A COMPREHENSIVE ANALYSIS OF MAJOR MARITIME ACCIDENTS IN CANADA: IDENTIFYING CAUSAL FACTORS THROUGH SYSTEMS-THEORETIC ACCIDENT MODELS

by

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Dalhousie University is located in Mi'kma'ki, the ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

To my family, my wife, and my two sons - this work is dedicated to you. Your unwavering support and love have been my strength. This achievement is a testament to our shared journey. Thank you for being my inspiration.

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ABSTRACT

In this research, a thorough examination of significant maritime accidents in Canada is conducted, utilizing the Causal Analysis based on Systems Theory (CAST) method to pinpoint prevailing causal factors. The study meticulously analyzes maritime accident reports from the Canadian Transportation Safety Board, offering a systematic exploration of changes in causality over time, across various ship types, and different accident categories. The research questions are centered on the systemic origins of these accidents, with a specific emphasis on inadequate control or feedback failures from controlled entities. The analysis is grounded in the Hierarchical Control Structure (HCS), a conceptual diagram that underscores feedback control loops within a functional system. The results indicate that the most recurrent causal factors are not merely specific to the ship and accident type, but are also deeply embedded in systemic issues. The data, obtained through a consistent and rigorous application of the CAST method, provide valuable insights for academics, policymakers, and industry stakeholders. The findings highlight the necessity for improved safety protocols and strategies for risk reduction in the maritime sector. Moreover, the research underscores the significance of comprehensive investigations and the broad dissemination of their results to effectively address safety concerns in the global marine industry.

LIST OF ABBREVIATIONS USED

1. CAST - Causal Analysis based on Systems Theory
2. STAMP - Systems-Theoretic Accident Modeling and Processes
3. TSB - Transportation Safety Board of canada
4. UK - United Kingdom
5. BC - British Columbia
6. IMO - International Maritime Organization
7. UNCTAD - United Nations Conference on Trade and Development
8. HCS - Hierarchical Control Structure
9. MOT – Ministry of Transportation
10. OOW – Officer of the watch
11. R&D Research and development
12. SMS – Safety management system
13. ISM: International Safety Management
14. VTS: Vessel Traffic Service
15. PMS: Planned Maintenance System

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1 Introduction

This thesis aims to address the existing gap in the literature by examining major maritime accidents in Canada and identifying the causal factors using a systems-theoretic accident theory and associated modeling approach, with a particular focus on reports published by the Transportation Safety Board (TSB) of Canada (Government of Canada, 2020). The TSB is an independent agency that conducts investigations into transportation-related incidents and accidents in Canada. Its mandate is to advance transportation safety and ensure that transportation accidents and incidents are investigated and lessons learned are applied to prevent future occurrences.

To achieve this objective, the study will pursue the following research questions:

Main Question: What are the dominant causal factors identified in maritime accident investigation reports, focused on those conducted by the TSB, using a systems-theoretic accident model?

> Sub-Question 1: How does the considered causality change with respect to time? Can a meaningful interpretation be given to possible temporal patterns?
>
> Sub-Question 2: How does the considered causality change with respect to ship type? Can a meaningful interpretation be given to possible patterns?
>
> Sub-Question 3: How does the considered causality change with respect to types of accidents? Can a meaningful interpretation be given to possible patterns?

To address these research questions, the study will undertake the following tasks:

1. Analyze Canadian TSB maritime accident reports from a systems-theoretic accident model perspective.
2. Evaluate the extent to which the findings can be utilized for enhancing maritime safety, while considering the limitations of the analysis and addressing the challenges associated with interpreting these results as an accurate representation of the underlying causes.

By accomplishing these objectives and answering the research questions, the study will contribute to a better understanding of the unique challenges related to major maritime accidents in the Canadian shipping context. This will provide valuable insights for the academic community, policymakers, and industry stakeholders, enabling them to conduct future research, enhance safety measures, and ultimately reduce the risks associated with maritime accidents.

The shipping industry plays a vital role in global trade, accounting for nearly 90% of the world's trade in volume (UNCTAD, 2021). Overall, while this industry maintains a relatively good safety record, it continues to face significant challenges regarding maritime incidents with potentially catastrophic consequences. Despite the introduction of safety-enhancing measures, maritime accidents continue to occur periodically, causing serious consequences, such as casualties, environmental damage, and property losses (Eliopoulou et al., 2016). Therefore, maritime safety remains a top concern for the global transportation sector because accidents have far-reaching consequences, like loss of life, environmental damage, and financial impact (Sánchez-Beaskoetxea et al., 2021; Psarros et al., 2010).

This has made maritime safety an increasingly important topic for regulators, industry actors, and academics, requiring comprehensive accident analysis to understand accident causes, enabling experts and regulators to devise measures to reduce the risk. Maritime accidents are commonly caused by complex technical, human, organizational, and environmental factors. To prevent such accidents, the International Maritime Organization requires analyzing each severe maritime accident to gain insight into its causes and develop measures to prevent similar incidents (K. Liu et al., 2021).

The pressures faced by the shipping industry, where the pursuit of profit and the need to meet deadlines often push ship operators and their crews to the limits, can lead to errors and failures occurring in various aspects of the complex shipping operations (Oltedal & Lützhöft, 2018). In cases where errors lead to a failure of critical safety barriers, accidents can occur, possibly leading to devastating consequences. Factors that contribute to error-inducing systems in shipping include social organization, economic pressure, industry structure, insurance, and challenges in international regulation. Insurance can contribute to error-inducing systems in shipping through mechanisms like "moral hazard," where the safety precautions might be overlooked due to the perceived safety net of insurance. Additionally, high premiums or complex claims processes might encourage ship operators to cut corners to avoid costs, further raising the risk of errors. The selective focus on risks based on insurance coverage can also lead to oversight of other crucial safety aspects. The maritime industry faces a unique combination of workplace dangers and demands, including fatigue (Shan & Neis, 2020), stress, work pressure, communication challenges, environmental factors, and extended periods away from home (Mazaheri et al., 2015). Extended absences from home in the maritime industry can lead to feelings of isolation and homesickness, causing emotional stress and impairing judgment. This is distinct from fatigue, which is immediate exhaustion from long work hours or lack of rest. Both can influence human error in ship operations, but they stem from different sources: one from emotional strain over long durations and the other from immediate physical or mental tiredness. Improvements in ship design and navigation aids have led to a reduction in the frequency and severity of shipping incidents. Findings of a decrease in technological failures has led to an increased focus on the influence of human error in accident causation (Hetherington et al., 2006). Human error is widely considered a major factor in maritime accidents, with numerous incidents resulting from it. Influential factors of human error include stress, fatigue, communication breakdowns, and inadequate training, which can all lead to unsafe conditions and accidents at sea (Kapoor et al., 2019).

Regarding human life, maritime occupations remain highly hazardous, with elevated risks of injuries and fatalities. Lefkowitz (2013) estimated the global shipping injury rate to be 850 per 100,000 seafarers. A multinational study found that 8.5% of seafarers experienced an injury during their latest tour of duty (Jensen et al., 2004), while a Danish study reported that the fatality rate in merchant shipping was ten times higher than in land-based industries (Hansen et al., 2002). In the United Kingdom, the fatal accident rate for seafarers between 2003 and 2012 was 14.5 per 100,000 workers, which was 21 times higher than the general British workforce, and 4.7 times higher than in the construction industry (Roberts et al., 2014). In Canada, the fatal accident rate for seafarers was 22 per 100,000 workers between 1996 and 2005, surpassing that of the United Kingdom (Roberts et al., 2014). Taking British Columbia's water transport industry as an example, the injury rate for seafarers including tug, barge, and other water transport workers, was approximately 400 per 100,000 workers, around half the global rate but still notably higher than the provincial average of 200 per 100,000 workers (Shan, 2020). Maritime workers face two main types of occupational hazards: accidents and diseases, which can affect both physical and mental health. Many marine occupational accidents are furthermore related to maritime disasters (e.g., collisions, foundering, and explosions involving ships), see for example (Roberts et al., 2014).

During the operation of ships, as they navigate toward their intended destinations, factors such as vessel traffic and geographic conditions may contribute to the occurrence of accidents. These accidents can potentially result in loss of stability or the spilling of cargo, which can adversely affect the surrounding environment. The situation becomes critical when the cargo comprises hazardous materials, such as chemical compounds or crude/product oil, posing significant risks to the environment, including living ecosystems and species. The environmental consequences of maritime accidents, examining the effects that extend beyond the immediate vicinity of the incident. The impact of such accidents can spread across vast areas, threatening the well-being of coastal communities and the overall health of the oceans. By understanding the complexities of maritime accidents and their environmental implications, it is important to emphasize the importance of enhanced safety measures and responsible practices within the shipping industry to minimize adverse effects on the marine ecosystem (Prabowo & Bae, 2019).

Ship accidents also can have significant economic consequences for the maritime industry and the wider global economy. They can result in substantial economic losses. These losses can include damage to vessels, cargo, and infrastructure, as well as costs associated with cleanup and recovery efforts. Additionally, accidents can cause disruptions to global supply chains, leading to delays in the delivery of goods and higher costs for businesses and consumers. Understanding the economic effects of ship accidents is therefore important for ensuring the safety and sustainability of the maritime industry (Weng et al., 2019).

As highlighted by Lin and Cheng (2021), human factors and a lack of professional training contribute significantly to marine accidents. Consequently, there is a continued need to improve maritime safety in general to reduce accidents, and to prevent similar incidents from occurring in the future.

Various studies have explored different aspects of maritime safety, such as administrative reforms (Lin & Cheng, 2021), effective implementation of safety codes (Bastug et al., 2020), and the development of safety performance evaluation methods (Yang et al., 2010). These approaches aim to establish a comprehensive understanding of the hazards and risks related to maritime safety, and to devise efficient strategies that enable prioritizing safety and prevention measures.

Moreover, the integration of advanced technologies and data analysis techniques can help monitor and manage maritime safety more effectively. For instance, Valdez Banda and Goerlandt (2016) discussed the application of Systems-Theoretic Accident Modeling and Processes (STAMP) theory to design safety intent specifications. Hänninen et al. (2014) propose a Bayesian network model to monitor and direct the safety performance of maritime safety management.

The maritime industry works tirelessly to enhance safety measures and minimize risks through risk and sensitivity analyses based on accident causation probability modelling frameworks (Hänninen & Kujala, 2012), safety culture development (Håvold, 2007), application of socio-technical systems theories to consider ships as organizations or complex systems, by investigating the role of power, and by creating dynamic safety capabilities for organizational learning of ship safety (Dominguez-Péry et al., 2021). Comprehending and tackling root causes of accidents is often considered a critical aspect for developing targeted improvements and prevention strategies to boost maritime safety (Celik & Cebi, 2009).

By successfully identifying and intelligently measuring accident-contributing factors, focused efforts can be directed towards addressing these factors to reduce the accident rate and, in turn, improve overall maritime safety. Through systematically analyzing past accidents and by identifying common contributing factors, it becomes possible to develop targeted strategies and preventive measures that mitigate risks and minimize the occurrence of similar incidents in the future. It is imperative that the industry and regulatory bodies continue to refine accident investigation methodologies and enhance the understanding of the complex interactions between human, technical, and environmental factors that contribute to accidents. By doing so, valuable insights gleaned from past accidents can be effectively integrated into safety assessments, leading to tangible improvements in maritime safety practices (de Maya et al., 2020).

Many accident investigation methodologies and tools have been developed as part of improving safety efforts to analyze and learn from past incidents (Oltedal & Lützhöft, 2018). By exploring contributing factors and understanding the intricate interactions between human, organizational, and technical elements, the maritime industry can make informed decisions to further improve safety measures and prevent future accidents (Kujala et al., 2009). Various authors describe the process of accident investigation somewhat differently. Some divide the process into three partially overlapping main phases including collection of evidence and facts; analysis of evidence and facts and development of conclusions; and development of judgments and the writing of the report. Other authors also include the implementation and follow-up of recommendations as part of the investigation (Sklet, 2004).

Regardless of the methods employed for accident investigation, numerous organizations, including companies and governmental agencies, actively engage in extensive measures to learn from accidents. Following a significant incident or accident, carrying out a comprehensive investigation is typically the subsequent course of action. Delving into the details of an accident or incident can reveal valuable insights about the organization's safety practices. Such investigations may expose previously unnoticed weaknesses in safety management or culture, as well as underappreciated, unknown, or inadequately controlled risks. The involvement of government agencies in the investigation and analysis of events can vary, with inspectorates, accident research boards, or criminal prosecutors in many countries examining some or all-serious occupational and industrial accidents that transpire. The examination of serious occupational and industrial accidents by governmental agencies, whether it is through inspectorates, accident research boards, or criminal prosecutors, can expose overlooked vulnerabilities in safety management, culture, or poorly managed risks. While the involvement of such agencies is often necessary, there is a valid concern about potential "ulterior motives" that may compromise the integrity of investigations. For instance, instances of regulatory capture, where regulatory agencies may prioritize the interests of the industry they regulate over public safety, can interfere with impartiality. Events like the Lac-Mégantic disaster underscore the necessity to ensure investigations are free from undue external influences to maintain public trust and ensure genuine safety improvements (Kampen & Drupsteen, 2013).

Different investigation bodies involved in maritime accident investigations possess distinct areas of focus and authority, according to their specific mandates. In the maritime industry, entities such as national maritime safety agencies, competent authorities, accident investigation bodies, flag states, shipping management companies, and ministries of transportation play crucial roles in the aftermath of maritime accidents. For example, flag states are responsible for overseeing accident investigations involving ships registered under their jurisdiction, ensuring thorough investigations and sharing findings with relevant organizations. Shipping management companies cooperate with investigations by providing information, access to crewmembers, and potentially conducting internal investigations for improvements. Ministries of transportation often oversee national maritime safety agencies and competent authorities, sometimes directly participating in or coordinating accident investigations to promote safety and protect the environment (European Parliament legislative resolution, 2008).

Each body has specialized knowledge and skills relevant to their area of focus. For instance, maritime safety agencies employ experts in vessel systems, navigation, and maritime operations, while organizations responsible for pollution prevention and response rely on professionals skilled in mitigating environmental hazards associated with accidents. The location and nature of an accident determine the organizations responsible for its investigation. Depending on the specific context, national or regional bodies may take the lead, while international agencies may also be involved in cases where accidents occur in international waters or involve multiple jurisdictions. Some investigation bodies operate independently, focusing solely on accident investigations, while others form part of larger organizations with multiple responsibilities, potentially influencing their approach and available resources. While certain bodies hold the authority to enforce regulations and impose fines or penalties, others may only offer recommendations for improvement in line with their mandate to enhance maritime safety and prevent future accidents (European Parliament legislative resolution, 2008).

Several studies have been conducted to investigate accidents in the maritime industry, contributing valuable insights into the factors that are involved in these incidents. For example, one study developed a new core task analysis-based method for accident analysis and applied it to maritime accidents that occurred in Finnish coastal waters, focusing on a generalization and integration of experts' work (Nuutinen & Norros, 2009). Another study reviewed 41 accident investigation reports related to machinery space fires and explosions, assessing the identification of organizational factors by maritime accident investigators (Schröder-Hinrichs et al., 2011).

In another study, a data-driven Bayesian network was used to investigate the effect of human factors on maritime safety through maritime accident analysis, highlighting the differentiation among the vital human factors against different types of accidents (Fan et al., 2020). A dedicated Human and Organisational Factors (HOFs) framework for maritime accidents investigation and analysis was also developed and named Human Factors Analysis and Classification System for Maritime Accidents (Chen et al., 2013). Akhtar and Utne (Akhtar & Utne, 2014) explored the impact of human fatigue on the risk of maritime groundings using a Bayesian Network modeling approach. Zhang et al. (2019) utilized the HFACS and fault tree model for collision risk factors analysis of icebreaker assistance in ice-covered waters. Lastly, an analysis of maritime incidents and accidents that occurred over the last decade involving passenger ships aimed to illuminate the prevailing causal factors, including systemic ones, and their role in accident causation (Puisa et al., 2018). Despite these extensive investigations in the maritime industry, there is a noticeable gap in the literature regarding a comprehensive analysis of major maritime accidents in Canada. Specifically, there is a need to better understand the causal factors represented in Canadian maritime accident reports.

The geographic location of Canada, with its expansive coastline along the Atlantic, Pacific, and Arctic Oceans, underscores the country's prominence in global maritime affairs. As a nation heavily invested in international trade and transport, the importance of maritime safety resonates deeply within Canada's shipping sector. The significance of understanding the causal factors behind maritime accidents on Canadian waters extends beyond national borders, impacting global shipping dynamics. Canada's strategic role as a major player in maritime trade and its proximity to critical trade routes magnify the importance of comprehending and mitigating maritime accidents within its territorial waters (*World Shipping Council*, 2021).

Beyond its geographical implications, this research addresses theoretical and methodological gaps in understanding maritime accidents. The complexity of maritime systems demands a comprehensive perspective that considers how various factors, from human errors to technical malfunctions, intertwine to trigger accidents (Rowbotham, 2014). This methodological choice stands to contribute significantly to the broader theoretical understanding of maritime accidents by offering a framework that embraces the multifaceted nature of their causality.

The focus on reports from the Transportation Safety Board (TSB) of Canada is paramount. As an independent agency responsible for investigating transportation-related incidents and accidents, the TSB plays a vital role in advancing transportation safety and translating lessons learned into preventive measures (Government of Canada, 2020). The insights garnered from this research are expected to have tangible applications in enhancing maritime safety practices, both within Canada and globally. By shedding light on the dominant causal factors, temporal patterns, and contextual nuances underlying maritime accidents, this study equips stakeholders in the academic, policy, and industry domains with valuable information for future research, safety enhancement, and risk reduction.

2 regulatory frameworks of marine accident investigation and related studies

2.1 Regulatory background for marine accident investigation

2.1.1 International actors approach and role

In accordance with SOLAS regulation I/21 and MARPOL articles 8 and 12, each Administration commits to investigating any ship casualties for vessels registered under its flag that fall within the scope of these conventions, and to provide the International Maritime Organization (IMO) with relevant information from such investigations. Additionally, the Load Lines Convention's Article 23 mandates the investigation of casualties (International Maritime Organization, 2008).

According to IMO A "Marine Casualty" is defined as an occurrence or a series of occurrences directly related to a ship's operations that has led to any of the following outcomes:

1. Death or serious injury to individuals.
2. Loss of an individual from a ship.
3. Loss, presumed loss, or abandonment of a ship.
4. Material damage to a ship.
5. Stranding or disabling of a ship.
6. Collision involving a ship.
7. Material damage to marine infrastructure external to a ship, posing a serious safety threat to the ship itself, another ship, or an individual.
8. Significant damage to the environment or the potential for substantial environmental harm caused by ship damage.

It is important to note that marine casualties exclude deliberate actions or omissions with the intention to cause harm to the safety of a ship, individuals, or the environment. These deliberate acts or omissions are not considered within the scope of marine casualties (International Maritime Organization, 2008).

In May 2008, during its 84th session in London, the Maritime Safety Committee (MSC) of the International Maritime Organization (IMO) adopted a new Code of International Standards and Recommended Practices for a Safety Investigation into a Marine Casualty or Marine Incident (Casualty Investigation Code). The primary aim of this Code is to establish a unified approach for States to undertake marine safety investigations into marine casualties and marine incidents. These investigations are not intended to assign blame or ascertain liability; instead, they focus on preventing future marine casualties and incidents.

According to the Code, this objective can be achieved by States through the following means:

- Employing a consistent methodology and approach, allowing for comprehensive investigations, where necessary, to uncover causal factors and other safety risks.
- Submitting reports to the Organization to facilitate widespread dissemination of information, which will help the international marine industry address safety issues (IMO, 2008).

The Code acknowledges that, under the Organization's instruments, each flag State bears the responsibility to investigate any casualties involving its ships, provided that such an investigation might contribute to identifying potential changes in current regulations or if the casualty has resulted in significant adverse environmental impacts. Furthermore, the Code considers that a flag State should conduct an inquiry, led by a suitably qualified person or persons, into specific marine casualties or marine incidents of navigation on the high seas. However, the Code also recognizes that if a marine casualty or marine incident occurs within a State's territory, including its territorial sea, that this State has the right to investigate the cause of any such marine casualty or marine incident regardless of the flag of the vessel involved in the incident that might pose a risk to life or the environment, involve the coastal State's search and rescue authorities, or otherwise affect the coastal State (IMO, 2008).

Providing mandatory casualty reports under the SOLAS Convention is one of the administrative responsibilities of a flag State as per the United Nations Convention on the Law of the Sea (UNCLOS). This responsibility entails that a State must initiate inquiries into serious casualties involving vessels flying its flag on international waters, and cooperate with other States acting as coastal states when a vessel flying its flag is involved in an incident in the territory of the other state in carrying out such inquiries. This mandate is enforced in international maritime law through SOLAS 74, which stipulates that each Administration is obligated to conduct an investigation into any casualty occurring to any of its ships that fall under the provision of the present Convention, when it deems such an investigation to be potentially informative or necessary (Mansell, 2009).

Building on the international framework for marine casualty investigations, Canada has implemented its own set of regulations pertaining to marine casualties. These Canadian regulations, in conjunction with international codes and conventions, serve to establish a comprehensive framework for the investigation and reporting of marine casualties (Branch Legislative Services, 2007). The Canadian Marine Casualty Investigation and Reporting Regulations outline the requirements for marine casualty reporting and investigation in Canada. Key aspects of the Canadian regulations include:

1. Definitions: The regulations provide definitions for terms such as "casualty," "ship," and "total loss," which help establish a clear understanding of the scope of the regulations.
2. Reporting Requirements: The regulations mandate that the master, owner, or agent of a ship involved in a marine casualty must report the incident to the nearest Marine Communications and Traffic Services Centre, a Canadian Coast Guard Radio Station, or to the nearest office of the Department of Transport. The report must include specific details about the casualty, such as the ship's name, the nature of the casualty, the location, and any assistance required.
3. Investigation: The authority to instigate an investigation into any marine casualty occurring within Canadian waters or involving a Canadian ship is vested in the Minister of Transport, Infrastructure and Communities. However, the operational responsibility for conducting these investigations typically falls under the purview of the

Transportation Safety Board (Government of Canada, 2006). A comprehensive examination of the TSB's role and responsibilities in these investigations is presented in Section 2.5. The investigation's purpose is to determine causes of the casualty, identify any contributing factors, and ascertain whether existing regulations were followed.

4. Preservation of Evidence: The regulations require the preservation of any evidence relating to the marine casualty, including the ship's logbook, charts, and any other relevant documents or objects.
5. Cooperation with International Investigations: In line with the international framework, the Canadian regulations recognize the importance of cooperation with other countries in investigating marine casualties that involve foreign-flagged ships in Canadian waters or occur in international waters involving Canadian flagged Ships (Branch Legislative Services, 2007).

2.1.2 Canadian organizations approach and role

Established by the Canadian Transportation Accident Investigation and Safety Board Act on March 29, 1990, The Transportation Safety Board of Canada (TSB) is an independent agency mandated to promote safety across air, marine, pipeline, and rail transportation sectors in Canada. The Board comprises up to five members, including a chairperson, and is bolstered by a staff of approximately 220, guided by the Chief Operating Officer and the Executive Committee. While the TSB's headquarters is in Gatineau, Quebec, field offices are strategically spread across the country, facilitating swift response to transportation incidents or accidents anywhere in Canada (Government of Canada, 2020).

The TSB is charged with conducting independent investigations into selected transportation occurrences, pinpointing safety deficiencies, and formulating recommendations to mitigate such deficiencies. It is also tasked with publicly reporting on its investigations and findings. While the TSB's remit does not extend to assigning fault or determining civil or criminal liability, it provides comprehensive reports on the causes and contributing factors of an occurrence. To ensure that its investigations, identification of safety deficiencies, and recommendations are free from conflict of interest, the TSB operates independently of other government departments and currently reports to Parliament through the President of the King's Privy Council for Canada. Its mandate sets it apart from organizations like Transport Canada, the Canadian Energy Regulator, the Royal Canadian Mounted Police, the Canadian Coast Guard, and the Department of National Defence. Nonetheless, it cooperates with these entities during investigations and safety recommendation formulation. Notably, when the TSB investigates an accident, no other federal department, excluding the Department of National Defence, is authorized to investigate with the aim of identifying the causes and contributing factors of the accident (Government of Canada, 2020).

TSB employs a three-phase methodology in its investigations. Initially, the field phase commences once the decision to investigate has been made. An investigator-in-charge (IIC) is appointed, and an investigation team is assembled, comprising various experts in operations, equipment, maintenance, engineering, science, and human performance, depending on the nature of the occurrence. The team's tasks during this phase include informing the public of TSB's deployment, securing and examining the occurrence site, inspecting and photographing equipment or wreckage, interviewing witnesses and relevant personnel, selecting wreckage for further examination, and reviewing documentation (Government of Canada, 2020).

The investigation transitions to the examination and analysis phase after the team leaves the occurrence site. This phase involves an extensive review of company, vehicle, government, and other records; examination of selected wreckage in the laboratory; testing of selected components and systems; reading and analyzing recorders and other data; creating simulations and reconstructing events; reviewing autopsy and toxicology reports; conducting further interviews; determining the sequence of events; and identifying safety deficiencies. Critically, if safety deficiencies are identified at any stage, those capable of rectifying the problem are informed immediately. The final phase is the report phase, where an investigation report is drafted, reviewed by the Board, and sent to designated reviewers for comments. The Board considers all feedback, makes necessary amendments, and upon approval, releases the final report to the public. While the TSB is committed to swift publication, it prioritizes thorough investigation and reporting to advance safety and meet public and industry expectations (Government of Canada, 2020).

The Transportation Safety Board of Canada (TSB) deals with a substantial number of transportation occurrences annually, ranging between 3000 and 4000. These occurrences, both mandatory and voluntary reports, necessitate investigation. However, practical constraints require that only a fraction of these occurrences can undergo comprehensive investigation(Government of Canada, 2020).

Under the Canadian Transportation Accident Investigation and Safety Board Act, the TSB's objective is to enhance transportation safety by conducting independent investigations into selected transportation occurrences, determining their causes and contributing factors. Notably, the TSB is not obligated to investigate all reported occurrences. The Board is granted the authority to establish policies concerning the types of occurrences to be investigated(Government of Canada, 2020).

The policy defines key terms, including "occurrence," "reportable occurrence," "foreign occurrence," "investigation," "report," "investigation summary," "incident," and "accident."

The policy's primary aim is to create a classification structure that facilitates tracking, investigating, and reporting transportation occurrences in alignment with the CTAISB Act's provisions. Additionally, the policy sets criteria for investigations within each class of occurrence, aiding decision-making, resource management, and stakeholder communication(Government of Canada, 2020).

The classification process involves categorizing occurrences as "accidents" or "incidents" and then further classifying them based on importance, complexity, and potential for safety insights. There are six classes of occurrences, each guiding the level of effort, investigation process, report type, and timeline. Foreign occurrences are classified similarly to Canadian ones, with instances where the TSB supports another investigation body being labeled as class 6 occurrences(Government of Canada, 2020).

The classification of occurrences can be adjusted when new information emerges, but upgrading or downgrading class 2, 3, or 4 occurrences requires Board approval. The policy is authorized by the Board and addresses Chair, Chief Operating Officer, and Directors' roles and responsibilities, ensuring compliance and accurate implementation(Government of Canada, 2020).

The "Guidance Notes on the Investigation of Marine Incidents" by the American Bureau of Shipping highlights several methodologies that can be beneficial in analyzing data during an accident investigation. These methods include relative ranking, Failure Modes, Effects and Criticality Analysis (FMECA), Fault Tree Analysis, What-if analysis, Hazard and Operability (HAZOP) analysis, influence diagrams, and design of experiments. Of these, Fault Tree Analysis had been identified as particularly effective and efficient for determining the incidents that need to be addressed during an investigation. This technique also offers the advantage of being a familiar tool to investigators, commonly used for organizing and analyzing data. The guidance notes also detail the application of these methods to Apparent Cause Analyses and Root Cause Analyses, which help determine which incidents require immediate analysis. The document further provides strategies for selecting near-miss incidents and chronic incidents for analysis, emphasizing that chronic incident analysis can occur at either the apparent cause or root cause analysis level (Palfy, 2005).

The process of conducting safety investigations necessitates a deep understanding the nature of accidents and the organizational frameworks within which they occur. This knowledge is often bolstered by academic research and the development of accident causation models. Despite the diversity and richness of these models, none completely encapsulates every aspect of accident development. Nevertheless, models like the Reason Model of organizational accidents, despite its limitations, are considered to provide valuable guidance. More recent models such as the Human Factors Analysis and Classification System (HFACS), Sequential Timed Events Plotting (STEP), HuMan – Technology - Organisation (MTO), Cognitive Reliability and Error Analysis Method (CREAM), and Casualty Analysis Methodology for Maritime Operations (CASMET) offer significant improvements, and are being integrated into the practices of marine safety investigators (*MAIIF Manual, 2014*).

2.2 Maritime Accident Investigations: Regional and Global Studies

Various regional studies have been conducted to analyze the contributory factors in maritime accidents in specific locations. Ma et al. (2022) focused on examining the contributory factors of maritime transport accidents involving dangerous goods in China. First, 20 contributing factors are identified based on reports of 22 accidents in China, expert knowledge and literature review. They analyzed accidents that occurred between 2000 and 2014, identifying contributing factors grouped into human factors, management factors, vessel factors, and environmental factors.

Using the DEMATEL (Decision Making Trial and Evaluation Laboratory) method, Ma et al. (2022) assessed the relationships and influence levels of these factors. Their findings suggested that human factors, particularly crew competence and experience, were among the most influential factors in maritime transport accidents involving dangerous goods. Additionally, management factors, such as safety management and emergency response, were also significant contributors.

The study underscored the importance of adhering to the International Safety Management (ISM) Code, which serves as a crucial framework for enhancing maritime safety and mitigating the risks associated with maritime transport accidents involving dangerous goods (Ma et al., 2022).

Liu et al. (2021) conducted a systematic analysis of 387 maritime accidents in Chinese coastal waters using machine learning techniques. They employed CFS (Correlation-based Feature Selection) and WFS (Wrapper-based Feature Selection) methods and trained machine learning classifiers on data obtained from the China Maritime Safety Administration (MSA) and the Marine Accident Investigation Branch (MAIB) including accident records. Their analysis identified common causal factors for accidents, including human error (accounting for 75.2% of the accidents), environmental conditions (accounting for 15.5% of the accidents), and management-related factors, such as inadequate safety management systems, insufficient crew training, and poor maintenance of vessels (accounting for 9.3% of the accidents). The study emphasized the need for improved safety management, more comprehensive crew training, and enhanced vessel maintenance to reduce the occurrence of maritime accidents (K. Liu et al., 2021).

Deng et al. (2023) examined risk evolution, prevention, and control strategies for maritime accidents in China's coastal areas using complex network models. They constructed a maritime accident risk evolution network based on data from the China Maritime Safety Administration, which included 155 maritime accidents between 2010 and 2018. The findings revealed that the number of accidents in China's coastal areas had been decreasing over time but highlighted the prominent role of human factors in causing accidents. Based on their findings, they proposed targeted prevention and control strategies, emphasizing the need for enhanced maritime safety management, improved crew training, and the adoption of advanced technologies to prevent and mitigate accidents. They also stressed the importance of collaboration among relevant stakeholders and the implementation of comprehensive safety policies (Deng et al., 2023).

Sui et al. (2023) analyzed 206 maritime accidents on the Yangtze River between 2011 and 2020 using time series analysis techniques. They identified patterns and temporal variations in maritime accidents and found that the highest number of accidents occurred during the summer months, with 35.9% of accidents happening in July and August. The analysis revealed that human factors contributed to 64.1% of accidents, vessel factors contributed to 29.1%, and environmental factors contributed to 6.8%. Based on their findings, they proposed recommendations for improving maritime safety in the Yangtze River region, including enhancing crew training, strengthening safety management systems, and promoting the use of advanced navigation technologies. They also suggested the implementation of risk assessment (Sui et al., 2023).

Md Hanafiah et al. (2022) assessed maritime transportation accidents in the Straits of Malacca using FAHP (Fuzzy Analytic Hierarchy Process) and Fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methods. They analyzed data from 2001 to 2016, including 120 accidents that occurred in the area. The study identified critical factors contributing to accidents, such as human factors (including fatigue, inadequate training, and poor decision-making), technical failures (including equipment malfunction and maintenance issues), and weather conditions (such as storms, strong currents, and fog). The research also revealed that groundings and collisions were the most frequent types of accidents. Based on their findings, they provided insights into developing effective measures to control accidents in the area, such as strengthening safety regulations, improving navigational aids, and enhancing cooperation among coastal states (Md Hanafiah et al., 2022).

Lee and Chung (2018) developed a new methodology for accident analysis by employing the Functional Resonance Analysis Method (FRAM), which considers the interplay between human and system interactions. The researchers implemented this methodology in two maritime case studies from diverse global locations, namely the North Sea and the East China Sea. The study's results demonstrated the effectiveness of this methodology in identifying potential causal factors and system vulnerabilities. The findings also suggested that the proposed approach could reveal concealed risks and offer some insights for accident prevention (Lee & Chung, 2018).

Yildiz et al. (2021) employed the HFACS-Performance Variability (HFACS-PV) approach to study 41 marine accidents in Turkey, using data from the Turkish Maritime Casualty Investigation Board. Their findings identified human and organizational factors influencing marine accidents, such as inadequate supervision, poor communication, and insufficient training. Moreover, the study found that 89.4% of the accidents involved human error, with perceptual errors, mental errors, and psychomotor errors being the most common types. The authors stressed the importance of considering performance variability in accident analysis and suggested that the HFACS-PV approach could serve as a valuable tool for improving maritime safety by providing a comprehensive understanding of human error patterns and underlying organizational factors (Yildiz et al., 2021).

Montewka et al. (2012) concentrated on collision criteria and causation factors in the Gulf of Finland, drawing on data from the Finnish Transport Safety Agency and the Estonian Maritime Administration. They developed a model for estimating the probability of maritime accidents based on collision criteria and causation factors. The findings highlighted the importance of considering ship domain, ship size, and traffic density in estimating the probability of accidents. The study also found that the risk of collision was higher in areas with dense traffic and that certain causation factors, such as poor visibility and misinterpretation of navigation rules, played a significant role in accident occurrence. The model provided ideas about the relationships between different factors and could be used for accident prevention and decision-making by assisting maritime authorities in identifying high-risk areas and implementing defined safety measures (Montewka et al., 2012).

In addition to the above regional studies, various global studies have also been conducted, such as those by Chauvin et al. (2013), Wang et al. (2022), and Puisa et al. (2018) which analyzed maritime accidents in multiple locations worldwide.

Chauvin et al. (2013) analyzed 100 collisions at sea from various locations worldwide, utilizing the Human Factors Analysis and Classification System (HFACS) and drawing data from the International Maritime Organization's (IMO) Marine Casualty and Incident Database. Their findings revealed that human error was present in 80% of the accidents, with the most frequent factors being situational awareness issues, decision-making errors, and communication problems. Organizational factors, such as inadequate supervision and operational processes, were also identified as contributing factors (Chauvin et al., 2013).

Wang et al. (2022) conducted a GIS-based analysis to explore the spatial patterns of global maritime accidents, aiming to identify areas with higher accident rates and pinpoint hotspots of maritime accidents. By analyzing data from various sources, including the Global Integrated Shipping Information System (GISIS) database, the authors were able to compile a comprehensive dataset that allowed them to map the distribution of maritime accidents worldwide. The findings of the study revealed that certain regions exhibited higher accident rates than others, indicating the presence of maritime accident hotspots. Wang et al. (2022) further examined the contributing factors that led to the increased accident rates in these hotspots, such as human factors, management factors, and environmental factors.

Based on their findings, the authors proposed targeted safety improvement measures that could be implemented in the identified hotspots to reduce the occurrence of maritime accidents. These measures included enhancing maritime safety management, improving crew training, and adopting advanced technologies to prevent and mitigate accidents. Wang et al. (2022) also emphasized the need for cooperation among relevant stakeholders and the implementation of comprehensive safety policies to ensure the effectiveness of safety improvement measures.

Puisa et al. (2019) investigated 100 maritime accident reports from various locations across the globe, using databases like the European Maritime Safety Agency's (EMSA) Accident Investigation Reports and the United States Coast Guard's (USCG) Marine Casualty and Pollution Data. Their objective was to identify causal factors and patterns. The results of their study showed that most accidents were caused by human and organizational factors, including poor communication, inadequate training, and insufficient maintenance. The authors also emphasized the importance of considering multiple factors when investigating maritime accidents and adopting an integrated approach to accident prevention (Puisa et al., 2018).

2.3 Accident Models and Analysis Techniques

In the analysis of maritime accidents, several techniques, though each with their inherent limitations, are commonly employed to address the complex aspects of such incidents. As indicated in the literature, these methods often fall into two key categories: human and organizational analysis techniques, and systemic investigation approaches. Each of these methods contributes distinctive insights into accident causation and prevention, recognizing the inherent diversity and complexity of maritime accidents.

Numerous studies have employed the Human Factors Analysis and Classification System (HFACS) or its derivatives to investigate the causal factors contributing to maritime accidents. These studies have employed a variety of methods to analyze human factors and their impact on maritime safety.

A study by Grazianoet al. (Graziano et al., 2016) stands out in its innovative use of the Technique for the Retrospective and Predictive Analysis of Cognitive Errors (TRACEr) taxonomy. Originally designed for air traffic control operations; however, as shown in figure 1, TRACEr was repurposed by the authors to categorize human errors in grounding and collision accidents in the maritime domain. Their methodology, applied to real-world case studies, allowed for systematic classification and analysis of human errors, providing a deeper understanding of how such errors contribute to maritime accidents.

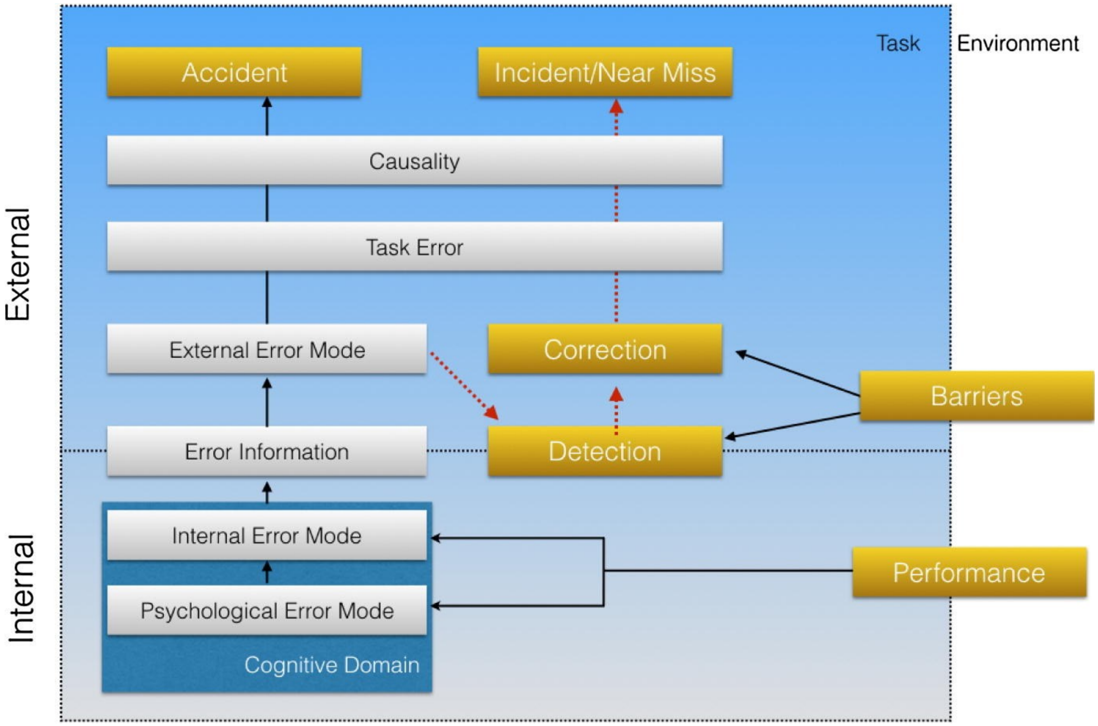

Figure 1 TRACEr framework adapted for Ship Accident Investigation (Graziano et al., 2016)

Another compelling approach was suggested by Stroeve et al. (Stroeve et al., 2022). They developed SHIELD (Safety Human Incident & Error Learning Database), a human factors taxonomy and data repository, with the express aim of systematically gathering and evaluating human factors contributing to safety occurrences within the maritime and aviation domains. This taxonomy is structured in four layers: the bottom layer delves into the direct actions of human operators during safety occurrences; the subsequent layer investigates the preconditions impacting human performance; the third layer scrutinizes the decisions or policies implemented by operations leaders that directly influence operational practices or conditions; while the topmost layer considers organizational decisions, policies, or methods that have overarching effects.

SHIELD's utility has been evidenced through its successful application by maritime and aviation partners to analyze over 400 incidents and accidents. The resultant human factors statistics and occurrence traceability not only serve as a feedback mechanism for designers and safety management to glean more holistic lessons about human contributions to safety occurrences, but also underscore the similarities and differences between the aviation and maritime sectors, enriching our understanding of human error in these complex systems (Stroeve et al., 2022).

Fan et al.'s (Fan et al., 2020) research focused on incorporating human factors into maritime accident analysis using a data-driven Bayesian network. They analyzed a dataset of maritime accidents, constructing a Bayesian network model based on the HFACS framework to identify the relationships between human factors and accident outcomes. This approach allowed for a more robust understanding of the complex interplay of human factors in maritime accidents and their causal relationships.

In the noteworthy study by Zhang et al. (Zhang et al., 2019b) an intricate Human and Organizational Factors (HoFs) model of ship collision accidents involving an assisted ship and an icebreaker was constructed and scrutinized to recognize and categorize collision risk factors. Initially, a bespoke model of the Human Factors Analysis and Classification System (HFACS), adapted for collision incidents between a ship and an icebreaker in icy waters, was put forth. This revised HFACS model served as a tool to interpret ship collision reports more effectively. Subsequently, a Fault Tree Analysis (FTA) model was leveraged to dissect the fundamental collision risk factors drawn from the statistical examination of accident reports and expert assessments, following the structure of the modified HFACS model (termed HFACS-SIBCI). The study culminated with a qualitative investigation of collision risk factors under the purview of icebreaker assistance, during which Risk Control Options (RCOs) were designed. This research offers crucial guidelines for managing the risk of ship collisions during icebreaker assistance in ice-covered waters, presenting valuable insights for legislators and shipping companies alike.

Qiao et al.'s (Qiao et al., 2020) study proposed a methodology to evaluate human factors contributing to maritime accidents by mapping fuzzy fault trees into artificial neural networks based on HFACS. The approach provided a systematic identification and evaluation of human factors in maritime accidents, enabling effective accident prevention strategies. The authors demonstrated the applicability of their methodology by analyzing a collision case between a fishing vessel and a cargo ship.

A different study (Chen et al., 2013) developed a Human and Organisational Factors (HOFs) analysis method for marine casualties using HFACS-Maritime Accidents (HFACS-MA). This method adapted the original HFACS framework to better suit the maritime context, enhancing its effectiveness in identifying and analyzing human and organizational factors in marine accidents.

Yildiz et al.'s (Yildiz et al., 2021) research applied the HFACS-PV approach, an extension of the original HFACS framework, to identify human and organizational factors influencing marine accidents. This approach integrated HFACS with the Performance Variability (PV) model, allowing for a more comprehensive understanding of the interrelationships between various factors like Organizational Influences, Unsafe Supervision, Pre-conditions for Unsafe Acts, Unsafe Acts, and Operational Conditions . The study found that inadequate supervision, decision-making errors, and violations of standard operating procedures were among the most significant contributors to considered maritime accidents.

Chauvin et al.'s (Chauvin et al., 2013) study used the HFACS framework as well to analyze human and organizational factors contributing to maritime accidents involving collisions at sea. By examining a sample of 100 collision cases, the authors were able to identify underlying causes such as inadequate communication, lack of situational awareness, and insufficient training. Environmental factors, such as poor visibility and misuse of instruments, along with deficits in situation awareness and attention were highlighted. Crucial personnel factors included failures in inter-ship communications and Bridge Resource Management (BRM). At the leadership level, inappropriate operation planning was common, and at the organizational level, failures in the Safety Management Systems (SMS) or the audit process were noted.

Systemic investigation techniques, such as the Functional Resonance Analysis Method (FRAM) and Systems-Theoretic Accident Model and Processes (STAMP), have also been increasingly used in recent years. FRAM maps out the functions and dependencies within a system, illustrating how changes can resonate across the entire system and potentially lead to accidents. For instance, Salihoglu and Beşikçi (2021) employed the FRAM Method in a maritime accident case study, the Prestige oil spill. They divided the incident into four parts to understand the critical decisions leading from initial damage to the sinking of the ship. The researchers identified five functions, each performed with different variabilities, which were crucial to the event: "Listing to starboard side", "Activating EPIRB and transmitting a distress message", "The Master of Prestige called to Finisterre Traffic", "The Master asked for a place of refuge", and "The meeting between Salvors and the Spanish Authority". The results showed that the timing, direction, and amount of each function significantly influenced the outcome of the disaster. The study suggested that early intervention, appropriate communication, and wise navigational decisions might have mitigated the disaster. The research contributed to the literature on maritime accident analysis by focusing on system functions and their variabilities, offering a functional tool for analyzing shipboard operations causing accidents. However, the authors noted the subjective nature of FRAM as a limitation, suggesting the method could be enhanced by combination with other methods (Salihoglu & Bal Beşikçi, 2021).

2.4 STAMP and CAST

Another systemic accident causality model concerns the Systems-Theoretic Accident Model and Processes (STAMP), which has also been used as a basis for understanding maritime accidents and to recommend safety improvements for maritime systems. At the core of the STAMP approach is that accidents are considered as the outcome of inadequate control of systemic safety constraints, focusing on control actions and feedback loops (N. Leveson, 2004). Because this model will be used as a basis for the methodology applied in this thesis research, the pertinent literature on this model is reviewed in some further detail.

The evolution of accident causation models traces a journey from the Swiss cheese model to STAMP, reflecting a shift in understanding of human involvement and the increasing complexity of socio-technical systems. The Swiss cheese model, introduced by Reason (Reason, 1997), revolutionized the understanding of accidents by illuminating the connection between latent and immediate accident causes. However, the advent of modern technology and automation has transformed human work from predominantly manual tasks to knowledge-intensive and cognitive activities. As a result, the human contribution to accidents has progressed from human error to human factors, a broader concept that goes beyond mere individual mistakes. To address this, various methods for human reliability analysis (HRA) and accident analysis were developed, such as ATHEANA, THERP, CREAM, HEART, HCR, ASEP, and HFACS (Swain D , 1983; Hannaman et al., 1985; Hollnagel, 1998; Wiegmann & Shappell, 2017; Williams, 1988).

Despite these advances, traditional sequential and epidemiological accident models have fallen short in capturing the intricate dynamics and non-linear interactions between system components in complex socio-technical systems. To account for new accident causes stemming from system component interactions, systems theory-based safety engineering emerged as a novel approach (N. G. Leveson, 2017). Systemic accident models, rooted in systems theory, aim to depict the system's overall performance instead of focusing on specific cause-effect mechanisms or epidemiological factors (Hollnagel, 2016). These models view accidents as emergent phenomena arising from non-linear and feedback loop-laden interactions among system components (Perrow, 1999). Following seminal works by Perrow (1999), Reason (1997), and Rasmussen (1997), the focus of accident causation studies shifted from the role of individuals towards underlying organizational factors, emphasizing 'self-organization' and the 'defense in depth fallacy'. This fallacy cautions against indiscriminately incorporating safety measures without grasping their interplay, as such additions might inadvertently pose new risks, induce operator complacency, or strain resources (Le Coze, 2015; Waterson et al., 2017). This marked the transition towards systemic accident models such as Rasmussen's AcciMap, Hollnagel's FRAM, and Leveson's STAMP (Hollnagel, 2016; N. Leveson, 2004; Rasmussen, 1997), which seek to model the complexity of socio-technical systems.

Nancy Leveson's Systems-Theoretic Accident Model and Processes (STAMP) and its related accident analysis method, Causal Analysis based on Systems Theory (CAST), have gained prominence in maritime accident investigation (Leveson, 2016). These models, rooted in Systems Theory, shift the paradigm from focusing on component failures and human errors to examining the complex interplay within socio-technical systems that leads to accidents (Ouyang et al., 2010).

STAMP, as an accident causation model, offers a systemic view of causality, focusing on the lack of control or enforcement of safety-related constraints during the system's design, development, and operation (Leveson, 2016). It acknowledges systems as hierarchical structures where each level imposes constraints on the level beneath it. Accidents occur when safety constraints are violated or inadequately enforced, allowing the system to move to states of increasing risk (Leveson, 2016). Unlike traditional accident analysis techniques such as Event Tree Analysis (ETA), Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), or Cause-Consequence Analysis which rely on a chain-of-event paradigm of causation (Qureshi, 2007), STAMP and CAST consider the dynamic nature of systems and the environment. These traditional methods often regard systems and their environments as static, unchanging designs (N. Leveson, 2004). This viewpoint is arguably insufficient for studying modern engineering systems, particularly those that are software-intensive, have complex human-machine interactions, and encompass both physical and organizational aspects (Dulac, 2009).

STAMP identifies missing or inappropriate features, those which fail to maintain safety constraints, and proceeds by analyzing feedback and control operations. This approach effectively replaces the traditional chain-of-events model (Leveson, 2011). CAST, developed based on the theoretical foundation of STAMP, provides a framework to scrutinize the entire accident process, identify crucial systemic causal factors, and focus on preventing future occurrences by understanding why the accident occurred (Leveson, 2011). Applying the Causal Analysis based on Systems Theory (CAST) to understand accidents involves adapting Leveson's original CAST steps (Leveson, 2011). This adapted analysis includes the following steps:

1. Define the complex system, system hazard, and safety constraints.
2. Create the safety control structure related to the accident.
3. Define the sequence of events.
4. Determine system components.
5. Define each component of the control structure using control and feedback actions.
6. Define the context in which decisions were made.
7. Determine flaws in mental models.
8. Designate actions, considering the dynamic structure.
9. Identify system deficiencies.

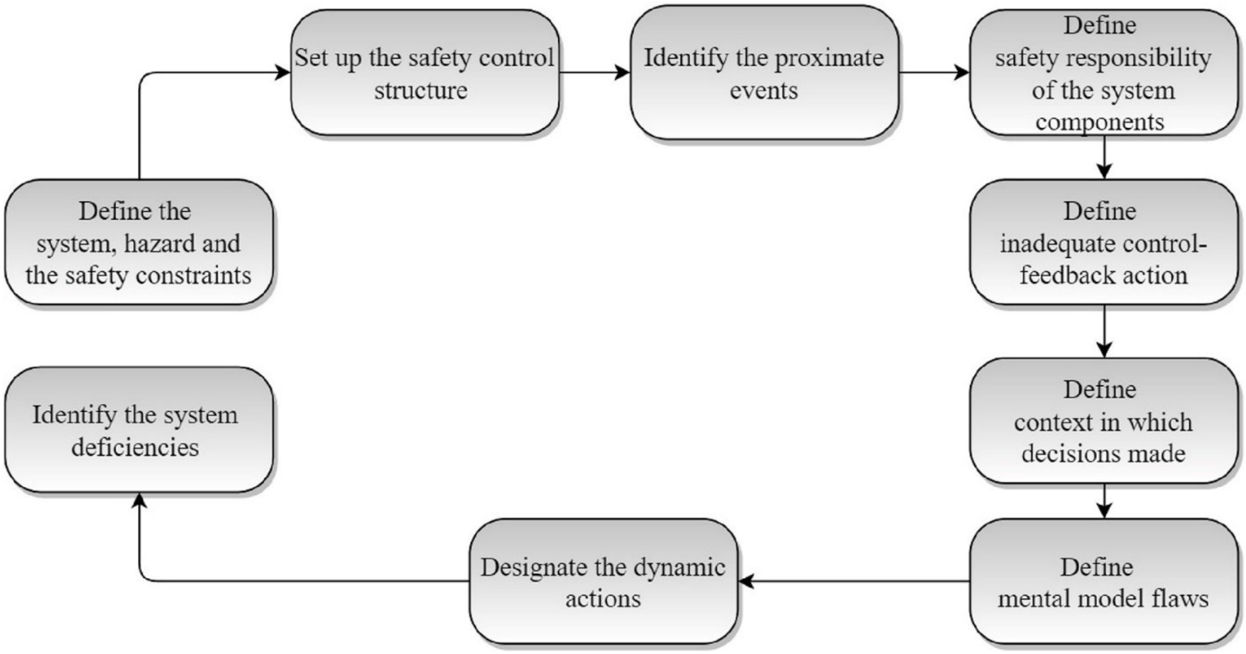

Figure 2 Graphical representation of CAST analysis steps (Leveson, 2011)

A graphical representation of these analysis steps is provided in Fig. 2 (Leveson, 2011). In their 2012 study, Salmon and his colleagues critically assess the effectiveness and practicality of three widely used methodologies for accident analysis: Accimap, HFACS, and STAMP. This discourse, however, will primarily concentrate on HFACS (Human Factors Analysis and Classification System) and STAMP (Systems-Theoretic Accident Model and Processes). HFACS is lauded by the authors for its unique taxonomic structure, which enhances error classification and reliability. Additionally, this method's usefulness is underscored through its ability to analyze a multitude of accident scenarios, potentially augmenting its viability for inclusion in safety management systems. However, the limitations of HFACS become apparent when utilized outside its primary domain of aviation due to the specificity of its error and failure modes. Furthermore, HFACS does not account for failures occurring beyond the scope of the organization, such as those related to government policies or local authorities.

The authors argue that STAMP provides a comprehensive methodology that considers the entire sociotechnical system and introduces a taxonomy of control failures that is not domain-specific. A unique attribute of STAMP is its focus on the context within which decisions are made, thus aiding in the comprehension of why certain decisions may have led to errors or inappropriate actions. Despite its complexity due to its roots in control theory and system dynamics, STAMP potentially provides a robust framework for identifying and classifying both technical and complex human decision-making failures. A significant drawback of STAMP, however, is its limited acceptance, which is currently restricted mainly to academic circles and has not yet permeated the field of safety practice (Salmon et al., 2012).

Empirical research has further substantiated the value of STAMP. Following the STAMP framework in the study "Systems-Theoretic Accident Model and Processes (STAMP) approach to analyses socio-technical systems of ship allision in narrow waters," Ceylan et al. (2021) delve into the complexities of merchant ships' operating environment, particularly the dynamic and intricate nature of engine rooms and bridges. Recognizing the critical role of human factors in managing interactions between crew, hardware, and software, they argue that traditional accident analysis methods, which typically focus on a chain of events, are becoming inadequate due to the escalating complexity of these socio-technical systems. To address this, they apply the Systems Theoretic Accident Model and Process (STAMP) to analyze a ship allision accident in narrow waters, demonstrating the model's potential to unravel the intricate system interactions leading to such accidents (Ceylan et al., 2021). This approach provides a broader, more systemic perspective on accidents, capturing the system's dynamic nature, structural errors, and the interplay between human, machine, and software elements. Furthermore, the STAMP model is effective in identifying violations of safety constraints across all control structure levels, even amidst complex and dynamic processes. The findings of the study emphasize that accidents in complex systems are not merely a cause-effect chain of events but represent system-based, dynamic, and complex situations. Consequently, the study provides a comprehensive analysis of all causes of the Vitaspirit Allison incident, illustrating the power of moving beyond a singular component focus to a systemic view (Ceylan et al., 2021).

Awal and Hasegawa (Awal & Hasegawa, 2017) conducted a comprehensive exploration of various accident theories, including the Swiss Cheese Model, the Systems-Theoretic Accident Model and Processes (STAMP), and the Normal Accident Theory (NAT), and applied them to maritime accidents. They argue that the traditional approach to maritime safety is generally reactive, indicating the unpredictability of accidents and underscoring the need for a more in-depth understanding of underlying accident theories for improved prevention strategies. By comparing the advantages and drawbacks of different accident models, their work provides crucial insights for selecting appropriate accident analysis techniques for maritime accident investigations. They further assert the significance of acknowledging the complex socio-technical context in which maritime accidents occur, pointing out that identifying a single root cause in the cause-effect chain may be insufficient for future accident prevention. To illustrate this, they reference the Titanic (1912) and Costa Concordia (2012) accidents (Awal & Hasegawa, 2017).

The utility of the STAMP/CAST model transcends accident investigation, proving its applicability for risk analysis as well. This is particularly evident in Yamada et al.'s (Yamada et al., 2022) study on the safety assurance of Maritime Autonomous Surface Ships (MASS). The study underscores the need for a standardized risk assessment method in the face of complex and multifaceted systems such as MASS, where traditional risk analysis centered on hardware failure falls short. Here, the system's intricacy extends beyond hardware to incorporate large-scale software and human interactions. As such, the authors turn to STAMP/STPA, a method designed specifically for large-scale and complex systems. They evaluated the usefulness of STAMP/STPA in the early design phases of MASS from a certification viewpoint. Their findings suggest that STAMP/STPA, with its systems-theoretic approach that considers hazards as interacting functions, is advantageous for early-stage risk analysis in designing such intricate systems. In addition, it assists in choosing the fitting analysis method relative to the design stage. This validation of STAMP/STPA's effectiveness underlines its potential in addressing the complexities brought about by rapid technological progress in the maritime field, especially regarding autonomous ship systems. The need for a comprehensive safety management framework is also addressed in the literature. Valdez Banda et al. propose a framework for designing and operating maritime safety management systems using STAMP, suggesting a transformative potential for the models in enhancing maritime safety (Valdez Banda et al., 2016).

Hu et al. (2022) conducted research to simulate the risk evolution characteristics of an LNG-fueled vessel, leveraging a systems-theoretic accident modeling and processes (STAMP) model in conjunction with a genetic algorithm (GA). They first established the STAMP model to dissect the structure of risk evolution, which is influenced by external environmental factors. Recognizing the time-bound nature of risk performance and maritime traffic, and the spatial dimension changes, they applied a GA to establish a timeline for the STAMP model. This integrated STAMP-GA model was then applied to the LNG-fueled vessel system. The team used a Cloud model, which is based on golden section ratios for risk performance levels, to supply input data for the GA model. Utilizing data specific to the LNG-fueled vessel and a route scenario from a specific anchorage to a designated berth, they simulated risk evolution performance to investigate the risk characteristics of the LNG supply process. The findings demonstrate that the risk evolution mode of the LNG-fueled vessel follows a bathtub-shaped distribution curve, and the innovative STAMP-GA model has proven effective in analyzing the mutation of risk components and the intertwined process in risk evolution (Hu et al., 2022).

Puisa et al. (Puisa et al., 2019) in their investigation of maritime accidents, focused on the engine room fire aboard the nearly new cruise ship "Le Boreal". Their systemic analysis using CAST revealed gaps in maritime safety control and suggested improvements, offering a more comprehensive approach than the official accident report. Further findings indicated overlooked interactions in the accident investigation report, contributing and systemic factors violating safety constraints, and dysfunctional interactions. Additionally, there were unanswered questions about the Chief Engineer's responsibilities and actions, the Company's potential inadequacies, and design limitations that might have been overlooked by the shipyard or design agent (Puisa et al., 2019).

In another effort for extending the STAMP domain to maritime environment, the STAMP-Mar research concept developed by (Aps et al., 2016), offers a novel perspective on maritime navigation safety management, particularly in the Gulf of Finland within the Baltic Sea Area. This globally unique ecosystem, with a daily traffic of over 2,000 ships, necessitates an innovative, dynamic safety management approach. STAMP-Mar applies the System Theoretic Accident Model and Processes (STAMP) to create a network of existing and forthcoming safety management systems, emphasizing connectivity and situational awareness. The concept acknowledges and integrates hierarchical regulatory levels, safety constraints, and control structures of maritime navigation. It underscores the significance of both the International

Maritime Organization's International Regulations for Preventing Collisions at Sea (COLREGs) and the SOLAS Convention's requirements for integrated bridge systems. Furthermore, it employs the mandatory ship reporting system in the Gulf of Finland (GOFREP) as a practical testbed for system development, with a notable emphasis on the Next Generation Smart Response Web (NG-SRW) application. An NG-SRW represents a sophisticated and intelligent web-oriented system strategically crafted to furnish instantaneous responses and solutions across a spectrum of scenarios or circumstances. Environmental considerations are incorporated via the Regional Environmental Sensitivity Index (RESI), informing safety management and environmental constraints for Maritime Spatial Planning (MSP) processes (Aps et al., 2016).

3 Data and Methodology

The methodology used for this study is based on the accident analysis technique known as CAST (Causal Analysis based on Systems Theory), as initially proposed by Leveson (2004) and further developed by Leveson and colleagues (N. G. Leveson et al., 2003). The CAST model provides a robust approach to analyze accidents within complex socio-technical systems, based on the STAMP model for accident causation. It evaluates individual variables as well as systemic factors that contribute to causality, enabling a comprehensive understanding of intricate systems (N. Leveson, 2004).

The Causal Analysis based on Systems Theory (CAST) has demonstrated its usefulness in investigating accidents across diverse industries. This includes sectors such as mining (Qiao et al., 2021) and oil (Gong & Li, 2018), and extends to the field of transportation. A notable application of the CAST methodology in transportation was conducted by Puisa et al. (2018), who meticulously identified the underlying systemic causes of maritime incidents and accidents. Their research method forms the foundation of this study. In our investigation, we sought to answer more extensive questions using varied data, with a particular focus on the Canadian maritime shipping industry.

Originating from the Systems-Theoretic Accident Model and Processes (STAMP), CAST supports a comprehensive understanding of the entire accident process, as well as all the systemic factors contributing to the accident. It provides a holistic view, allowing for a more in-depth investigation into these complex events (Leveson, 2011).

STAMP underscores that accidents typically result from inadequate enforcement of safety constraints during the system's design, development, and operation stages. However, STAMP itself does not provide a specific procedure for accident investigation; this is where the CAST technique has a role (Leveson, 2004).

The CAST technique is underpinned by the Hierarchical Control Structure (HCS), a model that describes the safety control system, i.e. the multi-level system of different actors and organizations, and their control and feedback loops to keep the system within acceptable safety limits. The HCS serves as a functional model, facilitating comprehension of the control processes that ensure safety within a system. Sections 3.2 and 3.3 elaborate on the specific application of the CAST technique and related analysis based on HCS. Prior to this, Section 3.1 provides details of the data used as a basis for the analysis. Section 3.4 is devoted to the application of the method to a specific accident report, to illustrate how the methodology is applied and how the results are obtained. Lastly, Sections 3.5 and 3.6 impart information about an additional method for calibrating temporal results, and provide insight into the qualitative features of the identified causal factors, to enable a contextualized understanding of the systemic causal factors in shipping accidents.

3.1 Data

In an effort to enhance transportation safety, the Transportation Safety Board (TSB) makes data from its Marine Safety Information System (MARSIS, 2018) publicly available. These data include narrative and graphical information on reportable accidents and incidents, collectively referred to as occurrences, for utilization by both industry actors, research organizations, and the general public. The TSB accumulates these data during its investigations, which are then used to examine safety shortcomings and recognize risks within the Canadian transportation system.

This research entails an in-depth analysis of 134 marine accident investigation reports furnished by the Transportation Safety Board (TSB) of Canada, as depicted in Figure 3. A selection of these reports is made, specifically to enable a comparative analysis of different vessel and accident types. Out of the 537 available reports on the marine section of TSB Canada website, 520 of them were completed and the rest 17 of them were in progress at the time of this research. The study focuses on three categories of accidents, namely grounding, collision, and fire (Figure 3).

The types of ships at the center of this investigation are Bulk Liquid carriers, Bulk Solid carriers, Ferries, and Passenger ships. The rationale behind focusing on these ship types among all the cases investigated by the TSB lies in their adherence to a similar System Control Structure, which is due to the similar organizations and actors interacting with a vessel when navigating in Canadian waters. This provides a cohesive and consistent platform for analysis. On the other hand, vessels like Tugs, Barges, and Fishing vessels have been excluded from the study because of their contrasting System Control Structure, which could introduce unwanted complexity and inconsistencies in the analysis.

In the context of the System Control Structure, maintaining uniformity in the systems under analysis is vital to ensure the reliability and validity of the results (Leveson, 2011). Tugs, Barges, and Fishing vessels, having differing system control structures, and will likely introduce qualitatively different factors and causes of accidents because these vessels do not interact with the same organizations to maintain safety, and because these vessels are subject to substantially different regulatory requirements. Hence, these vessels substantially differ from the Safety Control Structure pertaining to Bulk Liquid carriers, Bulk Solid carriers, Ferries, and Passenger ships.

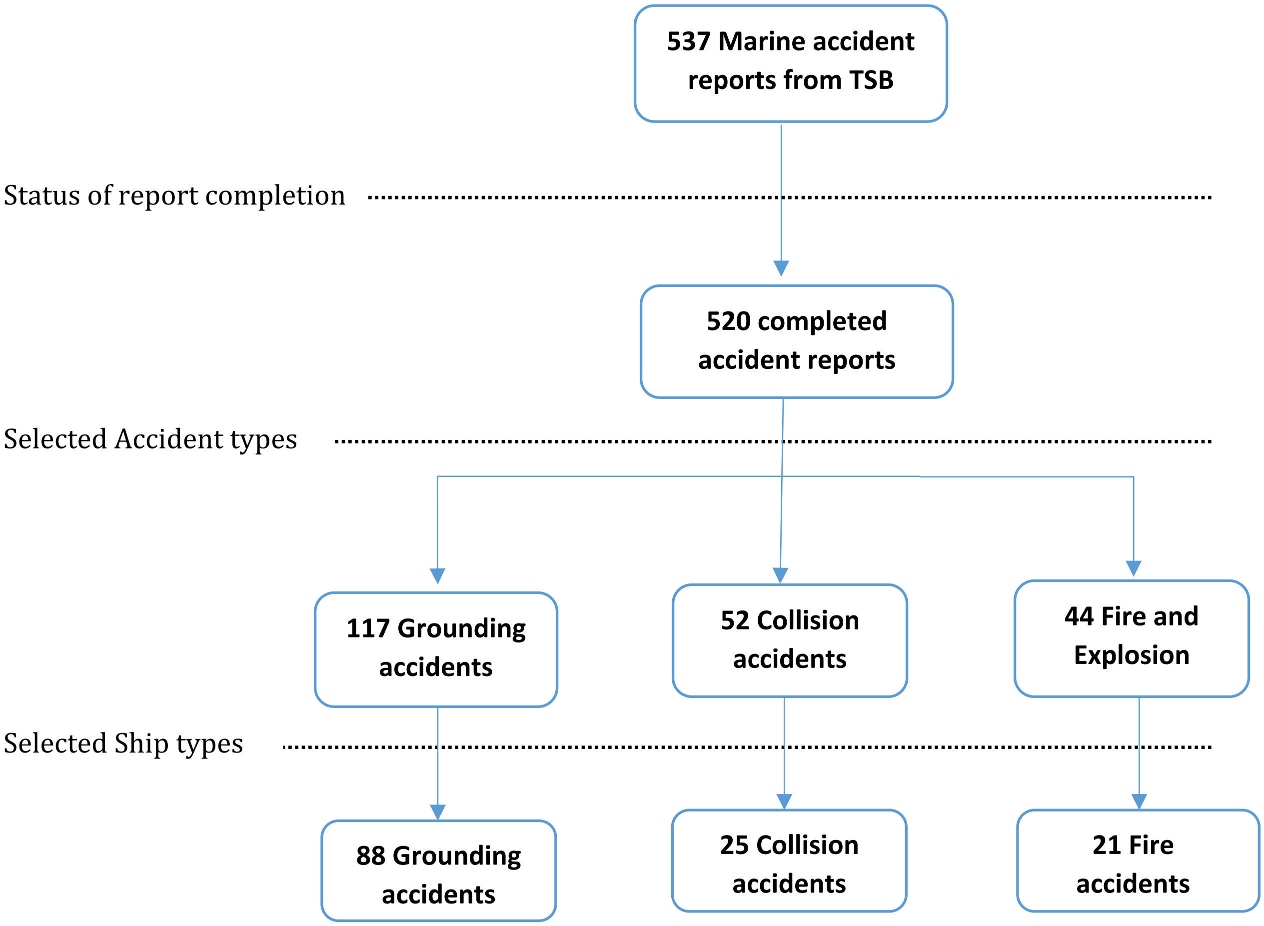

Figure 3 The schematic of TSB Marine accident investigation report filtration

The distribution of accidents, categorized by type, time, and ship types, is visually depicted through a pair of charts in Figure 4.

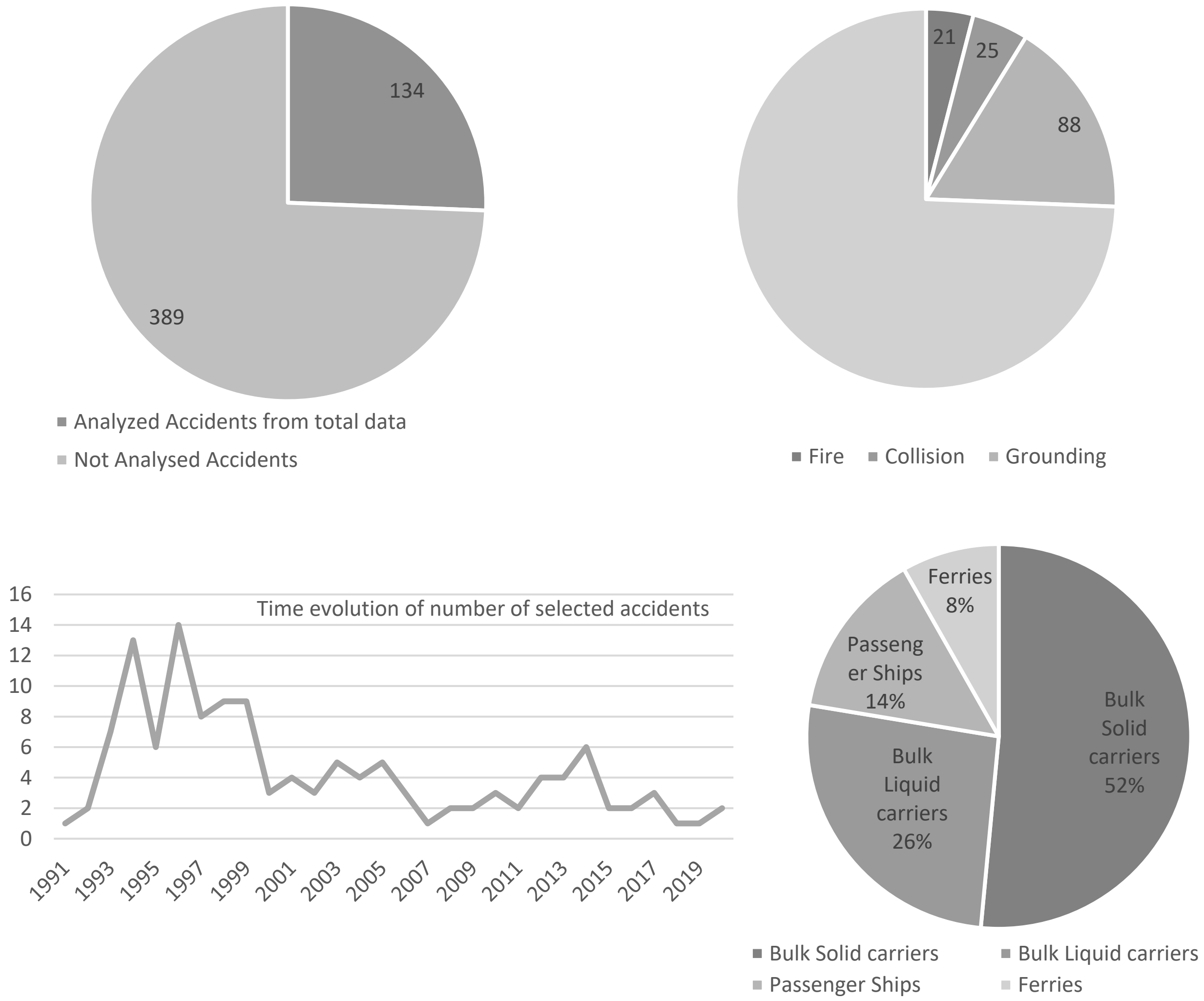

Figure 4 General Distribution of Data

3.2 CAST technique

A key component of the CAST technique is the Hierarchical Control Structure (HCS), a representation of the safety control system. The HCS offers a functional model for understanding the control processes involved in maintaining safety within a system.

A Hierarchical Control Structure (HCS) is conceptualized as a schematic diagram of a functional system, highlighting feedback control loops. Here, the term "system" specifically refers to the maritime safety control system, which encompasses various organizations and actors from international and state regulators to ships, their crews, and the equipment they utilize

(Kristiansen, 2013). An efficient HCS ensures that safety regulations govern the behavior of every constituent part of the system and their interactions, thus facilitating effective hazard management. From this vantage point, accidents occur when these safety controls are not properly enforced and/or when feedback is not effective to update the control actions.

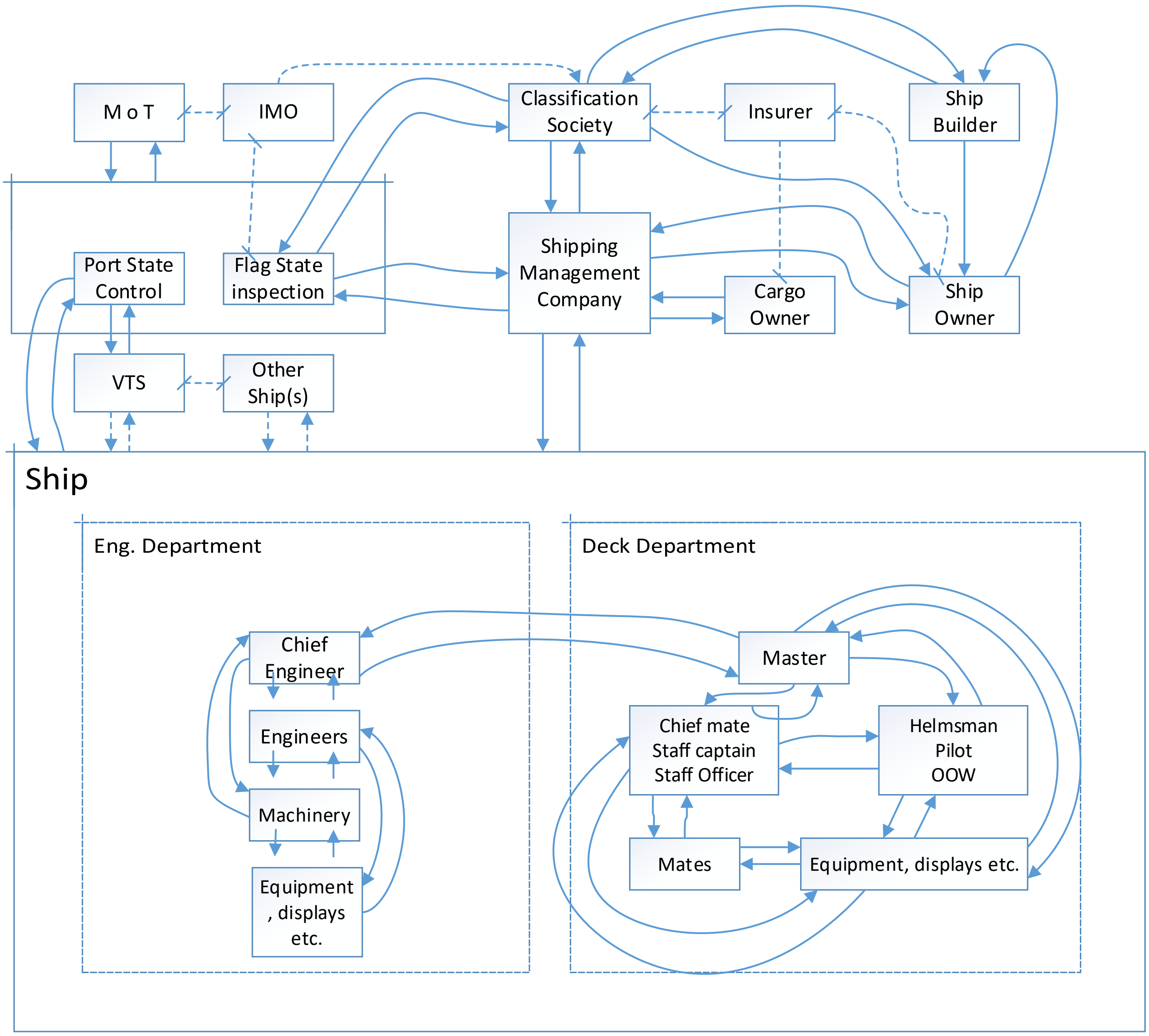

Figure 5 Generic safety control structure (maritime safety control system) based on Puisa et al. (2018)

Ordinarily, an HCS is developed for an existing system, incorporating its specific elements and their interconnections. For instance, an HCS could be crafted for a shipping company or a specific ship, akin to a detailed version of the company's or ship's organizational structure, supplemented with additional information. As an exemplar, Leveson et al. (2005) elucidate their methodology by incorporating an HCS for a typical regulated industry in the United States, using the Shell Moerdijk Chemical Plant explosion as a case study. The accuracy of such an HCS can be cross-verified by comparing it with technical and organizational documents and discussions with representatives from the organization. In this study, we are working on multiple cases, which means we either construct a separate HCS for each incident and accident, or we create an abstracted General Hierarchical System Control Structure (GHSC) applicable to all. Constructing a GHSC for the maritime safety control system is simplified because, as per Leveson (2016), we focus on functions ("What?") rather than physical elements ("How?"). This allows us to disregard physical differences between similar organizations and ships, which have similar functions on an abstracted level. The uniformity of our dataset of accident reports, all concerning a few types of similar-sized ships, further substantiates this approach. We also employed general guidelines (Leveson, 2011) and instances where STAMP HSC diagrams have been utilized (Puisa et al, 2017) to verify the GHSC.

We initiated with a high-level version of the GHSC, drawing on Puisa et al.'s work that utilized Kristiansen's research (2005) and our own expertise in maritime safety control. The GHSC used in this study evolved over time and included all elements implicated in causing the incidents and accidents examined (see Figure 5). The GHSC also delineates the control and feedback links between different elements. Therefore, they act as advisory, collaborative communication pathways. Table 1 presents the roles of the primary elements (subsystems) within the GHSC, in line with the following aspects (Leveson, 2011):

- The safety requirements and constraints that must be applied to a component underneath, or communicated with other components.
- Controls, which refer to particular methods for implementing the constraints and thus exercising control, or particular methods for conveying safety information.
- Feedback, which signifies specific ways of understanding the status of safety constraints enforcement, or specific methods for providing feedback.
- Context, which denotes environmental disturbances and factors that shape behavior, which could compromise the execution of safety constraints or proper communication.

Table 1. Contribution of Individual Elements in the Standard Safety Control Framework (STCW, 2010; Kristiansen, 2013)

Component/Subsystem	*Safety Role/Purpose*	*Control, Feedback Mechanisms, and Context*
International Maritime Organisation (IMO)	Oversight for safety regulation development and maintenance for shipping	Establishes safety standards for ship construction, equipment, and operation. Accepts feedback, including R&D studies, from member states, inter-governmental, and non-governmental organisations. Tasks of enforcing international safety regulations are delegated to flag states as the IMO lacks the power to enforce such regulations.
Ministry of Transportation (MoT)	Implementation of international safety regulations and directives that are ratified/adopted by the state	Enforces safety regulations and directives through national maritime administrations and port authorities, which provide feedback to the MoT on safety-related issues.
Flag State (Maritime Administration)	Enforces international safety regulations, issues and controls safety certificates, and acts on behalf of the state	Conducts inspections of sailing vessels, surveys and approves new buildings, approves manning, audits SMS under ISM Code, monitors maritime traffic and hazardous cargoes, and investigates and analyses maritime accidents. Some functions, such as surveys and SMS audits, are usually contracted out to classification societies.
Port Administration/Authority	Ensures safety in port and harbor approaches	May control safety standards of vessels and can deny access to substandard vessels.
Vessel Traffic Services (VTS)	Oversees marine traffic monitoring system established by harbor or port authorities, akin to air traffic control for aircraft	Provides information, organises traffic, and offers navigational assistance services to ships. VTS has an advisory role only.
Insurer	Undertakes majority of the risk on behalf of the ship management company and cargo owner (i.e., vessel, cargo, third party/protection and indemnity insurance)	May conduct independent assessment of the SMS quality of the ship management company.

Component/Subsystem	*Safety Role/Purpose*	*Control, Feedback Mechanisms, and Context*
Classification Society	Ensures technical standards during design and operation on behalf of the insurer. Carries out safety control functions on behalf of the flag state	Validates and reports that construction and operation of a vessel comply with relevant safety standards and conducts regular surveys in service to ensure continuing compliance with the standards.
Ship Builder/Supplier	Constructs the vessel/equipment as per owner specifications and safety rules (statutory, industrial). Develops operational and maintenance requirements regarding safety	Tests the vessel and its systems, carries out repair work, communicates design assumptions and limitations to ship owners/operators in operational and maintenance manuals. Might receive feedback on the vessel/equipment operation and maintenance issues.
Ship Owner	Owns the vessel and decides whether technical standards will exceed the minimal safety requirements as stated in the safety regulations	Selects crew or management company for crew and operation. Decides on operational and organisational safety policies and communicates them to a ship management company (if different from the owner company).
Ship Management Company	Handles crewing, operation and maintenance of the vessel on behalf of the shipowner. May also provide services such as inspection before purchase, supervision during construction, and ship lay-up solutions	Develops and maintains a safety management system (SMS) according to the ISM Code. Specifies responsibility, authority and interrelation of key personnel. Ensures provision of adequate resources (including their training and selection) and shore-based support.
Cargo Owner	Pays for the transport service and thereby also the quality and safety of the vessel operation	May undertake independent assessment of the SMS quality of the ship management company.
Master (Captain)	Holds superior responsibility for safe ship operation and implementation of the SMS onboard	Motivates the crew, issues orders, verifies adherence, reviews SMS, and reports events.

Component/Subsystem	*Safety Role/Purpose*	*Control, Feedback Mechanisms, and Context*
Chief Mate/Staff Captain/Safety Officer	Second in command to Captain, heads the deck department and, usually, a watchstander. In charge of the ship's cargo and deck crew	Supervises and trains crew in areas such as safety, firefighting, and flooding control, search and rescue. Oversees the loading, stowage, securing and unloading of cargoes, and the care of cargo during the voyage. Enforces all applicable safety regulations during navigation, loading and unloading in port. Responsible to Captain for the safety and security of the ship. Typically stands the 4–8 navigation watch as officer in-charge of the navigational watch, directing the bridge team.
Helmsman/Pilot/Officer of the Watch (OOW)	Steers the ship/keeps watch on the bridge	Executes helm orders or commands which fall into two categories: rudder commands and heading commands. Maintains clear and exact communication with the officer on the bridge for safe navigation and ship handling. Executes turns and the lookout reports dangers such as approaching ships.
Mate(s)	The second mate is the third/fourth in command and a watchkeeping officer. Often is the medical officer and in charge of maintaining distress signaling equipment. The third mate is a watchstander and usually the ship's safety officer, focusing on firefighting equipment, lifeboats, and various other emergency systems	Keeps the watch, and ensures the safety of the ship, its crew, and its cargo, according to all applicable regulations and the safety management system. Mates generally stand watch with able seamen who act as helmsman and lookout.
Equipment, Displays, etc.	Navigation equipment/controls and aids on the bridge	Sends signals to actuators to change the speed, heading and other parameters of the vessel. Displays feedback information about the propulsion performance, ship speed, heading, global and relative positions, etc., thereby supporting safe navigation.
Chief Engineer	Overseeing the engine/engineering department and is of equal	Ensures compliance with the rules and regulations laid down by the flag state administration, IMO, and port state authorities.

Component/Subsystem	*Safety Role/Purpose*	*Control, Feedback Mechanisms, and Context*
	rank to the captain. Responsible for all operations and maintenance of machinery equipment. Ensures safety of subordinate maritime professionals working in the engineering department	Carries out frequent inspections of equipment at regular intervals (life-saving, fire preventing and other equipment). Issues standing orders for each crew member under his command, in accordance with the routine maintenance schedule as laid down by the Planned Maintenance System (PMS), which is prescribed by the manufacturer. Makes sure that his crew attends all shipboard emergency drills and safety meetings, providing guidance (based on the company guidelines and procedures) to his crew during drills so that they know how to get out of an emergency situation safely in the minimum time possible. Must maintain proper conduct with his crew members and address their queries and requirements to the best of his abilities.
Engineers	Second, third (sometimes electro-technical officer), fourth engineers, and engine ratings responsible for supervising the daily maintenance and operation of the engine department. Reports directly to the chief engineer	In charge of boilers, fuel, auxiliary engines, condensate and feed systems by carrying out inspections, overhauls and repairs (planned and unplanned) according to technical manuals and a safety management system.
Machinery, etc.	Generates power (mechanical, electrical, thermal) and provides means for its safe utilization onboard	Provides physical control (passive and active) of hazardous physical processes such as internal combustion. Provides feedback on physical parameters (pressure, temperature, voltage, etc.) for safe operation and maintenance by crew.
Automatic and Passive Controllers (insulation, ventilation, detection, etc.)	Safety systems (safety-instrumented systems) that detect and control safety hazards (e.g., oil leaks, high temperature surfaces) in the machinery spaces	Alerts and alarms hazardous situations for the crew to take action. Actively suppresses hazards (e.g., fires).
Contract Engineers	External engineers that typically represent manufacturers of installed equipment	Carry out onboard overhauls and repairs according to technical manuals and agreed safety procedures.

Component/Subsystem	*Safety Role/Purpose*	*Control, Feedback Mechanisms, and Context*
Deck Crew 1 and 2	Crewmembers looking after safety in accommodation, public areas, cargo, and other areas. The crew is split into the two groups to represent potential dysfunctional interactions between the crewmembers	Carry out active guidance and supervision of passenger and cargo safety, enforcing onboard procedures and policies of safety management. Accountable to the chief mate/staff captain/safety officer.
Equipment, Services, etc.	Equipment and services such as tender and pilot boats, cargo loading facilities on cargo decks and others	Provides crew and passenger transfer, cargo handling and other functions according to safety management procedures.

While the GHSC operates at a higher tier, it is adept at identifying primary and contributory (organisational) causal factors. These factors include errors in technology and human actions, design inaccuracies, lack of adequate feedback from navigational aids to the deck officers, among others. As an example, within the GHSC, safeguards such as automatic and passive control systems against hazards like machinery malfunctions or excess noise levels are consolidated into one overarching controller. This aggregation is justified at a functional level, as these controllers, despite their differing methods, primarily execute the same task - hazard prevention - even if not all have feedback mechanisms. Similar reductions were also applied in illustrating the interactions among system components. For instance, we depicted the links between the flag state and the company, but left out the interaction connections between the flag state and the ship, and between the classification society and the ship. We made this assumption on the premise that the ship is almost always a part of these interactions.

3.3 Analysis and classification

When analyzing an accident report, the steps outlined in Table 2 are followed as part of the CAST analysis.

Table 2 Overview of Standard CAST Steps applied in the current analysis based on Puisa et al. (2018)

CAST Steps	*Related Insights*
Step 1: Identification of the system(s) and hazard(s) related to the loss	This information is extracted from the report
Step 2: Identification of system safety constraints and system requirements linked with the hazard	These constraints and requirements are defined in Table 3
Step 3: Ascertainment of the immediate events leading to the loss	Information regarding these events is derived from the report
Step 4: Analysis of the loss at the physical system level and identification of hazard control flows' contribution to the loss	This step also involves using information from the report
Step 5: Examination of the safety control structure, determining how each successive higher level permitted or contributed to inadequate control	This involves analysing the GHSC with the guidance of the STAMP accident model
Step 6: Review of the overall coordination and communication contributing to the loss	This involves assessing the links among different system components
Step 7: Determination of the dynamics and changes in the system and its control structure relating to the loss and any safety control degradation over time	This tracks changes in the system over time and identifies any patterns
Step 8: Formulation of recommendations	This involves prevention of similar losses in the future

Table 2 demonstrates that the necessary information for performing the analysis is already present in the accident investigation reports. Additional information was inferred during the systematic inspection of the Generic Hazard Control Structure (GHCS). The elements within the GHCS are interconnected through functional causal links of control, feedback, and communication channels, enabling systematically going from one element to another to understand the what and why of the incident. This systematic inspection is directed by a set of standard control flows related to the control algorithm, process model, feedback, and other factors (refer to Table 1).

The CAST-based analysis is underpinned by the assumption that individuals and organizations acted to the best of their knowledge, abilities, tools, and information available at the time. As long as the information about the state of the controlled process is accurate, the training is appropriate, and the tools are suitable, no unsafe action is anticipated. This aligns with the contemporary perspective that human error is not the conclusion, but the commencement of accident investigation and analysis (Dekker, 2014). The goal is to comprehend why individuals acted as they did and why they could not have acted differently (Dekker, 2016). The same principle is applicable to machine controllers, with the closely related question being why designers (or regulators) accepted certain design assumptions that proved incorrect in a specific situation.

Table 3 Hazards at the System Level and Corresponding Constraints based on Puisa et al. (2018)

Hazards	*Safety Constraints and Their Decomposition at Lower Levels (Subsystems)*
H1. Hazardous scenarios overlooked during design process	C1. Adequate risk identification in design • Up-to-date design rules and standards • Correct application of pertinent design rules and standards • Adequate hazard analysis methods to identify all plausible safety hazards
H2. Manufacturing deviates from design assumptions	C2. Adequate risk identification during manufacturing • Well-documented design assumptions communicated to manufacturers • Adequate communication between designers and manufacturers • Design review and validation/testing (e.g., sea trials)
H3. Onboard safety management system inadequately addresses safety hazards	C3. Alignment of design assumptions and actual operation (work as imagined vs. work as done) • Well-documented design assumptions communicated to the shipping company • Safety management system (SMS) accurately reflects all design assumptions, especially design limitations
	C4. Verification, validation, and continuous updating of SMS • SMS approval by relevant authorities • Well-documented design modifications and operational changes reflected in SMS • Maintenance of adequate hazard control measures (engineering and management) • Timely identification of new hazards and implementation of control measures • Crew's thorough familiarity with the ship and its safety procedures at all times • Ensured continuous communication/information exchange between the company and the ship

The relevance of the interactions explored to the incident or accident in question was determined based on system-level hazards and corresponding safety constraints (refer to Table 3). Safety hazards are defined as "a system state or set of conditions that, together with a particular set of worst-case environmental conditions, will lead to a loss" (Leveson, 2011). For clarity, safety constraints are translated—through system engineering decomposition—into safety constraints of corresponding subsystems and individual components.

The result of the analysis is a collection of dysfunctional interactions (for instance, insufficient control or feedback) among the system elements. These dysfunctional interactions are categorized as depicted in Table 4.

Table 4 Hierarchical Categorization of Dysfunctional Interactions based on Puisa et al. (2018)

Cause of Dysfunctional Interaction (What/Who Failed?)	*Condition Leading to Dysfunction (Failure Mode)*
• *Control (↓)*	• Not Given (N)
• *Feedback (↑)*	• Incorrectly Given (W)
	• Given Too Early/Late (EL)

The dysfunctional interactions that have been identified shed light on the events that transpired both immediately before and long prior to an incident or accident. These interactions can serve as direct (proximate), contributing, or systemic factors in the causation of the accident, as per Johnson's classification (1980). This categorization aligns with the intended scope of marine safety investigation as outlined in IMO Resolution MSC.255(84), (2008). Accordingly, the dysfunctional interactions were classified based on these broad and somewhat ambiguously defined categories, as presented in Table 5.

In the study conducted by Puisa et al. (2018), the CAST technique was employed to perform a gap analysis. This involved contrasting the causes of accidents as reported in investigations with those identified during their CAST analysis. This method was instrumental in their pursuit of systemic causal factors, particularly highlighting the interactions between ship operators and equipment manufacturers, and their role in accident causation.

In our current research, which also adopts the CAST method, this is applied somewhat differently due to the distinct research questions. The investigation is centered on major maritime accidents in Canadian (TSB) accident reports, with the objective of identifying causal factors using a systems-theoretic accident theory and associated modeling approach. As outlined in Section 1, the research questions aim to identify the dominant causal factors determined from Canadian maritime accident investigation reports, comprehend how causality changes with respect to time, ship type, and types of accidents, and assess the potential of these findings to enhance maritime safety. Given these objectives, the application of the CAST method is customized to answer these specific research questions. Consequently, a gap analysis similar to that of Puisa et al. is not conducted, as the research questions necessitate a unique approach to data analysis.

Table 5 Categorization of Accident Causes into Three Causal Categories based on Puisa et al. (2018)

Role of Accident Causes	*Determination*	*Context and Traits*	*Violated Safety Constraints/Requirements*
Direct Factors (D)	Identified in Accident Analysis	Subsystem level. Events proximate to the accident within the same subsystem	Constraints on interaction with physical hazardous processes
Contributing/Underlying Factors (C)	Identified in Accident Analysis	Inter-subsystem level. Within the same subsystem or adjacent subsystems. Linear effect on proximate events	Constraints on procedures and processes, and on interaction between teams and individuals
Systemic Factors (S)	Inferred during Accident Analysis	System level. Between subsystems*. Nonlinear effect on contributing and proximate events *The ship management company and the ship are considered as one subsystem	System safety constraints on interaction between subsystems

3.4 Application of the method

In this section, we apply the described methodology to the incident involving the passenger vessel Stellar Sea (TSB CANADA, 2018). On the afternoon of October 1, 2016, the Stellar Sea, carrying 28 people, embarked on a bear-watching excursion from Tofino, British Columbia. At approximately 17:44 Pacific Daylight Time, while in Warn Bay, the vessel struck a charted rock and ran aground. The passengers and crew abandoned the vessel and were evacuated with the assistance of the passenger vessels Pacific Springs and Rip Tide. Two passengers sustained minor injuries, and no pollution was reported.

The investigation found that the grounding of the Stellar Sea occurred because the master lost positional awareness due to the intense focus required to search the coastline for wildlife while the vessel navigated in confined shallow waters. The master was performing multiple tasks, including operating the vessel, tracking wildlife visually, repositioning the vessel, avoiding obstacles, maintaining positional awareness, and communicating via VHF.

At the physical level, the dysfunctional interaction between the master and the vessel was the direct cause of the accident. In particular, the control actions over the hazardous environment were inadequate. The reason why the master made this decision was related to the fact that there were no adequate feedback and prevention mechanisms in place to control the right sequence of actions. The absence of timely and accurate feedback led to a loss of positional awareness, i.e., the wrong understanding about the vessel's location.

The first question that arises is why the feedback and prevention mechanisms were not in place? The investigation report indicates that the master was performing multiple tasks, including visually searching for wildlife, which increased the workload and reduced the capacity for other visual tasks such as navigation. This leads us to question why the safety management system (SMS) or management allowed this risky practice? Alternatively, it could be that the master did not fully understand the safe navigation procedures or his responsibilities. This prompts another question: was the master familiar with the safe navigation procedures or his responsibilities, and did he receive adequate training?

More fundamental, systemic causes that help explain why an incident or accident happened were not mentioned in the report. Instead, they were inferred. For instance, we inferred that the design limitation (unprotected hazard) with respect to navigation in shallow, confined waters had inadequately been communicated by the vessel's operators and consequently was not reflected in the safety management system (SMS). If this were not the case, the company (as in this particular example) would have reflected the design limitation (i.e. no sounder set up) in the SMS. There is no particular reason that the company would operate the vessel with such a potential hazard. Similarly, there is no particular reason that the operators would have not communicated the design limitation had they known about it, suggesting that further causal factors such as the use of incomplete hazard analysis by the operators could be included.

Following the incident, Jamie's Whaling Station Ltd., the company operating the Stellar Sea, updated the vessel's emergency and operational procedures manual to emphasize the requirement to contact the Canadian Coast Guard in an emergency. The safety drills program was also updated to increase the frequency of drills conducted.

Table 6 enumerates the detected malfunctioning interactions after investigating the entire Grounding passenger vessel (GHCS), seeking answers to who was accountable for ensuring that the interactions are adequate and why they did not occur in the context of the Stellar Sea grounding accident.

Table 6 Summary of dysfunctional interactions in safety control of the passenger vessel Stellar Sea grounding accident

Controller	Controlled	What Failed	Condition[١]	Description as in the reports	Cause[٢]
Flag state (maritime administration)	Ship management company	Control	N	The vessel was in compliance with all applicable regulations. However, the regulations did not require the vessel to be equipped with an echo sounder, which could have helped detect the rock	S
Ship management company	Ship	Control	N	The investigation determined that there was insufficient passage planning prior to the occurrence voyage: neither the company nor the master assessed the risks of the planned voyage. Therefore, no risk mitigation was in place to guide the master's conduct of the vessel during the tour	C
Ship management company	Ship	Control	N	The company's safety management system did not have procedures for navigating in the vicinity of rocks and shoals.	C
Ship management company	Ship	Control/ Feedback	N	The master was alone in the wheelhouse and performed multiple continuous and sequential tasks that required his attentional resources	D
Master (Captain)	Equipment, displays, etc	Control/ Feedback	N	The master's use of binoculars to see a bear and the subsequent loss of positional awareness. The master was navigating the vessel visually, using the chart plotter as an aid. However, the chart plotter was not zoomed in to a level where the rock would have been visible on the screen."	D
Master (Captain)	Equipment, displays, etc	Control	N	However, companies and masters can mitigate risks in vessel operations by identifying them and proactively managing them through the effective implementation of risk management processes	C
Master (Captain)	Equipment, displays, etc	Control	N	Although the emergency position indicating radio beacon was easily accessible, it was not manually activated during the occurrence.	D

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[1] Refer to Table 4

[2] Refer to Table 5

Figure below presents a visual depiction of the dysfunctional interactions. The Red lines marked with numbers signify the interactions identified in the investigation report via the CAST analysis. These numbers represent the count of instances (across the accident reports; only one in this case) where this control/feedback was found to be insufficient. For example, the master executed one incorrect control action on the navigation equipment, and there was a single instance of missing feedback that could have informed the correct action. Additionally, the Shipping Management Company did not adequately manage the risk assessment aspect of the SMS and did not receive feedback about the Master's functions concerning his multiple tasks.

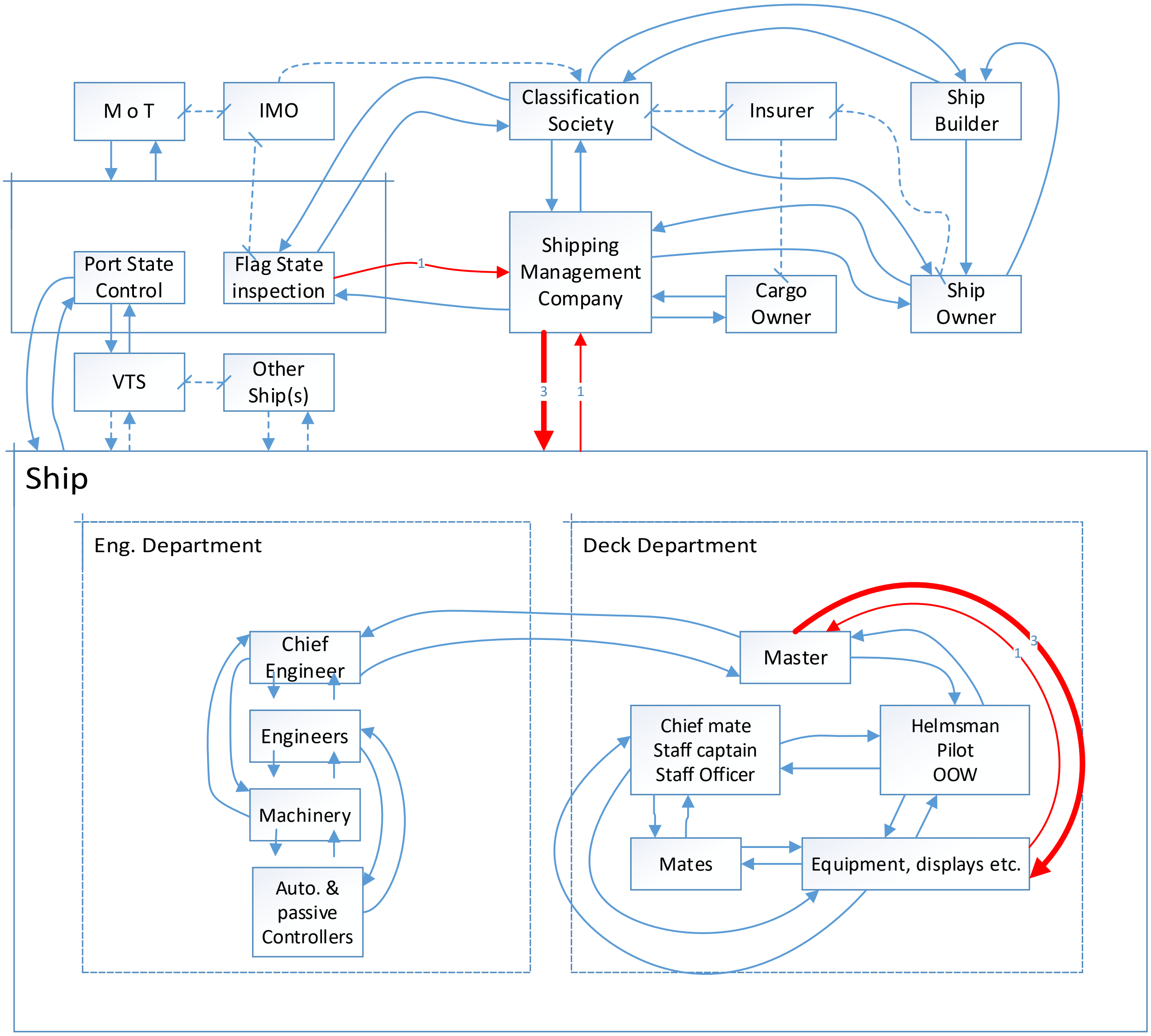


Figure 6 Dysfunctional interactions that led to the bulk carrier Tundra grounding accident

3.5 Temporal results

In this research, a statistical trend analysis (Kvaløy & Aven, 2005) will be employed to obtain insights into whether there is a discernible trend within the temporal results (i.e. the answer of first sub-question in section 1), specifically, whether the results exhibit an increase or decrease over time that cannot be attributed to randomness. This process will involve an examination of whether there is a deterioration or enhancement in safety levels that is not random in nature. If a trend can be conclusively identified, the causes can then be investigated. Addressing these queries will lay the groundwork for pinpointing risk-reducing measures that could potentially reverse an observed negative trends.

Kvaløy and Aven (2005) proposed a predictive Bayesian approach for trend analysis as an alternative methodology for a classical one. This approach places a strong emphasis on the use of observable data, employing probability distributions exclusively to express epistemic uncertainties. The focus there is on the actual data obtained from events. A trend measure, termed T_1, is constructed by comparing averages from different sections of the data, specifically the initial and final parts for all possible divisions into 'first' and 'last' segments. If T_1 deviates significantly from what would be expected in a situation with no trend, it is inferred that a trend exists in the data.

$$T_1 = \sum_{j=1}^{r-1} \left(\frac{\sum_{i=1}^{j} x_i}{j} - \frac{\sum_{i=j+1}^{r} x_i}{r-j} \right)$$

Here, $x_1, x_2, \ldots, x_r$ represent the number of events in year 1, 2, ..., r respectively. The formula calculates the averages of all possible divisions of the data into a 'first' and 'last' part and compares them. If there is a decreasing trend in the data, T_1 will become positive, and the more pronounced the trend is, the larger the positive value of T_1 will be. In the case of an increasing trend, the opposite would be true. This formula is used to detect trends in historical data by comparing averages of different segments of the data. In simpler terms, if the number of events in the earlier years is higher than in the later years, indicating a decreasing trend, T_1 will have a positive value. The stronger this decreasing trend, the higher the value of T_1. This can be useful for identifying patterns over time, such as a gradual reduction in the number of events or occurrences.

Additionally, a straightforward screening method is employed by Kvaløy & Aven (2005) to identify trends in historical data when no other pertinent information is available. This method involves calculating the average number of hazards over the years 1,2,…,j, and using the Poisson distribution with mean (r−j)mj to compute a 90% prediction interval for the total number of hazards during the years j+1,j+2,…,r. If the observed value falls outside this interval, an alarm is triggered, indicating that a trend is present. This process is repeated for some or all of j=r−1,r−2,…,1.

The term (r−j)mj is being used to calculate the mean of a Poisson distribution for a prediction interval. In this context, r represents the total number of years of data, j is a specific year, and mj is the average number of events (or hazards) for the years up to and including j.

The term (r−j) represents the number of years remaining after year j, and so (r−j)mj represents the expected total number of events for those remaining years, under the assumption that the rate of events stays the same as the average rate up to year j. If the actual observed number of events falls outside this prediction interval, an alarm is given, indicating a potential trend or change in the rate of events.

3.6 Qualitative results

In this study, the Pareto Principle, also known as the 80/20 rule, is applied to accident analysis. This principle suggests that approximately 80% of accidents are caused by about 20% of factors (Harvey & Sotardi, 2018). By focusing on the most frequent dysfunctional control-feedback links in the safety control structure, this approach allows for the identification and prioritization of the most common and impactful factors.

Causal factors are qualitatively categorized based on these dysfunctional control-feedback links. The most frequently occurring problematic links that contribute to accidents will be listed, along with all their associated causal factors. This method allows for a concentrated focus on the most common causes of accidents, thereby optimizing educational, training, and management efforts towards the most effective interventions.

This methodology is supported by studies such as those conducted by Mureșan et al., (2019) and Górny (2015) which highlight the effectiveness of the Pareto Principle in risk management and accident prevention. By prioritizing these high-frequency causes, the aim is to devise a more efficient and targeted strategy for accident prevention and further investigation.

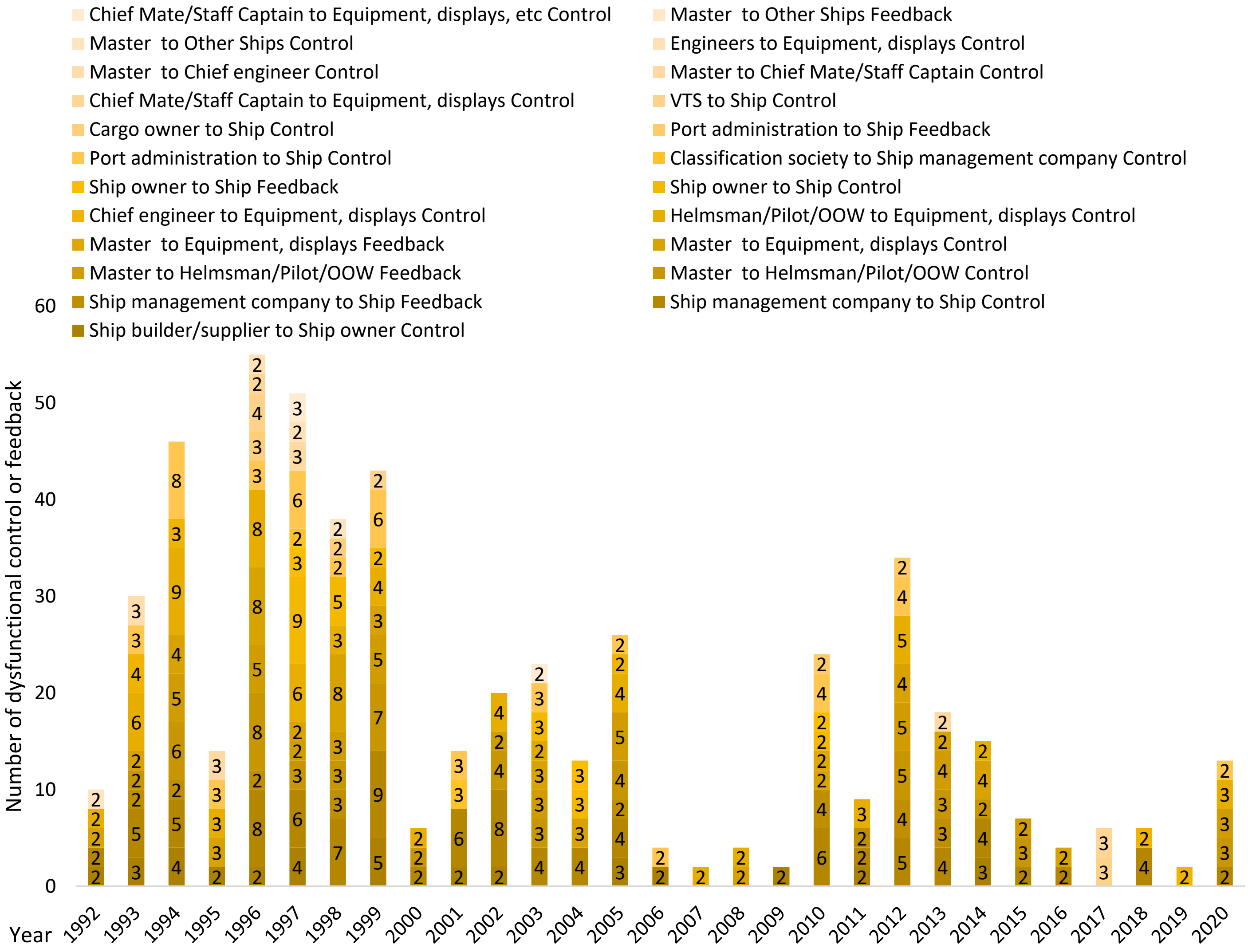
While the primary focus is on the predominant causes of accidents, it is also important to closely examine the less common causes, as they might appear as subtle hints or weak signals. These weak signals, often representing a minority of the causes, may go unnoticed or be underestimated. However, recognizing and interpreting these weak signals is crucial as they can provide valuable insights into underlying, often overlooked factors contributing to accidents. By employing a systematic approach to detect and analyze these weak signals through various lenses and scenarios, organizations can gain a more holistic understanding of the accident causes. This, in turn, enables the development of more robust and adaptive prevention strategies that address not only the common causes but also the subtle and emerging ones (Schoemaker & Day, 2009).

4 Results

In this Results section, we categorize the findings of our investigation into the causal factors of major maritime accidents in Canada, as outlined in Section 1. Our analysis, grounded in a systems-theoretic accident theory and modeling approach, focused on reports published by the Transportation Safety Board (TSB) of Canada. We sought to answer the primary research question posed in Section 1: What are the dominant causal factors identified in maritime accident investigation reports conducted by the TSB using a systems-theoretic accident model? Additionally, we explored the three sub-questions related to temporal patterns, ship types, and types of accidents. The insights derived from this analysis offer a deeper understanding of the unique challenges associated with major maritime accidents in the Canadian context.

4.1 All accidents over time

The examination of accident investigation reports, conducted on a temporal basis, demonstrated that the most common causal factors have changed over time. This analysis spans from 1992, the year when the archiving of these reports began at the Transportation Safety Board (TSB) of



Canada, up until 2020, the most recent year for which completed accident reports are available at the TSB Canada. Figure 7 illustrates all causal factors that have occurred more than twice. Each number in the columns represents the count of dysfunctional links for that specific year. For example, in 2007, there were two occurrences of the dysfunctional control link between the Pilot or OWW and the Equipment and displays. We have omitted factors that occurred only once or twice to maintain the scale of the figure within a single page, yet the figure remains dense in information. The whole data will be represented in Appendix A. Also for a more comprehensible and digestible view, the reader is referred to Figure 8, which only includes causal factors that have occurred five times or more.

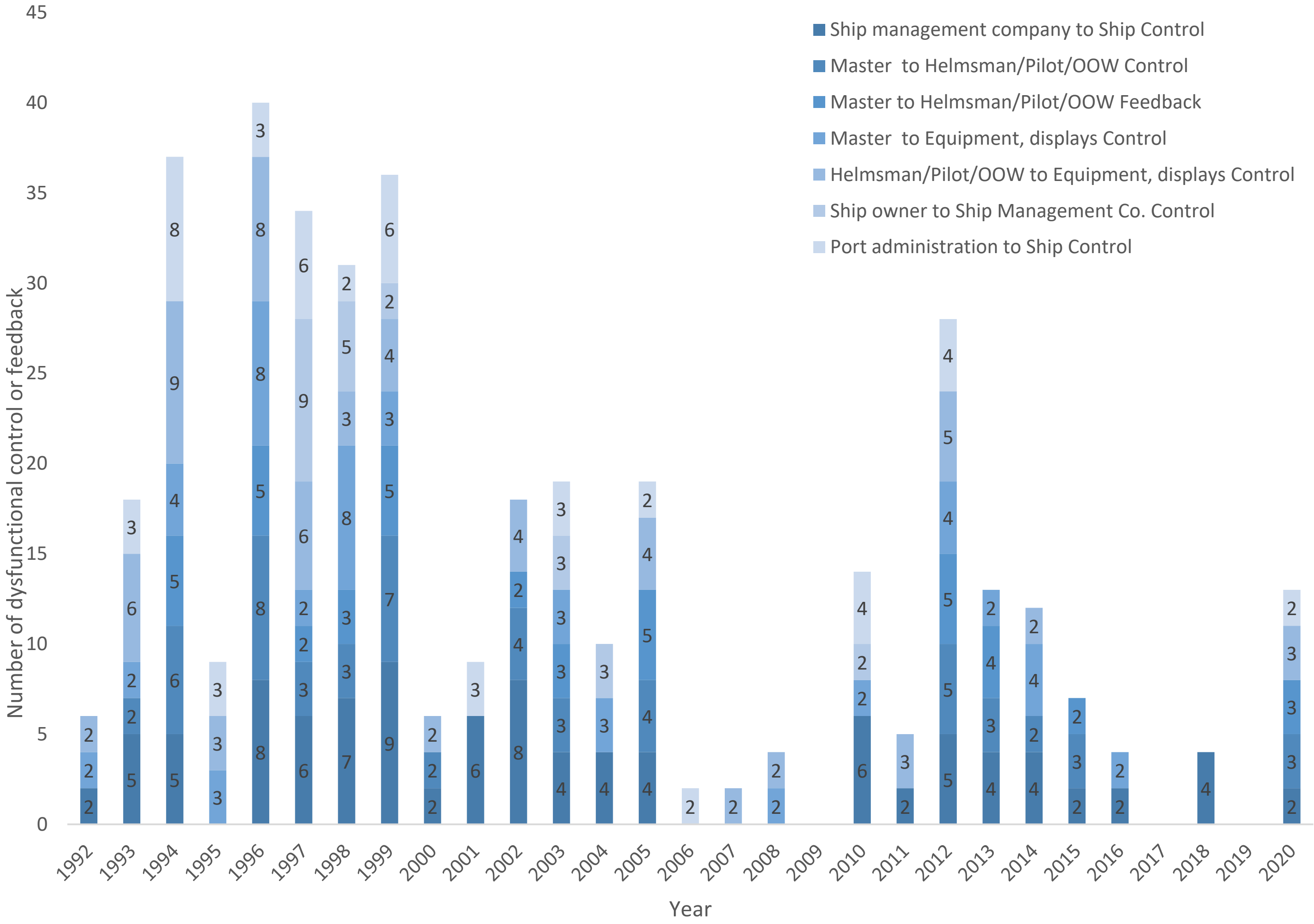


Figure 8 Frequent dysfunctional causal factors found 5 times or more over time

As mentioned earlier in Table 7, we present the results of our analysis of major maritime accidents in Canada, focusing on the trends over time. The analysis is based on the T_1 measure proposed by Kvaløy and Aven (2005), highlighted in section 3.5, which is a statistical tool used to detect trends in historical data. The T_1 measure compares averages of different parts of the data to identify whether there is a consistent increase or decrease over time.

The data used in this analysis spans from 1991 to 2020 and represents the number of accidents reported each year. The T_1 measure was calculated for the data set and the results are presented in Table 7.

Table 7 Trend Analysis of Maritime Accidents in Canada (1991-2020)

YEAR	NUMBER OF ACCIDENT	SCREENING	T_1 MEASURE
1991	1		22.82
1992	2	Increasing	
1993	7	Increasing	
1994	13	Increasing	
1995	6	Increasing	
1996	14	Decreasing	
…	…	…	
2019	1	Decreasing	
2020	2	Decreasing	

The T_1 measure, which equals 22.82 in our analysis, suggests that there is a decreasing trend in the number of accidents over the years. However, a potential trend can be inferred from the "Decreasing" pattern observed for the majority of the years (except the first 4 years), as shown in the screening column of Table 7. That is why in addition to the T_1 measure, we also applied a screening procedure that compares the number of accidents in the last two years with the number of accidents in the previous years. This procedure can be particularly useful for detecting less strong trends and for focusing on recent changes in the data.

The results of the screening procedure indicate a general decreasing trend in the number of accidents. This consistent finding from T_1 measure and the screening procedure provides evidence of a decrease in the number of maritime accidents in Canada over the period from 1991 to 2020.

Table 8 provides an in-depth analysis of the most frequently occurring dysfunctional links in maritime operations from 1992 to 2020 (occurring at least 5 times each year). It scrutinizes the control and feedback mechanisms within these links, encompassing interactions between various entities such as the ship management company, the master, the helmsman/pilot/Officer of the Watch (OOW), and the equipment. Interactions involving the ship owner and port administration are also included in the analysis.

The trend assessment within the data is conducted using the T_1 measure, as proposed in the methodology by Kvaløy and Aven (2005) in their work on trend analysis. The T_1 measure serves as an indicator of trends, with negative values signifying a decreasing trend.

The 'Screening result' rows in the table represent the trend for each category, determined based on the screening method from the same research by Kvaløy and Aven (2005). The abbreviations 'In', 'De', and 'No t' stand for 'Increasing', 'Decreasing', and 'No Trend', respectively. For instance, the row 'Ship management company to Ship Control' demonstrates a decreasing trend over the years, as indicated by the negative T_1 measure and the 'De' in the corresponding 'Screening result' row.

Table 8 Frequent dysfunctional links trend analysis over time

Year	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	T_1
Ship management company to Ship Control	2	5	5	0	8	6	7	9	2	6	8	4	4	4	0	0	0	0	6	2	5	4	4	2	2	0	4	0	2	21.371
Screening result	In[1]	In	In	In	In	In	De[2]	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	
Master to Helmsman /Pilot/OOW Control	0	2	6	0	8	3	3	7	2	0	4	3	0	4	0	0	0	0	0	0	5	3	2	3	0	0	0	0	3	16.224
Screening result	In	In	In	In	In	In	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	
Master to Helmsman/Pilot/ OOW Feedback	0	0	5	0	5	2	3	5	0	0	2	3	0	5	0	0	0	0	0	0	5	4	0	2	0	0	0	0	3	11.115
Screening result	In	In	In	In	In	In	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	
Master to Equipment, displays Control	2	2	4	3	8	2	8	3	0	0	0	3	3	0	0	0	2	0	2	0	4	2	4	0	2	0	0	0	0	8.8917
Screening result	In	In	In	In	In	Not[3]	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	
Helmsman/Pilot/OOW to Equipment, displays Control	2	6	9	3	8	6	3	4	2	0	4	0	0	4	0	2	2	0	0	3	5	0	2	0	0	0	0	0	3	6.1359
Screening result	In	In	In	Not	Not	Not	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	
Ship owner to Ship Control	0	0	0	0	0	9	5	2	0	0	0	3	3	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2.5208
Screening result	In	Not	Not	Not	Not	No t	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	
Port administration to Ship Control	0	3	8	3	3	6	2	6	0	3	0	3	0	2	2	0	0	0	4	0	4	0	0	0	0	0	0	0	2	0.9171
Screening result	Not	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	De	

4.2 All dysfunctional links including qualitative results

In Figure 9, the number of all the dysfunctional links are depicted without any distinctions based on time, ship type, or accident type. This comprehensive representation aggregates data from various time frames, ship categories, and types of maritime accidents. It provides an overview of

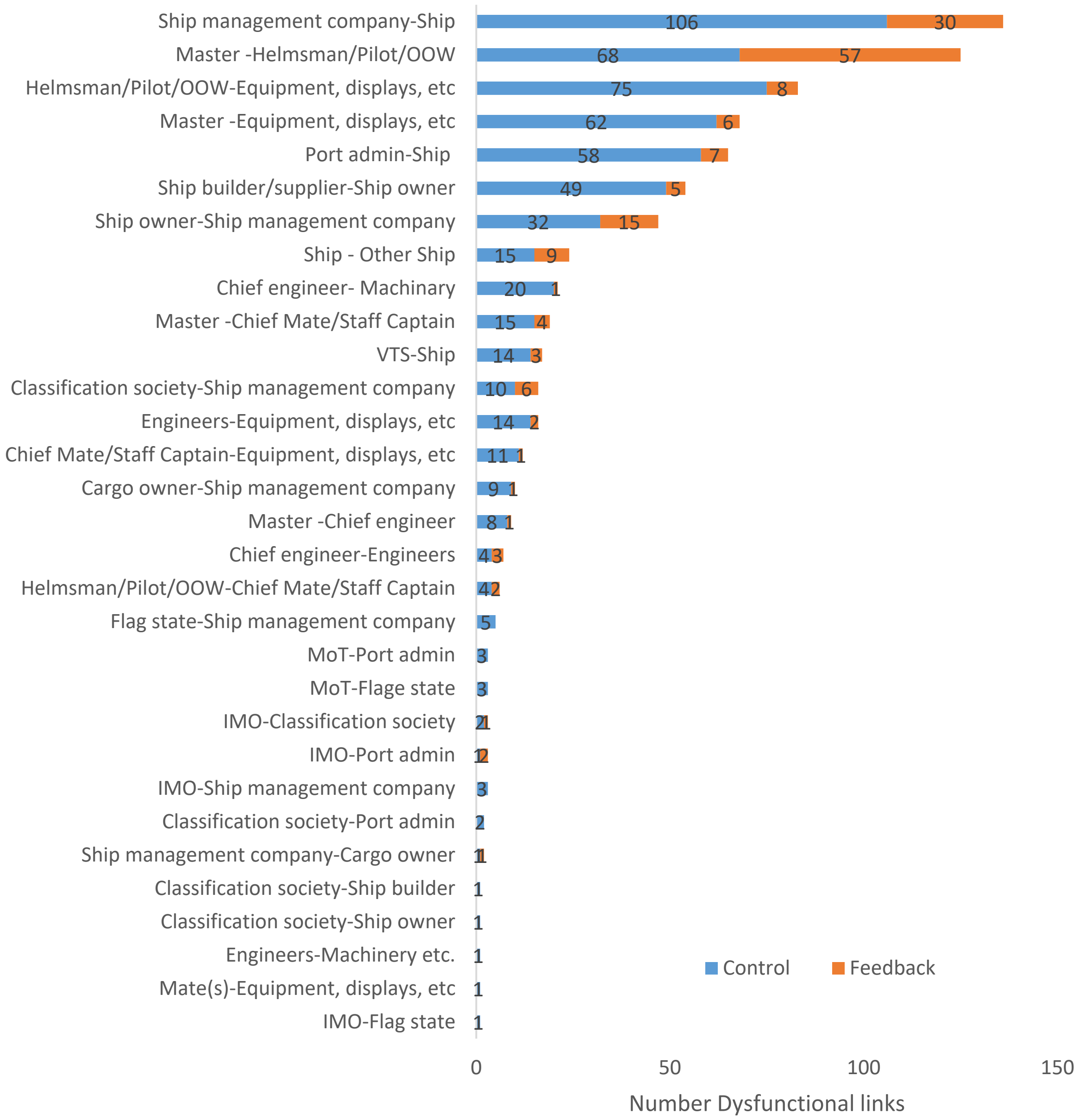


Figure 9 The number of all dysfunctional links regardless of time, ship type, or accident type specifications

the dysfunctional links in a consolidated manner, but does not offer detailed insights into specific scenarios or classifications.

Figure 10 represent the result of all accidents in generic safety control structure.

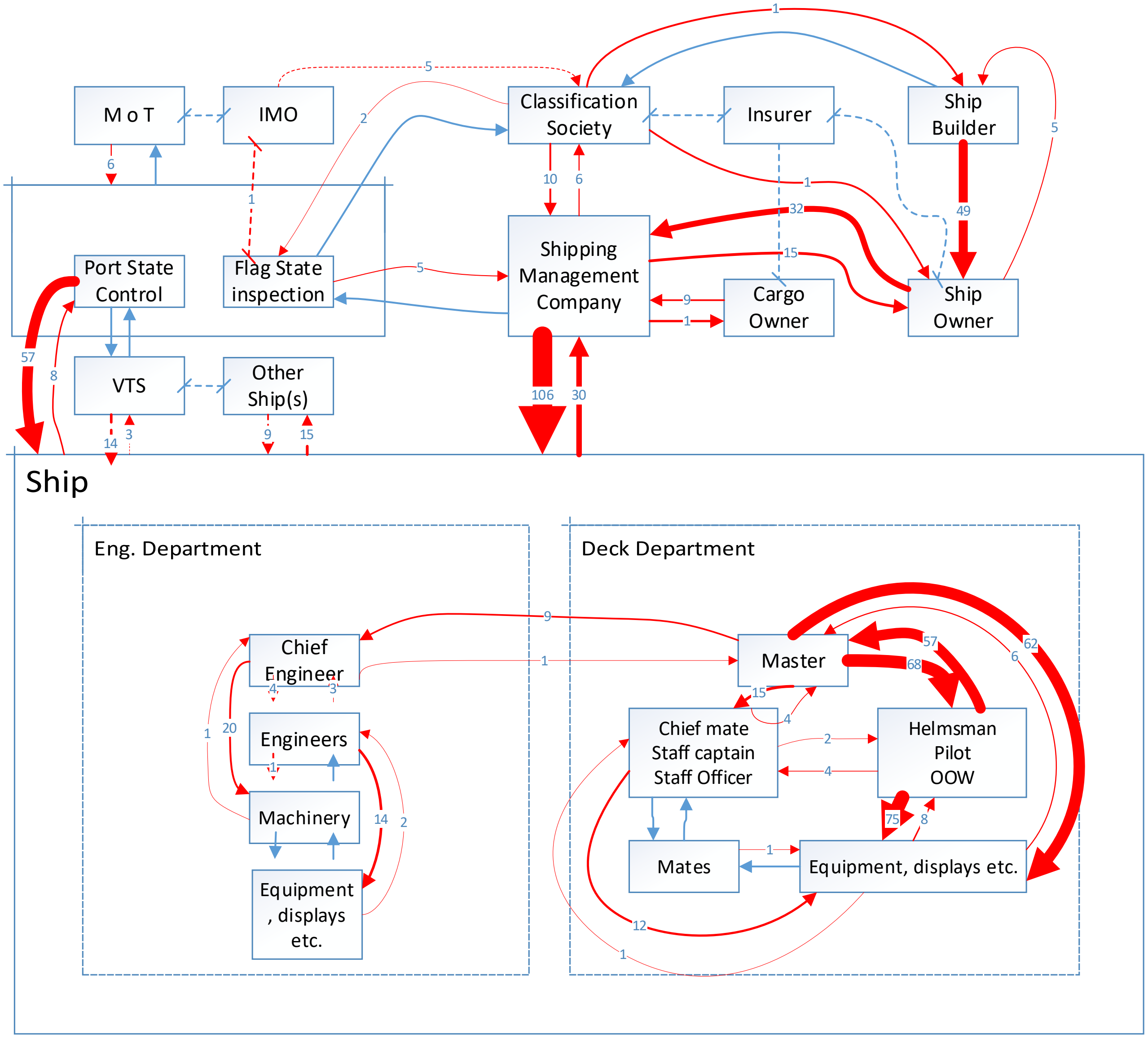


Figure 10 Result of all accident in generic safety control structure

Based on the Pareto Principle, which is referenced in Section 3.6, it is estimated that 20 percent of the approximately 770 dysfunctional links account for the majority of the issues, which equates to around 155 links. The most common dysfunctional link between the shipping management company (SMC) and the ship encompasses 129 distinct causes, as shown in Table 9. To provide a more comprehensive analysis, we will include an additional four dysfunctional links and summarize the top causes for each. These summaries will be presented in Tables 10 to 13.

Table 9 All causes considered for control and feedback failure of link between Ship Management Co. and Ship

ID #	causes for control and feedback failure of link between Ship Management Co. and Ship
1	Lack of guidance for documentation, testing, and maintenance schedules led to inadequate integrity of fuel hose assemblies, compromising safety.
2	Ineffectiveness in the SMS process failed to encourage the crew to identify hazards, leading to rapid fire development in the engine room.
3	The Engine Control Room was ill-equipped for emergencies and lacked proper escape routes, putting the crew at risk during a fire.
4	Life rafts were not maintained, and the crew lacked written procedures for emergencies, resulting in an uncoordinated response during a crisis.
5	Absence of procedures and practices regarding ventilation and inert gas use reduced the effectiveness of the vessel's SMS, increasing risks.
6	Stevedores handling explosive cargo lacked awareness and safe handling practices, posing a danger.
7	The welder's protective gear was inadequate, and the crew was not informed of the hazards of the work environment.
8	The primary fan essential for boiler operation was not repaired, compromising safety.
9	Crew members of non-Convention passenger vessels lacked training in crowd and crisis management, hindering effective emergency management.
10	The main switchboard was not electrically isolated, and there was a lack of emergency drills and preparedness in the engine room.
11	Individuals in positions affecting safety were not ensured to be fit for duty, posing safety risks.
12	The sprinkler system was improperly installed, rendering it ineffective during a fire.
13	The generator unit was not inspected or tested regularly, leading to operational issues.
14	Lack of guidance on vessel stability and inadequate maintenance of safety equipment contributed to the accident.
15	Crew members were unaware of the hazards of hydraulic oil mist and the improper use of equipment, leading to a fire.
16	Inadequate consideration of factors impacting dragging an anchor and lack of emergency preparedness led to unsafe operations.
17	The ferry was operated with suboptimal ergonomics for single-person operation in restricted visibility, compromising safety.
18	The master of the ship was unaware of the dangers to linesmen when increasing vessel speed, leading to unsafe operations.
19	The absence a training program for new tug masters led to operational inefficiencies and safety risks.

ID #	causes for control and feedback failure of link between Ship Management Co. and Ship
20	Absence of maintenance records inhibited the anticipation and prevention of problems with critical operational equipment.
21	The acetylene cylinder in use lacked safety features, leading to hazardous conditions.
22	The ship's fire main was unprepared for cold weather operation, and safety equipment maintenance was ineffective.
23	The main engine was in substandard condition due to ineffective monitoring.
24	The crew was unaware of the dangers of shipping activated carbon pellets without proper classification, leading to a fire.
25	The crew lacked training in safe handling of hydraulic oil and proper use of equipment, leading to a fire.
26	The crew was unaware of factors impacting thethe dragging of an anchor, and lacked guidance and emergency preparedness, contributing to the accident.
27	BC Ferries' procedures lacked guidance for identifying and supervising safety-critical maintenance tasks.
28	No one was designated to stand by during berthing operations, preventing the deployment of the anchor as an emergency tool.
29	The Horizon lacked equipment that would have provided the Officer of the Watch with early cues for decision-making.
30	The Great Century was not equipped for navigation on ice, leading to engine shutdown due to ice blockage.
31	The SMS documentation was not vessel-specific and lacked effective procedures for operating in ice-infested waters.
32	Vague instructions for trick wheel operation hindered effective action during emergencies.
33	Bridge Resource Management (BRM) principles were not effectively implemented, leading to isolated actions by the crew.
34	The company operated without a coordinated Safety Management System (SMS), affecting operational safety.
35	Lack of Bridge Resource Management reduced the effectiveness of vessel tracking and navigation assistance.
36	The company's ISM Code procedures contained a generic checklist, leading to reactive rather than structured responses to emergencies.
37	A coordinated approach to navigation-related emergencies was not used, hindering objective assessment of emergency response.
38	Communication during salvage operations was limited and casual, leading to the ineffective application of bridge resource management principles.
39	Fatigue and emotional stress hindered the pilot's self-assessment and performance, increasing the chances of an accident.

ID #	causes for control and feedback failure of link between Ship Management Co. and Ship
40	The Officer of the Watch was inhibited from asserting himself due to various obstacles.
41	The ship's crew lacked adequate policies and procedures for day-to-day operational decisions.
42	The JEAN PARISIEN was too deep to enter the channel, causing the ship's bottom shell to strike the river bank.
43	Some smaller companies operated with only one officer on the bridge in confined pilotage waters, compromising vessel safety.
44	The Algolake lacked a formal Bridge Resource Management regime, leading to unclear responsibilities and distractions.
45	The emergency generator room on the MORUY was corroded, allowing water to leak into the compartment.
46	The importance of division of responsibilities and effective teamwork was not reinforced through Bridge Resource Management training.
47	The master's apprehension and doubt, coupled with external influences, led to hesitancy in taking corrective actions.
48	There was no constructive Bridge Resource Management regime in place, and the crew's effectiveness was not supervised.
49	Time off between on-board watches was not effectively used for sleep, leading to fatigue and impaired performance.
50	The crew member's concern over the vessel's position did not lead to further advice or influence the operator to reduce speed.
51	The vessel used an outdated electronic chart, which led to inaccurate navigation.
52	The bridge crew was not adequately familiar with the vessel's steering control system.
53	Language and cultural differences hindered effective communication within the bridge team.
54	The company's Safety Management System did not provide safeguards to mitigate known risks.
55	The crew members were performing roles for which they were not qualified, leading to critical tasks being carried out ineffectively.
56	There was insufficient passage planning before the voyage, and risks were not assessed.
57	The company's SMS did not have procedures for navigating near rocks and shoals.
58	The vessel's destination changed unexpectedly, and the new route passed close to a charted shoal.
59	The radar was not cross-referenced, and navigational equipment was not optimized.
60	The crew did not report the accident promptly, delaying the response of authorities.
61	The manuals for the automated system were in a language not understood by the shipboard personnel.
62	The ship management company's SMS did not provide for a systematic process to proactively identify hazards and assess risks.

ID #	causes for control and feedback failure of link between Ship Management Co. and Ship
63	The master was not aware that pitch control had been lost at the time of the blackout, and only realized the vessel was not under command shortly before grounding.
64	The crew did not report the accident promptly, delaying the authorities' response and mitigation of environmental damage.
65	There were no reports of any liquid being sprayed out of the indicator cocks, indicating no significant accumulation of liquid in any of the cylinders prior to sbeforethe engine.
66	The master experienced sleep disturbances and fatigue due to quitting smoking and taking prescription drugs, which likely negatively impacted his performance.
67	The vessel did not have physical indications to prevent parallax errors due to its offset bridge configuration.
68	The company's Safety Management System (SMS) required that a blackout drill be carried out annually, but there were no records of blackout drills in the company documentation for the previous 2 years.
69	The company's voyage planning procedures did not contain any guidance or direction for entering and leaving hathe rbor, contained only minimal guidance for general passage, and did not establish minimum safety parameters such as under-keel clearance.
70	The company's SMS did not provide for a systematic process to proactively identify hazards and assess and mitigate risks.
71	The limited training, combined with the lack of a defined process in the company's SMS, meant that the masters' decision-making process was largely unstructured.
72	The bridge crew was not adequately familiarized with the characteristics of the Halit Bey's steering control system and did not know how to regain steering control after the autopilot override alarm was activated.
73	Language and cultural differences may have contributed to challenges in bridge team communication.
74	The radar was not cross-referenced by other means, nor was the navigational equipment set up to optimize the available information and facilitate the task of monitoring the vessel's position.
75	The crew didn’t follow how checklists were completed.
76	OSTC's voyage planning procedures did not contain any guidance or direction for entering and leaving the harbor, contained only minimal guidance for general passage, and did not establish minimum safety parameters such as under-keel clearance.
77	Although OSTC had voluntarily adopted an SMS and been audited for compliance with the International Safety Management (ISM) Code, the SMS did not provide for a systematic process to proactively identify hazards and assess and mitigate risks.
78	This limited training, combined with the lack of a defined process in the company's SMS, meant that the masters' decision-making process was largely unstructured.
79	There was no risk assessment conducted before resuming operations for the 2012 season.
80	The switch to softer brushes may have introduced new maintenance needs. However, maintenance and inspections of the brushes were not consistently documented, hampering the crew's ability to accurately determine when the brushes should be replaced.

ID #	causes for control and feedback failure of link between Ship Management Co. and Ship
81	Using an outdated electronic chart, which no longer displayed the channel or buoy positions accurately, to verify the wheel-over position likely led the master to initiate the turn later than intended.
82	The bridge crew was not adequately familiarized with the characteristics of the Halit Bey's steering control system and did not know how to regain steering control after the autopilot override alarm was activated.
83	Lack of a clear voyage plan and assessment of the chief mate's understanding of navigational requirements and insufficient crew familiarization with emergency procedures.
84	The failure to verify the ongoing medical fitness of crew members may result in medically unfit seafarers in safety-critical positions continuing to work, thereby placing the vessel, crew, and passengers at risk.
85	The importance of the weather and its possible effects on visibility was especially relevant in the case of Le Survenant III as the vessel was not fitted with any electronic navigational equipment for navigating in restricted visibility.
86	In this occurrence, some features of the master's work/rest schedule fall short of the minimum acceptable levels identified in the requirements.
87	There were no regulatory or vessel inspection requirements that would have possibly led to the discovery of the missing 6 mm insulation piece that fell from its place between the bus bars and the bracket to the deck sometime before the occurrence.
88	Reliance on verbal communication and lack of detail in the work records may hinder the determination of appropriate corrective action following an occurrence.
89	In this occurrence, the bridge team consisted of two professional mariners, who were expected to work as a team and conduct the vessel safely up the river. Both were qualified for the job to be done, but their equipment-familiarization training was less than adequate in the areas of basic operation and emergency override.
90	With the increasing use of Integrated Navigation Systems (INS) in an Integrated Bridge Systems (IBS) environment, sufficient training and experience are necessary to take full advantage of this new technology.
91	Although the first mate's last instruction to the cadet was to obtain a position fix every half hour and observe what was happening, given the circumstances, a half-hour period between fixes was inadequate.
92	Some consideration must be given to the location of the vital switches, their marking, and the crew’s familiarization.
93	Better knowledge of the steering gear system as well as emergency procedures posted on the bridge would have enabled the watch personnel to act promptly and to regain control of steering.
94	The manuals for the automated system were on board, but they and some other system manuals were written in German, a language not understood by the shipboard personnel.
95	Because the "ZIEMIA CIESZYNSKA" was in a "no meeting area" shortly after midnight, she was committed to proceeding despite the sudden appearance of advection fog.
96	The ship management company's Safety Management System (SMS) did not provide the vessel's staff with safeguards to mitigate well-known risks, including revision of the voyage plan in conjunction with the management company; assurance that the forward-looking sonar unit was operable; use of the

ID #	causes for control and feedback failure of link between Ship Management Co. and Ship
	zodiacs with portable echo-sounders when necessary; assurance that the vessel transited at lower speed when operating in poorly charted areas; and acquisition of NOTSHIPs local navigation warnings.
97	The voyage planning practice on board the Clipper Adventurer did not fully comply with the ship management company's Quality, Safety, and Environmental Protection (QSEP) program by not using the Bridge Procedures Guide for a passage plan appraisal, which resulted in local warnings (NOTSHIPs) not being obtained.
98	A bridge management team is expected to navigate with particular caution where navigation may be difficult or hazardous. The Clipper Adventurer's bridge team was following a single line of soundings made in a 1965 survey, using less reliable technology than that available today, and was not aware of the NOTSHIP regarding the shoal.
99	Crew members performing roles for which they were not qualified. The investigation determined that, as a result of some crew members performing roles for which they were not qualified, certain critical tasks were not carried out, and others were performed ineffectively.
100	The investigation determined that there was insufficient passage planning before the occurrence voyage: neither the company nor the master assessed the risks of the planned voyage. Therefore, no risk mitigation was in place to guide the master's conduct of the vessel during the tour.
101	The company's safety management system did not have procedures for navigating in the vicinity of rocks and shoals.
102	The vessel's destination unexpectedly changed upon departure, and the new route passed in proximity to a charted 10.7-meter shoal.
103	The company's Safety Management System (SMS) documentation was not vessel-specific and did not provide the engine crew with effective procedures to follow for operating in ice-infested waters.
104	The Great Century was not equipped for navigation in ice, and the engine room was not prepared for the possibility of ice blockage of the seawater intakes.
105	The vessel's Safety Management System (SMS) did not provide the crew with effective procedures to follow for operating in ice-infested waters.
106	The vessel's procedures lacked guidance for identifying and supervising safety-critical maintenance tasks.
107	The company operated without a coordinated Safety Management System (SMS), affecting operational safety.
108	The company's ISM Code procedures contained a generic checklist, leading to reactive rather than structured responses to emergencies.
109	The vessel's emergency generator room was corroded, allowing water to leak into the compartment.
110	The importance of division of responsibilities and effective teamwork was not reinforced through Bridge Resource Management training.
111	The master's apprehension and doubt, coupled with external influences, led to hesitancy in taking corrective actions.

ID #	causes for control and feedback failure of link between Ship Management Co. and Ship
112	There was no constructive Bridge Resource Management regime in place, and the crew's effectiveness was not supervised.
113	Time off between on-board watches was not effectively used for sleep, leading to fatigue and impaired performance.
114	The crew member's concern over the vessel's position did not lead to further advice or influence the operator to reduce speed.
115	The vessel used an outdated electronic chart, which led to inaccurate navigation.
116	The bridge crew was not adequately familiar with the vessel's steering control system.
117	Language and cultural differences hindered effective communication within the bridge team.
118	The company's Safety Management System did not provide safeguards to mitigate known risks.
119	The crew members were performing roles for which they were not qualified, leading to critical tasks being carried out ineffectively.
120	There was insufficient passage planning before the voyage, and risks were not assessed.
121	The company's SMS did not have procedures for navigating near rocks and shoals.
122	The vessel's destination changed unexpectedly, and the new route passed close to a charted shoal.
123	The radar was not cross-referenced, and navigational equipment was not optimized.
124	The crew did not report the accident promptly, delaying the response of authorities.
125	The manuals for the automated system were in a language not understood by the shipboard personnel.
126	The ship management company's SMS did not provide for a systematic process to proactively identify hazards and assess risks.
127	The master was not aware that pitch control had been lost at the time of the blackout, and only realized the vessel was not under command shortly before grounding.
128	The crew did not report the accident promptly, delaying the authorities' response and mitigation of environmental damage.
129	The master experienced sleep disturbances and fatigue due to quitting smoking and taking prescription drugs, which likely negatively impacted his performance.

In Table 10, the top causes are examined in relation to control and feedback failure of the link between the Master and the Helmsman/Pilot/Officer of the Watch.

Table 10 Top causes considered for control and feedback failure of link between Master and Helmsman/Pilot/officer of the watch

ID #	causes for control and feedback failure between Master and Helmsman/Pilot/officer of the watch
1	The operator's performance was likely impaired due to substance and/or alcohol intoxication, as evidenced by confusion, slurred speech, impaired memory, and lack of appreciation for the seriousness of the event, which affected the decision to lower the vertical-lift span.
2	The crew did not collect essential weather information from various sources, resulting in a failure to follow established procedures to prepare the vessel and crew for adverse weather conditions.
3	The Master ordered a reduction in speed without being briefed by the OOW, leading to a decrease in the CPA and increasing the risk of collision with the Wilf Seymour.
4	The Stellanova's bridge team did not observe Bridge Resource Management principles such as effective communication and shared mental models, despite having received BRM training.
5	The exchange of information between the Master/OOW and the pilot was informal and incomplete, creating uncertainty about the intended course of action and contributing to the close-quarters situation.
6	The bridge team did not effectively share the workload and tasks of navigation and communications in accordance with Bridge Resource Management principles.
7	The bridge watch, including the helmsman, was distracted by another vessel, causing the vessel to stray beyond the heading ordered by the pilot.
8	The OOW did not provide significant inputs to ensure an effective river passage, and the Master did not seek input or have a contingency plan, leading to uncoordinated actions.
9	Communication among members of the bridge team was limited and casual, and effective use was not made of all available navigational equipment, leading to a fragmented working relationship.
10	The Master deviated from the voyage plan without collaborating with the OOW on strategies to ensure the safety of the maneuver, leading to a lack of shared understanding and ineffective actions.
11	The bridge team did not detect the charted shoal while planning the revised route or during monitoring, indicating a lack of thoroughness and attention to detail.
12	There was a lack of effective communication between the Master and the pilot, leading to a lack of shared understanding of the maneuver for the approach to the Iroquois Lock.
13	The Master and OOW did not discuss the deviation from the charted course or exchange navigational information after the vessel weighed anchor, leading to continued deviation.
14	The Jiimaan's team did not consider all necessary information, including up-to-date water level and bottom sounding data, to ensure sufficient water depths for safe arrival.
15	The Master of the Clipper Adventurer was overconfident in his choice of route and speed, despite the absence of bathymetric contour lines indicating an incomplete hydrographic survey.
16	Verbal exchange between the wheelsman and the Master was misinterpreted by both, leading to the vessel moving in the wrong direction.
17	No person was designated to stand by during berthing operations, preventing the deployment of the anchor as a potential emergency tool.
18	The OOW did not possess a mental model similar to that of the pilot, and communication on the bridge was incomplete, leading to ineffective navigation.
19	Comprehensive briefings between Masters and pilots are essential for awareness of local conditions and vessel maneuvering characteristics, but were not conducted effectively.
20	The Master confidently handed over the conduct of the vessel to a person who boarded at the pilot station without verifying qualifications, leading to grounding.

Table 11 focuses on the top causes examined for control and feedback failure of the link between the Helmsman/Pilot/Officer of the Watch and Equipment, displays, etc. This analysis delves into the primary factors that contribute to the breakdown in control and feedback between these individuals and the various equipment and displays they rely on for navigation and operational tasks.

Table 11 Top causes considered for control and feedback failure of link between Helmsman/Pilot/officer of the watch and Equipment, displays, etc

1.	Effective communication is critical, especially between the bridge operator and the crew. Language barriers can impede communication and contribute to poor Bridge Resource Management, which can increase the mental workload of the pilot and lead to errors.
2.	Proper use and monitoring of equipment, such as VHF radios, radar, and navigational equipment, are essential for safe navigation. The bridge team must be familiar with the onboard steering system and navigation equipment and ensure that these are set up to optimize available information.
3.	Adherence to established procedures and proper training are vital for safe maritime operations. The crew must follow procedures such as collecting daily local weather forecasts and inspecting generator units. Additionally, training is necessary to ensure that the crew can effectively use equipment and respond to emergencies.
4.	Vigilance and situational awareness are crucial, especially in high-density traffic or restricted waterways. The bridge team must be alert and continuously monitor the ship's position and surroundings to prevent accidents.
5.	The bridge team must be prepared to adapt to unexpected changes and must have a thorough understanding of the ship's capabilities and limitations. This includes understanding the hydrodynamic forces at work and the need for early and decisive action to prevent accidents.
6.	The bridge team must effectively utilize all available resources, including visual aids, radar, and electronic chart systems, to ensure safe navigation. Over-dependency on one form of navigation or failure to cross-reference can lead to navigational errors.
7.	Timely and appropriate responses to alarms and alerts are necessary to avert danger. The bridge team must be familiar with the alarm systems and must take immediate corrective action in emergencies.
8.	Planning and execution of maneuvers must take into account the vessel's behavior, environmental conditions, and available sea room. The bridge team should employ fundamental techniques to ensure a safe passage and must communicate any unexpected changes that could alter the navigation plan.
9.	The bridge team must be aware of the potential for human error, such as parallax errors or inadvertent button presses, and must be trained to mitigate these risks.
10.	The bridge team should ensure that navigation equipment is up-to-date and correctly configured, including setting alarms and ensuring the accuracy of electronic charts. This is essential for maintaining situational awareness and preventing groundings or collisions.

Table 12 examines the top causes considered for control and feedback failure of the link between the Master and Equipment

Table 12 Top causes considered for control and feedback failure of link between Master and Equipment, displays, etc

1.	Emergency procedures for fire were not fully followed, including sounding alarms in passenger areas, closing fire doors, accounting for passengers and crew, and keeping passengers informed.
2.	The master excluded weather deck cargo from regular checks due to safety concerns in winter, but more frequent checks could have led to early detection of fire hazards.
3.	The master ordered the anchor team to pay out more anchor chain to move the vessel away from another ship, but did not call for the main engine to be started.
4.	The Wilf Seymour did not sound whistle signals to indicate doubts about the Bulk Japan's intentions, which maintained course across the Wilf Seymour's bow, creating a risk of collision.
5.	The Stellanova's master was not actively involved in navigation, and the bridge environment did not promote good communication or shared understanding.
6.	The "LADY MEGAN II" maintained full speed ahead even after conditions changed, and the "EMERALD STAR" increased speed in a tight situation instead of reducing or stopping.
7.	The master of the "RIXTA OLDENDORFF" took decisive action to avoid grounding and reduce the impact between vessels.
8.	The master of the "QUEEN OF ALBERNI" used binoculars to see a bear, losing positional awareness, and did not use all available bridge resources to monitor the vessel's position.
9.	The pressure of seawater caused flooding in the engine room, leading the master to order a blackout, and the vessel began drifting.
10.	The Yong Kang was not anchored safely considering its size, draught, low keel clearance, currents, winds, and limited room for maneuver.
11.	The master of the "JEAN PARISIEN" did not follow the planned course, and the vessel was too deep to enter the east side of the Middle Neebish channel, causing it to run aground.
12.	The master of the "HANSEATIC" was not aware of the potential impact of the tidal stream in Simpson Strait, which may have contributed to the grounding.
13.	The pilot of the "HANSEATIC" was unsure of the gyroscopic error of the gyrocompass, and the main engine could not be engaged quickly due to the time taken to haul the line onboard.
14.	The master's use of binoculars and focus on external objects led to a loss of positional awareness, and the chart plotter was not zoomed in to show hazards.
15.	Companies and masters can mitigate risks by identifying them and implementing risk management processes, but in the case of the "QUEEN OF ALBERNI", the master was not using all available resources effectively.
16.	The master's attention was distracted by attempts to operate the ECDIS, and the light from the unit's display screen affected his night vision.
17.	The master did not confirm the vessel's position at the time of speed reduction, and no position check was made as the vessel approached a course-alteration point.
18.	The master did not become aware of the squall warning until after departure and relied solely on a car radio forecast, which did not mention storm force winds.
19.	The master did not have a comprehensive voyage plan and did not identify all pertinent navigational information, and the information from the sounding survey was not transferred to the navigation chart.
20.	The master and the officer of the watch did not interfere with or override the pilot's orders, and the sequence of maneuvers ordered by the pilot accumulated and resulted in grounding.
21.	The navigating personnel was aware of a current in the bay but did not assess the situation fully. The small-scale chart used was not appropriate for coastal navigation, and the radar's automatic radar plotting aid (ARPA) was not used.

Table 13 presents an exhaustive examination of all causes considered for control and feedback failure of the link between the Port authority and the Ship.

Table 13 All causes considered for control and feedback failure of link between Port authority and Ship

ID #	causes for control and feedback failure of Port authority and Ship link
1	There was no specific risk analysis or standard response scenarios for emergencies at the port.
2	No one was specifically assigned to call the city's fire department in case of a vessel fire.
3	Attempts to extinguish a fire were delayed as shore-based fire crews took hours to board the vessel.
4	The responding fire department lacked training and equipment for fighting shipboard fires.
5	The "PETROLAB" and "NORTHERN PRINCESS" were both docked at St. Barbe, engaging in potentially hazardous operations in close proximity.
6	A flash fire occurred due to the ignition of methane gas by a cigarette, exacerbated by a lack of safety notices and non-compliance with guidelines.
7	There were no instructions on emergency alert procedures for shore-based firefighters.
8	A previously unidentified area with a heightened risk for collision was revealed.
9	Neither the Laurentian Pilotage Authority nor the Corporation des pilotes du Saint-Laurent central had guidelines for reducing hydrodynamic interactions between vessels.
10	Reduced shore-side lighting may have hampered the pilots' ability to assess their vessels' positions.
11	The bridge team on the ferry was unaware of the tug's position.
12	Navigational safety communications were on frequencies not monitored by the Seaway.
13	The pilot had not received hands-on training on similar vessels in non-threatening environments.
14	The brightness level of navigation lights marking the channel was reported to be low.
15	The pilot had a severe alcohol addiction problem, and no steps were taken to monitor his abstinence.
16	The vessel approached the pilot boarding station outside of office hours, causing a lack of instructions.
17	The position of the pilot boarding station was not clearly marked on charts.
18	Limited distance and time for the vessel to make a safe approach due to delay in the pilot's boarding.
19	The pilot accidentally applied the wrong helm order due to unfamiliarity with the equipment.
20	Shortcomings in the vessel traffic management plan contributed to the grounding of the CWB Marquis.
21	The master of the John I delayed accepting tow offers, contributing to the vessel running aground.
22	Multiple entities involved in port operations failed to fulfill their roles effectively.
23	The CCG range lights no longer marked the best approach into the port due to silting in the channel.
24	Bank suction effect was not communicated by the ship crew.
25	The Clipper Adventurer ran aground on an uncharted shoal due to inadequate navigation.
26	NORDREG did not proactively advise vessels about active NOTSHIPs.
27	The master did not become aware of a squall warning until after departure and continued the voyage.
28	Absence of a detailed plan and shared mental model for a turn prevented effective error trapping.

ID #	causes for control and feedback failure of Port authority and Ship link
29	The Canadian Coast Guard did not undertake activities to stay aware of the latest placement of private aids to navigation.
30	The pilot of the "VENUS" was not assisted by another pilot and was probably fatigued.
31	The vessel grounded due to rock debris found at the bottom of the channel.
32	The master handed over the conduct of the vessel to an unqualified person.
33	The pilots did not communicate effectively and did not inform each other of their vessels' draughts.
34	The Sorel channel entrance was not buoyed.
35	Georgia Rock buoy and Ridley Island buoy had the same light characteristics, leading to confusion.
36	The crew took several minutes to haul in the line at the after end, which had been let go by the tug.
37	Astern thrust was not requested in time for the stopping distance available.
38	There were no adequate aids to navigation to indicate the limit of deep water southeast of berth No. 86.
39	The "ALGOLAKE" ran aground because the pilot and crew were unaware that a buoy had been displaced for dredging operations.
40	The signals requesting the opening of two bridges were not made consecutively, and the highway bridge signal was delayed.
41	The master believed he did not require a pilot for departure but lacked local knowledge for night sailing.
42	The only conventional navigational aid in the area was seasonal and had been removed for the winter.
43	The pilot mistook Georgia Rock buoy for Ridley Island buoy and made a premature alteration of course.
44	Divers found rock debris with paint scrapes at the bottom of the channel where the vessel sustained damage.
45	The master confidently handed over the conduct of the vessel to an unqualified person.
46	The pilots intended to carry out an overtaking maneuver but did not confirm this verbally.
47	The Sorel channel entrance was not buoyed, and the light characteristics of two buoys were the same, leading to confusion.
48	**The** pilot was possibly fatigued, affecting his performance.
49	The difference between dredged width and buoyed channel width was not communicated to navigators.
50	Information on the latest surveys of dredged channels was not distributed to coast pilots or ship's crew.
51	The pilot handover took place within the river, even when not warranted by conditions.

Additionally, Table 14 below displays the infrequently occurring dysfunctional interactions within the safety control structure (Table 14).

Table 14 Causes considered for control and feedback failure for least frequent link

Classification society	**Ship builder/supplier**	The design of the consoles, touch screen controls, and automation systems is the responsibility of the vessel's designer and the classification society, Bureau Veritas.
Classification society	**Ship owner**	There is a discrepancy between the vessel's certificate of inspection and the bridge team's certification of competency, which can lead to limitations on the ship's operations.
Engineers	**Machinery etc.**	The by-pass valve was found to be leaking during a post-explosion examination by the vessel's engineers, causing oil to accumulate on the piston crowns.
Engineers	**Machinery etc.**	The engineers failed to properly set the sea water cooling system, leading to the plugging of the sea water strainer and preventing circulation to the main engine heat exchangers.
IMO	**Ship builder/supplier**	The SOLAS requirement for multiple steering gear power units can paradoxically increase the risk of an accident due to potential malfunctions and lack of alarms.
IMO	**Ship builder/supplier**	International regulations do not require redundant electrical circuits for rudder angle indicators or alarm/indicator lights.
Mate(s)	**Equipment, displays, etc**	The vessel's speed reduced the efficiency of the bow thruster.
Ship management company	**Ship owner**	The ship management company, STQ, may operate ferries in restricted visibility without crew training due to lack of regulatory restrictions, but is aware of operational parameters and is required to employ certified personnel and provide directives.

In Figure 11, drawing from Table 4, the analysis reveals a series of dysfunctional interactions, including insufficient, wrong or dismissed control or feedback, which collectively represent all the accidents.

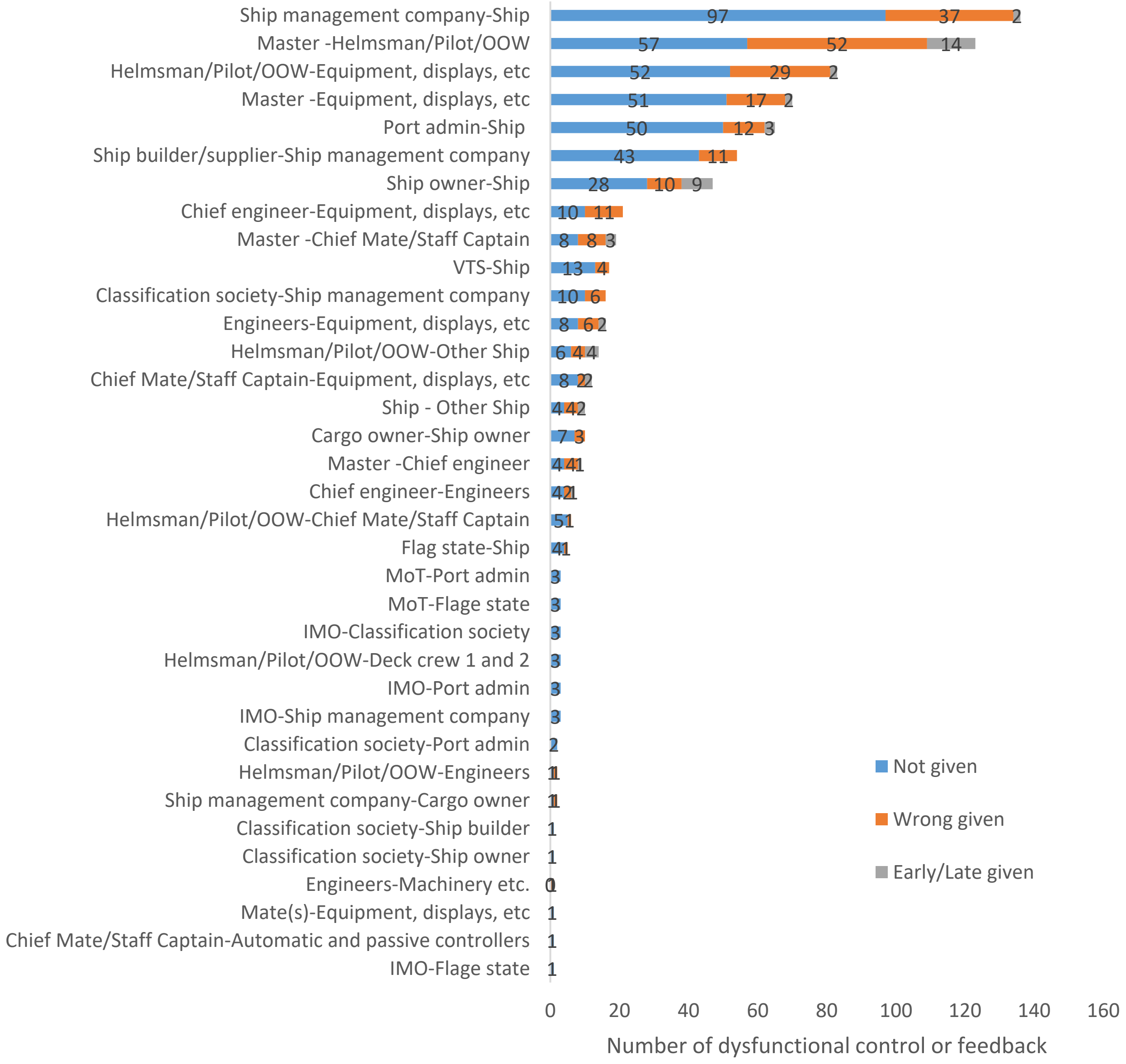


Figure 11 Distribution of conditions that made control dysfunctional

The categorization of accident causes into three causal categories is represented according to Table 5, and the distribution is depicted in Figure 12 as shown below.

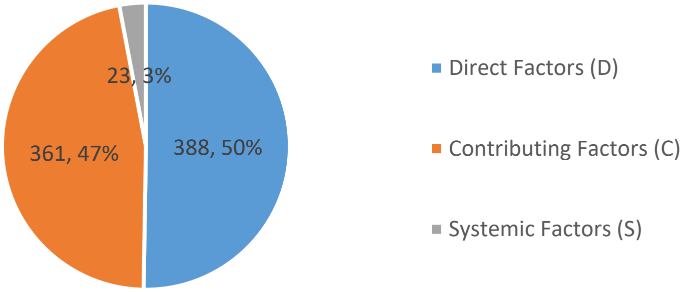


Figure 12 Shares of identified dysfunctional interactions across the three causal categories

4.2 All Accidents based on Ship Type

The analysis conducted on accident investigation reports, taking into account the type of ship involved, revealed that the causal factors leading to accidents tend to vary depending on the vessel type.

4.2.1 Bulk Liquid carriers

Figure 13 and 14[3] illustrate the dysfunctional links observed in accidents involving Bulk Liquid Carriers, categorizing them based on control and feedback levels between various maritime entities and components. The figures highlights that links such as Helmsman/Pilot/OOW with Equipment/Displays and Ship Management Company with Ship are critical, as they have high failed control values, indicating their frequent involvement in accidents. Conversely, links like Classification Society-Ship Builder/Supplier are depicted with lower control values, suggesting they are less critical in the context of accidents.

In terms of feedback, the links like Master-Helmsman/Pilot/OOW which show high feedback values suggest that communication levels may be either excessive or inadequate during accidents. Operational control, communication between crew members, interactions with equipment, and external entities like Port Administration are emphasized as significant factors.

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[3] Bold red color will be used in some of the figures to enhance clarity and distinction when there are large numbers and overlapping arrows for the control and feedback links

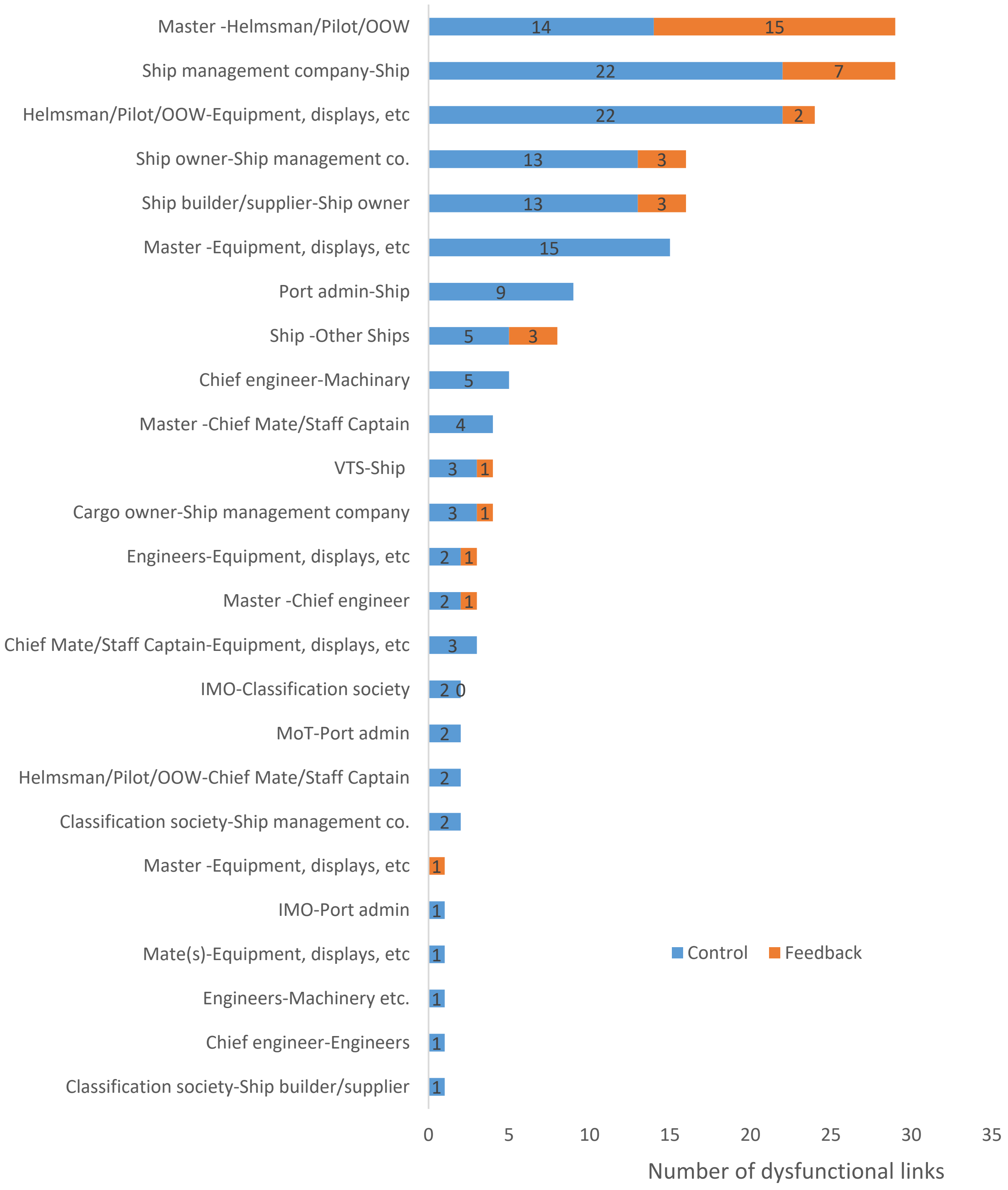

Figure 13 The dysfunctional links associated with Bulk Liquid carriers

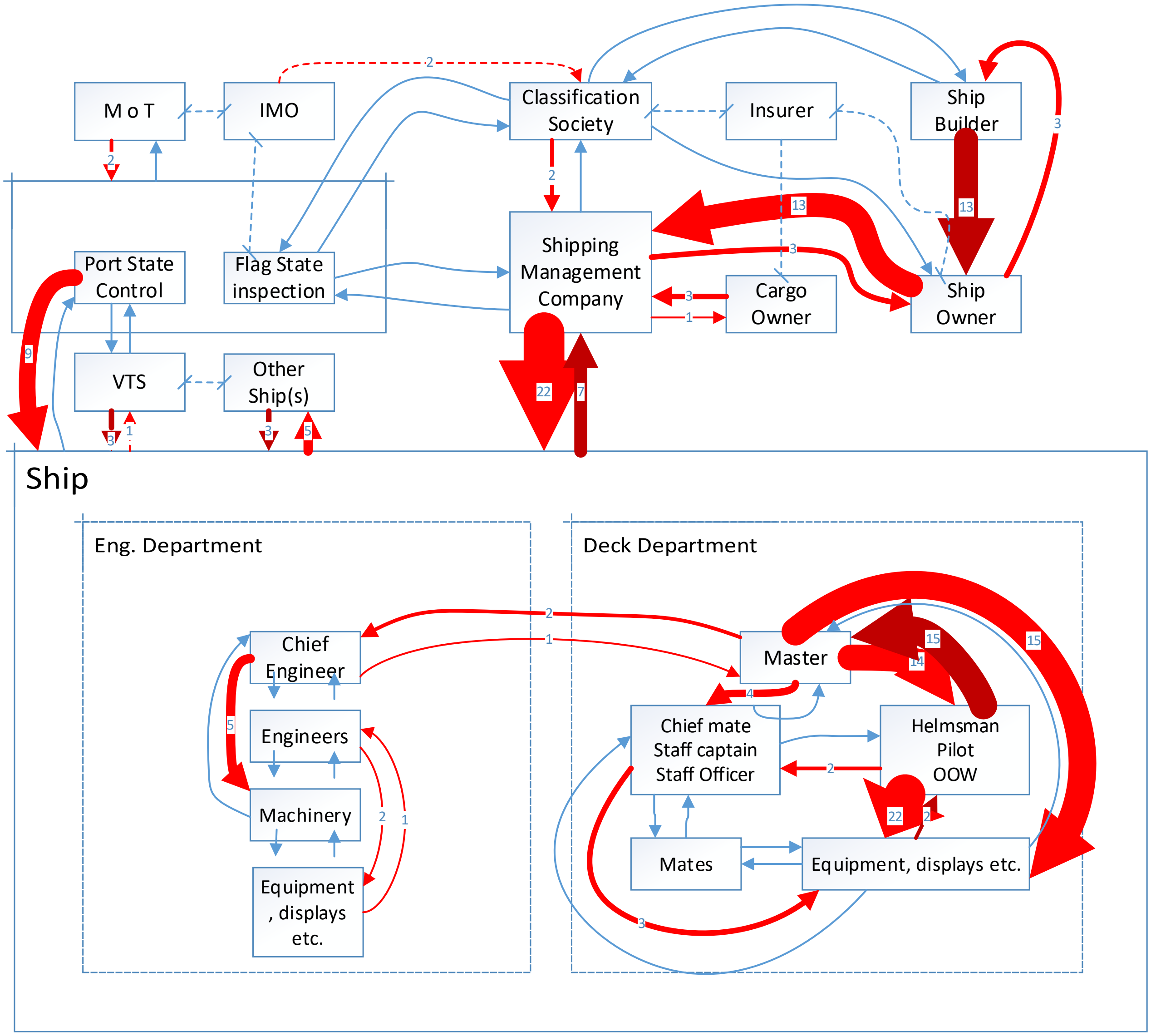

Figure 14 Illustration of dysfunctional links of bulk liquid carriers within the safety control structure

4.2.2 Bulk Solid carriers

Figure 15 and its illustration in Figure 16 portray the dysfunctional links observed in accidents involving Bulk Solid Carriers, categorizing them based on control and feedback levels between different maritime entities and components. The figures highlight that links, such as between Helmsman/Pilot/OOW and Equipment/Displays, as well as between the Ship Management Company and Ship, carry high control values. This suggests that these particular links play a pivotal role in accidents. Moreover, the connection between the Master and Helmsman/Pilot/OOW exhibits elevated values in both control and feedback. This implies that there is a marked presence of interaction and communication between these roles in the context of accidents. However, it is important to note that a 'significant level of interaction and communication' does not necessarily denote effective or positive communication. It merely underscores the frequency or intensity of such interactions during mishaps.

On the other hand, links like IMO-Flag State and Classification Society-Flag State have lower control values, suggesting they are less critical in the context of accidents. The figures, similar to liquid carriers emphasize the importance of operational control, communication between crewmembers, and interactions with equipment. Notably, the interactions between Port Administration and Ship, as well as Ship Management Company and Ship, are depicted as having high control values, indicating their significance in accidents involving Bulk Solid Carriers.

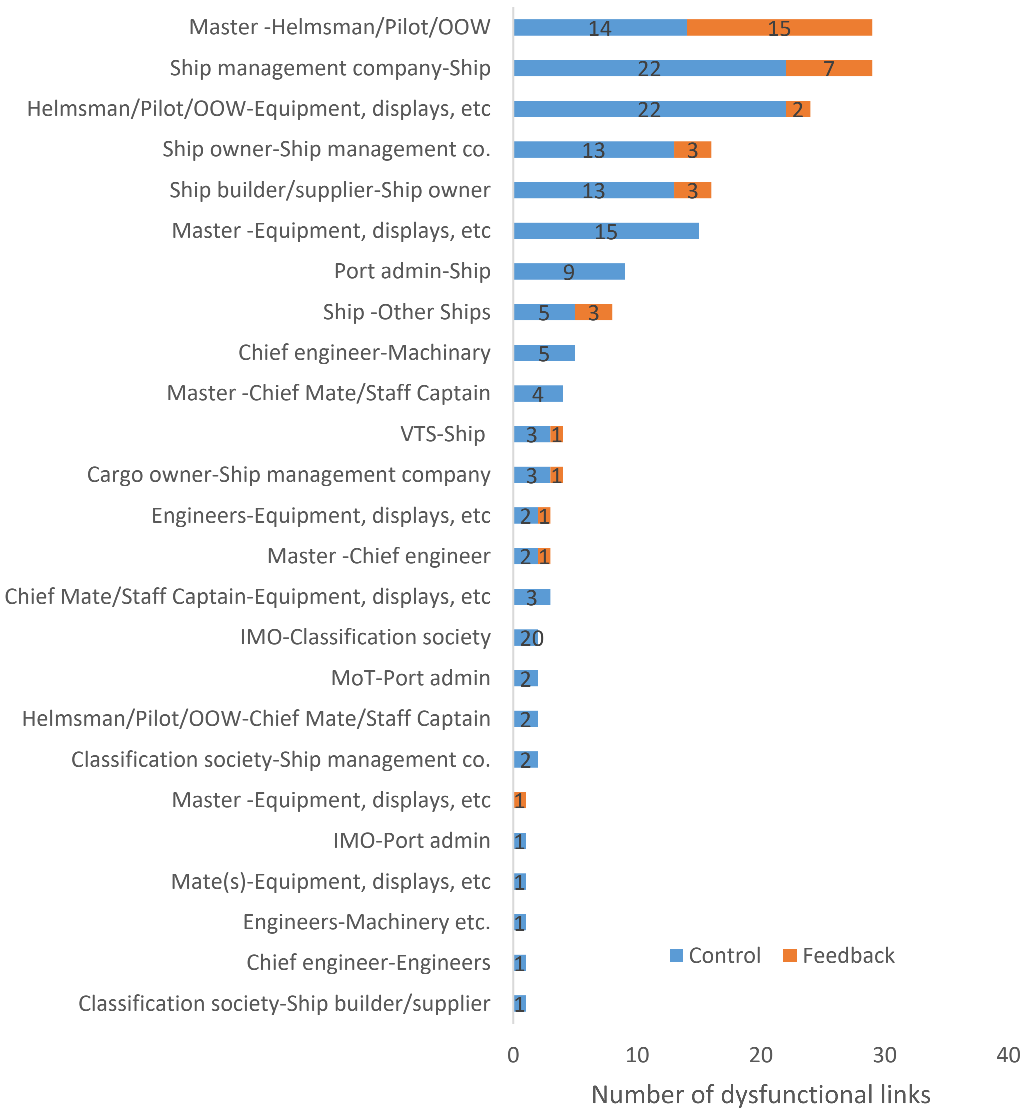

Figure 15 The dysfunctional links associated with Bulk Solid carriers

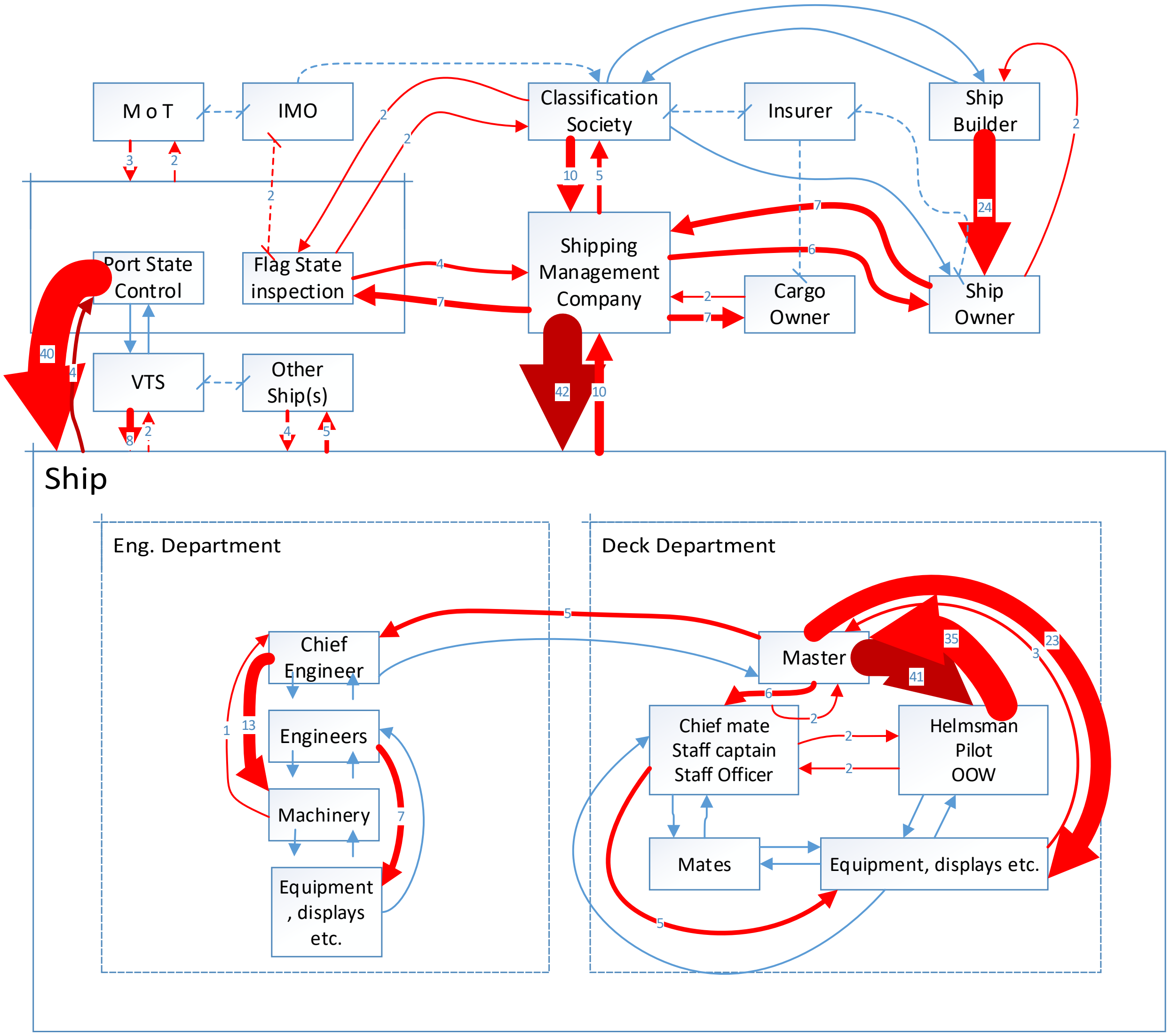

Figure 16 Illustration of dysfunctional links of bulk Solid carriers within the safety control structure

4.2.3 Ferries

Figures 17 and 18 illustrate two representations of the dysfunctional links observed in accidents involving ferries. The figures, similar to previous analyses, categorize these links based on control and feedback levels between various maritime entities and components.

The results highlight that control links such as Ship Management Company with Ship, and Master with Equipment/Displays have high control values, suggesting that these links are critical and frequently involved in accidents. In contrast, several links including Chief Engineer-Machinery, Cargo Owner-Ship Management Company, and Master-Chief Engineer have lower control values, indicating that they are less significant in the context of ferry accidents.

Additionally, the figures emphasize the feedback dimension. It shows that the link between Master and Helmsman/Pilot/OOW has a relatively high feedback value, indicating significant failure in communication or interaction between these roles during accidents. Moreover, the Ship Management Company-Ship link is depicted with a notable feedback value, suggesting communication issues may be a contributing factor in accidents.

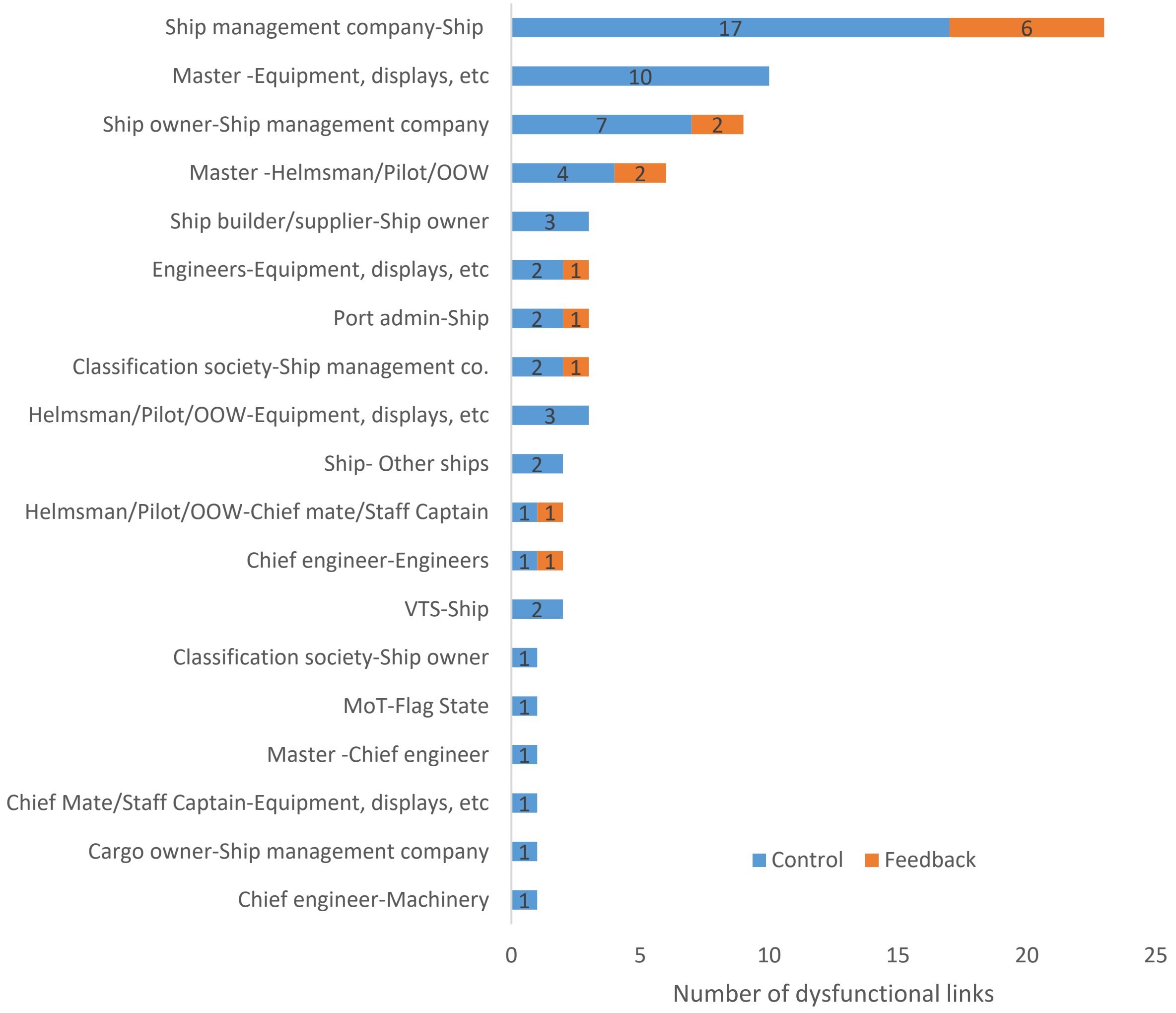

Figure 17 The dysfunctional links associated with Ferries

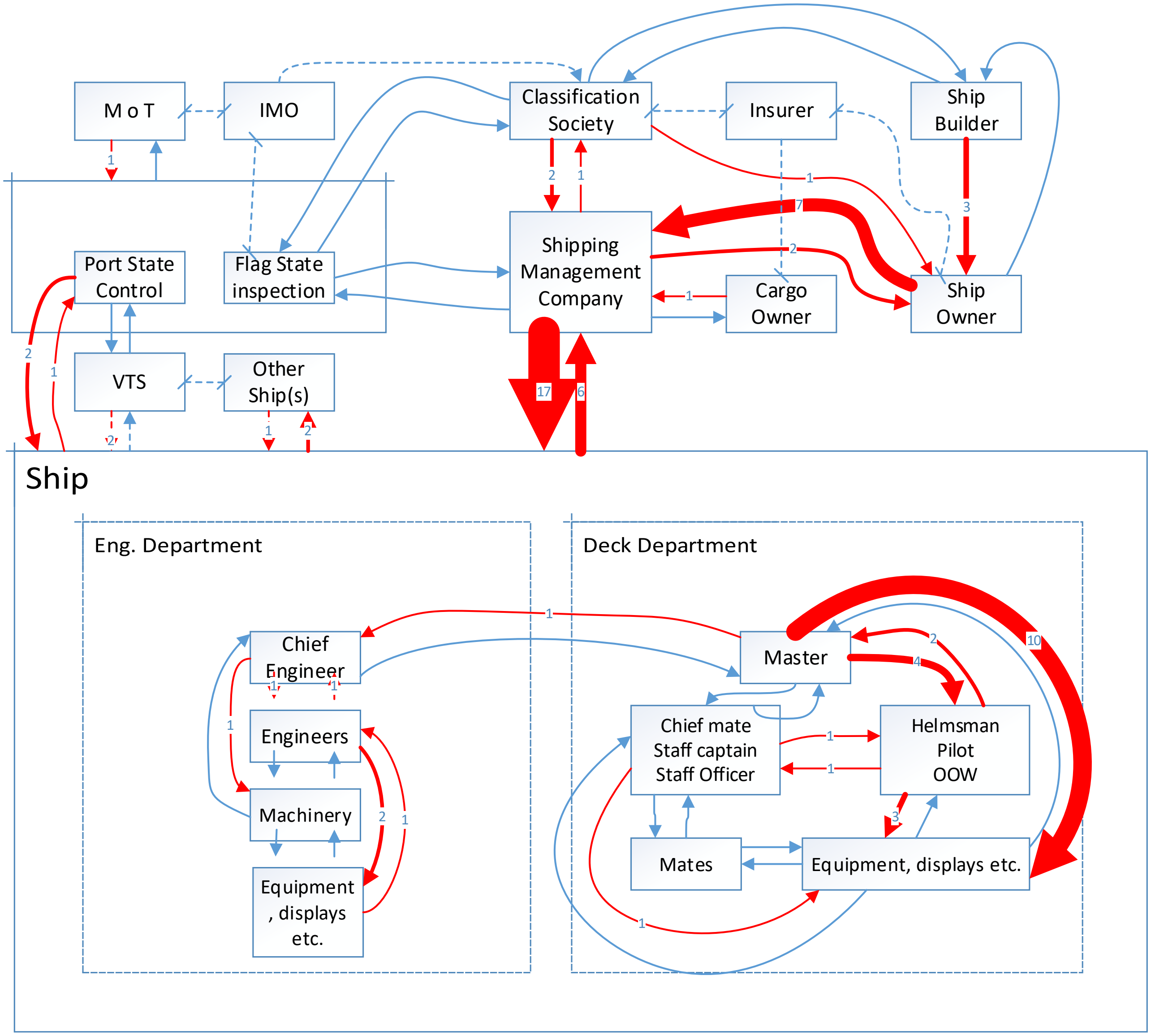

Figure 18 Illustration of dysfunctional links of Ferries within the safety control structure

4.2.1 Passenger Ships

Figures 19 and 20 analyze the dysfunctional links in accidents involving passenger ships. It is evident that the link between the Ship Management Company and the Ship, as well as the Master's interaction with Equipment/Displays, are critical areas, as depicted by high control values. This suggests that management issues and the handling of equipment by the Master are significant factors in passenger ship accidents. In contrast, links such as Chief Engineer-Machinery and IMO-Flag State are depicted with lower control values, indicating that they have a lesser impact on the safety of passenger ships.

Also for the feedback aspect, the Master-Helmsman/Pilot/OOW link has a substantial feedback value, signifying that communication between the ship's Master and the Helmsman/Pilot/OOW is a crucial element in the context of passenger ship accidents. The figures also indicate that the Ship Management Company-Ship link has considerable feedback, pointing towards communication as a key factor in the effective management of passenger ships

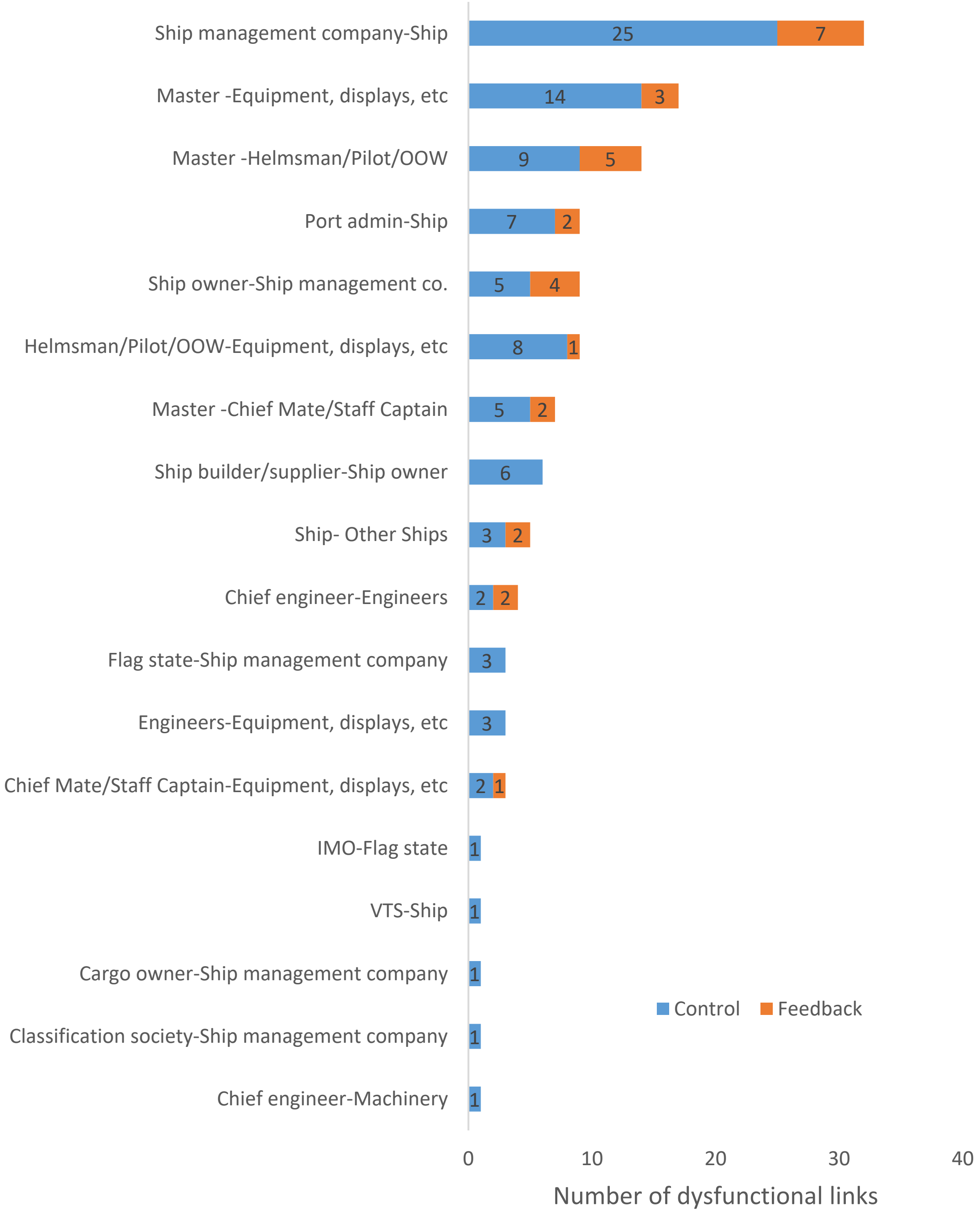

Figure 19 The dysfunctional links associated with Passenger Ships

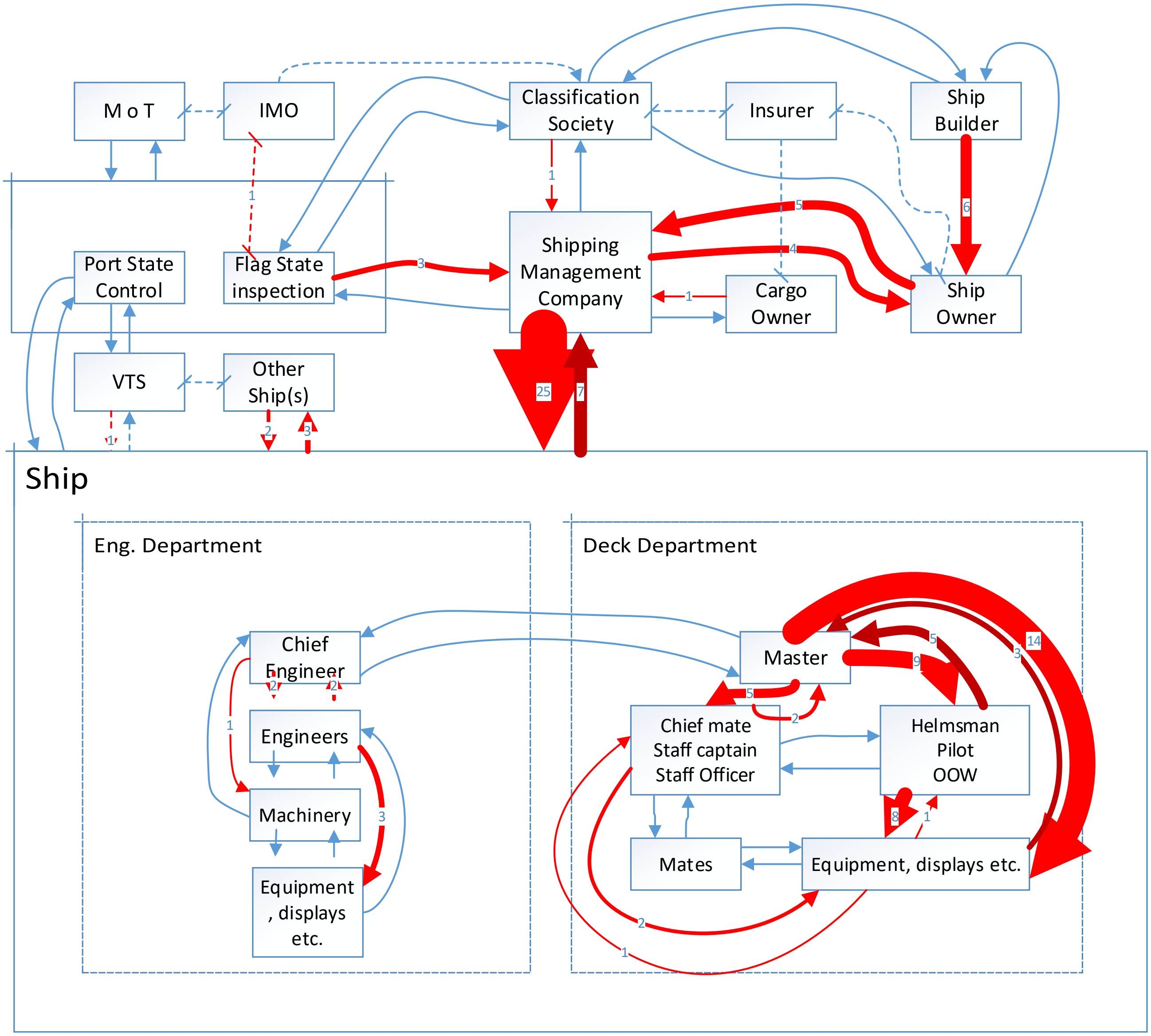

Figure 20 Illustration of dysfunctional links of Passenger Ships within the safety control structure

4.3 Causes based on accident types

In this section, a collection of figures conveys information illustrating the dysfunctional links related to various types of ship accidents, encompassing grounding, collision, and fire. Each figure visually portrays the diverse factors and entities implicated, and elucidates how their interplay or absence thereof plays a role in the corresponding type of accident.

4.3.1 Grounding

In Figures 21 and 22, which focus on grounding accidents, the data presents a range of dysfunctional links with varying degrees of control and feedback. The figures visually represent how different entities and factors interact, and how these interactions contribute to grounding accidents.

One of the most frequent dysfunctional links, as depicted in the figures, is between the Ship Management Company and the Ship, with a control value of 67 and a feedback value of 28. This suggests that issues in ship management play a significant role in grounding accidents. Another highly frequent link is between the Master and the Helmsman/Pilot/OOW, with a control value of 46 and a feedback value of 37, indicating that communication and interaction between the Master and the Helmsman/Pilot/OOW are critical factors in grounding accidents.

Additionally, the link between the Helmsman/Pilot/OOW and Equipment/Displays is notable with a control value of 48 and a feedback value of six, suggesting that navigation equipment and displays are significant contributors to grounding accidents.

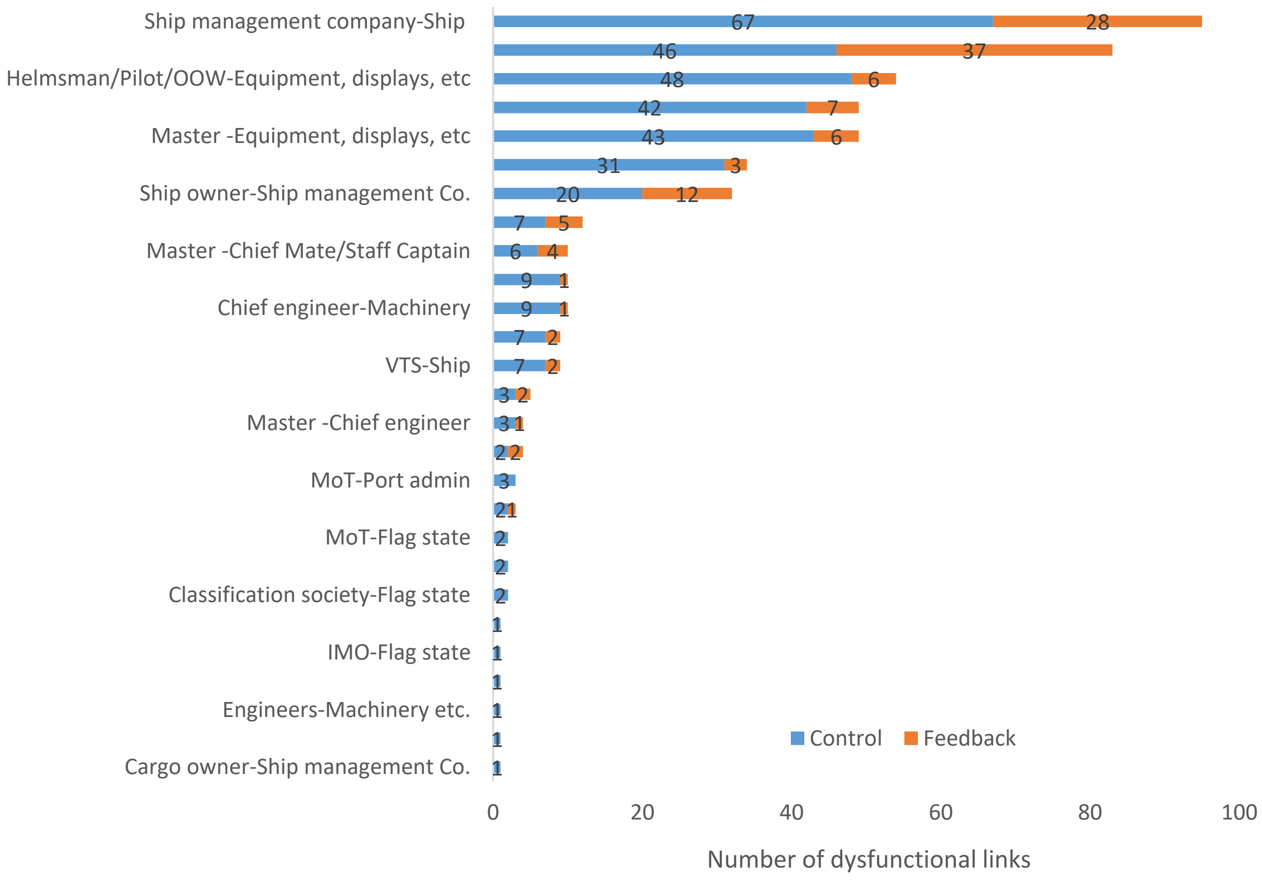

Figure 21 The dysfunctional links associated with Grounding accident

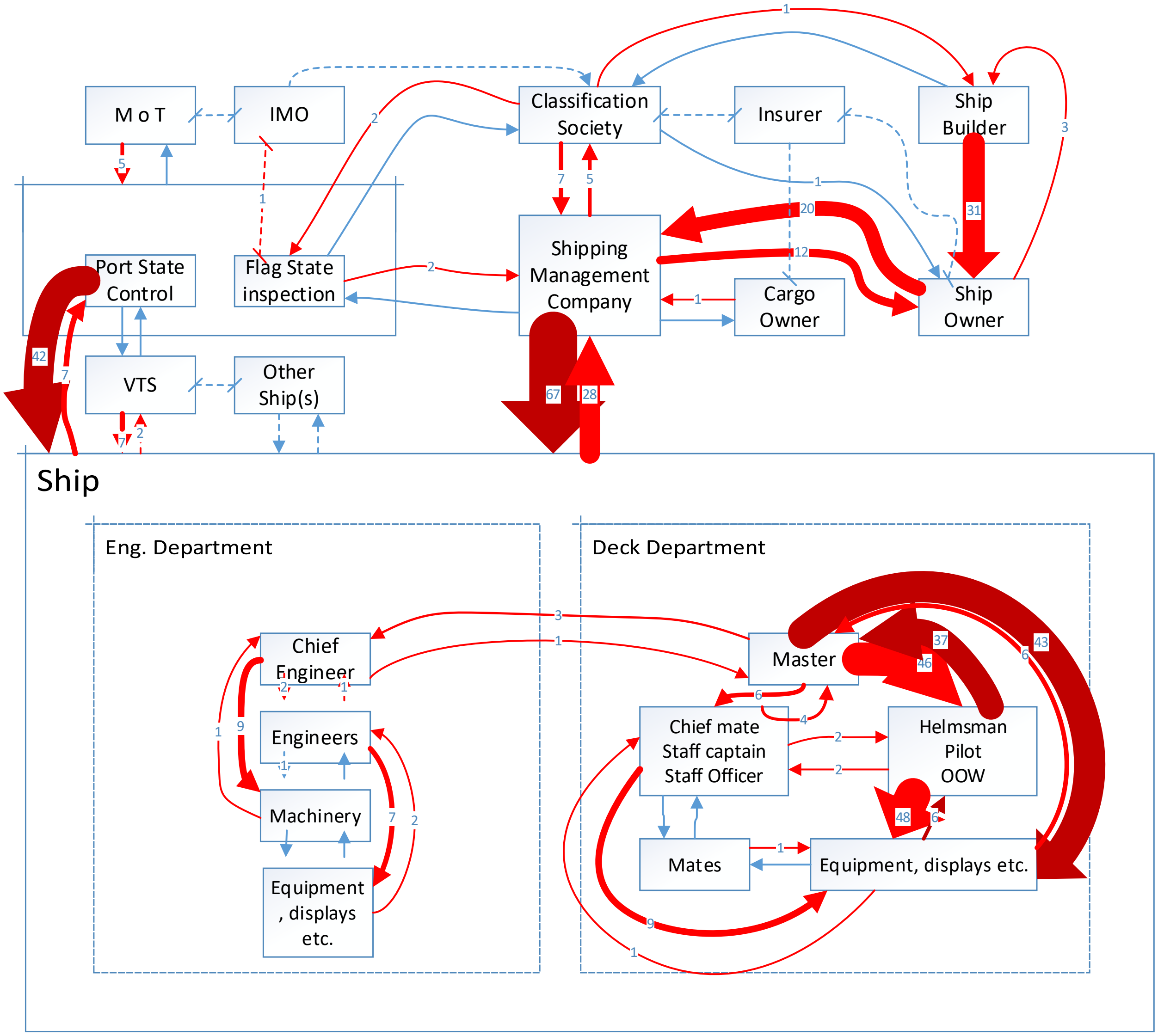

Figure 22 Illustration of dysfunctional links of Grounding accident within the safety control structure

4.3.2 Collision

In Figures 23 and 24, which are centered on collision accidents, the data illustrates a variety of dysfunctional links with different levels of control and feedback. A particularly noteworthy dysfunctional link in the context of collision accidents is between the Ship and Other Ships, with a control value of 15 and a feedback value of nine. This is especially significant as it directly relates to the nature of collision accidents, which involve contact between ships. This suggests that interactions and communications between ships are critical factors in collision accidents.

Another highly frequent link is between the Helmsman/Pilot/OOW and Equipment/Displays, with a control value of 23 and a feedback value of two, indicating that navigation equipment and displays play a significant role in collision accidents.

Additionally, the link between the Master and the Helmsman/Pilot/OOW is notable with a control value of 17 and a feedback value of 15, suggesting that communication and interaction between the Master and the Helmsman/Pilot/OOW are crucial factors in collision accidents.

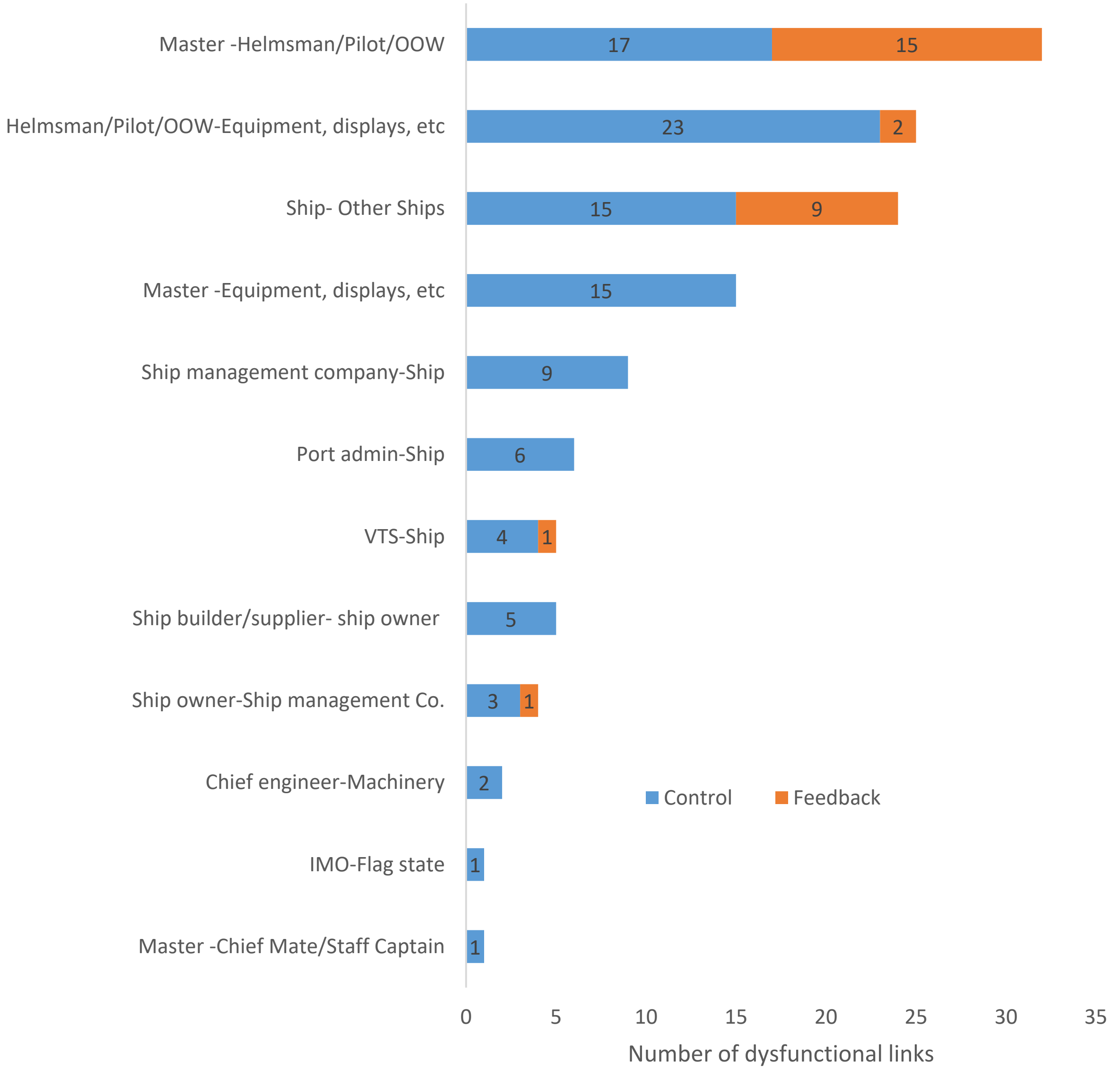

Figure 23 The dysfunctional links associated with Collision accident

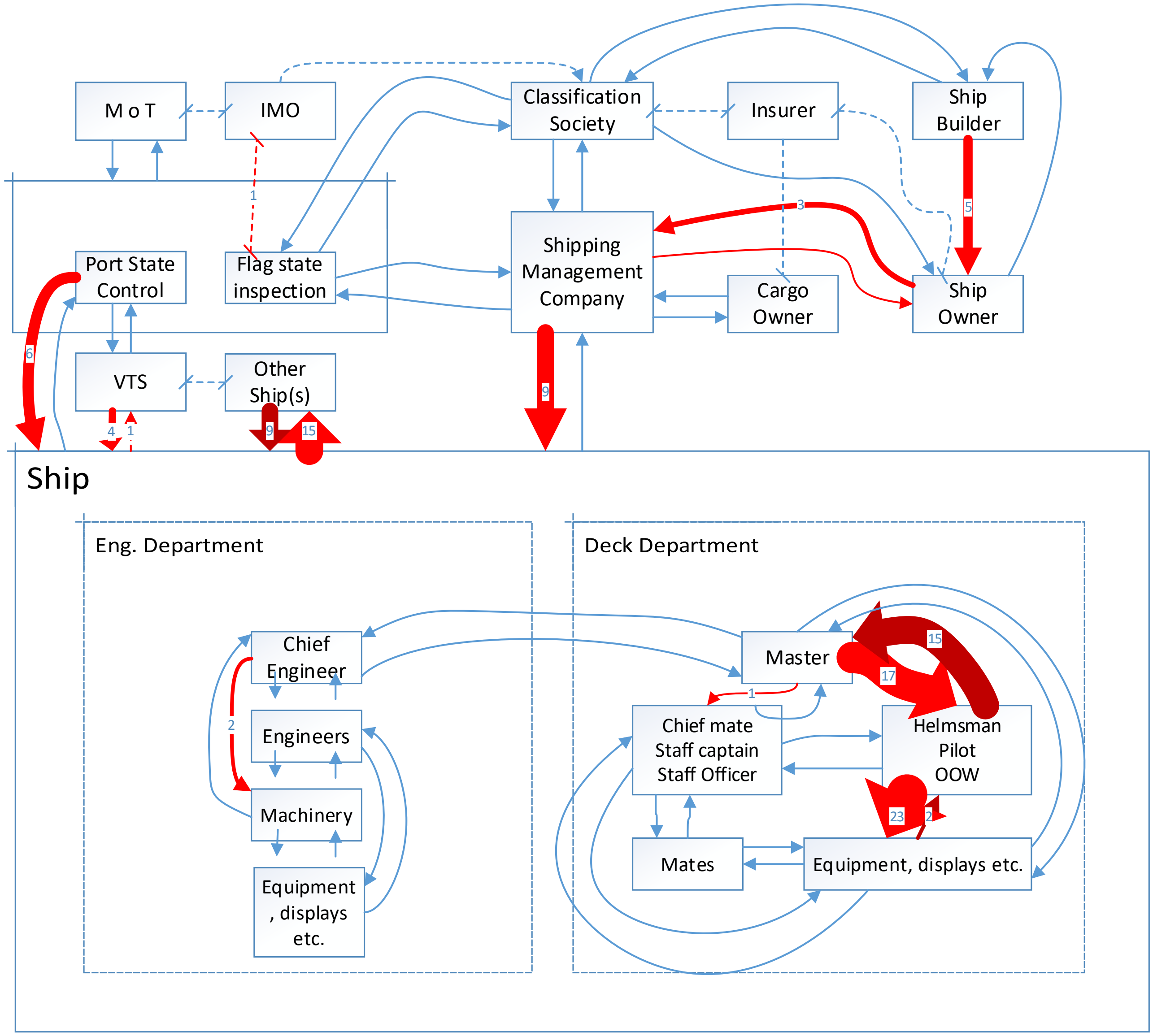

Figure 24 Illustration of dysfunctional links of Collision accident within the safety control structure

4.3.3 Fire

In Figures 25 and 26, which focus on fire accidents, the data presents a range of dysfunctional links with varying degrees of control and feedback. One of the most frequent dysfunctional links, as depicted in the data, is between the Ship Management Company and the Ship, with a control value of 29 and a feedback value of two. This suggests that issues in ship management, possibly related to maintenance and safety protocols, play a significant role in fire accidents. Another notable link is between the Engineers and Equipment/Displays, with a control value of 10. This indicates that technical issues with equipment and machinery, possibly due to malfunctions or maintenance issues are significant contributors to fire accidents.

Additionally, the link between the Chief Engineer and Machinery is depicted with a control value of seven, suggesting that the condition and management of machinery by the Chief Engineer are critical factors in fire accidents.

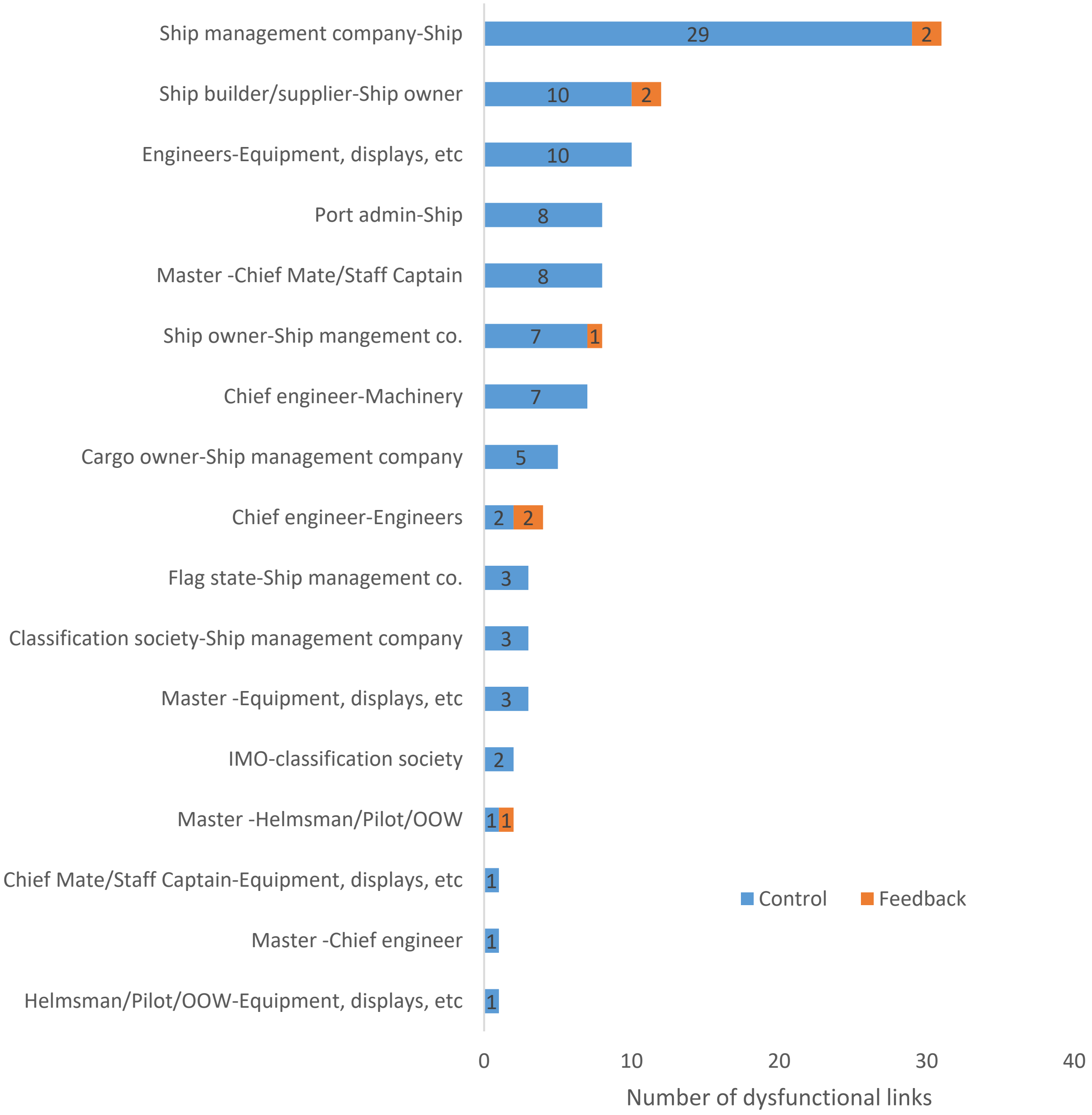

Figure 25 The dysfunctional links associated with Fire and explosion accidents

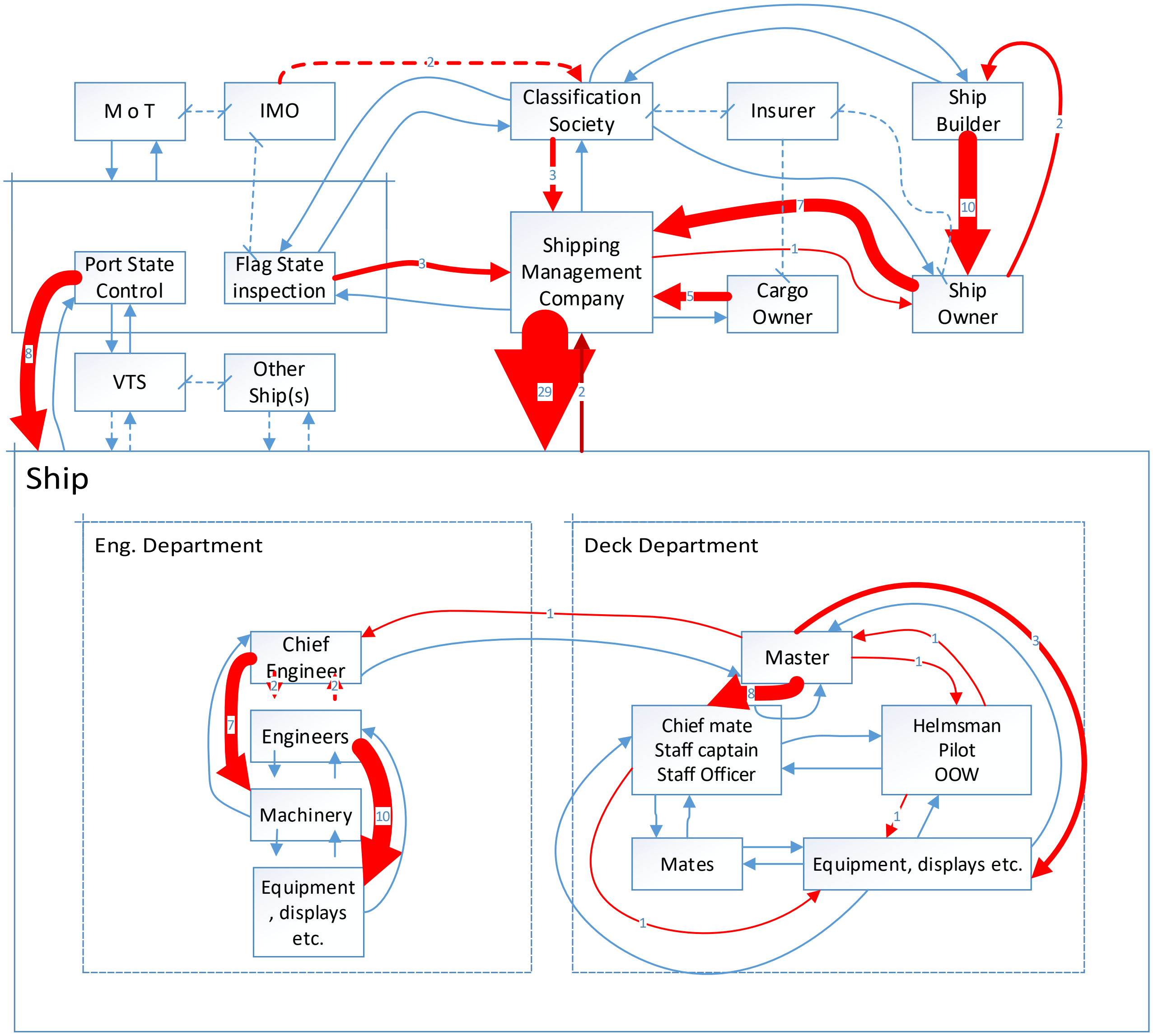

Figure 26 Illustration of dysfunctional links of Fire accident within the safety control structure

5 Discussion

This thesis seeks to bridge a significant gap in the existing literature by investigating major maritime accidents in Canada and identifying their underlying causal factors. The study employs a systems-theoretic accident theory and associated modeling approach, with a specific focus on reports published by the Transportation Safety Board (TSB) of Canada.

5.1 Reflections on the results

This research aims to answer several key research questions, including the dominant causal factors identified in TSB-conducted maritime accident reports, the potential temporal and ship type patterns in causality, and the variations in causality across different types of accidents.

Figure 7 represents the frequency of the most common dysfunctional links in Canadian maritime accidents from 1992 to 2020. These links have shown fluctuations over the years. For example, the control link between the ship management company and ship was prominent in the late 1990s, peaking in 1999, and then declined. It saw a mild resurgence in the 2010s. The control and feedback links between the master and helmsman/pilot/OOW were significant in the mid-1990s and early 2010s.

Interestingly, the control link between the ship owner and ship management company spiked in 1997 but disappeared after a few years. The control link between helmsman/pilot/OOW and equipment/displays was high in the mid-1990s and then became sporadic. The link between port administration and ship control had peaks in the mid-1990s and early 2000s. The data indicates that dysfunctional links have varied patterns, with some being consistently problematic. Notably, certain links such as the control link between the ship owner and ship management company, and others, have disappeared after periods of high frequency, indicating possible improvements or changes in maritime operations that addressed these issues.

Table 8 provides an analysis of the frequency of dysfunctional links in maritime accidents from 1992 to 2020, along with the T_1 measure and screening results. The T_1 measure quantifies the overall trend in the data, while the screening technique considers the trend in data point by point.

For the control link between the ship management company and ship, the T_1 measure is 21.371, indicating a significant overall decreasing trend. The screening results show an initial increasing trend, followed by a decreasing trend. This is consistent with the data, which shows high frequencies in the late 1990s, followed by a decline.

The control link between the master and helmsman/pilot/OOW has a T_1 measure of 16.224, with an increasing trend initially, followed by a decreasing trend. This reflects the high occurrences in the mid-1990s and early 2010s.

The feedback link between the master and helmsman/pilot/OOW has a T_1 measure of 11.115. Similar to the control link, it shows an increasing trend initially, followed by a decreasing trend.

The control link between the master and equipment/displays has a T_1 measure of 8.8917. The screening results indicate an initial increasing trend, but no trend is observed in the mid-1990s, followed by a decreasing trend.

The control link between helmsman/pilot/OOW and equipment/displays has a T_1 measure of 6.1359, with an initial increasing trend, followed by no specific trend and then a decreasing trend.

Interestingly, the control link between the ship owner and ship management company has a T_1 measure of 2.5208. It does not show a trend initially, but later shows a decreasing trend. This link seems to have disappeared after a few years of occurrence.

Lastly, the link between port administration and ship control has a T_1 measure of 0.9171, indicating a very weak overall trend. The screening results show no trend initially, followed by a decreasing trend.

Building upon the pioneering trend analysis technique introduced by Kvaløy and Aven (2005), a multitude of subsequent research endeavors have harnessed this method to shed light on the intricacies of accident causation. For instance, in the realm of China's construction sector, Shao and his team delved into identifying fatal accident patterns (Shao et al., 2019). Drawing from the Ministry of Housing and Urban-Rural Development's data, their rigorous use of frequency, correlation coefficient, and variance analyses unveiled specific patterns in accident occurrence, pinpointing temporal dynamics, geographic hotspots, and prominent causes. This paves the way for the constructing of informed preventive measures. In another significant contribution, Halim et al. pivoted their focus to offshore fire incidents in the Gulf of Mexico (Halim et al., 2021). Their research debunked the prevailing belief of consistent incident rates. By embracing the nonhomogeneous Poisson process (NHPP), they displayed the importance of considering time-varying failure rates, a revelation that promises to equip regulatory authorities with the tools for anticipatory actions. On the railway front, Jintao and associates introduced an innovative lens through network theory (J. Liu et al., 2019). Their methodology, built on the creation of accident causation networks and a bespoke topological analysis, was put to the test with real UK railway accidents. The outcomes were enlightening, highlighting core causative agents and unveiling underlying patterns, thereby acting as a beacon for the development of nuanced prevention tactics. Collectively, these studies serve as a testament to the transformative power of contemporary trend analysis, offering a more profound grasp of multifaceted accident data across diverse sectors.

In summary, the analysis reveals that most dysfunctional links initially increased and then decreased over time. Some links, such as the control link between the ship owner and ship management company, have disappeared after a period of occurrence, which could indicate improvements or changes in maritime operations addressing these issues.

The observation that certain links, like the control link between the ship owner and ship management company, disappeared after a certain period suggests potential improvements or adjustments in maritime operations addressing these issues. However, it is crucial to consider the methodologies and processes behind data collection and report preparation. Variations in the patterns could be influenced by changes in the data capture methods, variations in reporting standards, or even the inherent biases of the report preparers. Sometimes, the absence of specific issues in data might not signify their actual resolution but could indicate shifts in reporting focus, underreporting, or changes in the metrics used to evaluate these links. Hence, while analyzing such patterns, it is essential to account for the reliability and consistency of the data sources and the potential for evolving reporting standards or methodologies.

A bibliometric analysis conducted from 2000 to 2022, which revealed that one of the most common topics in maritime accidents research is human factors, could potentially be linked to the dysfunctional links between ship crews (Yurt & Şakar, 2023).

Human factors encompass various aspects such as communication, decision-making, and teamwork. Issues related to human factors might influence dysfunctional links between ship crews, such as those between the master and helmsman or between the ship management company and ship control.

For example, it could be hypothesized that ineffective communication between the master and helmsman might lead to misunderstandings and errors in navigation. Similarly, decision-making by the ship management company could potentially impact the control measures affecting the ship's operations.

In the late 1990s, this dissertation mentions a prominent control link between the ship management company and the ship, which peaked in 1999 and then declined. This period coincides with the adoption and implementation of the International Safety Management (ISM) Code, which became mandatory in 1998 (International Maritime Organization, 1993). The ISM Code required shipping companies to establish safety management systems. It is plausible that the implementation of the ISM Code played a role in the decline of the control link deficiencies between the ship management company and the ship, as it would have necessitated more stringent safety and management practices. This could have led to a reduction in accidents attributed to dysfunctional control links.

Similarly, this dissertation mentions significant control and feedback links between the master and helmsman/pilot/OOW in the early 2010s. This period is closely aligned with the Manila Amendments to the STCW Convention in 2010, which aimed at ensuring that seafarers' training standards remained relevant and effective (*STCW, 2010*). The amendments could have influenced the control and feedback links between the master and helmsman/pilot/OOW by improving communication and decision-making skills through better training standards. This, in turn, might have contributed to the changes in the frequency of dysfunctional links in maritime accidents as observed in the text. The correlation between the implementation of these regulations and the changes in dysfunctional links suggests possible improvements in maritime operations and safety due to regulatory interventions.

In Figures 9 and 10 one of the most frequent dysfunctional links is between the Ship Management Company and the Ship, with 106 instances in the Control category and 30 in the Feedback category. This suggests that there might be significant issues in the way ship management companies exercise control over ships and how feedback is communicated. A study by C. Soo et al (2014) discusses the challenges in maritime wireless communication and the importance of reliable communication for ship management. The specified failure in the link might have been caused by issues like miscommunication, certain management methods, or the way operations were carried out. Addressing these issues might have resulted in fewer accidents due to these problematic control links.

Another notable dysfunctional link is between the Master and the Helmsman/Pilot/OOW (Officer of the Watch), with 68 instances in the Control category and 57 in the Feedback category. This high frequency indicates that there might be communication and coordination issues between the ship's master and the helmsman or pilot. Effective communication and coordination between these roles are essential for safe navigation and operations. The concept of Bridge Resource Management (BRM) is crucial in this context, as it emphasizes the effective management of resources on a ship's bridge, including human resources and communication. A study by P. O'Connor (2011) evaluates the effectiveness of BRM training in the U.S. Navy by assessing attitudes toward and knowledge of human factors that contribute to accidents in high-risk organizations. The study found that BRM training did not have a significant effect on the attitudes and knowledge of Surface Warfare Officers (SWOs). However, it highlights the importance of BRM in addressing human factors that are causal to accidents in high-risk organizations.

Additionally, a study by Röttger et al. (2016) assesses the effectiveness of classroom-based BRM training for junior naval officers. The study found that while BRM training improved knowledge, it did not significantly impact attitudes, behavior, or performance during real-world exercises. This suggests that there is a need for BRM training to focus on the practical application of principles in real-world contexts.

The link between the Port Administration and the Ship is also significant, with 58 instances in the Control category and 7 in the Feedback category. This could indicate issues with how ports manage and communicate with ships, which could be critical in ensuring safe berthing and cargo handling operations. A study by I. Jurdana et al. (2021) discusses the importance of sustainable real-time maritime communication for remote voyage monitoring. Efforts to improve communication, coordination, and control in these dysfunctional links could potentially lead to a reduction in maritime accidents. Conversely, understanding why certain links have lower frequencies could provide insights into best practices that can be applied to areas that are more problematic.

Referring to the research conducted by Puisa et al. (2018) and this dissertation, it becomes evident that both studies have successfully identified recurring dysfunctional connections prevalent within the maritime industry. The central focus of these studies revolves around the failures in interaction between the ship management company and the ship, as well as between the master and the bridge crew. Moreover, the significance of the interaction between the bridge team and the equipment and displays has also been emphasized. The aforementioned findings strongly indicate that inadequate control, deficient communication, and insufficient feedback within these interactions significantly contribute to the emergence of dysfunctional links

Analyzing the data sets for four different types of ships - Bulk Liquid Carriers, Bulk Solid Carriers, Ferries, and Passenger Ships (Figures 13 to 20), we can discern distinct patterns in the dysfunctional links in maritime operations. These patterns reveal both commonalities and differences across the different types of vessels, providing valuable insights into the areas that require attention in maritime operations.

For Bulk Liquid Carriers, the most frequent dysfunctional link is between the Master and the Helmsman/Pilot/OOW (Officer of the Watch) in both Control and Feedback categories. This suggests that communication and coordination between the ship's master and the helmsman or pilot are critical in the operations of bulk liquid carriers. This might be due to the critical nature of transporting liquid cargo, which requires precise navigation and handling to prevent spills and accidents.

Bulk Solid Carriers, on the other hand, show a high frequency of dysfunctional links between the Port Administration and Ship, and between the Helmsman/Pilot/OOW and Equipment/Displays. This suggests potential issues in how ports manage and communicate with bulk solid carriers and how helmsmen or pilots interact with equipment and displays. This could be indicative of specific challenges in berthing and cargo handling operations for bulk solid carriers.

In the case of Ferries, the most frequent dysfunctional link is between the Ship Management Company and Ship. This indicates potential issues in the way ship management companies exercise control over ferries. Similarly, for Passenger Ships, the data shows a high frequency of dysfunctional links between the Ship Management Company and Ship, and between the Master and Equipment/Displays. This suggests that, similar to Ferries, there might be significant issues in how ship management companies exercise control over passenger ships, and how the master interacts with equipment and displays.

A commonality across all types of vessels is the high frequency of dysfunctional links between the Ship Management Company and the Ship. This is evident in all four data sets and suggests that issues in communication and control exercised by ship management companies are a widespread problem in the maritime industry, irrespective of the type of ship. This could be indicative of systemic issues in the way ship management companies operate and communicate with ships.

Analyzing the different ship types accidents, it is evident that one common dysfunctional link across all types of vessels is between the Master or other bridge team members and Equipment/Displays. This suggests that there might be a general issue with how ship masters interact with equipment and displays, which is critical for navigation and operations. This could be attributed to the rapid technological advancements in maritime equipment, which may sometimes outpace the training and adaptability of the crew. Supporting this observation, a study by Cherner et al. (2006) highlights the importance of simulation-based training for technical personnel in the maritime industry, particularly in understanding and applying engineering principles in emergency situations. The study emphasizes the importance of learning-by-doing and problem-based training methodologies, which are effective for all learners, including those with limited technical training. This is particularly relevant for bridge team members who need to interact with advanced equipment and displays.

Analyzing the Figures 21 to 26 for three different types of ship accidents - Grounding, Collision, and Fire, we can observe some distinct patterns in the dysfunctional links in maritime operations. For Grounding accidents, the most frequent dysfunctional link is between the Ship Management Company and the Ship, followed closely by the Master and Helmsman/Pilot/OOW (Officer of the Watch). This indicates that communication and coordination between the ship's management and the bridge team are critical in preventing grounding accidents. In contrast, for Collision accidents, the data shows a high frequency of dysfunctional links between the Helmsman/Pilot/OOW and Equipment/Displays, and between Ships (Ship-Other Ships). This suggests that issues in navigation and interaction with equipment, as well as communication between ships, are significant factors in collision accidents. For Fire accidents, the most frequent dysfunctional link is between the Ship Management Company and the Ship, similar to Grounding, but there is also a high frequency of dysfunctional links between Engineers and Equipment/Displays.

There are certain dysfunctional links that are prevalent across all types of accidents, as well as some that are unique to specific types of accidents. One commonality across all types of accidents is the high frequency of dysfunctional links between the Ship Management Company and the Ship. This suggests that issues in communication and control exercised by ship management companies are a widespread problem in the maritime industry, irrespective of the type of accident. Another common dysfunctional link across all types of accidents is between the Master and Equipment/Displays. As mentioned earlier this suggests that there might be a general issue with how ship masters interact with equipment and displays, which is critical for navigation and operations.

In contrast, there are also some differences. For instance, the dysfunctional link between the Helmsman/Pilot/OOW and Equipment/Displays is particularly prominent in Collision accidents, but not as much in Grounding or Fire accidents. This could be indicative of specific challenges in navigation and the use of equipment in avoiding collisions. Similarly, the dysfunctional link between Engineers and Equipment/Displays is significantly prominent in Fire accidents, which might be due to the critical nature of machinery and equipment maintenance in preventing fires on board.

Based on an in-depth analysis of maritime accidents in Canada, it is imperative for the Canadian Transportation Safety Board (TSB) to pivot towards a systems-based approach to maritime safety, which intricately meshes the dynamic interactions of people, systems, and the broader environment. Particular attention needs to be directed towards identified dysfunctional relationships, especially between key entities such as Ship Management Companies and the Ships, as well as between key personnel roles like the Master and the Helmsman/Pilot/OOW. There's an undeniable importance of human dynamics in maritime affairs, necessitating enhanced training, improved inter-crew communication, and refined decision-making processes. Moreover, to grasp a holistic view of maritime challenges, the TSB should consider expanding their data sources beyond their own reports. Given the nuanced challenges across different ship types, there's a clear call for ship-specific safety recommendations. This coupled with amplified communication and coordination efforts will bolster maritime safety. Concurrently, future research should be geared towards innovating risk mitigation strategies, informed by the findings of the current study. By implementing these strategies, the TSB can pave the way for a more robust and secure maritime environment in Canada.

5.2 Limitations of the study

Transportation safety research is a complex field that requires a multifaceted approach to consider the dynamic interactions between people, systems, and the environment. However, traditional linear accident investigation methods used in data collection may limit the scope of research findings, potentially leading to biased or incomplete results. Furthermore, this research relies on TSB (Transportation Safety Board) reports, which, if employing linear approaches to accident investigation, can impact the depth and breadth of our analysis (Lundberg et al., 2009). Recent studies emphasize the importance of a systems-based approach that considers the broader socio-technical system and the interactions between its components. The implementation of the CAST method in this study is an attempt to mitigate the limitations identified in the reports to a certain extent. This approach emphasizes the need to address organizational and cultural factors that may contribute to accidents, rather than solely focusing on individual errors or equipment failures. Additionally, by relying on TSB reports, there is an inherent limitation in the data, as the reports may not capture the complexity of accidents through a systems perspective, and this should be taken into consideration when interpreting the results.

Uncertainty, on the other hand, is an inherent aspect of the analysis due to the plethora of causal factors contributing to maritime accidents. The study is predicated on employing a systems-theoretic approach to discern the salient causal factors. However, the interpretation of the data is a complex endeavor, particularly in accurately delineating the fundamental causes. Given the critical role of interpretation in the analysis and the interplay of various actors within the maritime system, it is plausible that an alternative analysis conducted by a different researcher could yield nuanced results. This underscores the complexity of maritime systems and the interpretative nature of data analysis.

Another limitation of this research pertains to the geographical scope and the involvement of various actors in marine accidents involving Canadian-flagged vessels. The data utilized in this research are derived from reports by the Transportation Safety Board of Canada (TSB), which primarily investigates marine accidents within Canadian waters or involving Canadian-flagged vessels. However, it is important to note that when a Canadian-flagged vessel is involved in an accident outside Canadian waters, the investigation may be conducted by the authorities of the country where the accident occurred, in line with international maritime conventions.

In such instances, while TSB may still be involved, especially if the accident has significant implications for Canada or if TSB's expertise is solicited, the level of TSB's involvement can vary. This introduces an additional layer of complexity as the role of international actors such as foreign port authorities or Vessel Traffic Services (VTS) from other countries comes into play.

As a result, some of the dysfunctional links and interaction failures identified in the analysis may not be solely attributable to Canadian entities but may also involve actors and regulatory frameworks from other jurisdictions. This necessitates a cautious interpretation of the findings, as the data may encompass interaction failures and dysfunctional links that are not confined to the Canadian territory. It is, therefore, imperative to consider this geographical and jurisdictional nuance in the analysis and to acknowledge that the scope of the research extends beyond the Canadian maritime domain due to the involvement of international actors and regulations.

According to the trend analysis conducted over time, while examining trends in maritime accidents can provide valuable insights, it is important to acknowledge that these trends may be influenced by various factors beyond the scope of this research. In this context it is important to consider various factors. Research by Bye & Aalberg (2018) has explored additional measures like the number of fleet vessels, vessel age, and distance sailed. The study analyzed maritime accidents data and AIS data from Norwegian waters. They identified conditions associated with navigation-related accidents, such as vessel behavior, technical factors, and accident locations. Using statistical analyses, the research revealed strong predictors for navigation-related accidents. Certain vessel types, shorter length, poor visibility, and flags of convenience increased the probability of such accidents (Bye & Aalberg, 2018).

Moreover, it is crucial to exercise caution when interpreting significant decreases in certain accident links. In some cases, a decline in the occurrence of specific accidents may not necessarily indicate a need for immediate action. It is possible that existing control measures and feedback mechanisms are already effective in addressing those specific issues.

5.4 Future research

A fruitful avenue for future research involves investigating the evolution of causal factors over time, exploring the influence of regulations and technological advancements, and examining historical interventions that have correlated with trends in maritime accidents. By conducting a longitudinal analysis and studying past interventions, researchers can discern patterns and changes in causal factors, and assess the impact of regulatory measures and technological innovations, identify successful strategies, and learn from previous experiences. Such comprehensive analysis can provide valuable insights into the effectiveness of interventions, guide the development of future strategies, and inform policy decisions to improve maritime safety.

Another promising research avenue is conducting comparative studies of maritime accidents across different countries using systems-theoretic models. This comparative analysis can shed light on variations in accident causality, safety regulations, and industry practices. By examining the similarities and differences, researchers can identify best practices, regulatory gaps, and areas for international collaboration in improving maritime safety.

To enhance the understanding of maritime accidents, future research should delve into the role of human factors within systems-theoretic models. This involves investigating the impact of training, fatigue, and decision-making on accident causality. By integrating human factors into the analysis, researchers can identify critical areas for intervention, such as improving training programs, addressing fatigue management, and enhancing decision-making processes within maritime systems.

Building upon the insights derived from systems-theoretic models, future research should focus on developing targeted preventative measures. These measures can be based on the identified causal factors and their interactions within the system. By designing safety protocols and interventions that directly address the identified risk factors, researchers can contribute to the reduction of maritime accidents and the enhancement of overall safety. Evaluating the effectiveness of these measures through rigorous assessment methodologies will also be vital in ensuring their practical applicability.

Another potential research avenue involves utilizing qualitative causal factors derived from systems-theoretic models as criteria for risk identification in system-based risk assessment methods. By integrating qualitative causal factors into existing risk assessment frameworks, researchers can enhance the accuracy and comprehensiveness of risk identification, allowing for more effective mitigation strategies and resource allocation.

Further research should focus on conducting in-depth studies of the most frequent dysfunctional links identified within systems-theoretic models. By analyzing these links, researchers can gain a deeper understanding of the underlying issues and their systemic implications. This analysis can guide the development of targeted interventions and control measures to address the root causes of these frequent dysfunctional links, ultimately improving overall maritime safety. As an example, the concept of master-centered dysfunctional links within the context of maritime accidents presents an intriguing avenue for future research that promises to enhance our understanding of the complexities involved in such incidents. This research could delve into the intricate relationships between various factors and the role of shipmasters in contributing to or mitigating maritime accidents. Building upon the systems-theoretic accident theory and the investigation policies outlined by the Transportation Safety Board of Canada (TSB), this potential study would investigate the dynamics between human actions, operational practices, and the decisions made by shipmasters that lead to accidents.

6 Conclusions

In this research, a comprehensive analysis of maritime accidents in Canada was conducted using the Causal Analysis based on Systems Theory (CAST) method. By examining reports from the Canadian Transportation Safety Board, the study systematically explored the changes in causality over time, across various ship types, and different accident categories. The Hierarchical Control Structure (HCS) was employed to understand the feedback control loops within the maritime safety control system.

The findings reveal that the causal factors of maritime accidents are not only specific to the ship and accident type but are also deeply rooted in systemic issues. The dysfunctional links between various entities, such as the Ship Management Company and the Ship, and between the Master and Helmsman/Pilot/OOW, were found to be significant. The data indicate that dysfunctional links have varied patterns, with some being consistently problematic, while others have disappeared, possibly due to improvements or changes in maritime operations.

To bolster maritime safety, decision-makers should adopt a two-pronged strategy: delving into the reasons behind existing gaps in the safety control structure and formulating policies to mitigate identified causal factors.

This research provides valuable insights from a safety science standpoint. It has successfully pinpointed and analyzed dysfunctional relationships in maritime operations. Notably, certain links, such as those between ship owners and ship management companies, were prominent for a period but subsequently waned, suggesting possible operational enhancements in those segments. Additionally, the study underscores the pivotal role of human elements like communication and decision-making in these discrepancies, suggesting an amplified emphasis on these domains.

On the maritime management front, the findings shed light on critical areas that require meticulous scrutiny and fine-tuning. The persistent discrepancies observed between ship management entities and the ships themselves, as well as between senior crew members and their subordinates, flag potential vulnerabilities in oversight, communication, and feedback processes. It's imperative for decision-makers to harness these insights, both to comprehend the root causes of such gaps and to architect strategies that counter the identified causal triggers. Striking this equilibrium is crucial; it not only fosters a deeper understanding of the challenges but also catalyzes the formulation of forward-thinking solutions, paving the way for a more secure maritime environment.

Moreover, the study accentuates the consequential role of human dynamics, such as inter-crew communication, decision-making processes, and collaborative efforts, in maritime mishaps. Dysfunctional interactions, be it between the ship's captain and helmsman or between the managerial echelons and the ship, often have their roots in these human-centric issues.

Furthermore, the study delved into an analysis of the frequency of dysfunctional links in maritime accidents across various types of vessels, encompassing Bulk Liquid Carriers, Bulk Solid Carriers, Ferries, and Passenger Ships. The scrutiny revealed intricate patterns in the dysfunctional links within maritime operations specific to different ship categories. Interestingly, while there were distinct patterns unique to each ship type, there were also instances where commonalities emerged, with certain dysfunctional links aligning or matching across different vessel categories.

The study acknowledges the limitations of relying solely on TSB reports, as they may not capture the complexity of accidents through a systems perspective. Additionally, the geographical scope and involvement of various actors in marine accidents involving Canadian-flagged vessels introduce an additional layer of complexity.

The findings underscore the importance of a systems-based approach to maritime safety, which considers the dynamic interactions between people, systems, and the environment. The research highlights the need for improved safety protocols, communication, and coordination among various entities involved in maritime operations. Additionally, it emphasizes the significance of comprehensive investigations and the dissemination of their results to effectively address safety concerns in the global marine industry. Future research could focus on developing strategies for risk reduction and enhancing safety protocols based on the insights gained from this study.

References

Akhtar, M. J., & Utne, I. B. (2014). Human fatigue's effect on the risk of maritime groundings – A Bayesian Network modeling approach. *Safety Science*, *62*, 427–440. https://doi.org/10.1016/j.ssci.2013.10.002

Aps, R., Fetissov, M., Goerlandt, F., Kopti, M., & Kujala, P. (2016). STAMP-Mar based safety management of maritime navigation in the Gulf of Finland (Baltic Sea). *2016 European Navigation Conference (ENC)*, 1–8. https://doi.org/10.1109/EURONAV.2016.7530538

Awal, Z. I., & Hasegawa, K. (2017). A Study on Accident Theories and Application to Maritime Accidents. *Procedia Engineering*, *194*, 298–306. https://doi.org/10.1016/j.proeng.2017.08.149

Bastug, S., Asyali, E., & Battal, T. (2020). Beyond the ISM code: A conceptual proposal for an integrated system within the Seven C's approach. *Maritime Policy & Management*, *48*, 1–24. https://doi.org/10.1080/03088839.2020.1770884

Branch Legislative Services. (2007, July 1). *Consolidated federal laws of Canada, Shipping Casualties Reporting Regulations*. https://laws-lois.justice.gc.ca/eng/regulations/SOR-85-514/FullText.html

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. https://doi.org/10.1016/j.ress.2018.03.033

Celik, M., & Cebi, S. (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

Ceylan, B. O., Akyuz, E., & Arslan, O. (2021). Systems-Theoretic Accident Model and Processes (STAMP) approach to analyse socio-technical systems of ship allision in narrow waters. *Ocean Engineering*, *239*, 109804. https://doi.org/10.1016/j.oceaneng.2021.109804

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, S.-T., Wall, A., Davies, P., Yang, Z., Wang, J., & Chou, Y.-H. (2013). A Human and Organisational Factors (HOFs) analysis method for marine casualties using HFACS-Maritime Accidents (HFACS-MA). *Safety Science*, *60*, 105–114. https://doi.org/10.1016/j.ssci.2013.06.009

Cherner, Y., Lotring, A., Klein, R., & Campbell, T. (2006). *Innovative Simulation Based Online System For Learning Engineering And Training Sailors' Technical Skills* (p. 11.770.10). https://doi.org/10.18260/1-2--1225

Choi, M. S., Park, S., Lee, Y., & Lee, S. R. (2014). Ship to Ship Maritime Communication for e-Navigation Using WiMAX. *International Journal of Multimedia and Ubiquitous Engineering*, *9*(4), 171–178. https://doi.org/10.14257/ijmue.2014.9.4.18

D, S. A. (1983). Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications. *Final Report*. https://cir.nii.ac.jp/crid/1573950398818889600

de Maya, B. N., Babaleye, A. O., & Kurt, R. E. (2020). Marine accident learning with fuzzy cognitive maps (MALFCMs) and Bayesian networks. *Safety in Extreme Environments*, *2*(1), 69–78. https://doi.org/10.1007/s42797-019-00003-8

Deng, J., Liu, S., Shu, Y., Hu, Y., Xie, C., & Zeng, X. (2023). Risk evolution and prevention and control strategies of maritime accidents in China's coastal areas based on complex network models. *Ocean & Coastal Management*, *237*, 106527. https://doi.org/10.1016/j.ocecoaman.2023.106527

Dominguez-Péry, C., Vuddaraju, L. N. R., Corbett-Etchevers, I., & Tassabehji, R. (2021). Reducing maritime accidents in ships by tackling human error: A bibliometric review and research agenda. *Journal of Shipping and Trade*, *6*(1), 20. https://doi.org/10.1186/s41072-021-00098-y

Dulac, N. (2009). *A framework for dynamic safety and risk management modeling in complex engineering systems*.

Eliopoulou, E., Papanikolaou, A., & Voulgarellis, M. (2016). Statistical analysis of ship accidents and review of safety level. *Safety Science*, *85*, 282–292. https://doi.org/10.1016/j.ssci.2016.02.001

European Parliament legislative resolution. (2008). *Investigation of accidents in the maritime transport sector II*.

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*, 107070. https://doi.org/10.1016/j.ress.2020.107070

Gong, Y., & Li, Y. (2018). STAMP-based causal analysis of China-Donghuang oil transportation pipeline leakage and explosion accident. *Journal of Loss Prevention in the Process Industries*, *56*, 402–413. https://doi.org/10.1016/j.jlp.2018.10.001

Górny, A. (2015). *Application of the Pareto principle to accident analysis to improve working environment*.

Government of Canada, T. S. B. of C. (2006, January 10). *Transportation Safety Board of Canada*. http://www.bst-tsb.gc.ca/eng/qui-about/index.html

Government of Canada, T. S. B. of C. (2018, February 27). *Marine transportation occurrence data from January 1995*. https://www.tsb.gc.ca/eng/stats/marine/data-6.html

Government of Canada, T. S. B. of C. (2020, September 11). *Transportation Safety Board of Canada*. https://www.tsb.gc.ca/eng/

Graziano, A., Teixeira, A. P., & Guedes Soares, C. (2016). Classification of human errors in grounding and collision accidents using the TRACEr taxonomy. *Safety Science*, *86*, 245–257. https://doi.org/10.1016/j.ssci.2016.02.026

Halim, S. Z., Quddus, N., & Pasman, H. (2021). Time-trend analysis of offshore fire incidents using nonhomogeneous Poisson process through Bayesian inference. *Process Safety and Environmental Protection*, *147*, 421–429. https://doi.org/10.1016/j.psep.2020.09.049

Hannaman, G. W., Spurgin, A. J., & Lukic, Y. (1985). *A model for assessing human cognitive reliability in PRA studies*. IEEE Service Center.

Hänninen, M., & Kujala, P. (2012). Influences of variables on ship collision probability in a Bayesian belief network model. *Reliability Engineering & System Safety*, *102*, 27–40. https://doi.org/10.1016/j.ress.2012.02.008

Hänninen, M., Valdez Banda, O. A., & Kujala, P. (2014). Bayesian network model of maritime safety management. *Expert Systems with Applications*, *41*(17), 7837–7846. https://doi.org/10.1016/j.eswa.2014.06.029

Hansen, H. L., Nielsen, D., & Frydenberg, M. (2002). Occupational accidents aboard merchant ships. *Occupational and Environmental Medicine*, *59*(2), 85–91. https://doi.org/10.1136/oem.59.2.85

Harvey, H. B., & Sotardi, S. T. (2018). The Pareto Principle. *Journal of the American College of Radiology*, *15*(6), 931. https://doi.org/10.1016/j.jacr.2018.02.026

Håvold, J. I. (2007). National cultures and safety orientation: A study of seafarers working for Norwegian shipping companies. *Work & Stress*, *21*(2), 173–195. https://doi.org/10.1080/02678370701424594

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

Hollnagel, E. (1998). *Cognitive Reliability and Error Analysis Method (CREAM)*. Elsevier.

Hollnagel, E. (2016). *Barriers and Accident Prevention*. Routledge.

Hu, S., Li, W., Xi, Y., Li, W., Hou, Z., Wu, J., & Han, B. (2022). Evolution pathway of process risk of marine traffic with the STAMP model and a genetic algorithm: A simulation of LNG-fueled vessel in-and-out harbor. *Ocean Engineering*, *253*, 111133. https://doi.org/10.1016/j.oceaneng.2022.111133

IMO. (2008). *Casualty Investigation Code*. http://surl.li/gufup

International Maritime Organization. (1993). *Amendments to the ISM Code*. https://www.imo.org/en/ourwork/humanelement/pages/ISMCode.aspx#:~:text=The%20ISM%20Code%20in%20its,chapter%20IX%20into%20the%20Convention.

International Maritime Organization. (2008). *International Maritime Organization*. https://www.imo.org/en/OurWork/MSAS/Pages/Casualties.aspx

Jensen, O. C., Sørensen, J. F. L., Kaerlev, L., Canals, M. L., Nikolic, N., & Saarni, H. (2004). Self-reported injuries among seafarers: Questionnaire validity and results from an international study. *Accident Analysis & Prevention*, *36*(3), 405–413. https://doi.org/10.1016/S0001-4575(03)00034-4

Johnson, W. G. (1980, June 1). *Mort Safety Assurance Systems*. https://www.semanticscholar.org/paper/Mort-Safety-Assurance-Systems-Johnson/21db8f0ae664e14b3c0ede3d74eece6e90935b77

Jurdana, I., Lopac, N., Wakabayashi, N., & Liu, H. (2021). Shipboard Data Compression Method for Sustainable Real-Time Maritime Communication in Remote Voyage Monitoring of Autonomous Ships. *Sustainability*, *13*, 8264. https://doi.org/10.3390/su13158264

Kampen, J. van, & Drupsteen, L. (2013). *Accident investigation and analysis*. TNO. http://resolver.tudelft.nl/uuid:b554351a-c310-4dc7-be8c-b536856221f0

Kapoor, A., Maxwell, A., & Mehta, R. (2019). HUMAN ERROR ARE THE REAL CAUSE OF MARINE ACCIDENTS? *Review of Research*, *8*, 1–4.

Kristiansen, S. (2013). *Maritime Transportation: Safety Management and Risk Analysis*. Routledge.

Kujala, P., Hänninen, M., Arola, T., & Ylitalo, J. (2009). Analysis of the marine traffic safety in the Gulf of Finland. *Reliability Engineering & System Safety*, *94*(8), 1349–1357. https://doi.org/10.1016/j.ress.2009.02.028

Kvaløy, J. T., & Aven, T. (2005). An alternative approach to trend analysis in accident data. *Reliability Engineering & System Safety*, *90*(1), 75–82. https://doi.org/10.1016/j.ress.2004.10.010

Le Coze, J. C. (2015). Reflecting on Jens Rasmussen's legacy. A strong program for a hard problem. *Safety Science*, *71*, 123–141. https://doi.org/10.1016/j.ssci.2014.03.015

Lee, J., & Chung, H. (2018). A new methodology for accident analysis with human and system interaction based on FRAM: Case studies in maritime domain. *Safety Science*, *109*, 57–66. https://doi.org/10.1016/j.ssci.2018.05.011

Lefkowitz, R. (2013). Incidence Of Injury And Illness In Merchant Seafarers. *Public Health Theses*. https://elischolar.library.yale.edu/ysphtdl/1165

Leveson, N. (2004). A New Accident Model for Engineering Safer Systems. *Safety Science*, *42*, 237–270. https://doi.org/10.1016/S0925-7535(03)00047-X

Leveson, N. G. (2011a). Applying systems thinking to analyze and learn from events. *Safety Science*, *49*(1), 55–64. https://doi.org/10.1016/j.ssci.2009.12.021

Leveson, N. G. (2011b). *Engineering a Safer World: Systems Thinking Applied to Safety. MIT Press.*

Leveson, N. G. (2016). *Engineering a Safer World: Systems Thinking Applied to Safety*. The MIT Press. https://library.oapen.org/handle/20.500.12657/26043

Leveson, N. G. (2017). Rasmussen's legacy: A paradigm change in engineering for safety. *Applied Ergonomics*, *59*, 581–591. https://doi.org/10.1016/j.apergo.2016.01.015

Leveson, N. G., Barrett, B., Carroll, J., & Cutcher-Gershenfeld, J. (2005). *Risk analysis of NASA independent technical authority. Cambridge, MA. Google Scholar*. http://sunnyday.mit.edu/ITA-Risk-Analysis.doc

Leveson, N. G., Daouk, M., Dulac, N., & Marais, K. (2003). *Applying STAMP in Accident Analysis* [Working Paper]. Massachusetts Institute of Technology. Engineering Systems Division. https://dspace.mit.edu/handle/1721.1/102905

Lin, W.-C., & Cheng, H.-H. (2021). Enhancing marine administrative management based on human factor through safety criteria. *Journal of Marine Science and Technology*, *29*(3), 268–279. https://doi.org/10.51400/2709-6998.1432

Liu, J., Schmid, F., Zheng, W., & Zhu, J. (2019). Understanding railway operational accidents using network theory. *Reliability Engineering & System Safety*, *189*, 218–231. https://doi.org/10.1016/j.ress.2019.04.030

Liu, K., Yu, Q., Yuan, Z., Yang, Z., & Shu, Y. (2021). A systematic analysis for maritime accidents causation in Chinese coastal waters using machine learning approaches. *Ocean & Coastal Management*, *213*, 105859. https://doi.org/10.1016/j.ocecoaman.2021.105859

Lundberg, J., Rollenhagen, C., & Hollnagel, E. (2009). What-You-Look-For-Is-What-You-Find – The consequences of underlying accident models in eight accident investigation manuals. *Safety Science*, *47*(10), 1297–1311. https://doi.org/10.1016/j.ssci.2009.01.004

Ma, L., Ma, X., Lan, H., Liu, Y., & Deng, W. (2022). A methodology to assess the interrelationships between contributory factors to maritime transport accidents of dangerous goods in China. *Ocean Engineering*, *266*, 112769. https://doi.org/10.1016/j.oceaneng.2022.112769

MAIIF Manual, 2014. (n.d.). Retrieved May 17, 2023, from https://maiif.org/wp-content/uploads/2017/08/MAIIF-Manual-2014.pdf

Mansell, J. (2009). Flag State Responsibility: Historical Development and Contemporary Issues. In *Flag State Responsibility: Historical Development and Contemporary Issues* (p. 269). https://doi.org/10.1007/978-3-540-92933-8

Mazaheri, A., Montewka, J., Nisula, J., & Kujala, P. (2015). Usability of accident and incident reports for evidence-based risk modeling – A case study on ship grounding reports. *Safety Science*, *76*, 202–214. https://doi.org/10.1016/j.ssci.2015.02.019

Md Hanafiah, R., Zainon, N. S., Karim, N. H., Abdul Rahman, N. S. F., Behforouzi, M., & Soltani, H. R. (2022). A new evaluation approach to control maritime transportation accidents: A study case at the Straits of Malacca. *Case Studies on Transport Policy*, *10*(2), 751–763. https://doi.org/10.1016/j.cstp.2022.02.004

Montewka, J., Goerlandt, F., & Kujala, P. (2012). Determination of collision criteria and causation factors appropriate to a model for estimating the probability of maritime accidents. *Ocean Engineering*, *40*, 50–61. https://doi.org/10.1016/j.oceaneng.2011.12.006

Mureșan, P., Milosan, I., Senchetru, D., Reit, A., Machedon, T., & Oancea, G. (2019). Study of health and safety in the manufacturing industry using Pareto analysis. *MATEC Web of Conferences*, *299*, 05008. https://doi.org/10.1051/matecconf/201929905008

Nuutinen, M., & Norros, L. (2009). Core task analysis in accident investigation: Analysis of maritime accidents in piloting situations. *Cognition, Technology & Work*, *11*(2), 129–150. https://doi.org/10.1007/s10111-007-0104-x

O'Connor, P. (2011). Assessing the Effectiveness of Bridge Resource Management Training. *The International Journal of Aviation Psychology*, *21*(4), 357–374. https://doi.org/10.1080/10508414.2011.606755

Oltedal, H., & Lützhöft, M. (Eds.). (2018). *Managing Maritime Safety* (1st edition). Routledge.

Ouyang, M., Hong, L., Yu, M.-H., & Fei, Q. (2010). STAMP-based analysis on the railway accident and accident spreading: Taking the China–Jiaoji railway accident for example. *Safety Science*, *48*(5), 544–555. https://doi.org/10.1016/j.ssci.2010.01.002

Palfy, J. (2005). *Guidance Notes on the Investigation of Marine Incidents*.

Perrow, C. (1999). *Normal Accidents: Living with High Risk Technologies*. Princeton University Press.

Prabowo, A. R., & Bae, D. M. (2019). Environmental risk of maritime territory subjected to accidental phenomena: Correlation of oil spill and ship grounding in the Exxon Valdez's case. *Results in Engineering*, *4*, 100035. https://doi.org/10.1016/j.rineng.2019.100035

Psarros, G., Skjong, R., & Eide, M. S. (2010). Under-reporting of maritime accidents. *Accident; Analysis and Prevention*, *42*(2), 619–625. https://doi.org/10.1016/j.aap.2009.10.008

Puisa, R., Lin, L., Bolbot, V., & Vassalos, D. (2018). Unravelling causal factors of maritime incidents and accidents. *Safety Science*, *110*(Part A), 124–141. https://doi.org/10.1016/j.ssci.2018.08.001

Puisa, R., Williams, S., & Vassalos, D. (2019). Towards an explanation of why onboard fires happen: The case of an engine room fire on the cruise ship "Le Boreal." *Applied Ocean Research*, *88*, 223–232. https://doi.org/10.1016/j.apor.2019.04.020

Qiao, W., Chen, X., & Xia, W. (2021). STAMP-based causal analysis of the Coal Mine Major Accident: From the perspective of safety process. *Energy Reports*, *7*, 116–124. https://doi.org/10.1016/j.egyr.2021.10.048

Qiao, W., Liu, Y., Ma, X., & Liu, Y. (2020). A methodology to evaluate human factors contributed to maritime accident by mapping fuzzy FT into ANN based on HFACS. *Ocean Engineering*, *197*, 106892. https://doi.org/10.1016/j.oceaneng.2019.106892

Qureshi, Z. (2007). *A review of accident modelling approaches for complex socio-technical systems*.

Rasmussen, J. (1997). Risk management in a dynamic society: A modelling problem. *Safety Science*, *27*(2), 183–213. https://doi.org/10.1016/S0925-7535(97)00052-0

Reason, J. (1997). *Managing the Risks of Organizational Accidents* (1st edition). Routledge.

Res.MSC.255(84). (2008). *Res.MSC.255(84)CasualtyIinvestigationCode*. IMO. https://wwwcdn.imo.org/localresources/en/OurWork/MSAS/Documents/Res.MSC.255(84)CasualtyIinvestigationCode.pdf

Roberts, S. E., Nielsen, D., Kotłowski, A., & Jaremin, B. (2014). Fatal accidents and injuries among merchant seafarers worldwide. *Occupational Medicine*, *64*(4), 259–266. https://doi.org/10.1093/occmed/kqu017

Röttger, S., Vetter, S., & Kowalski, J. T. (2016). Effects of a classroom-based bridge resource management training on knowledge, attitudes, behaviour and performance of junior naval officers. *WMU Journal of Maritime Affairs*, *15*(1), 143–162. https://doi.org/10.1007/s13437-014-0073-x

Rowbotham, M. (2014). *Introduction to Marine Cargo Management*. CRC Press.

Salihoglu, E., & Bal Beşikçi, E. (2021). The use of Functional Resonance Analysis Method (FRAM) in a maritime accident: A case study of Prestige. *Ocean Engineering*, *219*, 108223. https://doi.org/10.1016/j.oceaneng.2020.108223

Salmon, P. M., Cornelissen, M., & Trotter, M. J. (2012). Systems-based accident analysis methods: A comparison of Accimap, HFACS, and STAMP. *Safety Science*, *50*(4), 1158–1170. https://doi.org/10.1016/j.ssci.2011.11.009

Sánchez-Beaskoetxea, J., Basterretxea-Iribar, I., Sotés, I., & Machado, M. de las M. M. (2021). Human error in marine accidents: Is the crew normally to blame? *Maritime Transport Research*, *2*, 100016. https://doi.org/10.1016/j.martra.2021.100016

Schoemaker, P., & Day, G. (2009). How to Make Sense of Weak Signals. *MIT Sloan Management Review*, *50*.

Schröder-Hinrichs, J. U., Baldauf, M., & Ghirxi, K. T. (2011). Accident investigation reporting deficiencies related to organizational factors in machinery space fires and explosions. *Accident Analysis & Prevention*, *43*(3), 1187–1196. https://doi.org/10.1016/j.aap.2010.12.033

Shan, D. (2020). Mapping the Maritime Occupational Health and Safety Challenges Faced by Canadian Seafarers. In A. Chircop, F. Goerlandt, C. Aporta, & R. Pelot (Eds.), *Governance of Arctic Shipping: Rethinking Risk, Human Impacts and Regulation* (pp. 191–205). Springer International Publishing. https://doi.org/10.1007/978-3-030-44975-9_10

Shan, D., & Neis, B. (2020). Employment-related mobility, regulatory weakness and potential fatigue-related safety concerns in short-sea seafaring on Canada's Great Lakes and St. Lawrence Seaway: Canadian seafarers' experiences. *Safety Science*, *121*, 165–176. https://doi.org/10.1016/j.ssci.2019.08.017

Shao, B., Hu, Z., Liu, Q., Chen, S., & He, W. (2019). Fatal accident patterns of building construction activities in China. *Safety Science*, *111*, 253–263. Scopus. https://doi.org/10.1016/j.ssci.2018.07.019

Sklet, S. (2004). Comparison of some selected methods for accident investigation. *Journal of Hazardous Materials*, *111*(1), 29–37. https://doi.org/10.1016/j.jhazmat.2004.02.005

STCW , 2010. (n.d.). Retrieved May 28, 2023, from https://www.mptusa.com/pdf/STCW_guide_english.pdf

Stroeve, S., Doorn, B., Jonk, P., Kirwan, B., & Navas de Maya, B. (2022). *SHIELD human factors taxonomy and database for systematic analysis of safety occurrences in the aviation and maritime domains*. https://doi.org/10.3850/978-981-18-5183-4_S31-04-422-cd

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. https://doi.org/10.1016/j.aap.2022.106901

TSB CANADA. (2018, January 4). *Marine Transportation Safety Investigation Report M16P0362*. http://www.bst-tsb.gc.ca/eng/rapports-reports/marine/2016/m16p0362/m16p0362.html

UNCTAD. (2021). *Review of Maritime Transport 2021*. https://unctad.org/system/files/official-document/rmt2021_en_0.pdf

Valdez Banda, O., Hänninen, M., Lappalainen, J., Kujala, P., & Goerlandt, F. (2016). A method for extracting key performance indicators from maritime safety management norms. *WMU Journal of Maritime Affairs*, *15*, 237–265. https://doi.org/10.1007/s13437-015-0095-z

Wang, H., Liu, Z., Liu, Z., Wang, X., & Wang, J. (2022). GIS-based analysis on the spatial patterns of global maritime accidents. *Ocean Engineering*, *245*, 110569. https://doi.org/10.1016/j.oceaneng.2022.110569

Waterson, P., Le Coze, J.-C., & Andersen, H. B. (2017). Recurring themes in the legacy of Jens Rasmussen. *Applied Ergonomics*, *59*, 471–482. https://doi.org/10.1016/j.apergo.2016.10.002

Weng, J., Liao, S., & Li, G. (2019). Bayesian Regression Model for Estimating Economic Loss Resulting from Two-Ship Collisions. *Transportation Research Record*, *2673*(1), 164–172. https://doi.org/10.1177/0361198118821599

Wiegmann, D. A., & Shappell, S. A. (2017). *A Human Error Approach to Aviation Accident Analysis: The Human Factors Analysis and Classification System*. Routledge.

Williams, J. C. (1988). A data-based method for assessing and reducing human error to improve operational performance. *Conference Record for 1988 IEEE Fourth Conference on Human Factors and Power Plants,* 436–450. https://doi.org/10.1109/HFPP.1988.27540

World Shipping Council. (2021). World Shipping Council. https://www.worldshipping.org/search?q=canada

Yamada, T., Sato, M., Kuranobu, R., Watanabe, R., Itoh, H., Shiokari, M., & Yuzui, T. (2022). *Evaluation of effectiveness of the STAMP / STPA in risk analysis of autonomous ship systems*. *2311*(1). Scopus. https://doi.org/10.1088/1742-6596/2311/1/012021

Yang, C., Liu, H., Zhan, X., & Zheng, H. (2010). Construction of Ship Safety Management Performance Evaluation System. *2010 International Conference on Management and Service Science*, 1–7. https://doi.org/10.1109/ICMSS.2010.5577607

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. https://doi.org/10.1016/j.ress.2020.107395

Yurt, A., & Şakar, C. (2023). The Bibliometric Analysis and Visualization Mapping of Research on Maritime Accidents. *Marine Science and Technology Bulletin*, *12*(1), Article 1. https://doi.org/10.33714/masteb.1224160

Zhang, M., Zhang, D., Goerlandt, F., Yan, X., & Kujala, P. (2019a). Use of HFACS and fault tree model for collision risk factors analysis of icebreaker assistance in ice-covered waters. *Safety Science*, *111*, 128–143. https://doi.org/10.1016/j.ssci.2018.07.002

Zhang, M., Zhang, D., Goerlandt, F., Yan, X., & Kujala, P. (2019b). Use of HFACS and fault tree model for collision risk factors analysis of icebreaker assistance in ice-covered waters. *Safety Science*, *111*, 128–143. https://doi.org/10.1016/j.ssci.2018.07.002

Appendix A

All dysfunctional links for all kinds of accidents and for all types of ships over time

Years 1991 To 2000

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Ship builder/supplier to Ship Owner Control	0	2	3	4	2	2	4	0	5	1
Ship builder/supplier to Ship Owner Feedback	0	0	0	1	0	0	0	0	1	0
Ship management company to Ship Control	0	2	5	5	0	8	6	7	9	2
Ship management company to Ship Feedback	0	0	2	2	0	2	0	3	1	0
Master to Helmsman/Pilot/OOW Control	0	0	2	6	1	8	3	3	7	2
Master to Helmsman/Pilot/OOW Feedback	0	0	1	5	1	5	2	3	5	1
Master to Equipment, displays, etc Control	0	2	2	4	3	8	2	8	3	1
Master to Equipment, displays, etc Feedback	0	0	0	1	0	0	0	0	0	0
Helmsman/Pilot/OOW to Equipment, displays, etc Control	1	2	6	10	5	8	6	3	4	2
Helmsman/Pilot/OOW to Equipment, displays, etc Feedback	0	0	0	0	0	1	0	0	1	0
Chief engineer to Equipment, displays, etc Control	0	0	4	3	0	1	1	1	1	0
Chief engineer to Equipment, displays, etc Feedback	0	0	0	0	0	0	0	0	0	0
Ship owner to Ship Management Co Control	0	0	0	1	0	1	9	5	2	0
Ship owner to Ship Management Co Feedback	0	0	0	1	0	1	3	0	0	0
Classification Society to Ship Control	0	0	0	0	0	1	2	0	0	0
Classification Society to Ship Feedback	0	0	0	0	0	0	0	0	0	0
Port authority to Ship Control	0	0	3	8	3	3	6	2	6	0

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Port authority to Ship Feedback	0	0	0	0	0	1	0	1	0	0
Cargo owner to Ship Management Co Control	0	0	0	0	1	3	0	2	0	0
Cargo owner to Ship Management Co Feedback	0	0	0	0	0	1	0	0	0	0
VTS to Ship Control	0	1	1	0	0	4	1	1	2	0
VTS to Ship Feedback	0	0	0	0	0	2	0	0	1	0
Helmsman/Pilot/OOW to Chief Mate Control	0	0	0	0	0	0	0	0	0	0
Helmsman/Pilot/OOW to Chief Mate Feedback	0	0	0	0	0	0	0	0	0	0
Chief Mate/Staff Captain/Safety Officer to Equipment, displays, etc Control	0	0	0	1	1	2	0	0	0	0
Chief Mate/Staff Captain/Safety Officer to Equipment, displays, etc Feedback	0	0	0	0	0	0	0	0	0	0
Classification Society to Ship Builder Control	0	0	0	0	0	0	0	0	0	0
Classification Society to Ship Builder Feedback	0	0	0	0	0	0	0	0	0	0
Master to Chief Mate/Staff Captain/Safety Officer Control	0	0	0	0	3	0	3	1	0	0
Master to Chief Mate/Staff Captain/Safety Officer Feedback	0	0	0	0	1	0	0	1	0	0
Engineers to Machinery Control	0	0	0	0	0	0	0	0	0	0
Engineers to Machinery Feedback	0	0	0	0	0	0	0	0	0	0
Master to Chief engineer Control	0	0	3	0	0	1	0	1	0	0
Master to Chief engineer Feedback	0	0	0	0	0	0	0	1	0	0
Engineers to Equipment, displays, etc Control	0	0	1	0	1	2	2	0	1	0
Engineers to Equipment, displays, etc Feedback	0	0	0	0	0	0	0	0	0	0
Chief Engineer to Engineers Control	0	0	1	0	1	3	2	0	1	0

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Chief Engineer to Engineers Feedback	0	0	0	0	0	0	0	0	0	0
Classification Society to Flag State Control	0	0	0	0	1	0	0	0	0	0
Flag State to Ship Control	0	0	0	1	0	0	1	0	0	0
Classification Society to Ship management company Control	0	0	0	0	0	0	0	0	0	0
MOT to Flag State Control	0	0	0	0	0	0	2	0	0	2
Classification Society to Ship Owner Control	0	0	0	0	0	0	0	0	0	0
Ship management Co to Ship owner Control	0	0	0	0	0	0	0	0	1	0
Ship management Co to Ship owner Feedback	0	0	0	0	0	0	0	0	1	0
IMO to Classification Society Control	0	0	0	0	0	0	0	1	1	0
Port authority to Ship Control	0	0	0	1	0	0	0	0	0	0
Ship to Other Ship Control	1	2	1	1	1	1	0	2	0	0
Ship to Other Ship Feedback	0	0	1	0	1	0	0	1	0	0
IMO to Flag State Control	0	0	0	1	0	0	0	1	0	0
IMO to Flag State Feedback	0	0	2	0	0	0	0	0	0	0
Chief Mate/Staff Captain/Safety Officer to Equipment, displays, etc Control	0	0	0	0	0	0	0	0	0	0
Chief Mate/Staff Captain/Safety Officer to Equipment, displays, etc Control	0	0	1	1	0	0	3	1	0	0
Master to Equipment, displays, etc Control	0	0	0	0	0	0	0	0	0	0
Master to Chief Mate/Staff Captain/Safety Officer Feedback	0	0	0	0	0	0	1	0	0	0

Years 2001 to 2010

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Ship builder/supplier to Ship Owner Control	2	2	1	1	3	2	1	1	2	1
Ship builder/supplier to Ship Owner Feedback	0	0	0	0	0	1	0	0	1	0
Ship management company to Ship Control	6	8	4	4	4	1	0	1	0	6
Ship management company to Ship Feedback	0	1	0	0	2	0	1	1	0	4
Master to Helmsman/Pilot/OOW Control	1	4	3	1	4	0	1	1	1	1
Master to Helmsman/Pilot/OOW Feedback	1	2	3	1	5	0	1	1	1	1
Master to Equipment, displays, etc Control	0	1	3	3	1	1	1	2	0	2
Master to Equipment, displays, etc Feedback	0	0	2	0	0	0	0	0	0	2
Helmsman/Pilot/OOW to Equipment, displays, etc Control	1	4	0	0	4	0	2	2	1	1
Helmsman/Pilot/OOW to Equipment, displays, etc Feedback	1	0	0	0	1	0	1	2	0	0
Chief engineer to Equipment, displays, etc Control	0	0	0	1	2	0	0	0	1	0
Chief engineer to Equipment, displays, etc Feedback	0	0	0	0	0	0	0	0	1	0
Ship owner to Ship Management Co Control	1	0	3	3	0	0	0	0	0	2
Ship owner to Ship Management Co Feedback	1	0	0	3	0	0	0	0	0	2
Classification Society to Ship Control	3	0	0	1	0	0	0	0	0	1
Classification Society to Ship Feedback	0	0	4	0	0	0	0	0	0	0
Port authority to Ship Control	3	0	3	1	2	2	0	1	1	4
Port authority to Ship Feedback	0	0	0	1	0	0	0	0	0	2
Cargo owner to Ship Management Co Control	1	1	0	0	0	1	0	0	0	0
Cargo owner to Ship Management Co Feedback	0	0	0	0	0	0	0	0	0	0

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
VTS to Ship Control	0	0	0	0	0	0	0	0	0	0
VTS to Ship Feedback	0	0	0	0	0	0	0	0	0	0
Helmsman/Pilot/OOW to Chief Mate Control	0	0	0	0	0	0	0	0	0	0
Helmsman/Pilot/OOW to Chief Mate Feedback	0	0	0	0	0	0	0	0	0	0
Chief Mate/Staff Captain/Safety Officer to Equipment, displays, etc Control	1	0	0	1	0	0	0	0	0	1
Chief Mate/Staff Captain/Safety Officer to Equipment, displays, etc Feedback	0	0	0	0	0	0	0	0	0	1
Classification Society to Ship Builder Control	0	0	0	0	0	0	0	0	0	0
Classification Society to Ship Builder Feedback	0	0	0	0	0	0	0	0	0	0
Master to Chief Mate/Staff Captain/Safety Officer Control	0	1	0	1	0	1	0	0	1	1
Master to Chief Mate/Staff Captain/Safety Officer Feedback	0	0	0	0	0	0	0	0	0	1
Engineers to Machinery Control	0	0	0	0	0	0	0	0	0	0
Engineers to Machinery Feedback	0	0	0	0	0	0	0	0	0	0
Master to Chief engineer Control	0	0	1	0	0	0	0	0	0	0
Master to Chief engineer Feedback	0	0	0	0	0	0	0	0	0	0
Engineers to Equipment, displays, etc Control	0	1	0	1	0	1	0	0	0	0
Engineers to Equipment, displays, etc Feedback	0	0	0	0	0	0	0	0	0	0
Chief Engineer to Engineers Control	0	2	0	1	0	1	0	0	0	0
Chief Engineer to Engineers Feedback	0	0	0	0	0	0	0	0	0	0
Classification Society to Flag State Control	0	0	0	0	0	0	0	0	0	0
Flag State to Ship Control	0	0	0	0	0	0	0	0	0	2

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Classification Society to Ship management company Control	0	0	0	0	0	0	0	0	0	1
MOT to Flag State Control	1	0	2	1	0	0	0	0	0	0
Classification Society to Ship Owner Control	0	0	0	1	0	0	0	0	0	0
Ship management Co to Ship owner Control	0	0	0	0	0	0	0	0	0	0
Ship management Co to Ship owner Feedback	0	0	0	0	0	0	0	0	0	0
IMO to Classification Society Control	0	1	0	0	0	0	0	0	0	0
Port authority to Ship Control	0	0	0	0	0	0	0	0	0	0
Ship to Other Ship Control	0	0	0	1	2	0	0	1	0	0
Ship to Other Ship Feedback	0	0	0	1	2	0	0	1	0	0
IMO to Flag State Control	0	0	0	0	1	0	0	0	0	0
IMO to Flag State Feedback	0	0	0	0	1	0	0	0	0	0
Chief Mate/Staff Captain/Safety Officer to Equipment, displays, etc Control	0	0	0	0	0	0	0	0	0	0
Chief Mate/Staff Captain/Safety Officer to Equipment, displays, etc Control	1	1	2	1	0	1	0	0	1	0
Master to Equipment, displays, etc Control	0	0	0	0	0	0	0	0	0	0
Master to Chief Mate/Staff Captain/Safety Officer Feedback	0	0	0	0	0	1	0	0	0	0

Years 2011 to 2020

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Ship builder/supplier to Ship Owner Control	2	1	1	3	0	0	1	1	1	0
Ship builder/supplier to Ship Owner Feedback	0	0	0	0	0	0	1	0	0	0

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Ship management company to Ship Control	2	5	4	4	2	2	1	4	1	2
Ship management company to Ship Feedback	2	4	3	1	1	0	0	0	0	0
Master to Helmsman/Pilot/OOW Control	1	5	3	2	3	0	1	1	0	3
Master to Helmsman/Pilot/OOW Feedback	1	5	4	1	2	0	1	1	0	3
Master to Equipment, displays, etc Control	1	4	2	4	0	2	0	1	0	1
Master to Equipment, displays, etc Feedback	0	0	0	0	0	1	0	0	0	0
Helmsman/Pilot/OOW to Equipment, displays, etc Control	3	5	0	2	0	1	0	1	0	3
Helmsman/Pilot/OOW to Equipment, displays, etc Feedback	0	1	0	0	0	0	0	0	0	0
Chief engineer to Equipment, displays, etc Control	0	0	0	1	0	0	0	2	2	0
Chief engineer to Equipment, displays, etc Feedback	0	0	0	0	0	0	0	0	0	0
Ship owner to Ship Management Co Control	1	0	0	1	0	0	0	1	1	0
Ship owner to Ship Management Co Feedback	1	0	0	1	0	0	0	1	0	0
Classification Society to Ship Control	0	1	0	0	0	0	0	0	1	0
Classification Society to Ship Feedback	0	1	0	0	0	0	0	0	0	0
Port authority to Ship Control	1	4	0	1	1	1	0	0	0	2
Port authority to Ship Feedback	0	2	0	0	0	0	0	0	0	0
Cargo owner to Ship Management Co Control	0	0	0	0	0	0	0	0	0	0
Cargo owner to Ship Management Co Feedback	0	0	0	0	0	0	0	0	0	0

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
VTS to Ship Control	0	0	1	0	0	0	3	0	0	0
VTS to Ship Feedback	0	0	0	0	0	0	0	0	0	0
Helmsman/Pilot/OOW to Chief Mate Control	0	1	0	0	0	1	2	0	0	0
Helmsman/Pilot/OOW to Chief Mate Feedback	0	1	0	0	0	1	0	0	0	0
Chief Mate/Staff Captain/Safety Officer to Equipment, displays, etc Control	0	0	0	0	0	1	3	0	0	0
Chief Mate/Staff Captain/Safety Officer to Equipment, displays, etc Feedback	0	0	0	0	0	0	0	0	0	0
Classification Society to Ship Builder Control	0	0	0	0	0	0	1	0	0	0
Classification Society to Ship Builder Feedback	0	0	0	0	0	0	0	0	0	0
Master to Chief Mate/Staff Captain/Safety Officer Control	0	0	2	0	0	0	1	0	0	0
Master to Chief Mate/Staff Captain/Safety Officer Feedback	0	0	1	0	0	0	0	0	0	0
Engineers to Machinery Control	0	0	0	1	0	0	0	0	0	0
Engineers to Machinery Feedback	0	0	0	0	0	0	0	0	0	0
Master to Chief engineer Control	0	0	1	0	0	0	0	0	1	0
Master to Chief engineer Feedback	0	0	0	0	0	0	0	0	0	0
Engineers to Equipment, displays, etc Control	1	0	1	1	0	0	0	1	0	0
Engineers to Equipment, displays, etc Feedback	1	0	1	0	0	0	0	0	0	0
Chief Engineer to Engineers Control	1	0	2	2	0	0	0	1	0	0
Chief Engineer to Engineers Feedback	1	0	2	1	0	0	0	0	0	0
Classification Society to Flag State Control	1	0	0	0	0	0	0	0	0	0

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Flag State to Ship Control	0	0	0	1	0	0	0	0	0	0
Classification Society to Ship management company Control	0	0	0	0	0	0	0	0	0	0
MOT to Flag State Control	0	0	0	0	0	0	0	0	0	0
Classification Society to Ship Owner Control	0	0	0	0	0	0	0	0	0	0
Ship management Co to Ship owner Control	0	0	0	0	0	0	0	0	0	0
Ship management Co to Ship owner Feedback	0	0	0	0	0	0	0	0	0	0
IMO to Classification Society Control	0	0	0	0	0	0	0	0	0	1
Port authority to Ship Control	0	0	0	0	0	0	0	0	0	0
Ship to Other Ship Control	0	1	1	0	0	0	0	0	0	0
Ship to Other Ship Feedback	0	1	1	0	0	0	0	0	0	0
IMO to Flag State Control	0	0	0	0	0	0	0	0	0	0
IMO to Flag State Feedback	0	0	0	0	0	0	0	0	0	0
Chief Mate/Staff Captain/Safety Officer to Equipment, displays, etc Control	0	0	0	0	0	0	0	1	0	0
Chief Mate/Staff Captain/Safety Officer to Equipment, displays, etc Control	0	0	0	1	0	0	0	1	0	0
Master to Equipment, displays, etc Control	0	0	0	1	0	0	0	0	0	0
Master to Chief Mate/Staff Captain/Safety Officer Feedback	0	0	0	0	0	0	0	0	0	0