data'.

Aggregated (combined) or anonymised data sets (all identifying information is removed) may also be created using your data (in a way which does not identify you individually) and be used for such research or commercial purposes where the purposes align to relevant legislation (including the GDPR) and wider aims of the study. Your data will not be shared with a commercial organisation for marketing purposes.

WHAT ARE YOUR CHOICES ABOUT HOW YOUR INFORMATION IS USED?
You can stop being part of the study at any time, without giving a reason, but we will keep information about you that we already have because some research using your data may have already taken place and this cannot be undone

- **OPTION if follow up data will be collected after withdrawal:** If you choose to stop taking part in the study (also known as opting out), we will stop collecting information about you.
- We need to manage your records in specific ways for the research to be reliable. This means that we may not be able to let you see or change the data we hold about you if this could affect the wider study or the accuracy of data collected.
- If you agree to take part in this study, you will have the option to take part in future research using your data saved from this study.

WHERE CAN YOU FIND OUT MORE ABOUT HOW YOUR INFORMATION IS USED
You can find out more about how we use your information:

- by asking one of the research team
- by sending an email to Iulia Manole at iuliamanole97@gmail.com or to Prof. Arnab Majumdar at a.majumdar@imperial.ac.uk, or
- by ringing Iulia Manole on +447936696372 (time zone UTC+1 / BST).

COMPLAINT
If you wish to raise a complaint about how we have handled your personal data, please contact the research team first by sending an email to Iulia Manole at iuliamanole97@gmail.com, Prof. Arnab Majumdar at a.majumdar@imperial.ac.uk , or by ringing us on +447936696372.

Following our response, if you are not satisfied please contact Imperial College London's Data Protection Officer via email at dpo@imperial.ac.uk, via telephone on 020 7594 3502 and/or via post at Imperial College London, Data Protection Officer, Faculty Building Level 4, London SW7 2AZ.
If you remain unsatisfied with our response or believe we are processing your personal data in a way that is not lawful you can complain to the Information Commissioner's Office (ICO) via www.ico.org.uk. The ICO does recommend that you seek to resolve matters with the data controller (us) first before involving them.

2) Consent Form

Consent Form for Participants Able to Give Consent

Full Title of Project: Safety In The Skies And Waters: Understanding Seaplane Pilot Decision Making In Critical Situations While Bringing Safety Awareness On Current Challenges - INTERVIEW

Please write your initials in the box

1.	I confirm that I have read and understand the participant information sheet version V3.0 dated 09Apr2024 for "Safety In The Skies And Waters: Understanding Seaplane Pilot Decision Making In Critical Situations While Bringing Safety Awareness On Current Challenges" and have had the opportunity to ask questions which have been answered fully.	
2.	I consent to take part in "Safety In The Skies And Waters: Understanding Seaplane Pilot Decision Making In Critical Situations While Bringing Safety Awareness On Current Challenges".	
3.	I understand that my participation is voluntary, and I am free to withdraw at any time, without giving any reason and without my legal rights being affected.	
4.	I give / do not give (delete/mark as applicable) consent to being contacted about the possibility to take part in other research studies.	
5.	I understand that data collected from me are a gift donated to Imperial College and that I will not personally benefit financially if this research leads to an invention and/or the successful development of a new test, medication treatment, product or service.	
6.	I give/do not give (delete/mark as applicable) consent for information collected about me to be used to support other research or in the development of a new test, medication, medical device or treatment (delete as applicable) by an academic institution or commercial company in the future, including those outside of the United Kingdom (which Imperial has ensured will keep this information secure).	
7.	I give/do not give (delete/mark as applicable) consent for my interview to be recorded and transcribed. The recordings will be deleted after the transcription is complete, and only accessible by the investigators of the study during that time.	

_____	_____	_____
Name of participant	Signature	Date
___IULIA MANOLE_____	_____	_____
Principal Investigator	Signature	Date

1 copy for participant; 1 copy for Principal Investigator

To ensure confidence in the process and minimise risk of loss, all consent forms must be printed, presented and stored in double sided format

Appendix P. Questions used for gathering pilot information, and booklet shared with the participants of the focus groups and interviews. The sheet about gathering pilot information was kept by the investigator.

1) Questions used for gathering pilot information

General details:

a) Age:
   i) Under 20
   ii) 21-30
   iii) 31-40
   iv) 41-50
   v) 51-60
   vi) 61-70
   vii) 70+

b) Years of experience flying (not only seaplanes):
   i) Under 2
   ii) 2-5
   iii) 6-10
   iv) 11-20
   v) 21-30
   vi) Over 30

c) Years of experience flying (only seaplanes):
   i) Under 2
   ii) 2-5
   iii) 6-10
   iv) 11-20
   v) 21-30
   vi) Over 30

d) Experience in flying seaplanes (in hours flown):
   i) Under 10
   ii) 10 - 100
   iii) 101 – 300
   iv) 301-500
   v) 501 - 1,000
   vi) Over 1,000

e) Seaplane training
   i) Seaplane Rating only
   ii) Insurance Checkout(s) on Type
   iii) 25 Hour Bush Pilot Course
   iv) 50 Hour Bush Pilot Course
   v) Underwater Egress Training
   vi) Other:

f) Last time a safety course/training related to seaplane operations or safety was completed:

Ending questions

a) What do you think the best methods of promoting safety and bringing awareness on current seaplane safety issues are?
   i) Annual questionnaires (such as this one)
   ii) Annual focus groups
   iii) Weekly newsletters / bulletins
   iv) Monthly newsletters / bulletins
   v) Weekly emails
   vi) Monthly emails
   vii) Seasonal emails
   viii) Designated website
   ix) Social media (Facebook, Instagram, Twitter, etc.)
   x) Other:

b) Are you willing to be contacted via email about taking part in future research? (e.g., surveys, interviews, seminars, workshops)
   i) Yes, I wish to be contacted for future research, and it will be my decision whether to take part or not.
   ii) No, I do not wish to be contacted.
   iii) **If yes**, please provide your email address:

c) Are you willing to be contacted via email for clarifications regarding your answers to this survey questions?
   i) Yes
   ii) No
   iii) If yes, please provide your email address:

2) Booklet shared with the participants of the focus groups and interviews

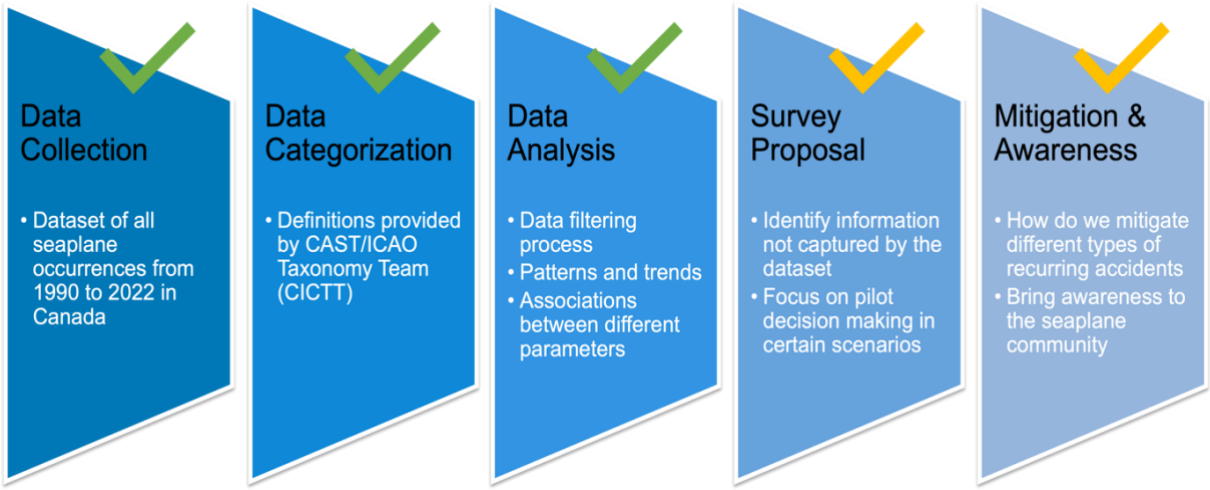
IMPERIAL

Analysis of Seaplane Accidents in Canada

1,005 private seaplane occurrences in Canada - 1990 to 2022

* Occurrences = Accidents + Incidents

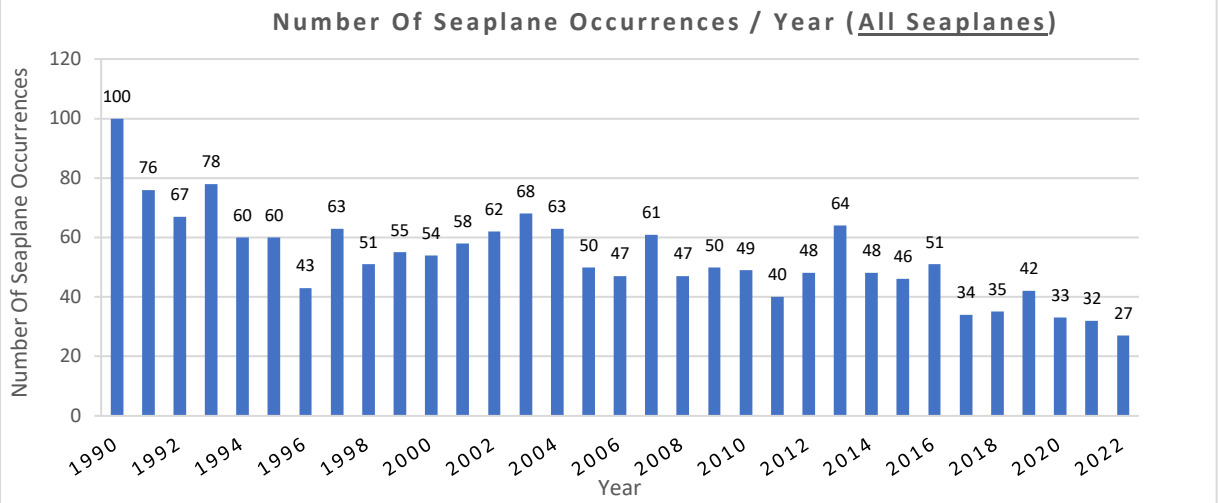
- General Aviation Safety Program
- Seaplane Working Group
- Imperial College London

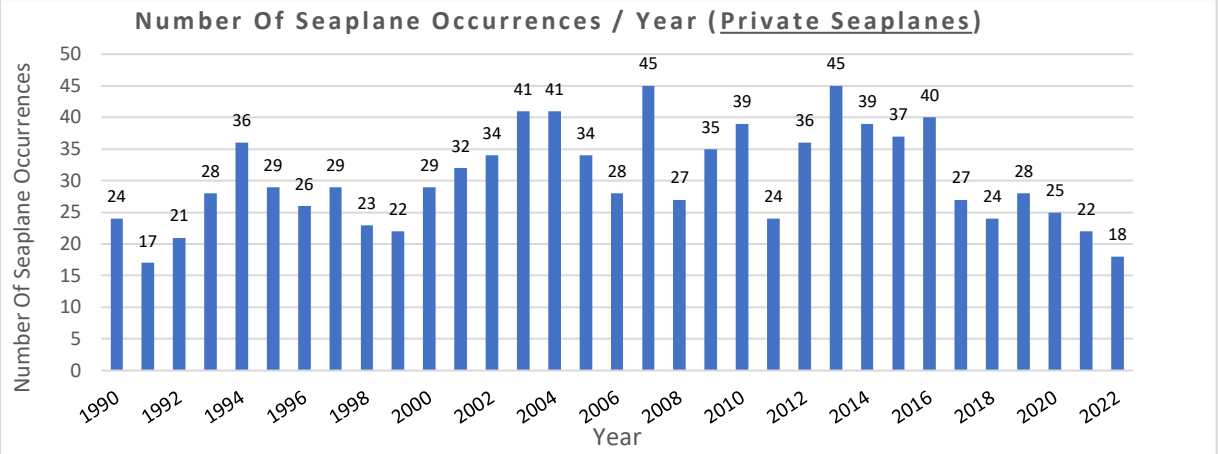


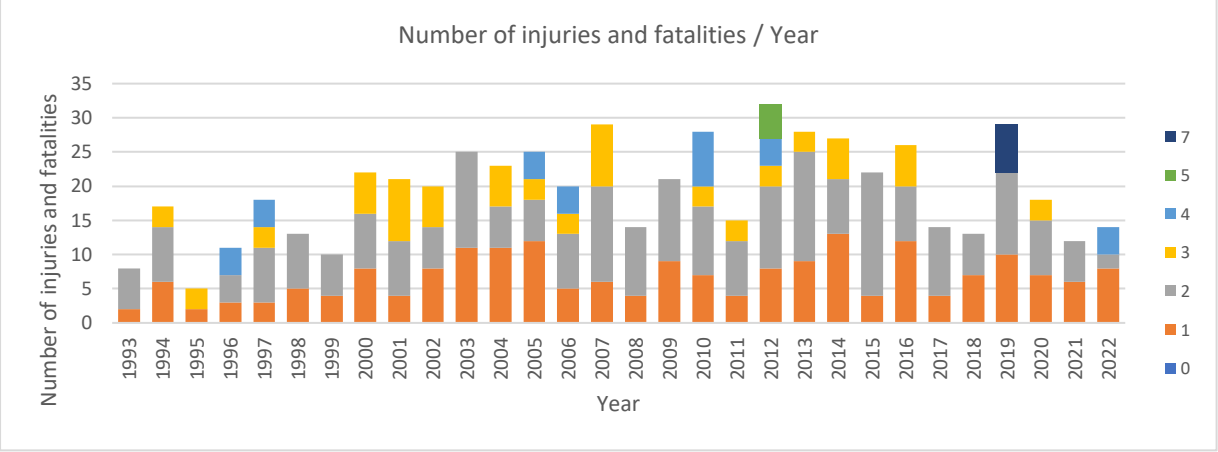
Data analyzed around specific variables:

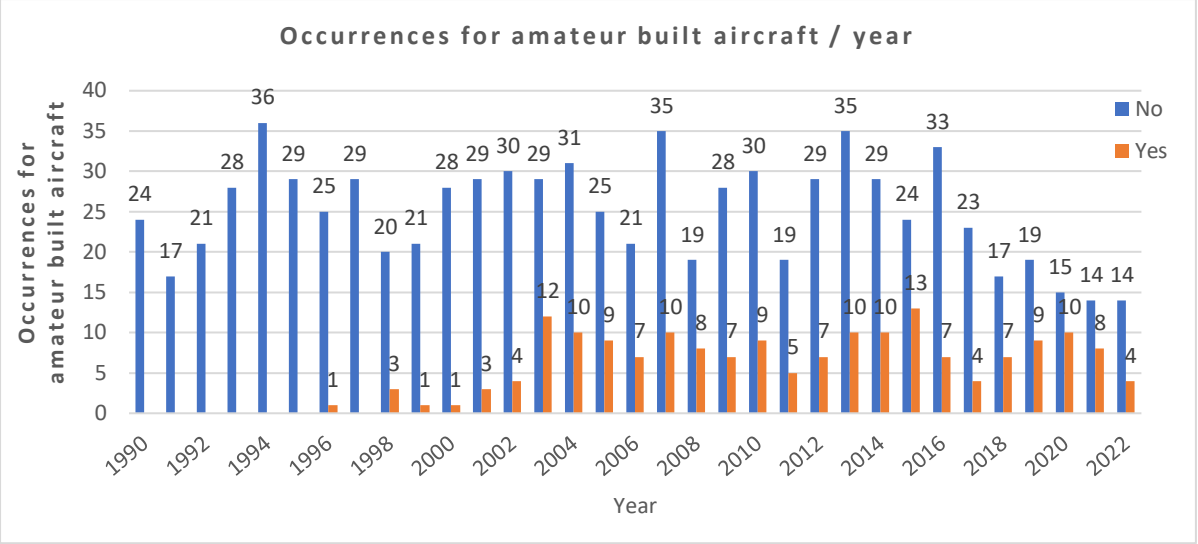
- Year
- Landing Gear
- Phase of Flight
  - Take-off
  - Climb
  - Landing
- Aircraft Damage Level (Destroyed Aircraft / Number of fatalities and injuries)
- Other

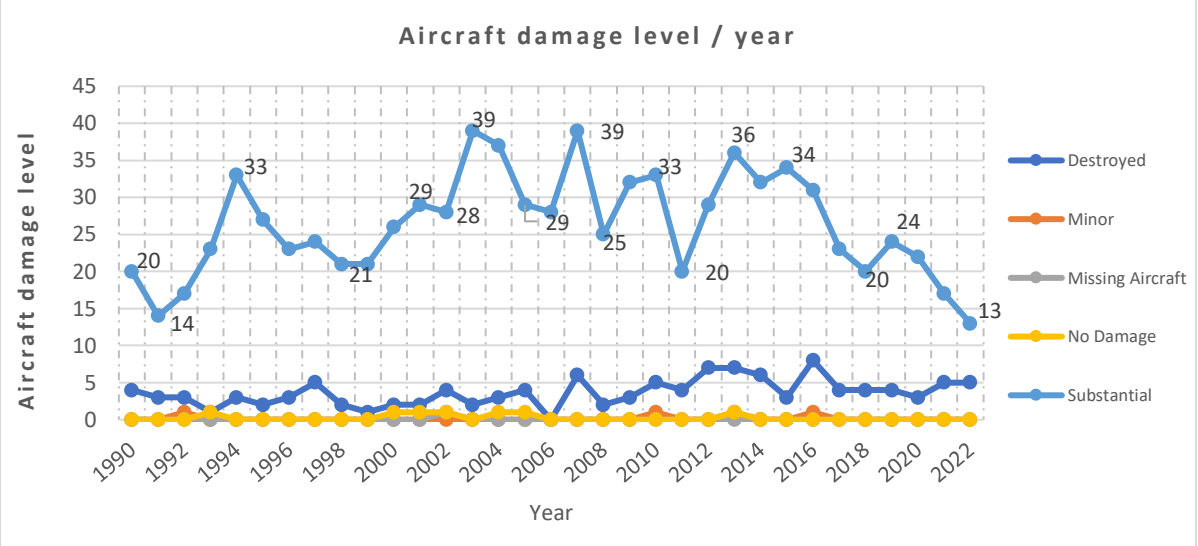
Statistics / **Year** of occurrence:

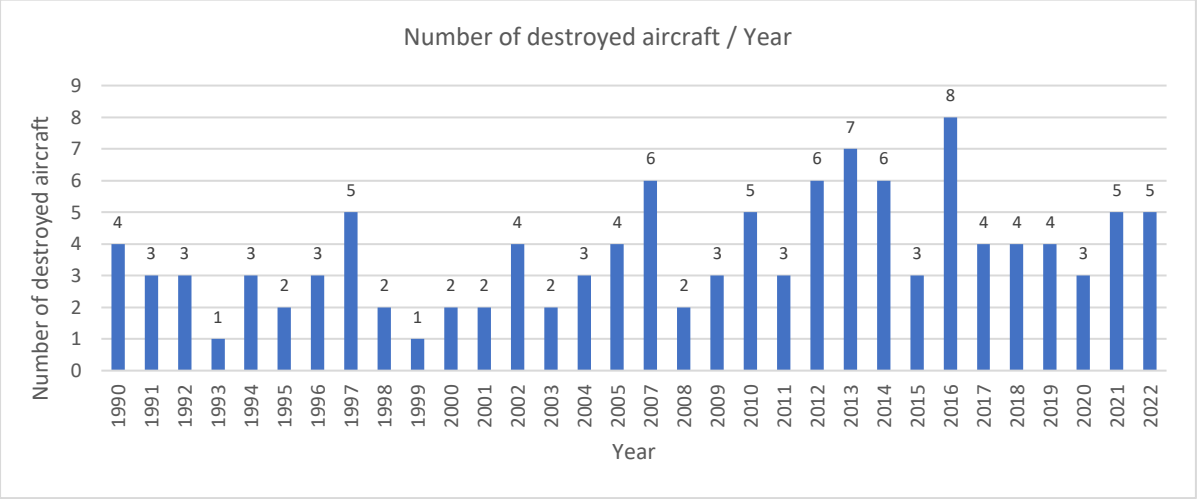


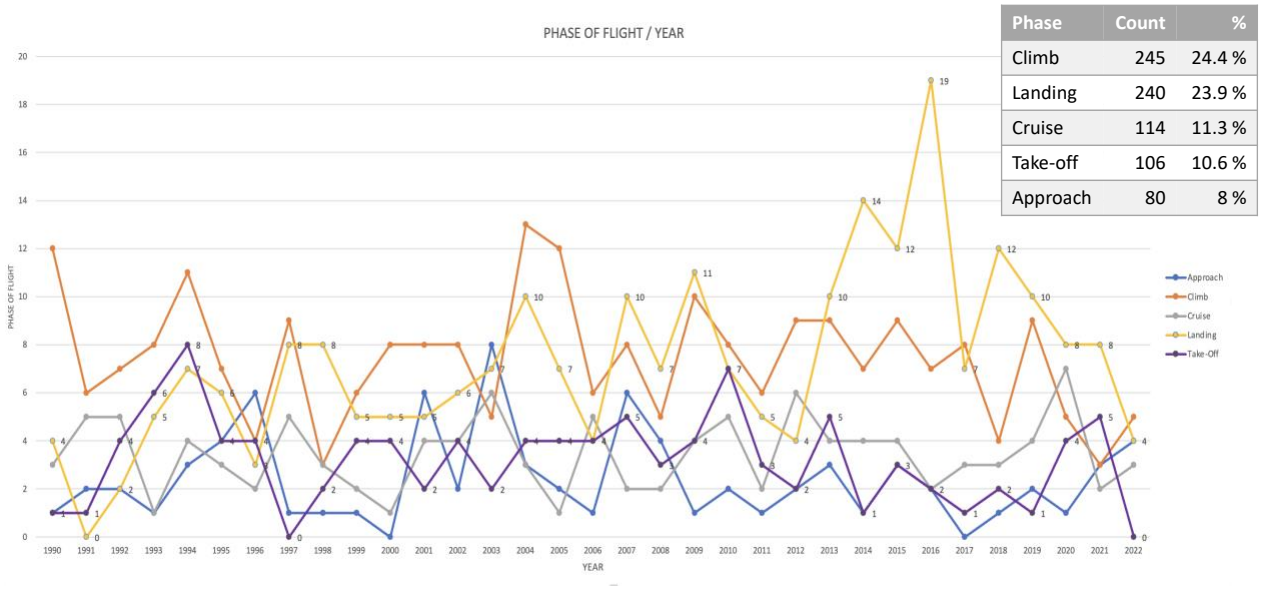





Occurrences for amateur built aircraft / year
Occurrences for amateur built aircraft
Year
No
Yes


Aircraft damage level / year
Aircraft damage level
Year
Destroyed
Minor
Missing Aircraft
No Damage
Substantial


Number of destroyed aircraft / Year
Number of destroyed aircraft
Year

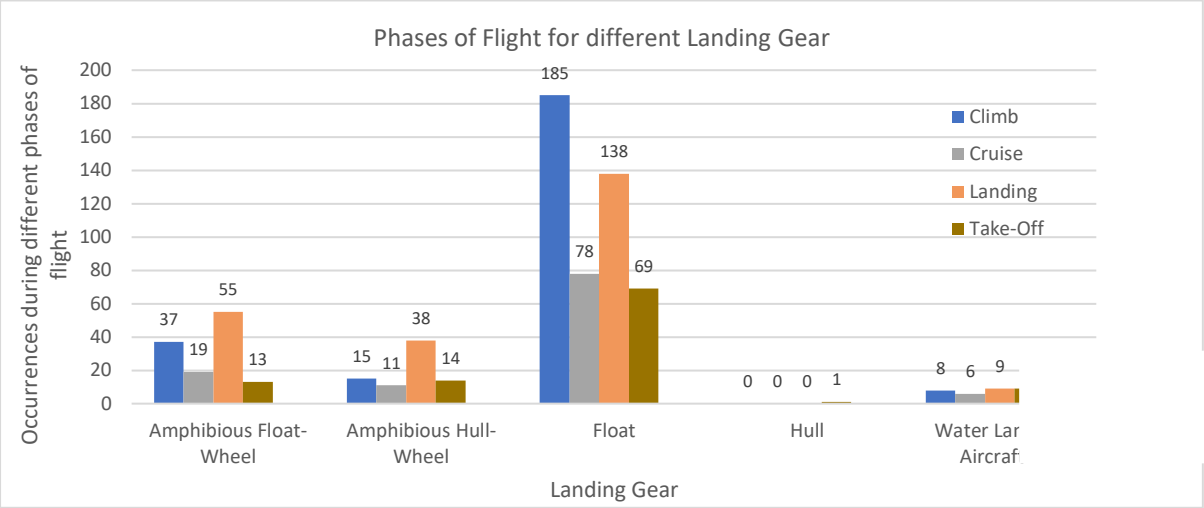


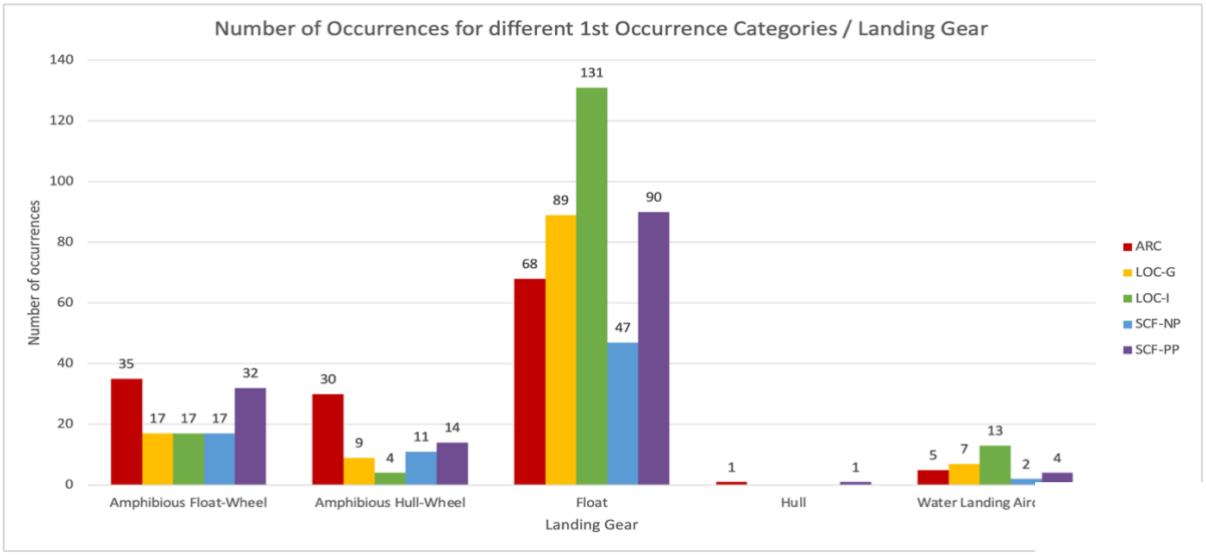
Phase	Count	%
Climb	245	24.4 %
Landing	240	23.9 %
Cruise	114	11.3 %
Take-off	106	10.6 %
Approach	80	8 %

Categorization	Description	Count	%
LOC-I	**LOSS OF CONTROL–INFLIGHT**	**165**	**16.4%**
SCF-PP	**SYSTEM/COMPONENT FAILURE OR MALFUNCTION (POWERPLANT)**	**141**	**14.0%**
ARC	**ABNORMAL RUNWAY CONTACT**	**139**	**13.8%**
LOC-G	**LOSS OF CONTROL–GROUND**	**122**	**12.1%**
SCF-NP	SYSTEM/COMPONENT FAILURE OR MALFUNCTION (NON-POWERPLANT)	77	7.7%
CTOL	COLLISION WITH OBSTACLE(S) DURING TAKEOFF AND LANDING	71	7.1%
UNK	UNKNOWN OR UNDETERMINED	65	6.5%
FUEL	FUEL RELATED	48	4.8%
UIMC	UNINTENDED FLIGHT IN IMC	32	3.2%
LALT	LOW ALTITUDE OPERATIONS	25	2.5%
AMAN	ABRUPT MANEUVER	24	2.4%
OTHR	OTHER	24	2.4%
CFIT	CONTROLLED FLIGHT INTO/TOWARD TERRAIN	12	1.2%
RAMP	GROUND HANDLING	11	1.1%
GCOL	GROUND COLLISION	8	0.8%
RE	RUNWAY EXCURSION	7	0.7%
TURB	TURBULENCE ENCOUNTER	7	0.7%
WSTRW	WIND SHEAR OR THUNDERSTORM	7	0.7%
MAC	AIRPROX/TCAS ALERT/LOSS OF SEPARATION/NEAR MIDAIR COLLISIONS/MIDAIR COLLISIONS	6	0.6%
USOS	UNDERSHOOT/OVERSHOOT	4	0.4%
ICE	ICING	3	0.3%
F-NI	FIRE/SMOKE (NON-IMPACT)	2	0.2%
ATM	ATM/CNS	1	0.1%
ADRM	AERODROME	1	0.1%
BIRD	BIRD	1	0.1%

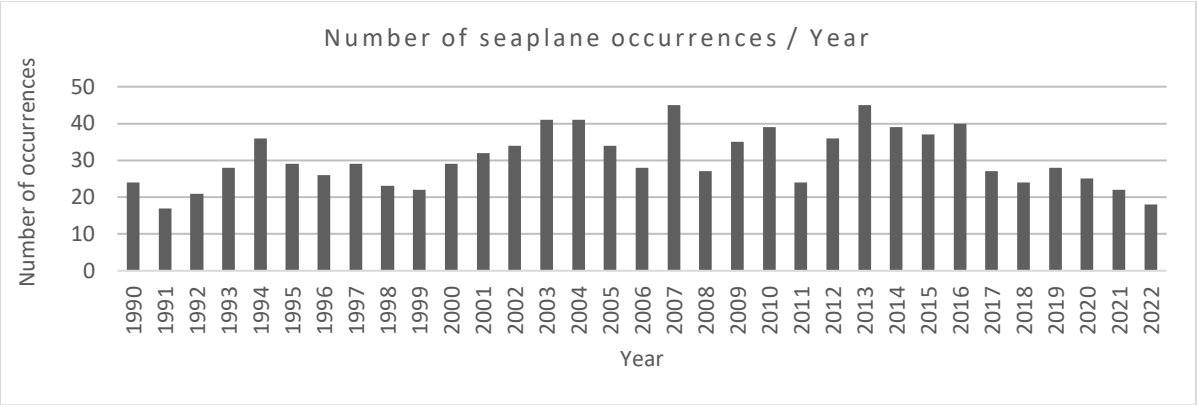
EXTL	EXTERNAL LOAD RELATED OCCURRENCES	1	0.1%
MED	MEDICAL	1	0.1%

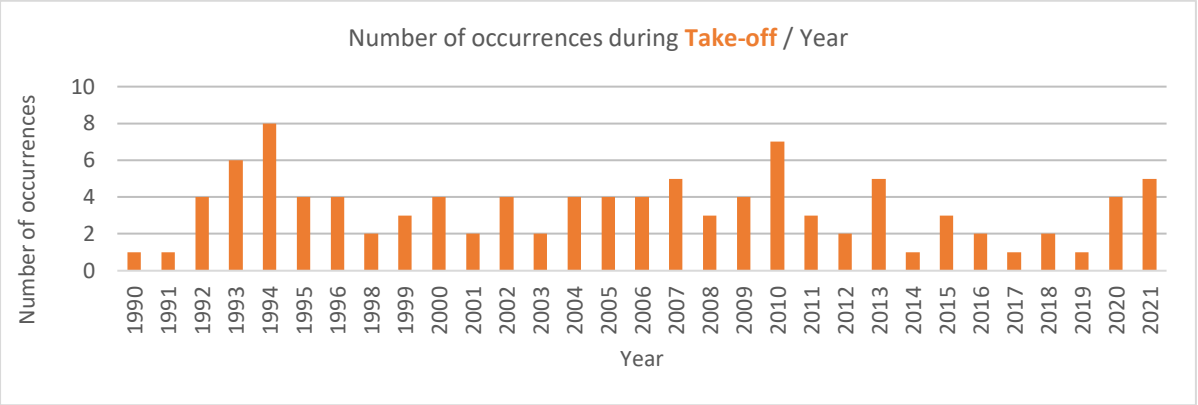
Statistics / **Landing Gear:**

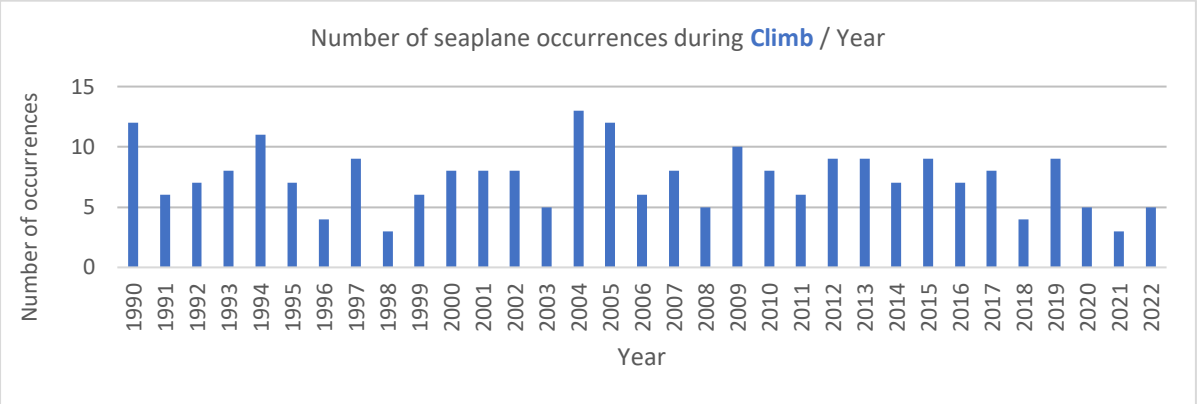


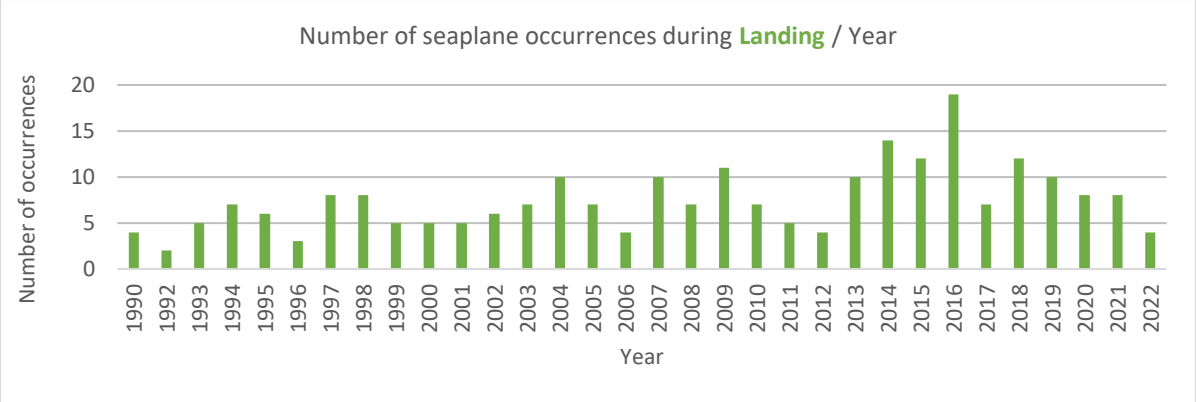


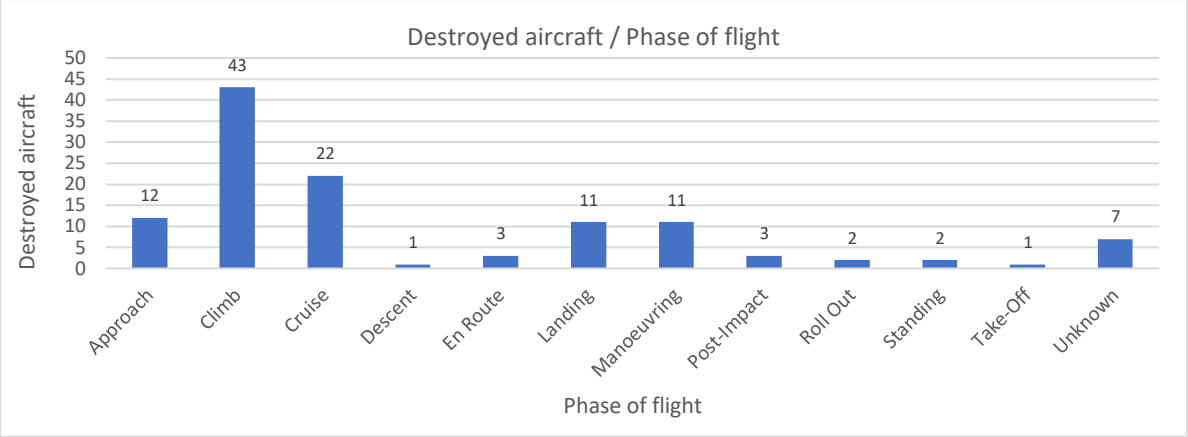
Statistics / **Phase of Flight:**

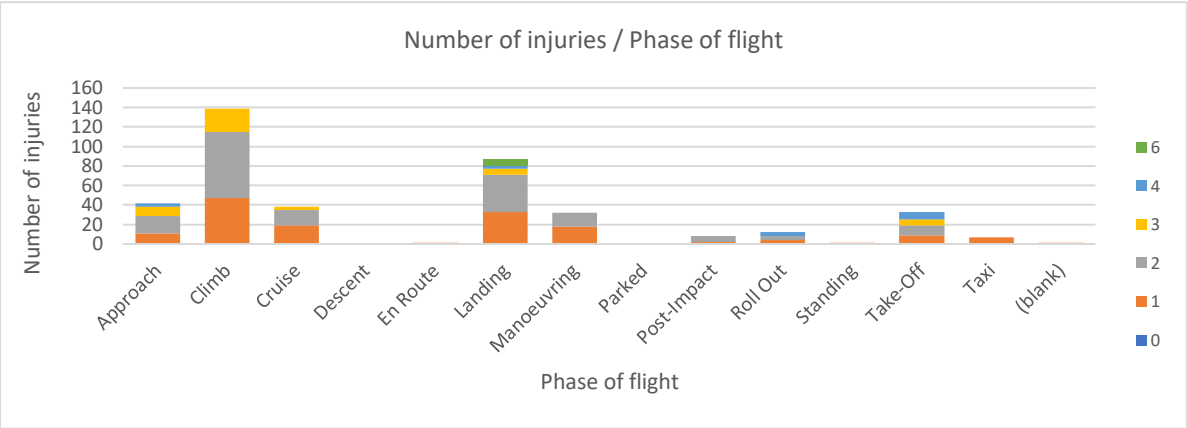


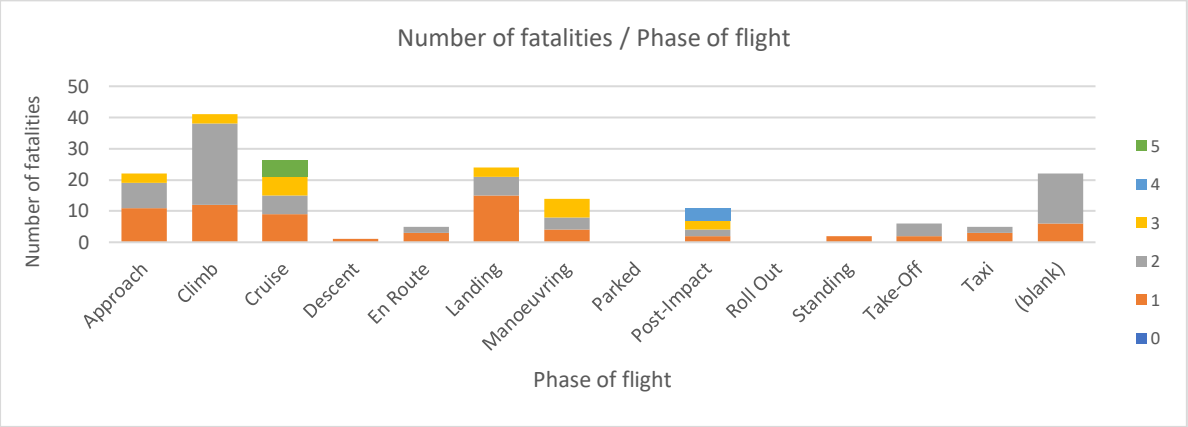


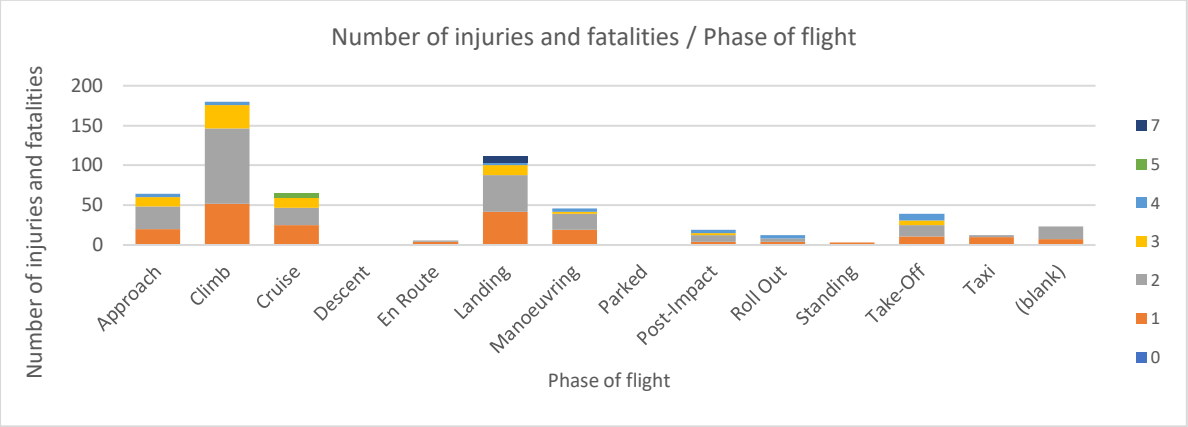



Number of seaplane occurrences during Landing / Year
Number of occurrences
20
15
10
5
0
1990 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022
Year

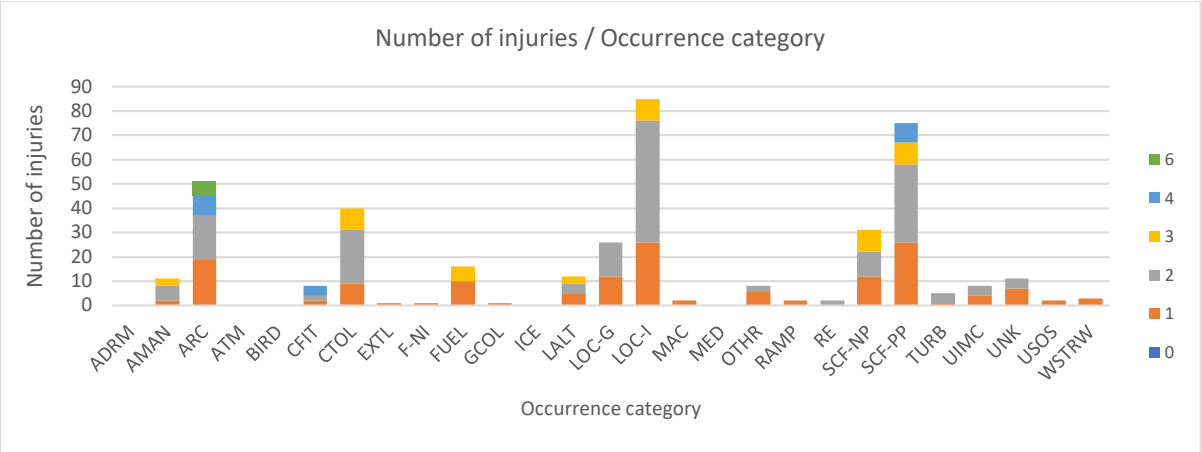

Destroyed aircraft / Phase of flight
Destroyed aircraft
50
45
40
35
30
25
20
15
10
5
0
12
43
22
1
3
11
11
3
2
2
1
7
Approach
Climb
Cruise
Descent
En Route
Landing
Manoeuvring
Post-Impact
Roll Out
Standing
Take-Off
Unknown
Phase of flight

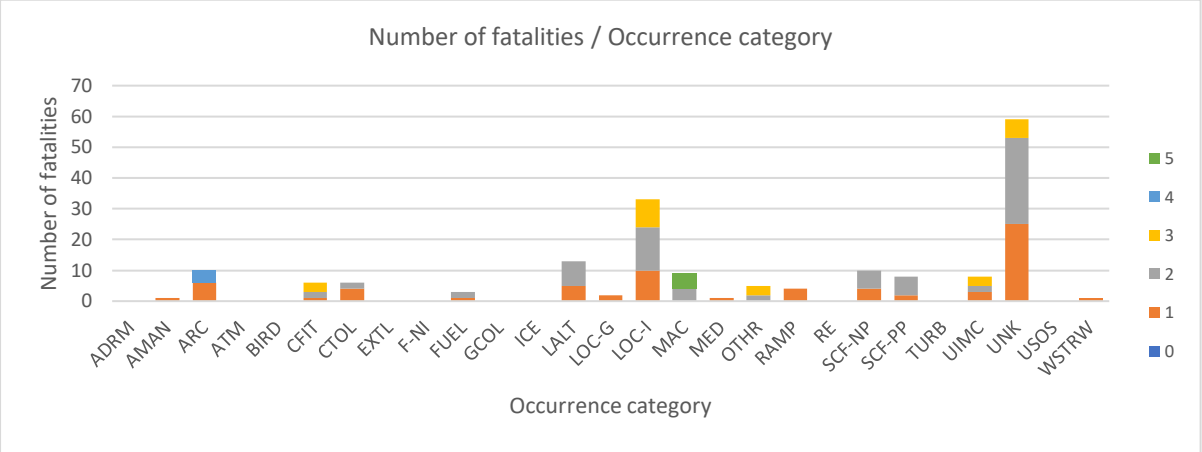

Number of injuries / Phase of flight
Number of injuries
160
140
120
100
80
60
40
20
0
Approach
Climb
Cruise
Descent
En Route
Landing
Manoeuvring
Parked
Post-Impact
Roll Out
Standing
Take-Off
Taxi
(blank)
Phase of flight
6
4
3
2
1
0

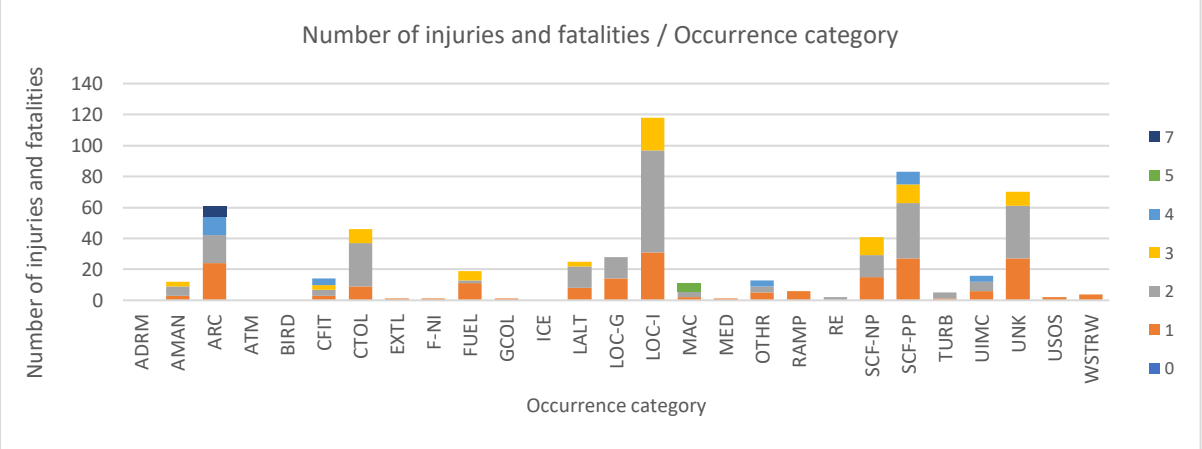

Number of fatalities / Phase of flight
Number of fatalities
50
40
30
20
10
0
Approach
Climb
Cruise
Descent
En Route
Landing
Manoeuvring
Parked
Post-Impact
Roll Out
Standing
Take-Off
Taxi
(blank)
Phase of flight
5
4
3
2
1
0


Number of injuries and fatalities / Phase of flight
Number of injuries and fatalities
200
150
100
50
0
Approach
Climb
Cruise
Descent
En Route
Landing
Manoeuvring
Parked
Post-Impact
Roll Out
Standing
Take-Off
Taxi
(blank)
Phase of flight
7
5
4
3
2
1
0

Statistics / **Occurrence Category:**







Iulia Manole: iuliamanole97@gmail.com

Appendix Q. Questions asked for the online questionnaire.

Analysis of Seaplane Accidents in Canada - Questionnaire

Start of Block: Participant information & Consent

Q001 We invite you, a valued member of the seaplane pilot community in Canada, to take part in a research study aimed at enhancing the safety of Seaplane General Aviation (GA). Your insights and experiences are crucial to our understanding and improvement of safety measures within the community.

Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully.

The purpose of this study is to bring awareness on Seaplane GA safety concerns in Canada that resulted from an in-depth analysis of past accident and incident data, as well as to determine further details in areas previously overlooked by existing data, such as pilot concerns and decision making during pre-determined scenarios (answer "What would you do in this scenario?").

If you decide to take part, your contribution will consist of completing 3 sections:
Section 1: General details - Share general information about yourself, including your age group, flying experience, and any relevant training.
Section 2a: Review and reflect on statistics and trends from past GA seaplane accidents and incidents in Canada, which are linked to the scenarios in Part 2b.
Section 2b: Scenarios - Engage with hypothetical scenarios to reveal your decision-making processes and flag any areas of concern.
Section 3: Ending questions

The results will be analysed and studied together with the findings from the analysis of past seaplane accidents/incidents. This will provide a comprehensive understanding of what is amiss, so that recommendations can be made on ways to improve seaplane safety.

The aim is to publish the results this year, so that the findings are not outdated. You will not be identified in any publication as grouped study data will be used and not individual data.

I confirm that I have read and understood the above information.

- ○ Yes (1)
- ○ No (2)

Q002 I understand what will be expected of me and I had the opportunity to ask questions that have been answered satisfactorily.

- ○ Yes (1)
- ○ No (2)

Q003 I understand that my data gathered in this study will be stored anonymously and securely by Imperial College London. Identifying me in any outputs, including publications, will not be possible.

- ○ Yes (1)
- ○ No (2)

Q004 I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason.

- ○ Yes (1)
- ○ No (2)

Q005 I consent to voluntarily participate in this study and understand how my responses will be used.

- ○ Yes (1)
- ○ No (2)

End of Block: Participant information & Consent

Start of Block: General details

Q1 What is your age group?

- Under 21 (1)
- 21-30 (2)
- 31-40 (3)
- 41-50 (4)
- 51-60 (5)
- 61-70 (6)
- 70+ (7)

Q2 How many years of flying experience do you have? (not only seaplanes)

- Under 2 (1)
- 2-5 (2)
- 6-10 (3)
- 11-20 (4)
- 21-30 (5)
- Over 30 (6)

Q42 How many years of flying experience do you have? (only seaplanes)

- Under 2 (1)
- 2-5 (2)
- 6-10 (3)
- 11-20 (4)
- 21-30 (5)
- Over 30 (6)

Q3 Number of seaplane flying hours

- <10 (1)
- 10-100 (2)
- 101-300 (3)
- 301-500 (4)
- 501-1000 (5)
- Over 1000 (6)

Q4 Seaplane training

- ☐ Seaplane Rating only (1)
- ☐ Insurance Checkout(s) on Type (2)
- ☐ 25 Hour Bush Pilot Course (3)
- ☐ 50 Hour Bush Pilot Course (4)
- ☐ Underwater Egress Training (5)
- ☐ Other (6) _____

Q11 Last time a safety course/training related to seaplane operations was completed

_____

End of Block: General details

Start of Block: Information gathering

Q5 What safety issues or concerns do you have?

_____

Q6 How do you stay current?

_____

Q7 How do you stay proficient?

_____

Q8 How often do you practice emergency procedures?

_____

Q9 How often do you practice engine failures?

_____

Q10 What do you think we need to do to reduce the number of seaplane accidents?

_____

End of Block: Information gathering

Start of Block: Scenario discussion - Take off

Q12 Striking obstacles - what have you done to mitigate this?

_____

Q13 Striking obstacles - what would you do to mitigate this?

_____

Q14 Floats digging in - what have you done to mitigate this?

_____

Q15 Floats digging in - what would you do to mitigate this?

_____

End of Block: Scenario discussion - Take off

Start of Block: Scenario discussion - Climb

Q16 Crosswind - what have you done to mitigate this?

_____

Q17 Crosswind - what would you do to mitigate this?

_____

Q18 Low or no airspeed indication - what have you done to mitigate this?

_____

Q19 Low or no airspeed indication - what would you do to mitigate this?

_____

Q20 Poor climb performance - what have you done to mitigate this?

_____

Q21 Poor climb performance - what would you do to mitigate this?

_____

Q22 Engine power loss - what have you done to mitigate this?

_____

Q23 Engine power loss - what would you do to mitigate this?

_____

End of Block: Scenario discussion - Climb

Start of Block: Scenario discussion - Approach

Q24 Unstable approach - what have you done to mitigate this?

_____

Q25 Unstable approach - what would you do to mitigate this?

_____

Q26 Entanglement/striking obstacles - what have you done to mitigate this?

_____

Q27 Entanglement/striking obstacles - what would you do to mitigate this?

_____

End of Block: Scenario discussion - Approach

Start of Block: Scenario discussion - Landing

Q28 Not able to clear terrain ahead - what have you done to mitigate this?

_____

Q29 Not able to clear terrain ahead - what would you do to mitigate this?

_____

Q30 Bounce / Floats digging in - what have you done to mitigate this?

_____

Q31 Bounce / Floats digging in - what would you do to mitigate this?

_____

Q32 Aborted landing - what have you done to mitigate this?

_____

Q33 Aborted landing - what would you do to mitigate this?

_____

End of Block: Scenario discussion - Landing

Start of Block: Ending questions

Q34 What do you think the best methods of promoting safety and bringing awareness on current seaplane safety issues are?

- ☐ Annual questionnaires (such as this one) (1)
- ☐ Annual focus groups (2)
- ☐ Weekly newsletters / bulletins (3)
- ☐ Monthly newsletters / bulletins (4)
- ☐ Weekly emails (5)
- ☐ Monthly emails (6)
- ☐ Seasonal emails (7)
- ☐ Designated website (8)
- ☐ Social media (Facebook, Instagram, Twitter, etc.) (9)
- ☐ Other (10) _____

Q35 Are you willing to be contacted via email about taking part in future research? (e.g., surveys, interviews, seminars, workshops)

- ○ No (1)
- ○ Yes, I wish to be contacted for future research, and it will be my decision whether to take part or not. (Please provide your EMAIL address) (2) _____

Q36 Are you willing to be contacted via email regarding the results of this study?

- ○ No (1)
- ○ Yes, I wish to be contacted for future research, and it will be my decision whether to take part or not. (Please provide your EMAIL address, if you have not done so in the previous question) (2) _____

Q43 Is there anything else you wish to tell us?

_____

End of Block: Ending questions