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# Development of an Environmental Impact Methodology for Arctic Shipping: Exploring FMEA and STPA applications considering a Dynamic (varying) Baseline

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## ABSTRACT

Arctic shipping poses environmental risks due to the region's fragile ecosystems and rapid climate changes. Effective risk assessment tools are needed to ensure sustainable expansion and to carry out environmental impact assessments. This paper explores applications of Failure Modes and Effects Analysis (FMEA) and Systems-Theoretic Process Analysis (STPA) coupled with the consequences of a "Dynamic baseline approach" for Arctic shipping environmental impact assessment.

Shipping entails complex interactions between environmental, technical, human, and organizational factors. FMEA identifies failure modes and their effects through component-level analysis. STPA examines how unsafe control actions can emerge from interactions between system components. Combining these techniques with a dynamic (variable) baseline, accounting for inherent ongoing changing Arctic conditions, offers a robust methodology.

A qualitative case study shows that prioritizing hazards by risk, yields highest concerns, as increased greenhouse gas emissions, black carbon deposition on ice and snow, and response delays to accidents represent some of the most important identified threats to the environment. The use of FMEA and STPA are complementary, and differences are highlighted.

The methodology applied, should be representative for the qualitative risk analysis methodology, and while the

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findings are impacted by the perspectives of the authors, the process followed is intended to identify and rank risks in a consistent manner.

Mitigations measures must be in place to target these issues. Constant monitoring of the changing ecological and socioeconomic Arctic baselines supports the responses.

This methodology offers a starting point for systematically addressing environmental impact risks in the data-limited Arctic. Integrating failure modes and effect analysis, system theories and dynamic baselines, account for identification of the complex interactions, influencing environmental risks in this rapidly evolving region.

***Keywords:*** Arctic shipping, Environmental impact analysis, Arctic baseline, Dynamic baseline, Risk analysis, FMEA, STPA, Risk mitigation prioritization.

List of Key Abbreviations

| | |
|---|---|
| AECO: Association of Arctic Expedition Cruise Operators | AIS: Automatic Identification System |
| ALARP: As Low As Reasonably Practicable | AMAP: Arctic Monitoring and Assessment Programme |
| ATR: Available Time to Respond | CAFF: Conservation of Arctic Flora and Fauna |
| EBSA: Ecologically and Biologically Significant Area | EIA: Environmental Impact Assessment |
| EPPR: Emergency Prevention, Preparedness and Response | FMEA: Failure Modes and Effects Analysis |
| GHG: Greenhouse Gas | GIS: Greenlandic Ice Sheet |
| HFO: Heavy Fuel Oil | ICC: Inuit Circumpolar Council |
| IMO: International Maritime Organisation | LH: Likelihood |
| MARPOL: International Convention for the Prevention of Pollution from Ships | MoU: Memorandum of Understanding |
| NGO: Non-governmental Organisation | NSR: Northern Sea Route |
| NWP: Northwest Passage | PAME: Protection of Arctic Marine Environment |
| PPR: Pollution Preparedness Response | RPN: Risk Priority Number |
| SAR: Search and Rescue | SCC: Shore Control Centre |
| SCR: Safety Control | SDWG: Sustainable Development Working Group |
| SOK: State of Knowledge | SOLAS: International Convention for the Safety of Life at Sea |
| STAMP: Systems-Theoretic Accident Model and Processes | STCW: International Convention on Standards of Training, Certification and Watchkeeping for Seafarers |
| STPA: Systems-Theoretic Process Analysis | SV: Severity |
| TSR: Transpolar Sea Route | UCA: Unsafe Control Action |
| VTS: Vessel Traffic Service | |

# 1. Introduction

The recent development of Arctic shipping activities has, and will lead to, various environmental impacts that will affect the livelihood and culture of the population of Arctic coastal communities in the Arctic countries: Norway, Russia, USA (Alaska), Canada, and Denmark (Greenland). Most vessels today operate close to coastal and ecologically fragile areas [1], thus meaning that potential accidents may result in significant environmental impacts. The prospected increase in Arctic shipping raises further concerns on the social effects on Arctic communities as well as the environmental effects on Arctic systems, even those associated with regular shipping operations [2], [3], [4].

Arctic shipping development and its growing impact on the environment need to be assessed to determine where risks can be addressed and reduced, and which opportunities shipping presents for the Arctic communities. An Environmental Impact Assessment (EIA) is an environmental assessment tool consisting of a systematic analysis of projects to determine their potential environmental impacts and their significance, and to propose measures to mitigate those negative impacts [5]. An EIA is a planning tool and a decision-making tool at the same time. EIA, as a planning tool, presents methodologies and techniques for identifying, predicting, and evaluating potential environmental impacts, while, as a decision-making tool, it can provide information to promote policy making and actions to ensure sustainable development of the ongoing projects.

An EIA identifies environmental risks of an activity, promotes community participation, minimises adverse environmental impacts, informs decision makers, and helps to lay the base for sustainable projects; the benefits of the integration of an EIA in all stages of a project have been observed [5]. An EIA is a flexible process that employs many evaluation methods and techniques, and it is becoming more and more relevant as a part of prefeasibility engineering. In this paper methodologies to identify and assess environmental risks, as well as proposing mitigation measures, is explored in the context of Arctic shipping based on STPA and FMEA.

According to [6] certain goals and principles of EIA are defined, hereby the three core values of EIA being Sustainability (the EIA process results in environmental safeguards), Integrity (the EIA process conforms to agreed standards), and Utility (the EIA process provides balanced and credible information). Eight guiding principles are defined as: Participation, Transparency, Certainty, Accountability, Credibility, Cost-effectiveness, Flexibility and Practicality; more on these principles can be found in [7].

Vessel traffic is unevenly distributed in Arctic waters due to different accessibility status. The Barents Sea is the most navigable and least limited by sea ice, it is estimated that 80% of all arctic shipping crosses the Norwegian sector of the Barents Sea [4]. The vessel traffic along the two main Arctic Sea routes, the Northern Sea Route (NSR) and the Northwest Passage (NWP), is seeing an increasing trend that does not look like stopping anytime soon [8], [9]. Navigation along a third route, the Transpolar Sea Route (TSR), may become feasible by the middle of the 21st century as sea ice keeps retreating [10]. These developments may have important consequence on the Arctic environment. For example, Arctic marine ecosystems display seasonal patterns, and a wide range of biological productivity could be endangered by increasing vessel traffic [1].

The purpose of this paper is to develop and demonstrate an effective methodology for conducting environmental impact assessments of Arctic shipping activities. Shipping entails complex interactions between technical vessel systems, human operators, organizational policies, and dynamic environmental condition. This research aims to integrate hazard identification techniques with a dynamic baseline approach that accounts for shifting Arctic conditions over time, to track the rapid ecological changes of the Arctic region.

Specifically, this paper explores applications of Failure Modes and Effects Analysis (FMEA) and Systems-Theoretic Process Analysis (STPA) coupled with consideration of a variable environmental baseline for Arctic shipping impact assessment. A preliminary case study demonstrates the methodology by identifying and ranking potential hazards. The scope is limited to developing and demonstrating the approach, subjective evaluation in ranking of hazards is presented while the subjectivity should be reduced through consultancy of groups of experts and potentially by implementation of quantitative data.

The paper is organized as follows. First, an overview of FMEA, STPA and their benefits for risk analysis is provided. Then an integrated methodology incorporating a dynamic baseline is proposed. Next, results from an initial case study application are discussed. Recommendations for mitigating highest priority risks are also presented, followed by conclusions and potential directions for further work.

## 2. Overview of Tools Used

Failure Mode and Effect Analysis (FMEA) is a hazard analysis technique based on reliability analysis, its process consists of defining the systems to be analysed, analysing the failure modes of the system's components and their effect on the system's operation [11]. After this, safety controls can be defined to mitigate the consequences and their potential causes. It is possible to divide the FMEA technique in four tasks:

- Definition of the systems and the processes under assessment.
- Identification of the failure modes of each of the components and its functions.
- Determination of the effects and potential causes of the failure modes.
- Definition of the safety controls to mitigate the consequences and potential causes.

To obtain a good FMEA it is necessary to identify known and potential failure modes, their causes, and effects and to prioritise them according to a risk priority number [12]. The strength of FMEA is to capture various failure modes of components, but it is not effective at capturing the effects of combinations of component failure. FMEA avoids the need for costly modifications in service by identifying problems early in the design process, while highlighting key features to be monitored and maintained [13]. The approach of this technique follows a bottom-up structure as the analysis is based on identifying what leads to a failure mode.

The outputs of FMEA are presented as a table containing information for each identified failure mode, with their effects, causes and possible controls as well as any recommended action to be incorporated in test plans [13]. Usually, risk is determined for each failure mode based on the severity, probability of occurrence and detection level. In this work the detection parameter has been swapped with a score related to the available time to respond to an identified failure mode, adapted from [14].

**Figure 1** illustrates the risk assessment process for an FMEA risk assessment analysis, scenarios are first identified and subsequently analysed to evaluate them and propose mitigation measures.


**Figure 1:** Conceptual Model of the Risk Assessment Process in FMEA

To support the identification and study of ongoing processes, after an environmental baseline study, it is recommended to provide system context diagrams and a system hierarchy diagram to showcase different stakeholders, their interactions with the system, and the processes under assessment.

While FMEA has proven effective in analysing component-level risk, it does not fully capture interactions within complex systems where interactions between components, controllers, and social factors can also be a source of significant risks. Systems-Theoretic Process Analysis (STPA) has been developed to address this limitation.

STPA is a new hazard analysis technique which treats safety as a problem that involves unsafe controls and the violation of system safety constraints [15]. The STPA process starts by assessing the organisational control structure in which the system operates and then models the system's functional control structure, showing the hierarchical arrangement of feedback control loops within the system [16]. The control loops are then used to identify the Unsafe Control Actions (UCAs) which can lead to a hazard. The identified UCAs should be specified with their source, control action, context, and link to resulting system-level hazards.

System-level constraints specify the conditions that need to be satisfied to prevent hazards, they can also define how the system must minimise losses in case the hazards occur. The system-level safety constraints should not, however, specify a particular solution or implementation [17]. System-level safety controls can be found through the analysis of the UCAs, and causal scenarios that can lead to the UCAs are generated to determine how each unsafe control action can occur, at this point new safety controls are generated to eliminate, prevent, or mitigate the UCAs in the design and operation of the system [15]. A STPA can become an iterative process where details are added continuously as the system design evolves, it is therefore important that in a top-down STPA analysis the refining causes are stopped when an effective mitigation can be identified.

The Systems-Theoretic Accident Model and Process (STAMP) framework, upon which STPA is based, was introduced in Leveson [16] to build safer systems, as the increased complexity caused by technological development, new nature of accidents and hazards, and complex relationships between system components, humans, automation, and regulations required a new philosophy to approach the safety problem. STAMP assumes that accidents occur because of inadequate control problems expanding the accident causality models to complex and unsafe interactions among system components. STAMP approaches safety as a dynamic control problem, including failures as a subset, instead than as a failure prevention problem [17].

Traditional STPA methodology does not include any evaluation process for UCAs and loss scenarios, as Leveson and Thomas [17] state that the probability of occurrence cannot be properly estimated in early design stages, or when the system is particularly complex, or when the system is highly innovative. The present study will integrate methodology from [14] to reduce the number of significant UCAs and loss scenarios and evaluate them through a Risk Priority Number (RPN rank), as well as proposing safety controls to mitigate UCAs and loss scenarios.

The four steps of a STPA, as proposed in [17], are shown in **Figure 2**.

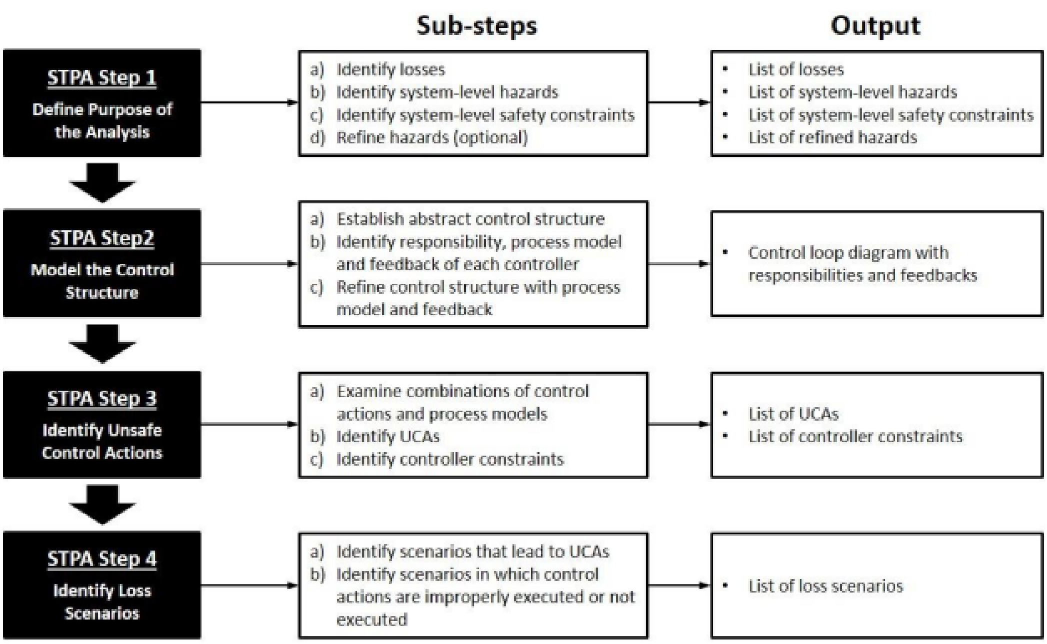


**Figure 2:** STPA Procedure and Output [14].

In order to address the problem arising from managing a large number of UCAs and loss scenarios, and prioritise important hazards while screening out minor ones, Kim et al. [14] came up with additional sub steps for evaluation and prioritization of hazards, as shown in **Figure 3**.

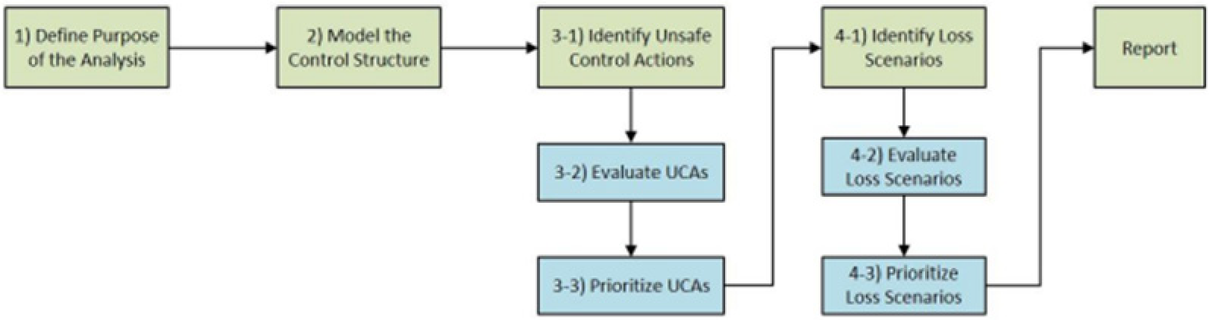


**Figure 3:** Modified STPA procedure according to Kim et al. [17]

Both FMEA and STPA rely on defined system baselines that may not fully capture dynamic conditions in the Arctic. Shipping risks are influenced not just by vessel technologies and operations, but also external drivers like climate change and ecological variability. A fixed baseline could underestimate future vulnerabilities as conditions evolve, while a "dynamic baseline" will better represent future changes to the environment due to factors external to the evaluated project.

## 3. Proposed Methodology and Case Study

The present study focuses on the creation of a methodology to integrate dynamic (variable) baseline information with hazard identification techniques as FMEA and STPA. Attention is placed on monitoring and updating of information and adaptation of classic FMEA and STPA methodologies to fit the case study of increased Arctic shipping traffic.

### 3.1 Baseline

The methodology proposed in this paper is based on a dynamic baseline, this should be established through the description of different Arctic environmental conditions that are supposed to change based on different inherent climate projections. Key parameters include sea ice coverage, temperature rise, oceanographic patterns, ecosystem distributions, community infrastructures, and regulations.

**Table 1** shows the main baseline threats identified in the Arctic environment, these issues are related to the current shipping traffic and to a continued shipping in the region with similar traffic rates as today. This table shows threats that are present, even without an increase in shipping traffic across the Arctic region. This traditional baseline is based upon the current rates of traffic in the Arctic.

**TABLE 1:** OVERVIEW OF THREATS AND POTENTIAL MITIGATION MEASURES IN BASELINE

| Baseline Threats | Possible Threats from Continued Traffic at Same Rates as Present | Potential Mitigation Measures |
|---|---|---|
| Declining sea ice extent and impacts on climate patterns and wildlife habitats [18][19]. | Ship traffic leads to risks of collisions with marine animals, noise and disturbance disruption, emissions harming air and water quality, risk of discharges from normal operations or accidents. | Designation of shipping lanes to avoid sensitive habitats, use of noise reduction technologies on ships, setting and enforcement of stringent emission controls, implementation of wildlife observation and avoidance procedures on ships. |
| Increased precipitation altering hydrology [20][21][22][23]. | The Arctic is becoming warmer and wetter, and the amount of evaporation has gradually increased. Arctic precipitation energizes the Arctic Ocean surface, promote the melting of sea ice, and affect the mass balance of high-latitude glaciers. | Consideration of climate impacts like heavier rains in project designs, and more common extreme events. Prepare more efficient and detailed plans for emergency in remote communities. |

| **Baseline Threats** | **Possible Threats from Continued Traffic at Same Rates as Present** | **Potential Mitigation Measures** |
|---|---|---|
| Accumulation of plastics and other contaminants spread by ocean current and air flow [24][25][26]. | Traffic volume brings risks of introduction of pollutants from losses or incidents during transport [27][28]. | Strengthening of international agreements on waste handling and disposal, mandatory equipment like gear marking to facilitate cleanup if lost, supporting sustainable fishing gear and practices, build adequate port waste reception facilities |
| Permafrost degradation threatens infrastructure stability from the thawing ground [29], [30]. | Construction projects could accelerate thawing through land clearing and other surface disturbance, thermal pollution from activities/development [29]. | Careful consideration of warming impacts and adaptation measures incorporated into all project designs, strict controls on emissions from all stages of projects. |
| Northward shift of treelines and conversion of tundra [31]. | Further changes to land use to build support facilities, would expand habitat alterations like those caused by resource extraction, transportation corridors, settlements. | Offset impacts through protection/restoration efforts and ensure that developing practices balance environmental and socioeconomic goals. |
| Challenges in waste and wastewater management in remote areas [32][33][34]. | Sustained shipping activities introduce needs for additional handling and treatment, risking further contamination if not properly managed. | Strategic, holistic waste management planning, treatment plant upgrades where needed to modern standards, contingency plans to rapidly address any issues. |
| Industrial and resource projects releasing contaminants [35][36]. | Proliferation of industrial/extraction sites multiplies diverse risk sources if not strictly regulated. | Requiring rigorous, science-based EIA and monitoring of all projects approving operation, mandating financial assurances for complete remediation of any issues. |
| Underwater noise from ship traffic and industrial activities [37][38]. | Shipping traffic increases chronic disruption risks plus acute risks like impairment of communication/navigation during critical life stages of marine mammals and fishes [33][39][40][41]. | Setting and enforcement of international standards on noise from ships, use of mitigation technologies demonstrated to reduce noise, spatial/temporal separation of noisy activities from sensitive areas and seasons. |
| Wildlife migrations overlapping heavily with shipping lanes [42]. | Danger of strikes as traffic expands in migration hotspots, as well as noise disturbance. | Adoption of precautionary transit practices during migration periods, factoring observations of wildlife patterns into routing/management, cooperation with groups monitoring wildlife to inform practices. |
| Impact risks from icebergs and drifting sea ice [43][44]. | Accident probability rises with traffic in ice-prone waters [45]. | Improve forecasting and reporting of ice conditions, strengthen ship designs/ice strengthening requirements, operator ice navigation training, establishment, and enforcement of safety corridors. |
| Emissions of greenhouse gases (GHG) from human activities [27]. | Maritime traffic implies sustained impacts, as the amount of GHG emitted is related to the traffic rates in the Arctic. The use of heavy fuel oil will enhance the melting of ice due to emission of soot particles [42][46]. | Setting and enforcing emission reduction targets and timelines through organizations like IMO, investment in development and adoption of zero emissions vessels, fuel, and power sources. It is important to avoid use of heavy fuel oil [47][48]. |

It is important to notice that shipping in the Arctic is already in place, so most of the threats related to the same level of shipping are the same as in case of an increased traffic just with a lower degree of severity as their impacts are not heightened by increased traffic rates.

Particular emphasis needs to be put on local assessment, as local acute impacts need to be regarded for each project involved in the development of Arctic shipping and its supporting infrastructure.

Another table is proposed to evaluate the threats going on in the Arctic even in a scenario where shipping is halted to a minimum level, see **Table 2** for an overview of baseline threats ongoing in the region. These threats will alter the Arctic environment as their causes are not led by marine traffic but by global factors and many processes in the region have already reached a tipping point. This type of baseline is hereby defined as a dynamic baseline, as it will evolve over time regardless of shipping traffic and other human activities.

**Table 2:** Overview of Main Threats and Effects unrelated to shipping affecting the Arctic region (The Dynamic Baseline).

| Hazard | Effects |
|---|---|
| Sea Ice and Iceberg melting [49]. | Disruption of Arctic ecosystems and habitats. Changes in ocean salinity and freshwater input. Release of stored pollutants. Socioeconomic impacts. |
| Atmospheric Circulation [50], [51]. | Disrupted weather patterns and extreme events. Altered climate zones and precipitation patterns. Economic losses. |
| Ocean Circulation [49]. | Altered climate patterns and weather systems. Changes in marine productivity and ecosystems. Disrupted carbon sequestration. |
| Greenland Ice Sheet (GIS) melting [49][52]. | Sea level rise. Changes in ocean salinity and freshwater input. Changes in ocean circulation. Infrastructure damage. Ecosystem impacts. |
| Shelf Seas [49]. | Ocean acidification. Loss of coastal habitats and marine biodiversity. Algal blooms. Changes in sea ice dynamics. |
| Land Surfaces [49]. | Habitat destruction. Soil degradation and contamination. Urbanization and land subsidence. Infrastructure damage. |
| Sea-Ice Loss [19][53]. | Amplified Arctic warming. Disrupted Arctic ecosystems and indigenous communities. Changes in ocean circulation and coastal erosion. |
| Sub-Polar Gyre Switch [49]. | Disrupted marine ecosystems and altered climate patterns. Changes in ocean heat transport and carbon sequestration. |
| Ocean Methane Release [54]. | Amplified greenhouse effect and accelerated warming. Increased atmospheric methane concentrations. |
| Yedoma Permafrost Collapse [55]. | Release of greenhouse gases. Land subsidence and infrastructure damage. Ecosystem disruption. |
| Tundra Loss [49]. | Permafrost degradation and greenhouse gas release. Loss of wildlife habitat and increased wildfire risk. |
| Arctic Ozone Loss [49]. | Stratospheric ozone depletion. Increased UV exposure and related health/ecosystem impacts. Accelerated melting of polar ice. |
| Wildfires Frequency [56] [57]. | Ecological damage. Infrastructure damage and economic losses. Impacts on air quality and human health. |

An important concept to highlight is that as different scenarios are evaluated a base effect and base mitigation action can be identified for all failure modes related to threats unrelated to shipping activity. This concept is summed up in Table 3, where the base effect, E, is amplified by the shipping traffic in the Arctic, as shown by the Δ coefficients, at the same time mitigation measures, Em, need to be more extensive and effective, as shown by the ε coefficients supporting the base mitigation factor b.

**Table 3:** Effects ($E + \Delta_i$) and Mitigation Measures (b and $\varepsilon_i$) for Arctic Shipping.

| Scenario | Effect | Mitigation Measure |
|---|---|---|
| Unrelated to Shipping | E | Em= E-b |
| Baseline Shipping | $E' = E+\Delta_1$ | $Em' = E'-b-\varepsilon_1 = E+\Delta_1-b-\varepsilon_1$ |
| Increased Shipping | $E'' = E'+\Delta_2 = E+\Delta_1+\Delta_2$ | $Em'' = E''-b-\varepsilon_1-\varepsilon_2 = E+\Delta_1+\Delta_2-b-\varepsilon_1-\varepsilon_2$ |

The need for mitigation measures is scaled up based on the traffic volumes occurring in the Arctic, which will heighten the effects of identified failure modes. The dynamic baseline will create varying situations and different needs for mitigation, base effects and base mitigation measures can be established referring to the situation where threats unrelated to shipping are evaluated, as those threats would pose a challenge in the region even if a total halt of maritime traffic would take place. When traffic level changes the effects will get heightened, as well as new effects will originate, leading to the need of further mitigation measures.

Baseline assumptions are important, as stated in [58], they can directly interact with the mitigation measures reducing their effectiveness. An example in the Arctic shipping context would be that if scrubbers and equipment to reduce emissions to air of vessels are extensively installed, a steep reduction of traffic volume would reduce the effectiveness of this measure, as the lower amount of traffic would reduce the reduction of GHGs intercepted by the installed systems. The evolution of the baseline conditions and its behaviour need to be monitored during the whole duration of the project to track and assess the effectiveness of mitigation measures.

Proper baseline analysis is required in order to create a prediction of the evolution of key parameters without the project implementation, this is helpful to propose effective mitigation measures as well as shielding the project stakeholders from possible legal responsibilities of adverse environmental effects.

## 3.2 FMEA

The FMEA analysis is supported by two system context diagrams where the external entities and their interactions with the system are shown, allowing the reader to identify the external entities influencing the project [59].

**Figure 4** presents the context diagram of Arctic shipping in relation to external stakeholders, while **Figure 5** shows the interaction between maritime traffic and environmental actors.

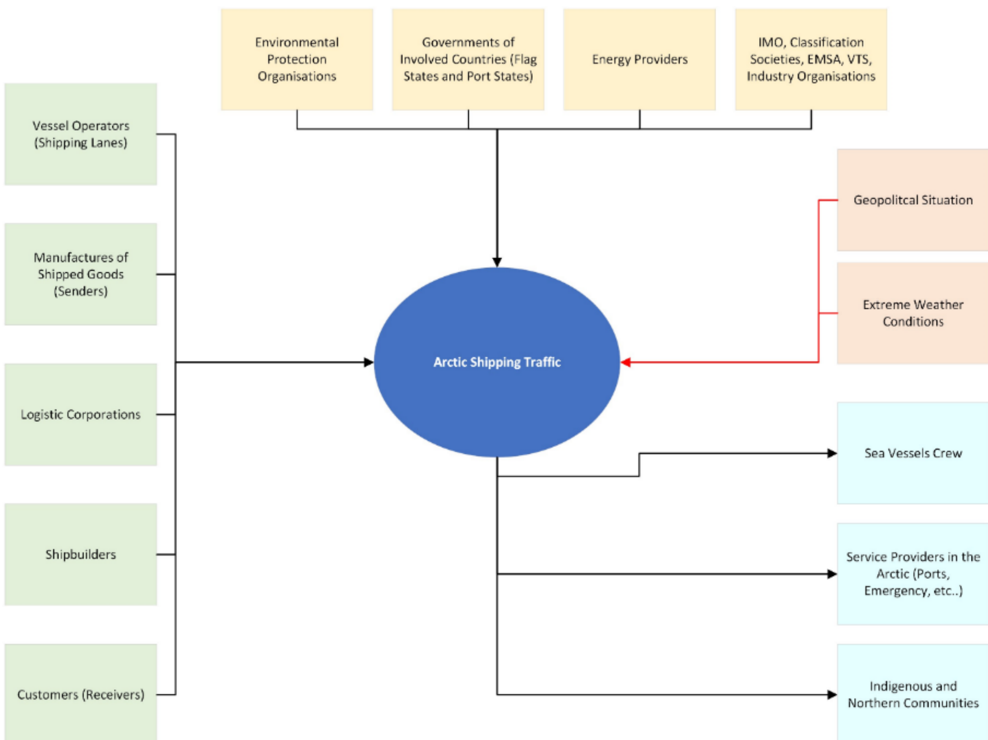


**Figure 4:** System Context Diagram of Arctic Shipping (Black Arrows: Active Stakeholders, Red Arrows: Passive Stakeholders).

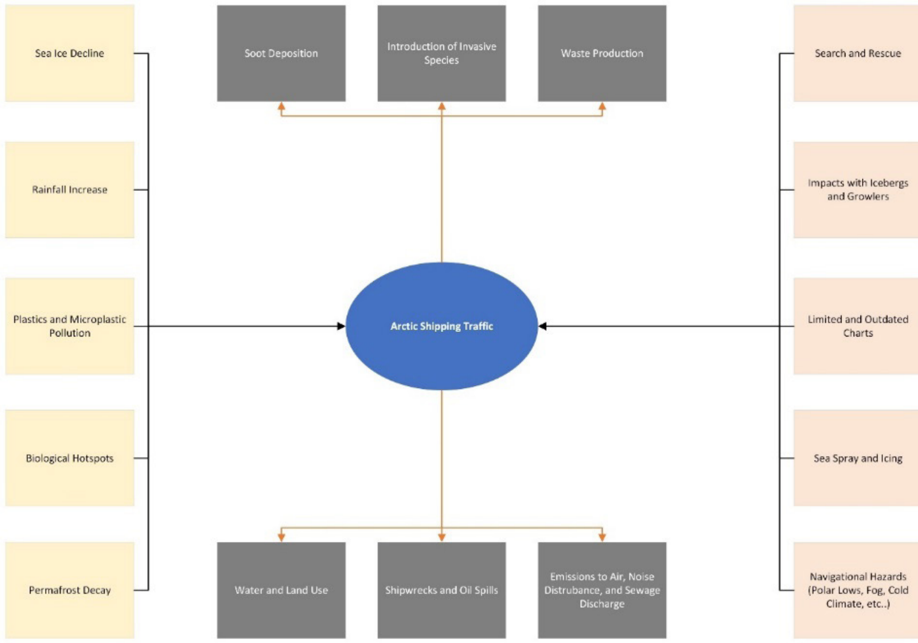


**Figure 5:** System Context Diagram of Environmental and Operational Factors

The system description required in the FMEA process is also supported by a system hierarchy, shown in **Figure 6**, which define the systems and the processes under assessment, giving a general idea of the connections between main equipment and components of a system.

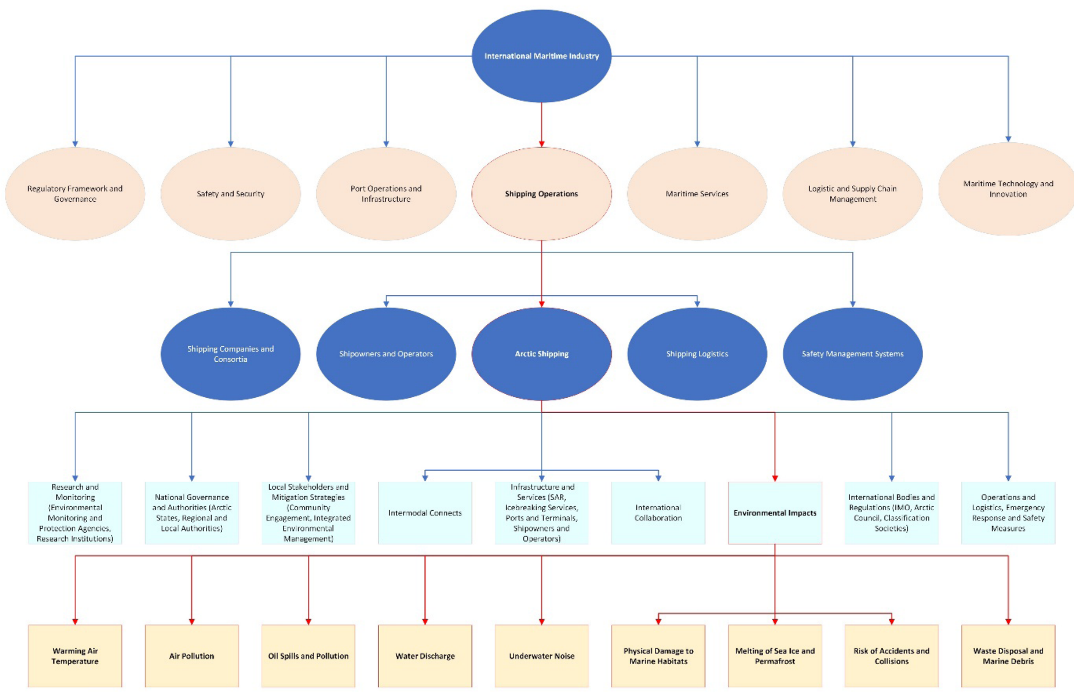


**Figure 6:** System Hierarchy of Arctic Shipping with Emphasis on Environmental Impacts

It is suggested that an FMEA analysis is based on different perspectives, in this case study three. **Figure 7** shows the investigation spaces of each proposed perspective and the contact point between them. The general arctic environment perspective refers to environmental impacts happening in the region and caused by different industries; the owners' perspectives are focused on items related to shipping activities and their impacts on the environment while the contractors' perspectives are based on items related to ships and their operation. The perspectives intersect in the ship operation activities which are common to all the three points of views. The general arctic environment perspective offers a wider look on the environmental impacts, while the owners and contractors perspectives offer a more in detail look on environmental and social impacts related to shipping activities. The use of different analysis perspectives allows a more focused approach to identify failure modes related to particular points of view of different stakeholders.

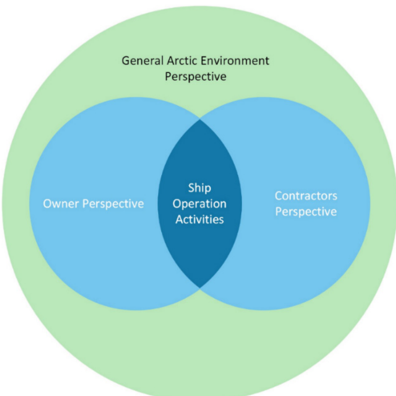


**Figure 7:** FMEA Investigation Spaces

A FMEA analysis is then carried out for each perspective, and failure modes are evaluated through a Risk Priority Number (RPN) based on Severity, Probability of Occurrence, and Available Time to Respond. Consequently, mitigation measures are proposed to reduce the RPNs of failure modes in the ALARP and Unacceptable Risk regions and then a re-evaluation is carried out to check the effectiveness of proposed measures.

It is to be noted that the FMEA here reported is influenced by the subjectivity of the authors' judgment, but it is used to showcase an application of the proposed methodology.

The failure modes with RPNs higher than 180 before mitigation are shown in Appendix A1, these failure modes are the ones carrying the biggest threats to the Arctic ecosystems.

Most items showed a 30-70% reduction in RPN after implementing recommended mitigation measures. However, some threats still present relatively high residual risks, although in the ALARP region. More details on the recommended mitigation measures for the items with the highest original RPNs are reported in Appendix A2.

Across the FMEA analysis commonly suggested mitigation measures are shown in the next paragraphs.

Training and drills were identified as important mitigation measures for many failure modes related to emergency response, environmental regulatory compliance, waste management, hazardous materials handling, and cold climate operations are other important mitigation measures.

Regular training programs, refresher courses, and simulation exercises help ensure personnel are properly equipped to respond effectively in the event of accidents or non-compliance incidents.

Monitoring and maintenance programs feature heavily for mitigating risks associated with emissions, ballast water discharge, noise pollution, fuel usage and storage, hull condition, navigation equipment, and structural integrity. Installing monitoring systems and implementing rigorous inspection and maintenance schedules help detect issues early before they escalate.

Technological upgrades also appear frequently, such as investing in cleaner fuels, advanced emission control systems, quieter propulsion and insulation, secondary containment, leakage detection, ballast water treatment, and ice navigation aids. Keeping vessel and port infrastructure updated with the latest techniques and equipment enhances environmental performance. The use of Best Available Technology is highly recommended.

Engagement of local communities and indigenous populations is highlighted for mitigating social impacts. Measures involve facilitating meaningful consultation, implementing benefit sharing agreements, and supporting cultural preservation initiatives.

Regulatory compliance also undergoes strengthening in many protocols, emphasizing stricter standards, compliance auditing, reporting procedures, and penalties to curb negligent practices.

Further mitigation measures might include private governance actions from insurance companies, which can direction traffic volumes and safety requirements by offering more or less convenient fees, as shown in[60] Insurance transfers risk from the shipowner to a third party, the insurance company, which can impose requirements for the vessel ice class and crew experience in icy and challenging conditions. Insurance prices are driven by factors as ship winterisation, class regulations, communication systems, stability, emergency Personal Protection Equipment (PPE), time of the year and route, crew experience, and different private insurances for passengers in cruise ships [60].

## 3.3 STPA

The STPA methodology proposed in [14], is integrated with the implementation of safety controls and the re-evaluation of UCAs and loss scenarios to evaluate the effectiveness of mitigation measures and to monitor the changes happening in the environment and policies. Proposed methodology for STPA is shown in **Figure 8**.

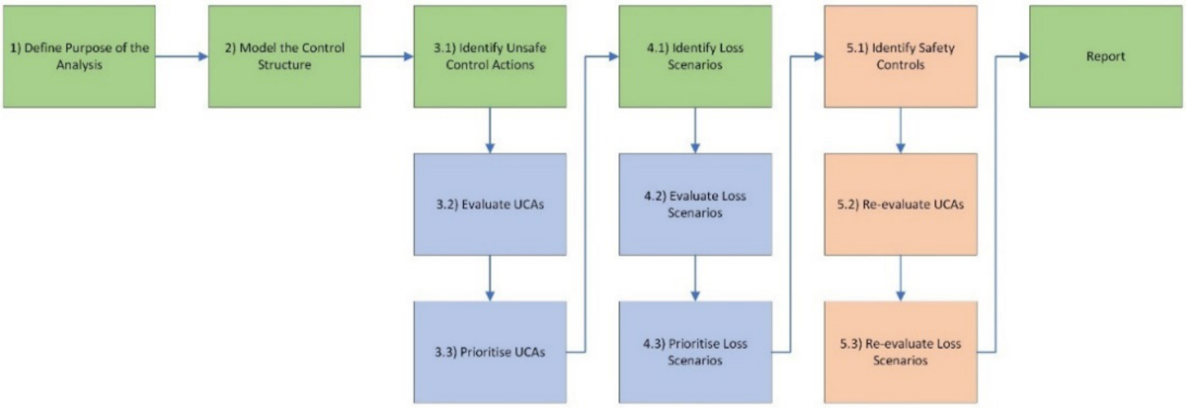


**Figure 8:** STPA Procedure Flowchart

The evaluation of UCAs and loss scenarios is carried out using RPNs (Risk Priority Numbers) following the present formulations:

$$RPN_{UCA} = SV \cdot ATR \cdot SOK_{UCA}$$

$$RPN_{loss\ scenario} = RPN_{UCA} \cdot LH \cdot SOK_{loss\ scenario} = SV \cdot ATR \cdot SOK_{UCA} \cdot LH \cdot SOK_{loss\ scenario}$$

The five criteria, as proposed in[14], are severity (SV), available time to respond (ATR), strength of knowledge on UCA ($SOK_{UCA}$), likelihood (LH), and strength of knowledge on loss scenario ($SOK_{loss\ scenario}$). Each criterion is evaluated on a 1-5 scale.

The control structure for the increased Arctic shipping traffic according to the STPA methodology is shown in Figure 9. The figure is derived from [61], [62]. Controllers are shown to exert actions on the system components (blue arrows), and receive feedback from them, (red arrows).

The STPA reported is, similarly to the FMEA, influenced by the subjectivity of the authors' judgment, and it is used to showcase an application of the proposed methodology.

Based on the control structure in **Figure 9**, 130 Unsafe Control Actions (UCAs) are identified, while after screening, 29 of them have been screened out, as their RPNUCA value were lower than 21. Some examples of screened out and highly ranked UCAs are shown in Appendix B1.

After the identification and screening of UCAs, loss scenario must be identified. Leveson and Thomas (17) use loss scenarios to describe the causal factors that can lead to UCAs and system level hazards. Two types of loss scenarios are considered answering the questions:

- Why would UCAs occur?
- Why would control actions be improperly executed or not executed, leading to hazards?

The scenarios identify specific causes leading to UCAs, feedback, and hazards. The 101 UCAs analysed resulted in 505 loss scenarios of which 40 (7.9%) have been screened out as their RPNloss scenario values were lower than 200. Some examples of screened out and highly ranked loss scenarios are shown in Appendix B2.

After the identification and screening of the loss scenarios, safety controls (SCRs) are applied to mitigate or prevent the UCAs and address their causes. It should be noted that the SCRs are the component-level and interaction-level actualization of the system-level safety constraints, following a similar relationship than the one between UCAs and system-level hazards.

The proposed safety controls focus on strengthening vessel standards, crewing qualifications, environmental protections, and emergency response capabilities for Arctic waters. Requirements are required for issues like ice-class ratings, equipment, crew training, waste handling procedures, spill response plans, and protected area designations. Emergency preparedness is bolstered through rescue vessels, infrastructure improvements, and multi-agency exercises. Compliance is monitored via inspections, audits and reporting, while impacts are assessed through environmental planning, depending on local conditions. Routing considers sensitive habitats and seasonal wildlife, with contingency plans for hazards. Enforcement is improved through certifications and international coordination. Overall, the controls aim to mitigate risks from increased shipping through stringent performance-based rules tailored for the challenging Arctic conditions and fragile ecosystems. Continual evaluation and stakeholder engagement further the goal of safe, responsible operations in this remote region.

The effectiveness of the safety controls needs to be evaluated, for this it is proposed that evaluation of the UCAs and loss scenarios is carried out again after the application of SCRs.

Re-evaluated UCAs and loss scenarios are summarised in Appendix B3.

# 4. Mitigation Measures

Different environmental mitigation measures are proposed across the two analyses, they are grouped and discussed in this section. It is possible to divide the measures in four main groups: the measures based on the Polar Code, the measures based on domestic actions, the measures based on private governance actors, and other measures based on different needs and by different actors.

The implementation and monitoring of this provisions is of vital importance to reduce the environmental impact of Arctic shipping traffic.

## 4.1 The Polar Code Measures

The IMO Polar Code [64], enforced since 2017, is implemented in Arctic Polar waters where sea ice is present north of latitude 60°N and all Polar waters south of latitude 60°S, by amending three key conventions as SOLAS, MARPOL, and STCW. It is divided into two main parts to deal with maritime safety and pollution prevention. It addresses hazard related to sea ice, topside icing, low temperatures, extended periods of darkness or daylight, high latitude, extreme weather conditions, remoteness, lack of charting data, lack of crew experience, lack of SAR equipment, reduced availability of navigational aids, and the sensitivity of the polar environments [65]. Measures proposed include structural requirements for ships operating in ice-covered areas and their navigational and communication equipment through the Polar Classes, as well as requirements on survival equipment and training obligations. The present Polar Code version does not apply to fishing vessels.

Environmental provisions are fewer than safety provisions, these measures are based mostly on MARPOL Annexes I, II, III, IV, and V and are also extended to fishing vessels. All discharge of oil is prohibited according to MARPOL Annex I, in the same manner discharges of noxious liquid substances or mixtures containing those substances is prohibited in compliance with Annex II. Sewage discharge is restricted near ice, as more than three and twelve nautical miles are required for discharge of treated and untreated sewage respectively. Garbage discharge is allowed 12 NM from land. When ice concentration is higher than 1/10 while, food waste and animal carcasses cannot be discharged onto the ice [65].

The environmental requirements have been criticized by scholars as [65], [66], as the code originally lacked a ban

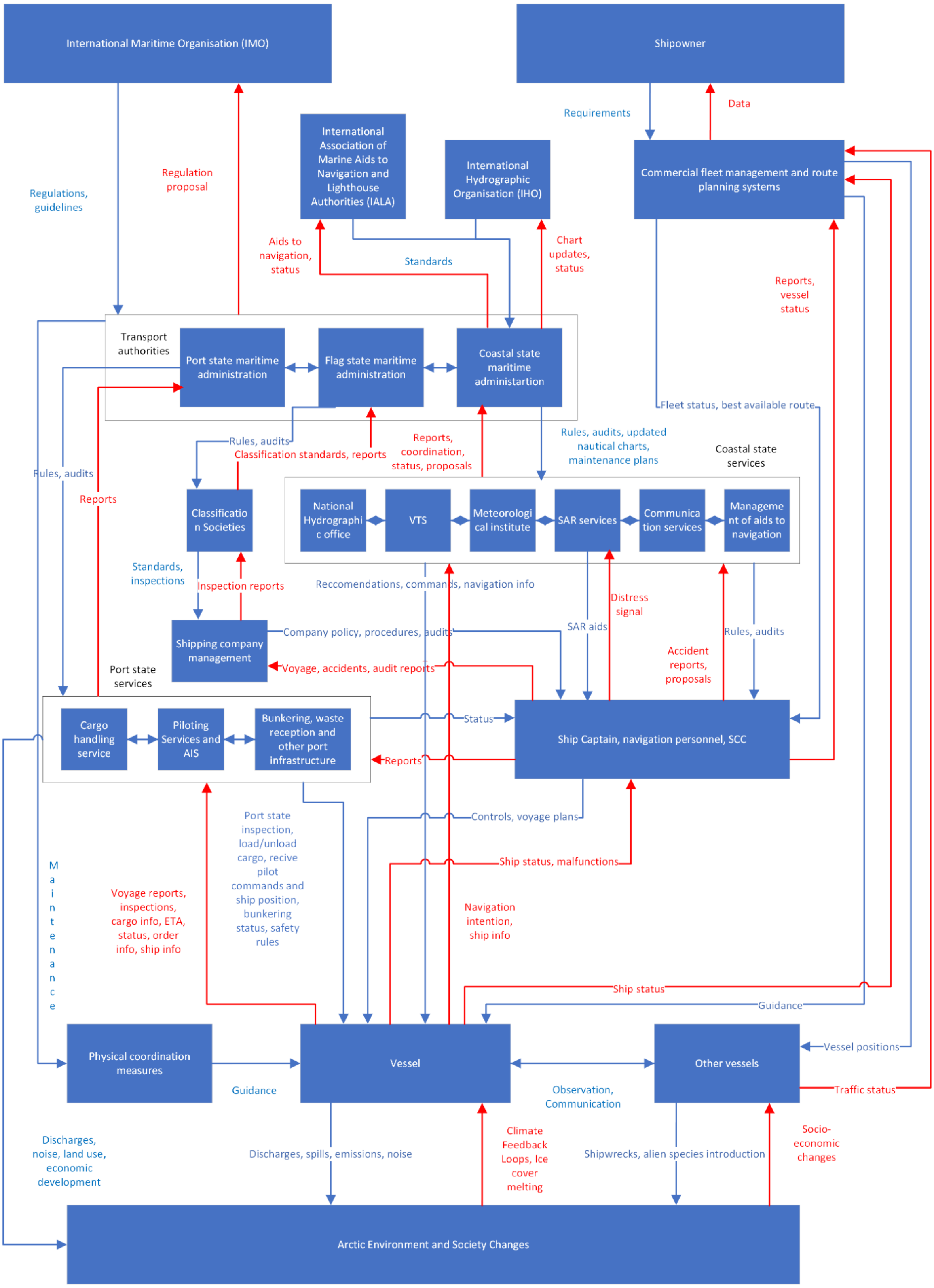


**Figure 9:** Hierarchical control structure of shipping traffic [63].

to transport and use HFO in the Arctic. Such ban is starting to be enforced only in present times as planned in [67]. At the same time the Polar Code does not refer to the mandator Annex VI of MARPOL on air pollution prevention and the Code only adopted the 0.5% sulphur content cap in 2020, as the Arctic Ocean is not protected by the status of Emission Control Area [65].

The Polar Code does not address carbon dioxide and black carbon emissions, which leads to catastrophic consequences in the Arctic region as the soot deposition increases the melting rates of the sea ice cover and the glaciers in the area. In a similar fashion the Polar Code does not regulate discharges of grey water and loss of containers packed with dangerous goods and it simply invites the vessels to adopt guidelines existing for the Antarctic area and for waters outside the polar regions.

It is of vital importance that Port State Control actively monitors the enforcement of the Polar Code through uniform guidelines, the Paris MoU and Tokio MoU should contribute to create standardised guidelines to enact between different MoUs to guarantee enforcement of the Polar Code provisions [65].

The adoption of the Polar Code exerts pressures on Arctic coastal states, as national regulations must, at least, comply to Polar Code regulations. Arctic members must enforce and respect the new Polar Code provisions and adapt their national legal framework, but they can as well maintain stricter specific local environmental requirements. Arctic states are now required to invest in SAR infrastructure, response capability, and reinforcement of their collaboration. It is important to consider the effects of climate change as an increase in drifting icebergs might be encountered in the coming years. Further shipping corridors must be identified and enforced to increase the response capabilities and ease the development of SAR infrastructure.

Different gaps exist in the Polar Code regulation and need to be addressed, to ensure a sustainable development of Arctic shipping with respects of the environment. It is highly suggested that Polar Code provisions are extended to non-SOLAS vessels, as fishing vessels, operating in the polar regions. Gaps in environmental protection are related to air pollution, where MARPOL Annex VI should be enforced in the Arctic, loss of dangerous cargo, grey water discharges, untreated sewage discharges, underwater noise, alien species introduction, use and carriage of HFO in the Arctic, spill PPR, and routeing measures [68].

Consequently, amendments to Chapter 4 of the Polar Code must be considered, as well as expansions of the code to tackle underwater noise and alien species introduction following PAME recommendations.

## 4.2 Domestic Responses

Arctic coastal states are implementing further mitigation measures than the one present on the IMO Polar Code. Following the enforcement of the Polar Code different states had to incorporate and integrate its provisions into their national legislation.

In Canada the Polar Code provisions are extended to foreign-flagged vessels as well, provided that they navigate in waters under Canadian jurisdiction. In Canadian Arctic waters additional requirements are present, limiting vessel operations to a certain navigational period, according to vessels' capabilities and limitations in ice as well as possible piloting. Several pollution prevention measures are harsher than in the Polar Code, as an example zero-discharge regimes are adopted for waste, oil, and oily mixtures. Carriage of noxious liquid substances is prohibited for certain vessel categories and a discharge restriction for sewage is imposed for vessels with a gross tonnage between 15 and 400. Cargo residue discharge is more strictly regulated, and it is prohibited to vessels navigating within the Canadian Arctic [69].

In Russia the Polar Code provisions have been incorporated in the Rules of Navigation, and further requirements are present. The Russian Rules of Navigation regulates the icebreaker assistance of ships and the pilot ice assistance, giving a precise framework for different operational activities [69][70].

In Norway, the Svalbard Environment Act banned the use and carriage of HFO in the territorial waters around Svalbard since 2022 [71]. Completing the process of reducing HFO usage in the area started in 2007 [48].

Different domestic responses are present in the Arctic states to tackle safety and environmental hazards in their region. It is recommended that Ecologically and Biologically Significant Areas (EBSAs) are identified within different states and special regulations are set in for these areas, as an example speed limits, and emission control areas should be extended to sensitive regions.

### 4.3 Private Governance Responses

Private governance, including commercial companies, NGOs, civil organisations, and other non-state actors, can also offer an answer to the environmental threats present in the Arctic region. Non-state actors can offer an innovative governance approach targeting different issues, as reported in [48]. Private governance seeks to fill the gaps left open by traditional state-based governance, an example of this is the Clean Arctic Alliance formed by civil society organisations and environmental NGOs to discuss fuel choices of companies operating in the Arctic. The business commitments taken to phase out HFO, as done by AECO starting from 2011 until a full ban for its members in 2019, are an excellent example of private responses to environmental issues. Other actions include the Arctic Corporate Shipping Pledge, which prohibits its members to use trans-Arctic shipping routes. Similarly, businesses associations could come together to enhance SAR capabilities and emergency responses.

Insurance companies can offer private governance responses setting requirements for lower fees and indexing traffic on routes that are considered safer to navigate. Environmental pollution can be considered a negative external cost, and insurances can internalise this negative cost in order to incentives businesses to enforce mitigation measures, in similar fashion requirements can be added to Polar Code provisions on crew training, and safety. Insurances enable risk-shifting, by transferring risks to insurers [60][72].

Indigenous and local knowledge needs to be accounted and integrated in Arctic governance, this would help to find better answers to issues as possible ship collisions with marine mammals in breeding areas and propose more accurate EBSAs and exclusion zones for shipping traffic. The ICC is the first indigenous organisation to achieve provisional status at the IMO, showing an increasing interest in the Inuit voice in the development of the Arctic. In Canada, Inuit organisations helped to improve the Low Impact Shipping Corridors by including co-governance and environmental protection [4]. Local communities in the Arctic Norway, especially in Longyearbyen, have been involved in the development of community guidelines, SAR, and visitor management to assist to mitigate negative effects caused by the expansion of cruise traffic in the region [4].

### 4.4 Other Measures

Different measures can be enforced to improve monitoring of environmental conditions and weather forecasting to guarantee more accurate information for decision making. Further research and improvements on shipbuilding techniques to encounter harsh conditions are also important to increase safety and reduce the probability of occurrence of accidents negatively impacting the environment.

Updated standards accounting for permafrost degradation are required for onshore infrastructure and ports, and attention to the interaction between shipping and other local transportation modes need to be placed to guarantee an efficient integration of the logistic industry in the Arctic.

Monitoring and maintenance programs need to be a priority to track changes of systems and their interactions and prevent the decay of performance of systems preventing safety hazards and environmental damage.

## 5. Discussion

### 5.1 Baseline Assessment

The necessity of monitoring and accounting for a dynamic baseline is evident, as the ongoing processes in the region are going to influence the further development of shipping and change the effectiveness of different mitigation measures. The additional environmental stressors brought by increased shipping activity are, also, already acting in the region.

Local baseline assessments are recommended for projects affecting specific regions where particular attention must be placed on local threats.

## 5.2 Monitoring Dynamic Variables

Dynamic Variables in the Arctic environment include melting of the Sea Ice cover, disrupted atmospheric and ocean circulation patterns, melting of ice of land origin, acidification of shelf seas, upwards treeline shift and increased land use, increased methane release due to permafrost collapse and ocean methane release mechanisms, and increased wildfire frequency in many Arctic regions.

These variables are expected to present significant changes in the future, even if an increase in shipping volume in the Arctic is not registered, hence, it is important to accurately monitor their evolution to determine the environmental conditions in which vessels' traffic is going to happen as well as protecting the Arctic shipping stakeholders against possible legal responsibilities for the effects on the changing environment.

Marques, Hradec and Rosenbaum [58] highlight the importance of baseline evolution as they can directly interact with the mitigation measures reducing their effectiveness. The interaction between a proposed mitigation measure and the evolution of the baseline variables is an area of concern, as an example the decrease in sea ice coverage might bring Arctic shipping to explore new seasonal routes pushing northwards exerting pressure on SAR capabilities requesting stronger investments than planned on SAR and Pollution Preparedness Response (PPR) equipment.

In order to monitor the main aspects of the Arctic environment, it is important to invest in remote sensing technologies, weather stations, sensors to measure water column properties, field surveys, subsea and terrestrial sensors. The integration and strengthening of Arctic observing systems as the International Arctic Buoy Programme (IABP), Sentinels for the Arctic Coastal Environment (SPACE), Terrestrial Ecosystem Monitoring Sites (TEMS), Circumpolar Biodiversity Monitoring Program (CBMP), Sustaining Arctic Observing Networks (SAON), Air Pollution, with a focus on Short-Lived Climate Forcers (SLCFS), Shoreline Treatment – Circumpolar Oil Spill Response Viability Analysis (S-COSRVA), and other monitoring systems lead by Arctic Council working groups as PAME, AMAP, SDWG, EPPR, and CAFF is a priority to constantly update the information about the conditions of the Arctic ecosystems.

The integration of traditional knowledge is also an important method to track environmental and societal changes in the Arctic, as traditional lifestyles might be disrupted by changes in climate and environmental conditions.

## 5.3 Environmental stressors from Arctic Shipping

Shipping activities brings additional stressors that can increase the impact of the ongoing changes in the Arctic. Shipping amplifies ongoing changes in the Arctic through elevated emissions to air and water, as levels of pollutants and GHGs rise with shipping traffic, strengthening the atmospheric warming and the ongoing feedback loops.

Deposition of black carbon, or soot, on snow and ice represents a main concern accelerating melting rates by diminishing surface albedo and accelerating climate change. Underwater noise is another concern, as chronic ecosystem disruption is introduced by vessel noise threatening animal communications and potentially impacting navigation over large areas and time periods, the impacts of noise can be intensified during sensitive life stages and in EBSAs.

Oil spills, although rare, can have severe and long-lasting effects on the Arctic's fragile coastal and marine environments as the response actions are challenging in vast and remote regions. Small regular discharges from ship operations also introduce an additional vector for contaminants to enter Arctic ecosystems. Alongside spills, biological introductions through ballast water or hull fouling present a risk for invasions of non-native species as climate changes enable their northward spread.

Expansion of onshore infrastructure to facilitate maritime activities may also accelerate localised habitat and cultural site damage, permafrost degradation, and increased contaminants emissions. The combination of impacts as collisions, emissions, and acoustic disturbance from shipping activities is contributing to influence the

Arctic ecosystems at an accelerating rate.

Careful mitigation is required to avoid exacerbating impacts of shipping on Arctic's ecosystems.

## 5.4 FMEA and STPA

FMEA and STPA are two widely used hazard identification methods. The STPA framework proposed in this work is used to identify unsafe control actions and loss scenarios as well as proposing safety controls to mitigate the consequences of hazardous system states that can fall outside the failure-centred problem space of FMEA [15].

The approach taken by FMEA makes it unable to identify non-failure scenarios that can lead to an accident. Failure scenarios correlate directly to reliability problems but not necessarily to safety problems which could arise even when reliability is guaranteed. STPA identifies critical failures, same as FMEA, but also hazardous system states that arise from unintended component interactions, inadequate design requirements, design flaws, human errors, and unsafe scenarios where no failures occur [15].

A major distinction between hazards identified through FMEA and STPA methodologies is based on the fact that FMEA results does not consider the timing and order of the actions leading to a failure mode, hence wise, most of the UCAs under the third column of the STPA has no exact equivalence in the FMEA, a specific example of this are UCA-34 (Piloting services are provided too early before entering the port/complicated itinerary) and UCA-44 (Transport authorities provide maintenance too late, after the services or the vessel already failed), their loss scenarios are outside the scope of the component emphasis that characterises FMEA.

A non-failure unsafe condition in STPA refers to a scenario where the system is operating as intended, but latent hazards that could lead to safety problems are present [15]. These hazards are often related to complex interactions, human factors, software issues, or emergent behaviour of the system that may not be immediately obvious. An example of this in the present study is given by UCA-2 (Route planning systems provide best available route based on outdated information) and UCA-32 (Piloting services are providing insufficient information to guarantee safe navigation), although in both cases the route planning systems or the piloting services provide routes or navigational aid under normal operation, there is room for human intervention to notice that the information provided is outdated or insufficient. This type of unsafe conditions cannot be detected within the FMEA scope.

A process model flaw refers to a deficiency or inadequacy in the way a process is conceptualized, designed, or executed, which can lead to safety hazards or undesired outcomes [15].

UCA-12 (Port management refuel vessels in unsafe sea states), UCA-25 (Cargo handling service is done in poor visibility situations), and UCA-41 (Transport authorities maintain services with too high frequency) are examples of process model flaws that can arise due to flawed modelling of sea state (UCA-12), meteorological conditions (UCA-25), or service conditions (UCA-41) that can lead the controller to execute a process in unsafe conditions due to lack of accurate feedback, inaccurate classification of visibility conditions, misinterpretation of correct sensor data, or abrupt changes in the environment.

FMEA presents a bottom-up approach which is used to identify potential failure modes with their causes for all the parts in a system to find negative effects [73]. The analysis starts with the lowest level components and proceeds up to the failure effect on the overall system, showing that a failure effect at a lower level becomes a failure mode of the component at the next higher level. The main purpose of FMEA is to identify potential problems in the early design process of a system and introduce countermeasures to mitigate or minimise the effects of the potential failure modes [74].

STPA, on the other hand, is a top-down method used to analyse the dynamic behaviour of the systems; it is based on a functional control diagram instead of a physical component diagram. Unlike FMEA, which is based on reliability theory, STPA is based on system theory and on STAMP where safety is approached as a system's control problem rather than a component failure problem [74]. According to [75], one of the most prominent benefits of STPA is its efficiency in analysing broader scenarios, as it takes in consideration the interaction of system components as a collection of interacting control loops.

The output of FMEA is presented in a table listing potential failure modes, their effects and causes; and potential mitigation measures and risk is evaluated through an RPN, based on severity, occurrence, and available time to respond. FMEA provides specific mitigation measures targeted at each failure mode instead than proposing controls and actions to enforce system-level safety constraints as in STPA. The outputs of STPA also include a model of the system's hierarchical control structure showing its feedback loops, a list of UCAs and possible loss scenarios highlighting the causal factors enabling the each UCA.

In summary, FMEA focuses on specific failures and proposed fixes, while STPA takes a more system-oriented view identifying unsafe control situations and proposing controls based on enforcing top-level safety constraints offering a more dynamic and convenient approach for complex and wide systems.

### 5.5 Future Framework Integration

It is worth noting how bottom-up techniques as FMEA start by identifying all possible failures, creating a very long list while STPA, a top-bottom approach, only identifies the failures and other causes that can lead to a system hazard and does not start by identifying all possible failures. STPA also offers the opportunity to stop refining causes at the point where an effective mitigation can be identified, thus leading to a difference in time and effort required by the analysis depending on the degree of mitigation deemed acceptable [76].

Both FMEA and STPA aim to manage and reduce risks associated with system failures or hazards, each method involves documentation of the analysis process, findings, and recommended actions for risk reduction. According to [74], there was no hazard type that was not found by any of the methods, although it was observed that FMEA and STPA complemented each other to find all identified hazards, this can be seen also in the present study, as both techniques identified specific hazards due to their different approach. It is possible to see that the different methods have different strengths for example in [74], FMEA identified more component failure hazards than STPA, but STPA found more software, component interaction, and system type error hazards; a similar trend can be seen in the present work. The degree of accuracy of the analysis influences the number of hazards identified by both techniques as a more developed STPA analysis should identify the total failure modes at component level as included in FMEA. However, a combination of FMEA and STPA analysis seems to yield a less resource-demanding approach to hazard identification.

## 6. Conclusions

This study developed and demonstrated a methodology for conducting environmental impact assessments of Arctic shipping activities by applying FMEA and STPA on a dynamic baseline. This approach allowed for a comprehensive evaluation of hazards from both component failures and unsafe control situations across the complex socio-technical system of Arctic shipping.

Key findings from applying the methodology included prioritization of risks related to air emissions, permafrost degradation, ship collisions and groundings, spills, and impacts on marine noise levels. Mitigation measures focused on strengthening regulatory compliance, environmental monitoring, crew training, emergency preparedness, and technological innovations. Revaluation found these measures reduced risk levels for the highest priority hazards.

A critical aspect of the proposed framework was incorporation of a dynamic baseline approach that accounts for changing Arctic conditions over time. Key variables influencing the operating environment, like sea ice cover, temperatures, and ecosystem distributions were identified. This dynamic perspective is crucial given the rapid ecological changes currently altering the Arctic baseline in ways that traditional impact assessments may overlook.

While preliminary in nature, demonstration of the methodology provided proof of concept for its utility in complex systems like Arctic shipping that involve both engineered and natural components. Future work should focus on implementing the approach for real cases through stakeholder engagement and use of quantitative modelling and data where possible to enhance rigor. Standardization of tools like FMEA and STPA could also support their broader application across other Arctic development initiatives.

Overall, the study has presented an impact assessment framework that integrates systems safety thinking with consideration of a variable environmental context. Such an integrated, evolving perspective appears well-suited for managing risks in the dynamic Arctic region and supporting sustainable growth of activities like shipping in tandem with protection of its vulnerable ecosystems. Continued evaluation and refinement will be important as Arctic conditions and operations change in a warming world.

## Author Contribution

The first author prepared the first draft of the paper. The second author contributed with introduction of the concept of a "dynamic baseline" and a thorough document review.

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## Conflict of Interest

The authors declare no conflict of interest.

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# Appendices

## Appendix A – FMEA

## Appendix A1 – Failure Modes with estimated RPNs>180

General Perspective

- 1.1 Increased GHGs emissions from ships (RPN=378, Mitigated RPN=90)
- 1.2 Reduction in surface albedo (RPN=504, Mitigated RPN=144)
- 1.4 Thawing of Permafrost (RPN=360, Mitigated RPN=105)
- 2.1 Emissions of air pollutants from ship (RPN=240, Mitigated RPN=64)
- 2.4 Emissions of nitrogen oxides (NOx) (RPN=210, Mitigated RPN=75)
- 2.5 Emissions of Sulphur Oxides (SOx) (RPN=224, Mitigated RPN=64)
- 2.6 Emissions of Black Carbon (BC) (RPN=360, Mitigated RPN=72)
- 3.10 Hull breaches from ice impact (RPN=200, Mitigated RPN=48)
- 3.11 Leakage from abandoned or sunken vessels (RPN=180, Mitigated RPN=48)
- 3.19 Collision with icebergs or submerged obstacles (RPN=200, Mitigated RPN=81)
- 5.4 Shipping Traffic (RPN=189, Mitigated RPN=60)
- 7.2 Thawing of Arctic Permafrost (RPN=180, Mitigated RPN=90)
- 9.9 Microplastic Contamination (RPN=200, Mitigated RPN=120)

Owner Perspective

- 3.5 Lack of emergency response training for personnel (RPN=225, Mitigated RPN=84)
- 4.4 Engine exhaust emissions contributing to air pollution (RPN=180, Mitigated RPN=72)
- 11.5 Vessel traffic noise (RPN=192, Mitigated RPN=108)

Contractors Perspective

- 1.1 Increased Oil Spills (RPN=180, Mitigated RPN=48)
- 1.5 Inadequate Engine Exhaust System Maintenance (RPN=180, Mitigated RPN=72)
- 4.4 Lack of Emergency Response Preparedness (RPN=225, Mitigated RPN=84)
- 6.1 Ineffective Exhaust Gas Cleaning Systems (RPN=180, Mitigated RPN=75)
- 6.3 Fuel Sulphur Content Non-compliance (RPN=224, Mitigated RPN=64)
- 9.4 Inadequate Crew Awareness of Recycling Practices (RPN=210, Mitigated RPN=84)
- 14.6 Insufficient Social Infrastructure (RPN=180, Mitigated RPN=84)

## Appendix A2 – Mitigation Measures for high RPNs Failure Modes

General Perspective:

- 1.1 Adoption of very low sulphur fuel oil (VLSFO) or distillate fuels, IMO HFO ban (IMO, 2021), regular maintenance of ship engines, use of emission control technologies, slow steaming. Complete phase out of HFO as early as possible, switch to LNG as a fuel, retrofitting ships with emission control devices, enhance monitoring and reporting of GHG emissions. CO2 and GHG emissions to decline to at least 70% and 50% respectively by 2050 [77].
- 1.2 Phase out of HFO, implementing particulate filters and exhaust scrubbers on ships, monitor and reduce BC emissions.
- 1.4 Implement standards for design in permafrost regions. Regular inspection and maintenance of structures. Implement adaptive infrastructure designs resilient to permafrost thaw (i.e.: build structures on embankments or cool the ground), enhanced monitoring, and warning systems for permafrost decay, consider climate change into planning and design of infrastructures.
- 2.1 Adoption of low sulphur fuels, IMO HFO ban (IMO, 2021), use of emission control technologies. Compliance to MARPOL Annex VI. Introduce stricter emission

standards, enforce regulations. Extend Emission Control Areas (ECAs) to the Arctic region. Increase required EEDI for Arctic vessels.

• 2.4 Use of low NOx combustion technologies, exhaust gas recirculation systems. Compliance to MARPOL Annex VI. Implement selective catalytic reduction systems, use alternative fuels.

• 2.5 Use of low-sulphur fuels, installation of exhaust gas cleaning systems. Compliance to MARPOL Annex VI. Implement stricter sulphur content regulations, use alternative fuels.

• 2.6 Use of low-sulphur fuels, installation of particulate filters. Compliance to MARPOL Annex VI. Enhance combustion efficiency through advanced engines, develop cleaner fuels. Ban of HFO fuels.

• 3.10 Implementation of reinforced hull designs, use of ice-strengthened vessels, improved ice navigation technologies

• 3.11 Removal and remediation of derelict vessels, implementation of vessel recycling programs, surveillance of abandoned vessel sites

• 3.19 Implementation of collision avoidance technologies, improved vessel manoeuvring protocols, regular risk assessments, improved routing

• 5.4 Implement speed limits for vessels, use quieter vessel designs, establish quiet shipping lanes, promote vessel noise reduction technologies.

• 7.2 Implement permafrost monitoring systems, design modifications for climate resilience.

• 9.9 Develop filtration systems, ban microplastics in personal care products.

Owner Perspective:

• 3.5 Enhanced training programs, regular refresher courses

• 4.4 Implementation of emission control technologies, adoption of alternative energy sources

• 11.5 Implement speed limits for recreational vessels, promote eco-friendly boating practices, establish quiet zones for wildlife observation.

Contractor Perspective:

• 1.1 Implement rigorous inspection and repair protocols.

• 1.5 Conduct regular emissions testing and system maintenance.

• 4.4 Establish comprehensive inspection and repair protocols, rigorously implement inspection of ballast water systems.

• 6.1 Implement rigorous inspection and maintenance procedures.

• 6.3 Implementation of emission control technologies, adoption of cleaner fuel alternatives

• 9.4 Continuous training programs, regular updates on regulations

• 14.6 Enhance monitoring and collaboration to assess and address social issues.

# Appendix B – STPA

## Appendix B1 – Highly Ranked and Screened Out UCAs

**Table 4:** Screened out and Highly Ranked UCAs

| **Screened out UCA - Examples** | **RPN** |
|---|---|
| UCA-9: Fleet management provides vessel positions too early, and is not updated frequently | 8 |
| UCA-19: Port state control inspect vessels already inspected in previous ports | 6 |
| UCA-29: Cargo handling service takes too much time to unload cargo | 8 |
| UCA-34: Piloting services are provided too early before entering the port/complicated itinerary. | 12 |
| UCA-41: Transport authorities maintain services with too high frequency. | 6 |
| UCA-74: Shipowner provides requirements too early, when vessel status and fleet management information is unknown. | 6 |
| **Highly Ranked UCA - Examples** | **RPN** |
| UCA-30: Piloting services does not provide piloting commands in port's waters or in complicated itineraries under normal situations | 64 |
| UCA-44: Transport authorities provide maintenance too late, after the services or the vessel already failed | 75 |
| UCA-67: IMO provides guidelines too late, after the scale of the threat surpassed a tipping point | 100 |
| UCA-89: Management of aids to navigation coordinate navigational aids, without effectively weighting the needs of vessels | 64 |
| UCA-90: VTS provides navigational recommendation too late, after the vessel already navigated the area | 100 |

| | |
|---|---|
| UCA-97: Meteorological institute provides meteorological data with little knowledge of models to predict evolving situations | 80 |

The screened UCAs can be categorised in different groups, to ease their use in further steps of the process. The proposed groups of UCAs for this case study are:

- Port operations
- Piloting services
- Maintenance
- SAR services
- Distress signalling
- Accident reporting
- Regulation and guidance
- Navigation services
- Meteorological services
- Safety rules
- Pollution prevention
- Invasive species
- Noise reduction
- Socioeconomic impacts

## Appendix B2 – Highly Ranked and Screened Out Loss Scenarios

**Table 5:** Screened out and Highly Ranked Loss Scenarios

| **Screened out Loss Scenario - Examples** | **RPN** |
|---|---|
| LS-16-4: Port management refuels vessel for too little time due to distraction during critical operation leading to distress in navigation | 96 |
| LS-18-5: Port state control inspects vessels following incorrect provisions because inspectors lacked proper training leading to possible accidents in navigation, routing error, and dangerous discharges | 120 |
| LS-28-4: Cargo loaded in wrong order due to distraction or fatigue of loading supervisor, leading to unchecked errors, loss of oversight and potential to exceed vessel design parameters | 144 |
| LS-33-1: Piloting services misinterpreted because of language barriers during information exchange, leading to safety-critical terms being misunderstood and non-conforming manoeuvres from miscommunication | 144 |
| LS-77-2: Wrong area charts provided due to misfiling replacing intended issue, leading to potential misrouting risks if representation was inappropriate for voyage. | 96 |
| LS-99-1: Wrong chronological order of meteorological data because of errors in manual data compilation, potentially compromising sequence integrity and trend/change analyses relying on timing. | 108 |
| **Highly Ranked Loss Scenario - Examples** | **RPN** |
| LS-15-3: Port management executes bunkering procedures in wrong order because of time pressure to reduce port stay leading to fuel spills and port scheduling congestion | 576 |
| LS-26-2: Cargo handling done disregarding dangerous goods due to failure to acquire proper permission from port, leading to non-compliance, improper stowage plans and increased risks of dangerous cargo interactions | 720 |
| LS-53-1: SAR aids stopped too soon due to overconfidence in survivability with limited information, leading to premature assumptions instead of thorough verifications, potential increased risks to persons if conditions changed or were misunderstood | 768 |
| LS-65-1: Unclear polar rules because environmental conditions were complex to characterize fully, leading to incomplete/inaccurate guidance and increased likelihood of unexpected/inadequately managed risks. | 960 |
| LS-67-1: Late guidelines because issue did not trigger attention until severity was extensive, leading to delayed risk mitigation prolonging hazardous periods. | 1200 |
| LS-120-1: Late action because noise issues did not gain prominence until severe impacts occurred, risking tolerance of effects that proactivity could have curtailed | 1200 |

The established safety controls can be categorised in the following groups:

- Construction and Equipment Standards
- Crew Training and Certification
- Emergency Response
- Environmental Protection
- Planning and Risk Management
- Port Infrastructure and Services
- Regulations and Enforcement
- Research and Technology Development
- Wildlife Protection

# Appendix B3 – Re-evaluated UCAs and Loss Scenarios

**Table 6:** UCAs and Loss Scenarios evaluated after Safety Controls implementation.

| UCA/Loss Scenario | RPN | RPN after Safety Controls |
|---|---|---|
| UCA-30: Piloting services does not provide piloting commands in port's waters or in complicated itineraries under normal situations | 64 | 36 |
| UCA-44: Transport authorities provide maintenance too late, after the services or the vessel already failed | 75 | 36 |
| UCA-67: IMO provides guidelines too late, after the scale of the threat surpassed a tipping point | 100 | 32 |
| UCA-89: Management of aids to navigation coordinate navigational aids, without effectively weighting the needs of vessels | 64 | 36 |
| UCA-90: VTS provides navigational recommendation too late, after the vessel already navigated the area | 100 | 36 |
| UCA-97: Meteorological institute provides meteorological data with little knowledge of models to predict evolving situations | 80 | 36 |
| LS-15-3: Port management executes bunkering procedures in wrong order because of time pressure to reduce port stay leading to fuel spills and port scheduling congestion | 576 | 216 |
| LS-26-2: Cargo handling done disregarding dangerous goods due to failure to acquire proper permission from port, leading to non-compliance, improper stowage plans and increased risks of dangerous cargo interactions | 720 | 324 |
| LS-53-1: SAR aids stopped too soon due to overconfidence in survivability with limited information, leading to premature assumptions instead of thorough verifications, potential increased risks to persons if conditions changed or were misunderstood | 768 | 324 |
| LS-65-1: Unclear polar rules because environmental conditions were complex to characterize fully, leading to incomplete/inaccurate guidance and increased likelihood of unexpected/inadequately managed risks. | 960 | 324 |
| LS-67-1: Late guidelines because issue did not trigger attention until severity was extensive, leading to delayed risk mitigation prolonging hazardous periods. | 1200 | 288 |
| LS-120-1: Late action because noise issues did not gain prominence until severe impacts occurred, risking tolerance of effects that proactivity could have curtailed | 1200 | 270 |