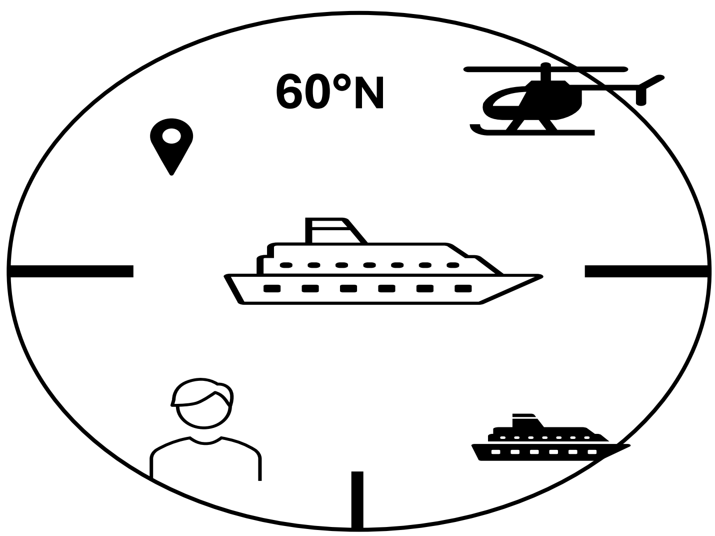
Efficiency of Emergency Response System in the Arctic: A Cruise Ship Perspective



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Abstract

This study evaluates evacuation preparedness and search and rescue (SAR) feasibility for Arctic cruise ships, as climate change increases tourism in remote, high-risk waters. Using a mixed-methods approach, it integrates regulatory review and agent-based simulation via Pathfinder to model evacuation under both normal and obstructed egress scenarios. Results show that even moderate disruptions significantly increase evacuation time, travel distances, and crew response delays. The model's validity was cross-checked against the Le Boréal incident. A combined assessment of SAR capacities in Norway, Iceland, and Greenland reveals that, in the absence of air rescue, a coordinated sea-based operation using Norwegian vessels could evacuate all passengers within 30.5 hours. In contrast, uncoordinated national efforts would require between 9.6 and 14.6 days, underscoring the critical importance of multinational cooperation in Arctic emergencies. To address systemic interdependencies, the study introduces a Functional Resonance Analysis Method (FRAM)-based framework for Arctic SAR planning. Key findings emphasize the need to revise survival time assumptions, enhance joint training exercises, and adopt inclusive planning protocols. Future research should integrate real-world incident data and consider passengers with mobility impairments to improve simulation realism.

Preface

The idea of this research came from a simple yet important question: *What happens when something goes wrong in the most remote parts of our world?* With climate change opening new routes and tourism booming in the Arctic, I was drawn to the real-life consequences of emergencies in places where help may be days away.

This thesis became an opportunity to explore the limits of preparedness, both technical and human, in the unforgiving Arctic environment. Through digital evacuation modeling, SAR analysis, and system thinking, I have tried to contribute meaningfully to an area where failure can cost lives.

I am sincerely grateful to my supervisors, especially Dewan Ali Ahsan and Anders Schmidt Kristensen, for their patient mentorship, and to Thunderhead Engineering for the software support that made this study technically possible.

Above all, this work reflects my commitment to safety, realism, and international cooperation in maritime risk management.

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Acronyms

Acronyms	Definition
ABMS	Agent-Based Modeling and Simulation
AECO	Association of Arctic Expedition Cruise Operators
EPIRB	Emergency Position-Indicating Radio Beacon
EPPR	Emergency Prevention, Preparedness and Response
IMO	International Maritime Organization
JRCC	Joint Rescue Coordination Centre
LSA	Life-Saving Appliance
MCI	Mass Casualty Incident
n.d.	No Date
PAME	Protection of the Arctic Marine Environment
SAR	Search and Rescue

Chapter 1: Introduction

1.1 Background and Context

The Arctic region, also known as the High North or Polar region, comprises eight countries: Canada, the United States (Alaska), Russia, Norway, Sweden, Finland, Iceland, and Denmark (Greenland). The region is both ecologically sensitive and strategically important, containing indigenous people, endangered wildlife, and rich natural resources. In more recent years, the Arctic has also become a target for cruise tourism. Among the Arctic nations, the growth has been mostly centered in Iceland, Norway, and Greenland which are now associated with the boom due to their remote beauty and wilderness.

Tourism in the area has improved because of the retreating sea ice, and the rise of “last-chance tourism”, where individuals wish to experience the delicate Arctic climate before it vanishes. The years between 2004 and 2007 experienced a 400% increase in cruise activity in the Arctic and in 2019, global cruise tourism revenue exceeded $154 billion. Though this growth harnesses economic opportunities, the dangers of the Arctic’s remoteness and extreme environmental conditions add complex safety challenges (Poo et al., 2024).

The unpredictability of weather patterns, poor visibility, harsh sea ice conditions, and long durations for emergency support all make Arctic maritime activities extremely difficult. These environmental elements are highly detrimental for cruise ships operating within the region. Furthermore, Denmark’s Greenland relies heavily on Danish naval assistance and Iceland relies on international alliance often resulting in slow SAR response, particularly in peripheral zones. These issues are exacerbated by the increasing number and size of inadequately outfitted polar-capable cruise ships, which raise the likelihood of extreme emergencies occurring

The Arctic region is incapable of handling Mass Casualty Incidents (MCIs), which further aggravates the operational risks. The inter combination of harsh weather, underdeveloped infrastructure, and limited emergency response resources concentrate the extremes of a region’s environment, which intensely hinder the ability to manage an effective response during a crisis. Isolated geography along with severe weather complicate rescue operations while dangerous icy waters delay rescue operations and complicated logistics. unreliable communication systems, scarce transportation routes and aging structures compromised by melting permafrost further delay an already hampered response. The absence of both weather- restricted drones and dedicated infrastructure bases which allow for easy navigation greatly complicates Search and Rescue (SAR) operations. Evacuating from these areas in the event of a disaster poses a problem as local health systems could be massively overwhelmed and coordination between response teams would become stressful. These interrelated factors focus on the Arctic’s vulnerability and highlight the urgent need for enhanced preparedness, infrastructure investment, and international cooperation to ensure the safety of cruise ship operations in this high-risk region (Malik et al., 2024).

The increase in cruise traffic through the Arctic region, combined with the unique risks associated with the area, focus on the need for further development of emergency preparedness techniques. Such systems need to be able to mobilize swiftly, even with the limited resources available in the region, and must accommodate its extreme weather. Solving these problems is critical in safeguarding human life and maintaining sustainable tourism.

This research investigates the efficiency of emergency response systems for cruise ships in Arctic waters, with a focus on Iceland, Norway, and Greenland. "Efficiency" is defined here as the ability of systems to ensure timely evacuations, coordinate across multiple agencies, and manage operations under extreme environmental stress. This study will examine the infrastructure for emergency response and the behavioral dynamics of passengers during emergencies.

Human behavior has a very noticeable effect on the efficiency of emergency evacuations. Characteristics such as age, movement, social interactions, and risk perception affect a passenger's ability to take appropriate action. During high-stress situations, especially within the Arctic where one experiences freezingly low temperatures, complete darkness, and motion instability, these factors become particularly important. Research indicates that confusion, panic, and poor decision-making can result in severely detrimental delays. Understanding these behavioral aspects is essential for effective evacuation plan strategies.

Simulation technologies are now more common for reproducing evacuation movements and assessing emergency response actions. Pathfinder, among other tools, provides sophisticated functionality for simulating evacuation processes associated with 3D environments and agent-based modeling. Simulations assist with risk assessment and route optimization when actual testing is inconvenient. This paper addresses the use of simulations in supporting Arctic cruise safety planning by improving emergency response preparedness through realistic depiction of conditions and anticipated behavior.

Maritime evacuation operations are not purely technical procedures; they are profoundly shaped by human factors. Elements like age, physical capability, stress-induced choices, and group relations significantly influence passenger actions in emergencies, especially in the harsh Arctic environment. Understanding this, the study incorporates these human factors into the Pathfinder simulation. Recognizing this, the study integrates these behavioral variables directly into the Pathfinder simulation. Agent-based modeling allows for differentiated attributes, such as varied walking speeds, reaction times, and role-based behaviors (e.g., trained crew vs. untrained passengers). By embedding these behavioral dynamics into the simulation, the model more accurately reflects real-world evacuation complexity and improves the reliability of insights for Arctic cruise preparedness.

1.2 State of the Art

Due to global warming-induced changes in navigation, there is a growing interest in remote tourism which is contributing to the rapid growth of the Arctic cruise industry. This development has raised new concerns regarding maritime safety and emergency preparedness. It appears that as cruise ships sail further into the High North, there is increasing concern and awareness about the risks associated with this remote, ice-filled, and underdeveloped region. To understand gaps in emergency response systems and identify areas for improvement, it is important to assess what systems currently exist.

Limited infrastructure in remote areas, harsh weather and sea ice all constrain Emergency operations in the Arctic. The lack of timely search and rescue (SAR) operations, which can sometimes exceed delays of over 11 hours (Hansen et al., 2016) is particularly dangerous in emergency situations (Protection of the Arctic Marine Environment [PAME], 2013). Increased capacity of cruise vessels escalates the issue as uncontested local ports and emergency services become unprepared for large scale evacuations (Johannsdottir et al., 2021).

Though the IMO Polar Code provides international regulatory standards, their actual application in Arctic conditions is unsteady. The region's emergency preparedness is further constrained by operational restrictions such as satellite communication, sparse port facilities, and low ice class capabilities. (Hansen et al., 2016).

Evacuation outcomes in maritime disasters are often shaped by psychological and behavioral variables. Case studies, such as the Costa Concordia disaster, show how panic, social ties, and decision-making delays can significantly hinder evacuation efforts (Andreadakis et al., 2024). In Arctic conditions, additional stressors such as cold temperatures, poor visibility, and physical instability complicate these responses.Such behavioral complexities require an understanding of passenger behavior under stress and how these stressors should dictate emergency response plans, crew training, and simulation frameworks. (Acejo et al., 2018)

Pathfinder and other agent-based modeling and simulation (ABMS) tools are rapidly gaining popularity in evaluating the efficacy of evacuation plans and emergency management systems. These systems not only model passenger movement in dynamic environments, but also allow modeling different demographics, mobility, and decision-making behavior (Zaman et al., 2021).

More recent research demonstrates that evacuation time can be changed by factors as reduced visibility, ship inclination, or numerous other factors (Wang et al., 2024). Unfortunately, most simulation models still seem to ignore the distinctive bounds posed by Arctic conditions. This study aims to fill the gap by incorporating SAR limitations, and other relevant features into existing models.

The Viking Sky incident in 2019 off the coast of Norway highlighted the gaps in Arctic cruise readiness. Even though passengers and crew members were saved, the crisis underscored the need for risk evaluation, backup propellers for engines, and comprehensive planning for emergencies associated with the Arctic complexity (Ibrion et al., 2021). Such incidents illustrate the consequences of inadequate planning and set cautionary examples for future readiness

The attention and focus given to the Arctic region has increased internationally, yet the enforcement of regulations continues to be inconsistent. The Arctic Ocean Review (PAME, 2013) has emphasized the importance of developing intra-regional safety policies along with fostering cooperation. However, gaps remain within cruise ship operations due to reliance on voluntary frameworks along with non-integrated governance which in turn escalates sociocultural concerns combined with environmental issues (Johannsdottir et al., 2021).

1.3 Motivation

During my studies on Risk and Safety Management, I have had the opportunity to analyze situations which involve intricate ecosystems with unique emergency systems. Cruise ship traffic is constantly growing in the Arctic region. However, the emergency preparedness in this area is quite rudimentary. The harsh climate, along with scarce Search and Rescue resources, slow response times, and limited SAR infrastructure all contribute to the risk management equation – which can be a matter of life and death.

The topic of my master's thesis was inspired by the daunting technological challenges, and the real-world concerns on safety it posed. The new developments in Arctic cruise shipping, unlike other areas, provided diverse opportunities for research. My goal was to affect the still developing field of maritime safety by proposing novel, data-driven tactics, especially with the use of computer simulations and international cooperation. This was an opportunity to merge my academic knowledge with an important problem in maritime safety

1.4 Research Objectives

The main objective of this research is to evaluate the efficiency and robustness of emergency evacuation and rescue procedures in the scope of Arctic cruise ship through simulation-based modeling, interview techniques, and risk analysis. The study has the following main objectives:

- Examine the operational and structural preparedness of principal high latitudinal states like Norway, Iceland, and Greenland (Denmark) from an organizational and administrative perspective regarding cruise ship tourism in the Arctic region, considering severe polar environment features. This includes an evaluation of both air- and sea-based Search and Rescue (SAR) assets.
- Integrate a systematic investigation with Arctic evacuation real-world incident reviews and identify critical threats.
- Use Pathfinder simulation software to create dynamic evacuation scenarios on cruise ships (e.g., blocked egress routes). The aim is to determine critical performance limitations, bottlenecks, and route vulnerabilities that probabilistically impact survival.
- Design strategies for enhancing ship evacuation procedures, interdisciplinary agency collaboration and search-and-rescue operations. These proposals focus is placed on remote Arctic regions regarding onboard emergency preparedness and external response effectiveness.

1.5 Problem Formulation

The expansion of cruise tourism along the Arctic Northeast Passage has brought forth new issues for emergency preparedness in one of the world's most remote and unforgiving environments. Even though international treaties provide safety frameworks, such as the Arctic Search and Rescue (SAR) Agreement and the IMO Polar Code, these agreements are more general in nature and do not account for the specific operational requirements of large cruise ships, which carry hundreds of passengers and have limited onboard medical and evacuation capabilities.

Cruise ships in this region face the greatest risk from potential onboard fires, ice-related incidents, and medical emergencies. The need for timely and effective response is critical; however, Arctic SAR operations are often impeded by Arctic complexity. These realities bring forth concerns regarding the responsiveness of current emergency systems and their ability to sustain the demands initiated by contemporary cruise tourism to polar waters

This research seeks to fill these gaps by analyzing the efficiency of Arctic emergency response systems as viewed from a cruise ship. It analyzes primary risk elements, evaluates domestic and international SAR capabilities, and incorporates scenario-based simulation modeling to evaluate evacuation execution under limited conditions. The objective is to formulate actions to improve Arctic cruise preparedness and promote safe maritime tourism in the region.

To guide this investigation, the following research questions are addressed:

- What are the primary risks associated with Arctic cruise ship emergencies?
- How can these risks be prioritized and addressed using a structured risk matrix?
- How does restricted access (e.g., blocked egress routes) affect passenger and crew evacuation timelines and flow dynamics onboard cruise ships?
- How capable are Arctic-bordering nations (Norway, Iceland, Greenland) in executing large-scale SAR operations in remote polar regions?
- How do the simulation results compare with historical cruise ship evacuation cases (e.g., *Le Boreal* fire)?
- What best practices can be extracted to inform future cruise ship design, and Arctic emergency planning?

This research seeks to answer these questions to establish and improve the efficiency of responding to emergencies, advance Arctic cruise operations readiness, and promoting coordinated action among key industry stakeholders towards integrated response efforts. This will contribute to the development of safe and sustainable cruise tourism in such a complex maritime setting.

1.6 Research Delimitations

This study outlines specific delimitations set to focus on key aspects of Arctic cruise ship evacuation and rescue operations.

- This study only concerns itself with emergency readiness and lifesaving activities pertaining to health. The scope deliberately neglects the ecological impact of maritime incidents.
- The analysis is confined to the three Arctic regions of Norway, Iceland, and Greenland (Denmark). The findings are specific to this area and cannot be generalized to other Arctic countries.
- As the study acknowledges the importance of psychological and social dynamics in evacuation behavior, it does not examine these aspects in detail. The study focuses on procedural aspects and movements involved in the evacuation process.

1.7 Research Limitations

This study has several limitations that should be acknowledged:

- Rather than conducting actual evacuation drills, the study relied on historical reports due to logistical challenges and the severe conditions of the Arctic environment.
- Primary data from cruise ship passengers and crew could not be collected. As a result, the analysis is based entirely on case studies and official reports used as secondary sources.
- There is very limited measured data available on actual Search and Rescue (SAR) performance in the Arctic. Therefore, SAR response modeling was carried out using metadata and detailed case study evaluations, rather than direct, situation-specific performance records.

In terms of simulation, some important constraints must be noted:

- The Pathfinder simulation includes nighttime conditions but does not consider key Arctic-specific challenges such as icy decks, snow accumulation, wind chill, and poor visibility. These environmental factors could significantly affect evacuation performance but were excluded due to technical limitations.
- The model also does not include disabled passengers, which may reduce the realism of the simulation in reflecting actual onboard conditions.
- Lastly, the simulation does not consider tilted or unstable vessels. Such conditions could significantly alter passenger movement and evacuation flow, and their absence is a limitation of the current model.

In addition to these limitations, the simulation relies on certain necessary assumptions, such as predictable reaction times for passengers and crew, and stable ship conditions during evacuation. These assumptions are further explained in Chapters 4 and 6, where the modeling approach and results are discussed in detail.

1.8 Outline of the Report

This thesis is structured as follows:

- **Chapter 2: Literature Review**
  Explores the international and regional systems which influence maritime safety in the Arctic region. This chapter studies the governance systems through IMOs, Polar Code, Arctic Council, AECO, and other constituents. Provides an overview of the Search and Rescue (SAR) systems in Norway, Iceland and Greenland. It describes the organizational structures, overall resources and resources for emergency response at sea on a regional basis.
- **Chapter 3: Methodology**
  Describes the research methodology, which integrates expert interviews, risk matrix analysis, and agent-based evacuation simulations using Pathfinder software. It explains how qualitative insights and quantitative modeling were combined to assess emergency preparedness and evacuation performance in Arctic cruise scenarios.
- **Chapter 4: Model Development and Simulation Setup**
  Details of the Pathfinder-based cruise ship evacuation model, covering layout setup, occupant profiles, behavior settings, and alignment with IMO evacuation guidelines.
- **Chapter 5: Risk Assessment**
  Describes and assesses principal risks associated with operating cruise ships in the Arctic Region. It provides a risk matrix assessing likelihood and consequences, offering a structured foundation for prioritizing emergency response strategies.
- **Chapter 6: Results**
  Discusses the results of evacuation simulations for both standard and constrained conditions. It also analyzes Arctic SAR coordination structures.
- **Chapter 7: Discussion**
  Analyzes the practical implications of simulation results, SAR response gaps, and functional system weaknesses, offering targeted recommendations for improving Arctic cruise evacuation preparedness. It outlines directions for future research.
- **Chapter 8: Conclusion**
  Concludes the study's critical insights and considers their impact on policy, strategy, and practical implementation.

Chapter 2: Literature Review

2.1 Governance Framework Supporting Emergency Response in the Arctic

The systematic international agreements, conventions, and regional collaborations supporting effective emergency response operations for Arctic cruises are critical for achieving a prompt and coordinated response due to the region's harsh and remote environment. As shown in Figure X: Governance Structure of Arctic Maritime Actors, which illustrates the operational network and relationships of various verticals of governance, the multi-tiered governance structure is important for optimal crisis management for Arctic cruise shipping, as illustrated in Figure 1.

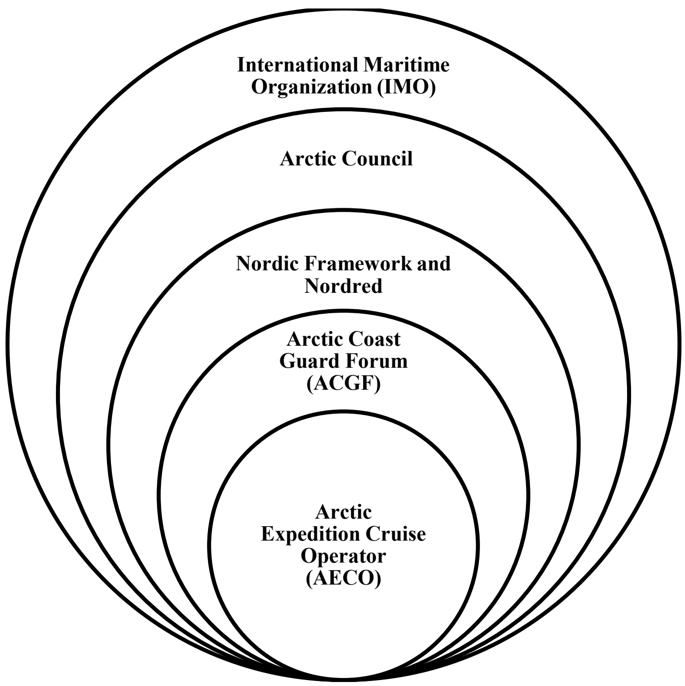

Figure 1: Governance Structure of Arctic Maritime Actors (Author-generated)

Figure 1 illustrates the governance levels relating to the maritime activities within the Arctic region. While on a global scale, the IMO incorporates international regulations on maritime safety, pollution prevention as well as crew standards of a ship. Also, within the region, the Arctic Council mainly provides "high level" the policy coordination among states and guidance on environmental protection and sustainable development.

The Nordic Framework and Nordred represent a sub-regional Nordic countries' cooperation on joint emergency preparedness and response. Moving inward, the Arctic Coast Guard Forum (ACGF) is a venue for operational interaction among the coast guards of Arctic states. It fosters joint exercises and protocols for communications as well as shared understanding of the operational environment.

At the core, Association of Arctic Expedition Cruise Operators AECO illustrates self-governing industry participation, with private cruise ship operators undertaking non-mandatory regulations aimed at improving safety, environmental protection, and coordination in the Arctic waters.

The Arctic maritime governance model presented in figure illustrates the various levels of engagement as multi-scalar and collaborative, needing the presence of international law, regional agreements, state policy, and private sector action.

2.1.1 Governance of Arctic Shipping

The governance of Arctic shipping is influenced by the International Maritime Organization, national governments, and regional agreements. These frameworks are designed to facilitate safe, eco-friendly, and sustainable shipping in the Arctic's delicate ecosystem. With respect to cruise ship operations, compliance with these regulations guarantees protection of the environment and safe operational practices.

2.1.1.1 International Maritime Organization (IMO)

The International Maritime Organization (IMO) was established in 1959 as a specialized agency of the United Nations, tasked with maintaining and developing maritime regulations. The three most important international conventions managed by the IMO are given here:

The International Maritime Organization (IMO) is responsible for maintaining and developing international regulations for maritime activities. It was established in 1959 as a specialized agency of the United Nations; here are the three major international conventions which are overseen by IMO:

1. SOLAS 1974 (The International Convention for Safety of Life at Sea)
2. MARPOL (The International Convention for the Prevention of Pollution from Ships)
3. STCW (The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers)

The SOLAS deals with:

- Fire Safety: Fire Safety Systems designed to operate under freezing temperatures (Chapter 7).
- Life-Saving Appliances: Mandatory provisions for survival craft suitable for Arctic evacuation (Chapter 8).
- Navigation Safety: Requirements for ice navigation tools and real-time data (Chapter 9).
- Communication Systems: Distress signaling and SAR coordination (Chapter 10).
- Crew Training: Specialized polar training under the STCW Convention (Chapter 12).

Strict compliance with the SOLAS enhances both ship safety and the overall effectiveness of emergency responses during Arctic cruise voyages (PAME, n.d.). Appendix 1 contains an outline of all specifications and regulatory requirements for each chapter from fire safety to crew training.

2.1.1.2 Polar Code

The Polar Code is a major advancement in the regulation of maritime activity in the polar regions. This code was developed by the International Maritime Organization (IMO) And the Polar Code is not a standalone convention; rather, it enhances and strengthens existing provisions of two core IMO Conventions: SOLAS (Safety of Life at Sea) and MARPOL (Marine Pollution Prevention).

Both SOLAS and MARPOL provide baseline global standards for ship safety and environmental protection. However, the IMO identified the need for a specific document to cope with the specific challenges found in the Arctic and Antarctic region ice hazard, isolation, and extremely rough weather.

The Polar Code became mandatory on January 1, 2017, for all ships governed by SOLAS and MARPOL and sailing in polar waters. This indicates that cruise ships, cargo vessels, and tanks sailing these waters are required to comply with special additional requirements provided in the Code, which include:

- Ice navigation and polar-specific training for masters, officers, and crews.
- Ice-strengthened hulls and systems designed for polar conditions.
- Enhanced life-saving appliances suitable for freezing environments.
- Strict pollution control measures to protect the fragile polar ecosystems.

In essence, the Polar Code acts as an additional protective layer over SOLAS and MARPOL, ensuring that ships operating in polar waters are equipped, operated, and managed to the highest standards of safety and environmental stewardship. Chapter 12 of the Polar Code requires that masters, chief mates, and navigational officers on ships in polar waters complete specialized training in accordance with the STCW Convention (International Maritime Organization [IMO], 2016).

For a detailed summary of the Polar Code's safety, equipment, and operational requirements, please refer to Appendix 2.

2.1.2 Arctic Council

The Arctic Council is an international forum that brings together Arctic states, Indigenous peoples, and other entities to advance cooperation and address common Arctic issues of concern. Established in 1996, the Council prioritizes sustainable development and the protection of the environment, facilitating dialogue and consensus throughout the region. The Council does not have the authority to establish treaties; however, it has helped member states reach important binding agreements regarding search and rescue operations, oil spill response, and scientific collaboration. The following are key agreements adopted under the auspices of the Arctic Council:

2.1.2.1 International Convention on Maritime Search and Rescue (SAR Convention) (1979)

The SAR Convention set a global system for the international coordination of maritime search and rescue operations. All coastal states, including Arctic nations, are obligated to have adequate SAR services. This is especially important due to the recent expansion of remote Arctic cruise tourism and the lack of available rescue facilities.

Key features of the SAR Convention relevant to Arctic cruise operations include:

- Establishment of Rescue Coordination Centers (RCCs) and Rescue Sub-Centers (RSCs) manned by trained personnel who will operate 24/7.
- Cross-border cooperation, allowing rescue units to enter another country's waters when needed.
- Established consistent protocols for communication during emergencies for effective collaboration in high stress scenarios.

Cooperative efforts with the Arctic nations like Norway, Denmark, Canada, and Russia enable more responsive and optimal rescue efforts due to their advanced infrastructural support in the Arctic region. Moreover, the IAMSAR manual serves as a supplement to the SAR convention by detailing how maritime and aeronautical operations should be coordinated, this is critical for rescues performed in the Arctic where helicopters are frequently used (International Maritime Organization [IMO], 1979).

2.1.2.2 Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic (2011)

The Arctic SAR Agreement facilitates cooperation to the north of the 60th parallel in the Arctic Region between the eight signatories: Canada, Denmark (and Greenland), Finland, Iceland, Norway, Russia, Sweden, and the United States.

The agreement specifies,

- The establishment of SAR Regions of Responsibility for each of the Arctic states.
- The Establishment of Designation Competent Authority (e.g. Danish Maritime Authority, JRCC Bodø in Norway, JRCC Iceland).
- Shared Use of Rescue Coordination Centers (RCCs) and Maritime RCCs permit cross-border national responses.

This structure emphasized that these policies allow for enhanced efficiency when responding to emergencies because every cruise ship in Arctic waters, regardless of judicial control, has immediate access to SAR services (Arctic Council, 2011).

Moreover, the Search and Rescue Expert Group under the EPPR working group of the Arctic Council strengthens implementation through best practice sharing, training evaluations, and reviewing incidents (Arctic Council, 2011).

2.1.2.3 Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic (2013)

The Marine Oil Pollution Preparedness and Response Agreement (MOSPA) emphasizes enhancing the capability of the Arctic countries to respond to oil spills, a critical issue for cruise ships due to the high volumes of fuel they transport.

Key provisions include:

- Protocols for coordinated actions in cases of spill response.
- Mechanisms for aid, including information exchange and cross-border assistance.
- Defined areas of responsibilities for Denmark, Iceland and Norway regarding their Arctic maritime zones.

MOSPA guidelines are executed by the Emergency Prevention, Preparedness, and Response Working Group (EPPR WG) and the Marine Environmental Response Expert Group (MER EG) in a post-need proactive MOSPA compliance to sustain Arctic environmental protection (Arctic Council, 2013).

2.1.3 Regional Collaboration: The Nordic Framework Agreement and Nordred

The purpose of both the Nordic Framework Agreement (1989) and the Nordred Agreement is to promote cross-border collaboration for swift aid and emergency response operations within the Nordic region consisting of Denmark, Norway, Sweden, Finland, and Iceland.

Some of the key provisions include:

- Facilitation of cross-border rescue operations.
- Coordination of relief teams and equipment sharing.
- Joint training exercises and legislative information sharing.

This system ensures that cruise ships sailing in Arctic waters under Nordic jurisdiction receive increased emergency response coverage and resource integration (Nordred, n.d.).

2.1.4 Arctic Coast Guard Forum (ACGF)

The Arctic Coast Guard Forum (ACGF) serves as an operational platform for the Arctic states including Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, the United States, and the United Kingdom. It is focused on the coordination, safety, and environmental protection of the Arctic maritime region. Currently, under Norway's chairmanship from 2023 to 2025, The ACGF enhances safety and security in the region through constructs for operational planning, information sharing, and multinational exercises.

Each member contributes through national guard units. Denmark's Coast Guard Command is located in Nuuk where they supervise SAR, sovereignty, and environmental protection in Greenland and the Faroe Islands. Iceland's Coast Guard is responsible for both maritime and aviation SAR and stationed in Reykjavik under the Ministry of Justice. while Norway's Coast Guard, integrated into the armed forces, conducts Arctic surveillance, fisheries control, and environmental response from its headquarters in Sortland. These organizations are the pillars of coordinated Arctic emergency response, particularly in circumstances where multi-national maritime response is essential (Arctic Coast Guard Forum, n.d.). For detailed information on the Arctic Coast Guard Forum and the national SAR structures of Denmark, Iceland, and Norway, please refer to Appendix 3.

2.1.5 Industry Collaboration: Association of Arctic Expedition Cruise Operators (AECO)

AECO participates actively in safety management of Arctic expedition cruise companies by:

- Collaborating with SAR organizations (e.g., JRCC Iceland).
- Conducting joint Arctic SAR drills.
- Enhancing ship safety through tools like vessel tracking and risk assessments.
- Assisting with the promotion of cruise vessels as "Vessels of Opportunity" for emergency responses.
- Contributing to crowd sourced data to enhance navigational safety.
- Promoting collaboration between the industry and SAR partner agencies, AECO enhances the emergency preparedness and response capabilities for Arctic tourism (AECO, n.d.).

Despite the presence of multiple international agreements and organizations, Arctic maritime governance still faces significant challenges. Enforcement is often inconsistent, and much of the cooperation between countries remains voluntary. This fragmented approach leads to delays, overlaps, and resource gaps during emergencies. While frameworks like the SAR Agreement and the Polar Code provide structure, their practical application varies widely between nations, making coordinated Arctic emergency response more difficult.

2.2 Current Search and Rescue Infrastructure and Emergency Preparedness for Arctic Maritime Emergencies

Due to the harsh environmental conditions, great distances, and lack of available emergency frameworks, navigating the Arctic waters is a notable challenge for cruise ships. The presence and timeliness of external assistance systems, especially Search and Rescue (SAR) capabilities, is critical to the efficiency of evacuation operations on these ships. This chapter analyzes the SAR support from three main Arctic countries: Norway, Iceland, and Greenland, paying particular attention to their organizational infrastructure, resource potential, and impact on evacuation operations.

2.2.1 Overview of Arctic SAR Zones

The Arctic maritime region spans millions of square kilometers, including ice-covered seas, and sparse human population centers. Due to geographic and climatic conditions, SAR interventions are often heavily constrained within the region's vastness of space. Figure 2 represents the approximate boundaries of the Arctic SAR zones as set in the "Arctic Search and Rescue Agreement" which underscores the remoteness and size of the regions where national SAR centers are mandated to operate.

Figure 2: SAR areas of responsibility according to the Arctic SAR Agreement (2011).
source: Adapted from Christodoulou et al. (2022)

2.2.1.1 Arctic Ship Accidents (2005–2017)

Figure 3 presents the breakdown of maritime incidents on a yearly basis within the Arctic jurisdiction of each state. The data shows that Iceland has had a steady increase of reported accidents after 2013, likely due to an increase in monitoring and traffic in the Arctic region. Norway and Greenland show a slower rate of reporting incidents compared to Iceland, but both have very different geographic and geo-political SAR coverage and ice conditions which pose unique operational difficulties. Overall, this data highlights the need for enhanced communication and regional coordination.

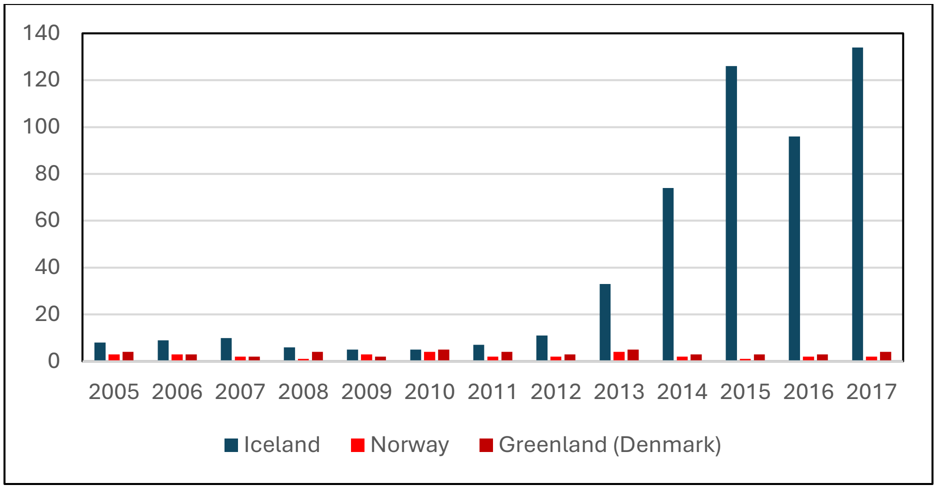

Figure 3: Arctic Ship Accidents in Iceland, Norway, and Greenland from 2005–2017.

Source: Adapted from CASA (2019).

2.2.2 Country-Specific SAR Profiles

This study examines the Search and Rescue (SAR) facilities of Norway, Iceland, and Greenland. It specifically analyzes the SAR assets of these three Arctic coastal countries to comprehend Arctic maritime emergency response operational range and shortcomings. Every nation possesses distinct SAR resources, including air rescue helicopters and ice class patrol ships, deployed to cope with polar maritime incidents situated deep within the polar seas. These profiles examine the SAR system of each country, including the extent of their geographic coverage, operational efficiency, and relevance to mass passenger evacuation from cruise ship in the High Arctic.

2.2.2.1 Norway's Arctic Search and Rescue Infrastructure

Norway is one of the biggest countries in the European continent and has a coastline of over 15,000 miles. Almost half of its total area forms part of the Arctic Circle, which includes the mainland counties of Nordland, Troms, Finnmark, and the island territories of Svalbard and Jan Mayen. Moreover, it contains an exceptional 1.5 million square kilometers of Arctic maritime territory. Its economy has transformed from the predominantly subsistence activities of fishing and livestock to include aquaculture, energy, mining, maritime transport, and even tourism. Norway has five Arctic ports such as Tromsø, Hammerfest, Vardø, Honningsvåg, and Kirkenes. Norway is also one of the world leaders in renewable energy, investing heavily in hydroelectric and wind power infrastructure located within its Arctic region.

The focus of Norway's Arctic policy encompasses sustainable development, resource management, and safeguarding of Indigenous rights. In conjunction with other members of the Arctic Council, Norway has an active focus on climate change adaptation, pollution, and conservation of marine biodiversity. Norway was the chair of the Arctic Council from 2007 to 2009. During this period, Norway promoted integrated resource management, cross-border scientific collaboration, and strategic resource management. One achievement during this period was the 2011 Arctic Search and Rescue (SAR) Agreement which put in place international cooperation for emergency response operations in the Arctic area. Through these initiatives, Norway continues to position itself as a responsible and proactive Arctic nation (Norwegian Ministry of Foreign Affairs, n.d.).

Norway coordinates its Arctic search and rescue (SAR) capabilities through the Joint Rescue Coordination Centre (JRCC), which is the focal point of their response systems. Norway's Arctic fleet comprises essential elements of its SAR mission including advanced helicopters and patrol vessels tailored for the harsh conditions of the Arctic, which greatly increases their operational efficiency. These vessels help respond to emergencies, protect vulnerable marine habitats, and assist Arctic populations in some of the world's harshest living conditions (Norwegian Ministry of Foreign Affairs, n.d.).

As one of the leading providers of Arctic search and rescue (SAR), Norway has developed a centralized, highly advanced emergency response system geared towards the region. This system is effective in particularly harsh northern latitudes and areas and provides speedy, coordinated responses. Land, maritime and aerial SAR (Search and Rescue) operations are the responsibility of the Ministry of Justice and Public Security. The country is organized in two SAR zones, with the 65th parallel north serving as the international border for maritime and administrative borders defining land-based zones.

At the forefront of these operations is Joint Rescue Coordination Centre of Northern Norway (JRCC NN) which is situated in Bodø. Founded in 1970, JRCC NN supervises Search and Rescue (SAR) operations in all Norwegian areas above the 65th parallel including Svalbard, but not Jan Mayen (Wikipedia contributors, n.d. -i). The center is manned by 23 dedicated personnel where at least two rescue controllers are on duty 24/7 to ensure continuous readiness. It operates at the strategic level in cooperation with an extensive network of resources which includes 21 police districts, fire and ambulance. The Norwegian Coast Guard, and the Royal Norwegian Air Force's 330 Squadron, which operates SAR queen helicopters for Arctic deployment. The center also works with private and volunteer groups to create a unified national SAR service (Christodoulou et al., 2022)

There are 28 Rescue Sub-Centers (RSCs) throughout Norway's police districts, including one on Svalbard. Every RSC is operated by a local police officer who works with other relevant agencies and has on call a wide network of expert advisers. After a SAR operation is initiated, the RSC designates a local on-scene coordinator which is mostly from the police, fire, or medical services. In some of the more remote areas, this position is often filled by a local sheriff, who provides valuable local knowledge regarding the navigation of the local terrain.

These operations are further supported by advanced communication systems such as satellite technology, and coastal radios, to ensure swift response to maritime distress calls. This multi-layered, cooperative approach demonstrates Norway's strategic commitment to Arctic emergency preparedness, ensuring efficient and resilient SAR operations in one of the world's most challenging environments (Christodoulou et al., 2022; Wikipedia, n.d. -i).

The 330 squadron has its base at Bardufoss Air Station and is part of the Royal Norwegian Air force. They Operate the AW101 "SAR Queen" helicopters to perform search and rescue missions, medical evacuation, and emergency missions In one of the most remote areas of the world. The helicopters have been designed for extreme environments, equipped with anti-ice systems, advanced radar, and a mobile phone detection system to enhance rescue operations in remote areas. The AW101 fully operational since 2020, it has an endurance of over 50 people and is able to carry patients in biocontainment stretchers, which is a distinct advantage for medical and large-scale disaster scenarios (Asian Defence Journal, 2020).

With several detachments across Norway, including in Banak, Bodø, Ørland, Rygge, and Florø, the squadron is always on standby for rapid deployment. It has international cooperative reach with Iceland and Russia which improves Arctic region readiness and response (Wikipedia contributors, n.d. -j).

The Jan Mayen-class offshore patrol vessels Jan Mayen (W310), Bjørnøya (W311), and Hopen (W312) greatly enhance Norway's vast coastal naval powers. These vessels support operations for over 60 days, can carry a crew of 100, and are equipped with sophisticated navigation and communication systems to ensure smooth operations in even the harshest conditions (Wikipedia contributors, n.d. -c).

Norway's Arctic fleet features advanced vessels like the RV Kronprins Haakon - a multifunctional icebreaker-class research ship designed for year-round operation in the Arctic. It has sonar and seismic tools, a moonpool, and remote submersibles, and other equipment for scientific research and other activities, which support during evacuation, fire, oil spill containment, and towing operations in ice-covered seas (Norwegian Polar Institute, n.d; Wikipedia contributors, n.d. -h).

The NoCGV Svalbard (W303), a Norwegian Coast Guard icebreaker and patrol vessel, is primarily used in the Arctic region. It possesses double acting icebreaking, a helicopter deck, and advanced navigation systems. This allows icebreakers to perform auxiliary roles such as offshore patrol, emergency response, icebreaking, and towing operations in polar waters in addition to their primary function. The NoCGV Svalbard can also tow vessels up to 100,000 tons (Wikipedia contributors, n.d. -f).

2.2.2.2 Svalbard 's Arctic Search and Rescue Infrastructure

Svalbard, an Arctic Archipelago owned by Norway, is roughly located midway between the North Pole and mainland Norway. While it is a part of Norway, most settlements are placed on the biggest island called Spitsbergen. It is also home to the two northern Arctic ports known as Longyearbyen and Barentsburg. Longyearbyen functions as the hub for several notable regional industries including coal mining, tourism and scientific research that's especially developed considering Svalbard's geo strategic position. Although it is remote and has a rough climate, does not change the fact that Svalbard is significant for Norway in terms of Arctic presence, international research cooperatives, and environmental observation policies (Christodoulou et al., 2022)

The Norwegian Governor of Svalbard oversees the enforcement of Norway's rights and duties in the Svalbard Treaty, as well as acting as the Chief of Police for the region. These responsibilities include the coordination and management of search and rescue (SAR) operations in Svalbard, SAR mission ships, and supplies. In relation to these tasks, the Governor is provided with two Super Puma long-range SAR helicopters stationed at Svalbard year-round which are set to the region's sole SAR assets. The Polarsyssel supply ship stationed in Longyearbyen for nine months each year. While the Coast Guard vessel KV Svalbard periodically visits the archipelago but primarily focused on supporting the fishing fleet, immediate availability to respond to maritime distress incidents in the area is limited.

Svalbard's health services cannot manage serious accidents independently. However, there are pre-established systems designed to reinforce medical resources from the mainland. Unfortunately, these medical resources are often late to the emergency site because of the long mobilization and deployment times. Considering the vast geographical border surrounding Svalbard, it is clear that the existing rescue capabilities, especially in terms of urgent response, are severely constrained. Most of the ships operating in the area are recreational and many of these have limited resources, expertise, and capacity to handle emergencies effectively (Kruke & Auestad, 2021).

2.2.2.3 Iceland's Arctic Search and Rescue Infrastructure

Iceland, an Arctic nation with a population of 365,000, is an actively participating country in Arctic affairs and plays an active role in the region. Served as the first Chairmanship of the Arctic Council from 2002 to 2004, Iceland was concerned with human developments, the telecommunications sector, and the cooperation of research activities in the Arctic. During its current Chairmanship, improvement of the marine environment is its priority, working to resolve issues in plastic waste, sustainable shipping practices, and the blue bioeconomy. Likewise, emphasis tends to focus on climate and green energy solutions aimed at lowering emissions and improving air quality. Advocates also work towards broadening economic prospects, gender-inclusive policies, and enhanced telecommunications for the arctic regions to strengthen inter-council cooperation through the Arctic Council.

Iceland has one Arctic port which is in Akureyri. Search and Rescue (SAR) along with maintaining the safety of the North Atlantic region is done through modern vessels and helicopter fleets which have rapid response ability. These resources are crucial in providing support and aid to vessels facing peril in the North Atlantic. (Arctic Council, n.d. -a).

The search and rescue capabilities around Iceland are managed by the Rescue Coordination Center and search and rescue (SAR) activities are supported by Icelandic Coast Guard aircraft and patrol vessels.

The Icelandic Coast Guard (ICG) manages the entire area within Iceland's coastline through the Joint Rescue Coordination Centre (JRCC), which handles search and rescue (SAR) operations in Iceland's vast Iceland's vast ocean. The Centre operates 24/7 with three to four controllers on watch all through the year. The Centre is the central hub for communication, coordination, and monitoring of maritime activities. It reacts to emergency calls, detects incoming radio frequencies, initiates patrols, and organizes rescue teams in real time.

JRCC performs various tasks. In addition to SAR, they manage Iceland Vessel Traffic Service, law enforcement at the ocean, serve as the communication line for the air and maritime vessels, rescue coordination for Civil Protection system in Iceland and the surveillance of fishing tourism, movement at border, Schengen security under the Schengen Agreement and control of territory waters.

The Centre can operate during interruptions to the power supply or the network due to its satellite stations, communication systems, and its autonomous power sources. Sophisticated data and tracking technology make use of a computer network which tracks data, collects information, and calculates SAR areas in real time. Because of these capabilities, the JRCC can respond to emergencies quickly and effectively, which is essential for search and rescue operation, maritime security, and law enforcement in Iceland. For emergencies, call 112. The ICG Operations Centre is available 24/7 at 545 2100 (Icelandic Coast Guard, n.d.).

The Icelandic Coast Guard (ICG) operates a fleet of helicopters and a surveillance aircraft which represents Iceland's search and rescue (SAR) capabilities within the 1.9 million km^2 SAR area. Their participation in maritime and land rescue, medical evacuation (medevac), and surveillance operations contribute crucial aerial support.

ICG replaced its entire fleet of helicopters from 2019 to 2021, acquiring three Airbus Super Puma H225 helicopters: TF-GRO, TF-EIR, and TF-GNA. The fleet is now comprised of three helicopters, each of which carries up to nineteen passengers. A crew consisting of two pilots, a rescue specialist, a hoist operator, and a doctor are on board during each flight. These helicopters are equipped with advanced autopilot systems, thermal cameras, searchlights, and high-performance cargo hooks, enhancing their effectiveness in search and rescue missions. They are fitted with external floats for sea landings and de-icing equipment, making them more adaptable to intense weather conditions prevalent in Iceland (Icelandic Coast Guard, n.d.).

With the commissioning of the Dash 8 Q300 surveillance and rescue aircraft TF-SIF, the Icelandic Coast Guard (ICG) received long range search and rescue (SAR) capabilities in 2009. The ICG's SAR capabilities are now multifaceted; the TF-SIF features modern radar, thermal imaging equipment, and even lifeboat deployment systems, making it a vital asset for rescues beyond the range of helicopters. The aircraft has a range of 2,100 nautical miles and can carry 12-14 passengers, though it can be re-configured to 22 seats. Furthermore, TF-SIF can be adapted for medical evacuation (medevac) missions with stretcher accommodations. Together with the Coast Guard's helicopter fleet, TF-SIF enables quick response throughout the waters of Iceland and beyond, augmenting the search, rescue, and law enforcement efforts in the North Atlantic (Icelandic Coast Guard, n.d.).

The patrol vessels of the Icelandic Coast Guard (ICG) participate in law enforcement, search and rescue, and fire-fighting activities at sea. They are equipped with world-class technology; have remarkable towing capabilities and are thus able to assist and rescue larger vessels in the waters around Iceland. According to Icelandic law, these vessels also assist isolated regions and entire populations by performing evacuation missions when overland transport is blocked due to natural disasters.

The ICG operates three patrol vessels, Þór, Freyja and Baldur, which each have a defined function in maritime safety and law enforcement and environmental protection.

Þór (operational since 2011) is the flagship of the ICG and one of the most advanced vessels of its type. It contributes significantly to the monitoring of fisheries, law enforcement, search and rescue operations, and pollution control. In addition, Þór has strong towing capability and can serve as a mobile control center in case of an emergency to ensure communication during any major outages (Icelandic Coast Guard, n.d.).

Freyja (arrived in 2021) is similar in size and facilities to Þór but has greater towing capacity which makes it critical to respond to maritime incident response especially with rising arctic traffic. Operating from Siglufjörður, it improves ICG's national response capabilities with better coverage of Iceland's waters (Icelandic Coast Guard, n.d.).

Baldur (operated since 1991) is a hydrographic survey and patrol vessel primarily used for nearshore surveying and monitoring. It is equipped with sonar and positioning systems capable of precise depth measurement, allowing for sophisticated chart production. The ICG Hydrographic Department, alongside, is responsible for the fundamental hydrological surveying and cartographic operations required for safe navigation. All ships are required to carry updated nautical charts.

Collectively, these vessels form a integral part of Iceland's search and rescue network, ensuring maritime safety in the challenging North Atlantic environment (Icelandic Coast Guard, n.d.).

2.2.2.4 Greenland's Arctic Search and Rescue Infrastructure

Greenland, which is the largest non-continental island, is extremely important in the Arctic region Due to its distinct geography and immense natural resources. Even though it is in North America, geopolitically it is linked to Europe. Covering only 19% of its landmass, Greenland's coastline is ice capped and permanently inhabited leading to one of the lowest population densities globally. The Indigenous people of Greenland, majorly the Inuit Thule Culture's descendants, have always depended on hunting for their day to day living. Greenland's hunting workforce is down to 10% and has shifted their focus towards fishing, which is the primary economic driver of the country. Major exports are shrimp, cod, and Greenland halibut. Within the North, Greenland has access to minerals like oil, rubies, diamonds, gold, copper, and Rare Earth Elements. This allows the nation to grow economically. Recently, the tourism sector has become more prominent, with an emphasis on eco-friendly tourism to preserve the region's delicate ecosystem.

Greenland, as part of the Kingdom of Denmark, has considerable self-governing authority, and increasingly so over the years. In international forum such as the Arctic Council, Greenland participates alongside Denmark and the Faroe Islands, and all three speak with a unified voice for Arctic issues. Important milestones were achieved during Denmark's Chairmanship of the Arctic Council from 2009 to 2011, including the first legally binding Arctic search and rescue (SAR) agreement which was signed during this period. This agreement enhanced inter-state cooperation between the Arctic nations towards emergency response in the region.

The isolated and harsh terrain of Greenland necessitates search and rescue capabilities for sea and aeronautical safety. Two of its Arctic ports are Nuuk Port and the Port of Ilulissat. The region is supported by a squad of vessels and helicopters that help during distress calls and guarantee swift response to emergencies in the bad arctic weather. (Arctic Council, n.d. -b)

Greenland's Search and Rescue (SAR) functions by integrating different actors within a multi-agency collaboration framework to enable timely and effective delivery in the Arctic environment. The Sea and Air Rescues are operated under the Danish Ministry of Defence, which supervises the coordination at sea and air across the vast and remote regions of the island. The Joint Arctic Command (JACO) is one of the primary actors in SAR activities through Joint Rescue Coordination Centre (JRCC) Greenland, which oversees emergency, resource mobilization, and response management. The Greenland Police is responsible for Search and Rescue missions on land, who employ their deep understanding of local area and severe weather to navigate difficult terrain. Additionally, Air Greenland also assists SAR by lending helicopters for other emergency needs (Malik et al., 2024).

Greenland's search and rescue (SAR) functions are supported by a fleet of ships and aircraft to perform in the difficult conditions of the Arctic. The Danish Navy operates four Thetis-class patrol vessels, with each one having a helicopter as an addition enhancing their performance range. Alongside them, three Knud Rasmussen class vessels are equipped with vital helicopter supporting functions such as landing and refueling, which enable advanced flight operations in more isolated areas.Greenland recently advanced its SAR capabilities through the purchase of two Airbus H225 heavy helicopters. The H225 SAR team consists of eight pilots and eight hoist operators stationed in Kangerlussuaq. These helicopters have a greater range, payload capacity, and all-weather capabilities (Air Greenland, 2023). A CL-604 Challenger surveillance aircraft based in Kangerlussuaq, about 190 miles north of Nuuk, is outfitted with emergency locating and monitoring systems which aid in the rapid response of scanning and tracking lost aircraft or vessels (Malik et al., 2024).

Greenland has been involved in national scale search and rescue exercises (SAR's) to improve response protocols for the changing Arctic conditions. The first Greenland SAREX 2012 brought all Arctic nations together for the first major coordination and effectiveness drill to test how all nations could work together to handle various emergency scenarios. Exercise Argus is another noteworthy drill where the US, Denmark, Greenland, and France jointly focused on both SAR and environmental response efforts (Malik et al., 2024).

This analysis of national SAR capabilities in Norway, Iceland, and Greenland demonstrates the fulfillment of the study's objective to assess the preparedness of Arctic states in managing cruise ship emergencies. By evaluating their organizational structures, SAR infrastructure, and international coordination, this section highlights both the strengths and limitations of Arctic SAR systems under extreme operational conditions.

Chapter 3: Methodology

3.1 Research Design

This research conducted a qualitative and quantitative analysis of crisis management and evacuation effectiveness for cruises in the Arctic region. The qualitative part analyzes important issues like perception of risks, preparedness of crew members, national SAR integration, and regulatory gaps via literature review, expert interviews, and case studies. The quantitative part analyzes simulations using Pathfinder, which measure system performance against realistic conditions. This approach allowed for data triangulation together with incorporating insights emerging from regulatory frameworks, actual incidents, and simulated emergency scenarios, thus enhancing the reliability of the results.

3.2 Data Collection Methods

a. Primary Data – Expert Interview

Interviews of a semi-structured nature were conducted with three practitioners including a command-and-control officer of a cruise vessel, a senior officer of a national Coast Guard authority, and an official with the Norwegian Maritime Authority. This step aims to integrate the study with practical perspectives and provide operational knowledge. Each participant described in detail the aspects of intra-agency cooperation, enforcement of laws, and emergency response procedures for the maritime domain in the Arctic region. Insights from the maritime authority interview were directly used to calibrate assumptions in different evacuation scenarios, particularly regarding reaction times, coordination delays, and resource availability during Arctic emergencies

b. Secondary Data – Literature and Regulatory Review

A comprehensive review of past Arctic cruise ship incident, SAR procedures, and evacuation protocol research was performed utilizing academic databases such as ScienceDirect, Scopus, SpringerLink, and ProQuest. Information was also critically evaluated from accident reports and case studies along with other IMO or Arctic Council documents to make evacuation estimates alongside hazard classification and response strategy formulation. Operational SAR data was obtained from Lloyd’s Register, Arctic Council libraries, and several national institutions from Norway, Iceland, and Greenland.

3.3 Risk Assessment Framework

The research uses a systematic risk assessment method to identify, evaluate, and prioritize risks impacting cruise ship emergency response in the Arctic. Such an approach helps understand clearly the risks presented by polar operational environment and response challenges within polar conditions. Risk assessment is defined as “the process of calculating the potential adverse effects of exposure to hazards, including measuring the magnitude of the risk, the severity of the outcome, and estimating the uncertainties involved” (Potter, 1996).

$$\text{Risk} = \text{Probability} \times \text{Consequence}$$

While the ISO 31000 standard defines risk as the effect of uncertainty on objectives, this study adopts a more operational model commonly used in safety-critical industries, where risk is quantified as the product of probability and consequence.

3.3.1 Risk Identification

The primary risks were classified into five domains: crew-related human risks, passenger-related human risks, ship-related risks, navigation and operational risks, and electronic communications risks. The investigations were carried out by consultations with other experts, reviews of literature, and the analysis of past incident reports.

3.3.2 Risk Matrix

A risk matrix tool was used to assign numerical values to the probability and consequence of each risk. The Risk Matrix presented in this report was accomplished through a clear methodology which included the review of available literature along with structured brainstorming. It follows a two-dimensional approach with consequences in the x-axis and probability in the y-axis.

Probability is quantified in five levels namely Very Unlikely, Unlikely, Possible, Likely, and Very Likely. Probability measures the chance of the occurrence of a risk. In the case a risk happens, its consequence does fall under one of five levels which are Negligible, Minor, Moderate, Significant and Catastrophic. A composite score of risk is achieved through multiplying the score of probability with consequence and establishing a total risk measurement.

The Risk Matrix enables organizations to systematically identify, assess, and prioritize hazards by considering both the likelihood and severity of potential events. This structured methodology supports the development and implementation of effective mitigation strategies, helping to ensure that overall risk exposure remains as low as reasonably practicable.

The probability levels together with relevant secondary data sources are provided in the table below. Each level consists of a score, category, and an estimated frequency range which is expressed both quantitatively and qualitatively:

Table 1: Probability Classification for Risk Matrix

Probability	score	Description
Very Unlikely	1	Once in 5+ years (≤ 0.2/year)
Unlikely	2	Once in 2–5 years (0.2–0.5/year)
Possible	3	1–2 times per year (0.5–1.5/year)
Likely	4	2–5 times per year (1.5–5/year)
Very Likely	5	More than 5 times per year (> 5/year)

The following outlines the classification of the consequence of a risk, if it occurs.

- **Negligible:** Operationally, there is no impact. Small problems of minor nature like tiny cuts, bruises, or mild exposure to extreme cold requiring basic first aid.
- **Minor:** Injuries that are low in severity, requiring minimum medical attention, and having little to no disruption. Light recovery period expected.
- **Moderate:** Greater disruption due to the need for hospital treatment for injuries such as broken bones or moderate hypothermia.
- **Significant:** Severe life-threatening conditions like extreme frostbite or heart problems due to the cold which require immediate evacuation, leading to major delays.
- **Catastrophic:** Loss of life or multiple injuries requiring vessel evacuation due to fire, out of control sinking, or severe arctic storms leading to an operational zone considered total disruption.

The final risk score (calculated by multiplying probability and consequence) is used to classify risks into five distinct categories:

- **Minimal risk (Light Green):** Minimal risks with scores ranging from 10 to 12, no or very less immediate intervention required.
- **Manageable risk (Green):** Manageable risks with scores ranging from 10 to 12, monitoring and basic precautions recommended.
- **Moderate risk (Yellow):** Moderate risks with scores ranging from 10 to 12, situations should be monitored and mitigated where feasible.
- **High risk (Orange):** High risks with scores ranging from 13 to 16, indicating situations require proactive mitigation and planning.
- **Critical risk (Red):** Critical risks with scores ranging from 15 to 27, indicating situations that demand immediate action required to prevent severe consequences.

3.4 Pathfinder Simulation

In this thesis, the simulation tool chosen was Pathfinder. It is an agent-based egress and human movement simulator developed by Thunderhead Engineering. Evacuation procedures need to be modeled to analyze the evacuation timelines, movement dynamics, and possible bottlenecks during emergencies. It simulated the emergency exit and escape route, lifeboat boarding processes to analyze the efficiency of evacuation strategies. It also models some negative factors which may cause delays, for example, passengers physically inhibiting movement. Pathfinder is known for its advanced simulation capabilities and realistic modeling of crowd decision processes, enabling identification of gaps and improvements required within prevailing procedures. The motion itself can be implemented in two modes, that are SFPE mode and steering mode. Steering mode generates an outline which an agent can follow to move. In this study, the steering mode was utilized to simulate the movement and navigation of evacuees during the evacuation modelling process. These steering behaviors included things like keeping to the current path, avoiding other agents and obstacles, preferring paths that are less populated, forming lanes during counterflow situations, attempting to stay behind faster agents, and turning corners without cutting off other agents. (Reynolds, 2002) All of these factors were computed to assign a particular score to a direction, and the velocity and acceleration required to perform the action are computed.

3.4.1 Simulation Framework

Pathfinder simulation software was integrated into the system to create realistic onboard evacuation simulations. Its Steering Mode was selected due to its responsive agent action customization, which includes route selection, avoidance of collisions, and crowd dynamics consideration. The geometric representation of the vessel along with the egress pathways was constructed using publicly available videos of the walkthroughs and deck plans, guaranteeing geometric accuracy.

For this study, two evacuation scenarios were created based on distinct conditions:

- **Standard Access Scenario (S1):** all routes and exits are accessible.
- **Starboard Blocked Scenario (S2):** egress routes located on the starboard side are obstructed.

The building occupants were simulated based on actual demographic and behavioral data, differing in walking speeds, reaction times, and designated evacuation roles. The movement of the crew was executed concerning a command hierarchy comprised of muster briefings, passenger check, room check, and coordination.

3.4.2 Arctic Evacuation Contextualization

To provide context for the simulation outcomes in an Arctic operational setting, a worst-case scenario was modeled: hull breach due to iceberg collision. This scenario incorporated:

- Delayed crew response due to off-duty hours.
- Increased risk of hypothermia.
- Progressive listing and flooding of the vessel.

This allowed evaluation of how internal evacuation performance is influenced by extreme environmental, with the simulation serving as a proxy for time-sensitive decision-making in Arctic maritime incidents.

3.5 Air and Sea-Based SAR Integration

Understanding the restricted self-rescue potential of lifeboats in polar conditions, the study included a comparison assessment of Arctic SAR capabilities. Air evacuation (SAR Queen helicopters, Airbus) was compared with sea-based evacuation timelines (Jan Mayen class vessels, ICG Þór, Polarsyssel). The national assets were evaluated both individually and collectively to calculate best and worst-case scenario rescue timeframe and constrained timelines. This two-level analysis is representative of real-world emergency coordination under the 2011 Arctic SAR Agreement.

3.6 Ethical Considerations

Ethical issues were given consideration at every step of the research process. Consent was secured from each participant who took part in collecting primary data by means of an expert interview. Participants were provided with the purpose, scope and voluntary nature of participation in detail to maintain transparency and autonomy. Also, all qualitative and quantitative data was collected, stored, and analyzed in accordance with the Aalborg University's ethics guidelines and The Danish Data Protection Agency's standards. This guaranteed confidentiality and proper handling of all research material.

Chapter 4: Model Development and Simulation Setup

This model was designed to reproduce evacuation scenarios and emergency procedures on a cruise ship with an emphasis on analytics of passenger and crew cross movement on different ship decks. Its aim is to find the most effective vertical and horizontal routes for evacuation considering areas of possible congestion while evaluating the influence of the ship's layout on evacuation efficiency.

The simulations were initially based on publicly available deck plans of cruise ships supplemented by walkthrough videos that were available online which clearly showed the design features like stairs, rooms, and arrangement of furniture. Detailed specifications of the model ship design, deck layout, crew structure, and evacuation command hierarchy are provided in Appendix 4.

4.1 Geometry Construction

The geometry of the cruise ship in Pathfinder was built based on online deck plans and walkthrough videos to ensure accuracy. Each deck was modeled in Pathfinder using the imported floor plan images as background references. Instead of creating full wall structures, major hindering furnishings, like large furniture that could obstruct evacuation paths, without modeling full wall structures. This approach created models that were less complicated and focused on evacuation dynamics.

Realistic vertical circulation was added into the model with two staircases and three elevators after analyzing deck plans alongside video footage. A staircase is located aft (stern), with the other adjacent to the reception area, right next to the bank of elevators. Two starboard side lifts located near the stern service decks 2-6 and each holds a maximum of fourteen passengers, and one port side lift mid ship serves decks three to six and has a capacity of twenty-one persons. Agents were allowed to use these elevators under specific preset conditions during evacuation scenarios which ensure control and safety in vertical movements between decks.

For the simulation, Pathfinder's Steering Mode was activated, which enabled agents to navigate around obstacles and interact with restricted areas in a realistic way. This choice enhances the realism of collision avoidance and route selection during evacuation flows. The detailed ship model created for the simulation is provided in figure 4.

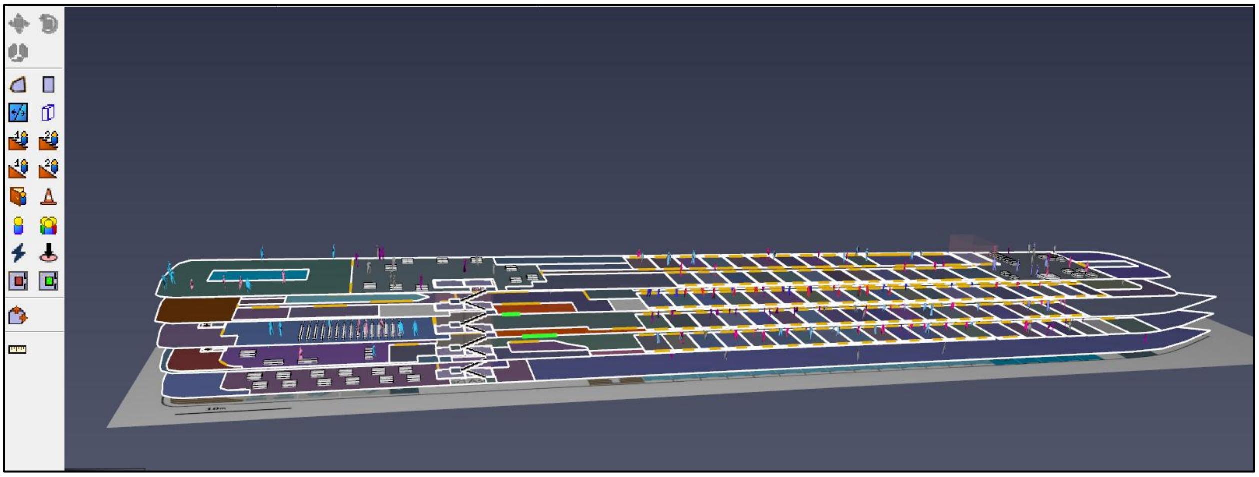

Figure 4: Model Ship in Pathfinder Simulation (Author-generated)

4.2 Deck-by-Deck Layout

On Deck 2, which contains the buffet and restaurant areas, dining tables were crafted as obstacles to facilitate an evacuation simulation. In order to ease computation, the chairs were omitted. Deck 3 consists of the passenger cabins located along with the public areas including a bar, boutique and an excursion office. The mixed-use design introduces variable occupant densities and movement patterns.

This deck is one of the main areas containing accommodation sections and a central theater; therefore, it tends to have high concentration zones. Also, it serves to be one of the main access points for embarkation from the lifeboat evacuation, mandating detailed stairway design which is vital. Deck 5 includes leisure areas such as fitness centers, massage rooms, and spa services where occupants have slower walking speeds to represent relaxation. Deck 5 contains premium suites and outdoor observation points, with direct access to open spaces influencing evacuation flow.

4.3 Occupant Modeling

Accurate occupant modeling is essential to replicate realistic evacuation scenarios and assess the effectiveness of safety protocols onboard the expedition vessel. This section explains about the settings assigned to passengers and crew members in the Pathfinder simulation model which include:

1. Demographic characteristics
2. age distribution
3. gender
4. walking speed and reaction time
5. Occupant Distribution in the Ship
6. occupant profile
7. Behavior Modeling and Scenario Integration

4.3.1 Demographic Characteristics

The vessel has two primary occupant categories: Passengers and Crew Members. There are approximately 200 passengers on board, representing a diverse group varying in age, physical activity levels, and mobility. Additionally, the vessel has 100 crew members, who are further divided into hospitality staff, technical crew, and medical personnel. The structured hierarchy is necessary for management of operations, navigation, and hospitality during the voyage.

4.3.2 Age Distribution

Most of the passengers are within the ages of 40-60 (50%), next comes 30-40 years (30%), with smallest percentages in the 20-30 years (10%) and 60-70+ years (15%) categories. For the crew members, most are between 20-40 years (60%); while 40% fall into the 40-60 years group. To present the data clearly, Figure 5 illustrates the distribution of passengers and crew across different age groups on board.

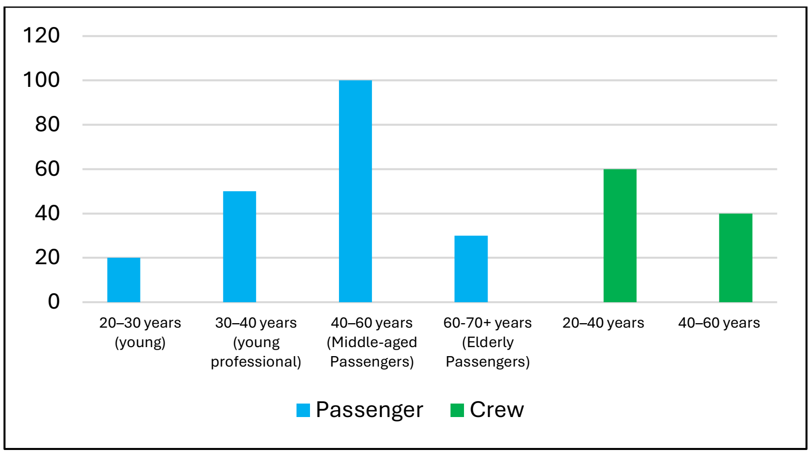

Figure 5: Occupant Distribution (Author-generated)

4.3.3 Gender

The occupants on board are divided by gender to replicate realistic evacuation actions and interaction patterns. Among the passengers, the gender distribution is quite proportional, with males accounting for about 55 percent and females for 45 percent. Figure 6 visually presents the gender distribution among passengers and crew used in the simulation model. However, the crew composition is male dominated, with approximately 65 percent male and 35 females. This subdivision into male and female categories is critical for processing the simulation because gender differences affect movement, speed, physical strength, and actions during different phases of an evacuation. To achieve reliable results, the model attempts to represent gender distribution as accurately as possible to achieve dependable evacuation results.

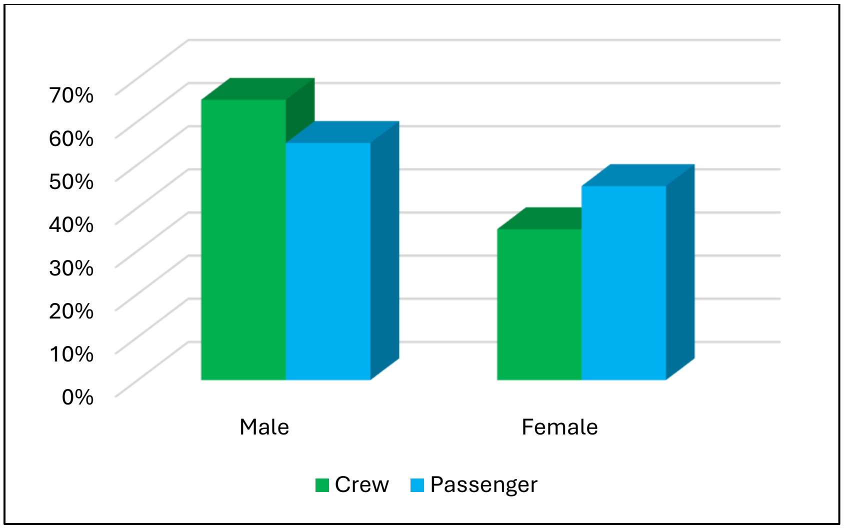

Figure 6: Gender (Author-generated)

4.3.4 Walking Speed and Reaction Times

Walking speeds were given according to criteria such as age, gender, and mobility condition. Crew members show faster movement speeds because of their physical training and readiness. Here is walking speeds by age which assists in understanding evacuation dynamics (International Maritime Organization, 2016; Browne et al., 2022).

- Young Passengers (Female): Speed ranges from 0.93 m/s to 1.55 m/s.
- Young professional (Female): Speed ranges from 0.71 m/s to 1.19 m/s.
- Middle-aged Passengers (Female): Speed ranges from 0.56 m/s to 0.94 m/s.
- Elderly Passengers (Female): Speed ranges from 0.37 m/s to 0.61 m/s.
- Young Passengers (male): Speed ranges from 1.11 m/s to 1.85 m/s.
- Young professional (male): Speed ranges from 0.97 m/s to 1.62 m/s.
- Middle-aged Passengers (male): Speed ranges from 0.84 m/s to 1.4 m/s.
- Elderly Passengers (male): Speed ranges from 0.74 m/s to 1.06 m/s.
- Crew (Females): Speed ranges from 0.93 m/s to 1.55 m/s.
- Crew (Males): Speed ranges from 1.11 m/s to 1.85 m/s.

In the evacuation model, reaction times are allocated based on the occupants' position and physical capacity. Crew members are trained for emergencies and as a result, have fast reaction times and start moving between 1 to 5 seconds after the alarm is raised. In contrast, Passengers have a wider range of reaction times with 60-120 seconds. This range considers differences in age and fitness as well as knowledge of emergency protocols. Bounding the simulation with realistic reaction times increases its accuracy and credibility.

4.3.5 Occupant Distribution in the Ship

Occupants were distributed across the vessel according to operational areas and room types. Table 2 outlines the spatial distribution of occupants throughout the vessel, based on deck level, zone, and functional role.

Table 2: Occupant Distribution (Author-generated)

Occupant Type	Deck Number	Zone	Number of Individual	Notes
Passenger	6	Cabins D (Midship)	20	Middle-aged Passengers
	6	Restaurant (back)	10	Young professional
	6	Pool (Fore)	10	Young Passengers
	5	Cabins C (Midship)	50	Middle-aged Passengers
	5	Fitness & Hammam (back)	10	Middle-aged Passengers
	4	Theatre (back)	20	Middle-aged / Young Passengers
	4	Cabins B (Midship)	10	Young professional
	3	Salon Principal (back)	10	Young Passengers
	3	Cabins A (Midship)	60	Elderly Passengers
Crew	2	Engine Room	10	Technical crew
	3	Cabins A (Midship)	20	Engineer crew
	4	Cabins B (Midship)	30	Officer & service crew
	5	Bridge & Emergency Stations (Fore)	20	Officers, safety crew
	6	Service Areas (kitchen, cleaning)	20	Service crew

In the simulation, cabin occupancy reflects real world arrangements. Senior officers and designated emergency crew are programmed to assist and manage passenger movement prior to self-evacuation, maintaining command and control during an incident. This occupant setup ensures that the Pathfinder simulation realistically reflects the diversity in age, gender, mobility, and crew responsibilities. Consequently, the evacuation analysis can thoroughly evaluate the vessel's preparedness to handle emergencies.

4.4 Occupant Profiles

In the Pathfinder simulation, occupant profiles have been carefully designed based on an extensive literature review and realistic operational assumptions. To reflect differences in movement capacity, body size, and reaction time among different groups, customized profiles were developed separately for crew members and passengers.

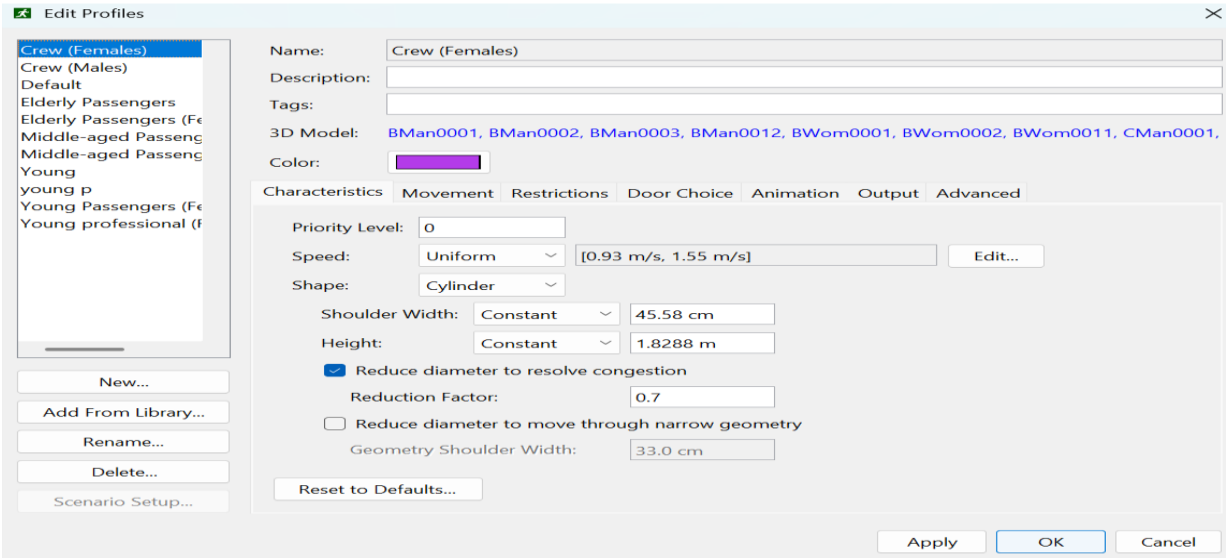

Figure 7: Pathfinder setup of occupant profiles (Author-generated)

As shown in Figure 7, the profiles are organized into two main categories:

Crew Profiles:

A. Crew (Female)
B. Crew (Male)

Passenger Profiles:

- Young Passengers (Female)
- Young Professional Passengers (Female)
- Middle-aged Passengers (Female)
- Elderly Passengers (Female)
- Young Passengers (Male)
- Middle-aged Passengers (Male)
- Elderly Passengers (Male)

Age and gender distributions among passengers and crew have been set according to Graph 1 and Graph 2 (presented earlier in the *Occupant Modeling* chapter), based on typical cruise ship demographics. Walking speeds, as described earlier and assigned based on age, gender, and physical condition, have been accurately implemented within Pathfinder to realistically simulate occupant behavior.

4.5 Behavior Modeling and Scenario Integration

Behavioral aspects during emergency evacuation such as mobility differences between occupants, individual decision making on route selection, and crew leadership dynamics are covered in this section. In Pathfinder, Customized behavioral parameters were made to accurately model the flow of evacuation and the level of congestion experienced.

For the delays attributed to pre-movement behavior, task-specific expectancy tracking was used. Trained crew members commenced movement within 0 to 10 seconds after receiving notification. On the other hand, passengers exhibited additional delays because of Sequential alarm activation, the time taken to put on thermal clothing, and initial mental disorientation, resulting in delay times between 30 and 180 seconds.

Congestion modeling was done to reflect crowding at critical choke points, such as stairwells and lifeboat stations. Pathfinder's steering mode and crowd dynamics tools were used without artificial distancing, allowing realistic representation of movement bottlenecks and group clustering during evacuation.

Distinct behaviors were created for each operational group to support structured evacuation flows. All passengers were initially directed to the theater muster station on Deck 4 using the "GoTo Room" command, followed by a 5-minute "Wait" behavior to simulate safety briefings. After the muster, Passengers then moved to their allocated lifeboats on Decks 4 and 5 along designated corridor access routes.

To distribute movement evenly and reduce congestion, four evacuation groups were assigned with specific behaviors: "D4 Boat Right," "D4 Boat Left," "D5 Boat Right," and "D5 Boat Left." Each group contained approximately 50 passengers and was guided along predefined paths toward lifeboat stations. This strategy facilitated orderly loading, reduced overlap in corridor use, and supported lifeboat deployment efficiency

As shown in Figures 8, distinct behaviors were created for each group:

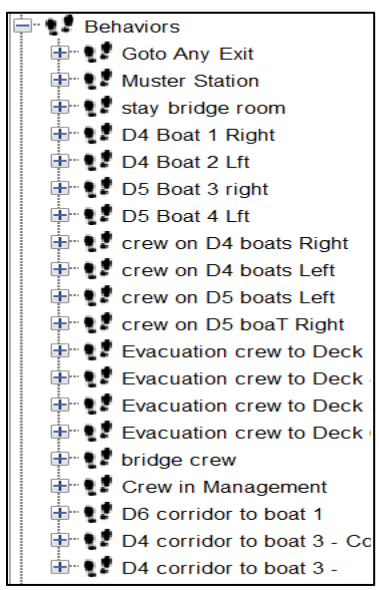

Figure 8: Pathfinder setup of Behavior (Author-generated)

A defined set of behaviors was developed in Pathfinder to systematically manage evacuation and allocate a path and role to each crew member. These behaviors include: “Crew on D4 Boats Right”, “Crew on D4 Boats Left”, “Crew on D5 Boats Left”, “Crew on D5 Boats Right”, “Evacuation Crew to Deck 3”, “Evacuation Crew to Deck 4”, “Evacuation Crew to Deck 5”, “Evacuation Crew to Deck 6”, “Bridge Crew”, and “Management Crew”.

Some bridge crew are also provided with the “Stay Bridge Room” behavior to monitor general ship functions during an emergency. These members are supervising the ship while automatic and semi-automatic systems are controlling various processes. The remaining evacuation team members are assigned to check Decks 3, 4, 5, and 6 to verify whether all cabins are vacated and all passengers are actively ready to board. After a 300-second "Wait" behavior at the theater (allowing initial passenger mobilization), evacuation crew move systematically through designated corridors ("Goto D6 Corridor"), conducting room-to-room checks. These checks include staged "Wait" periods of 600 seconds on each deck to simulate the time required for thorough inspections.

After checking the cabins, the assigned crew are escorted to their designated boat loading positions corresponding to their sides and decks, using behaviors such as “D4 Boats R Crew,” “D4 Boats L Crew,” “D5 Boats L Crew,” and “D5 Boats R Crew.” This disciplined flow of movement supports immediate evacuation assistance at all critical locations, thus ensuring that all passengers are assisted to step into lifeboats without delay and in an orderly manner. Figure 9 depicts the Pathfinder crew setup, highlighting crew role-based movement behaviors across decks.

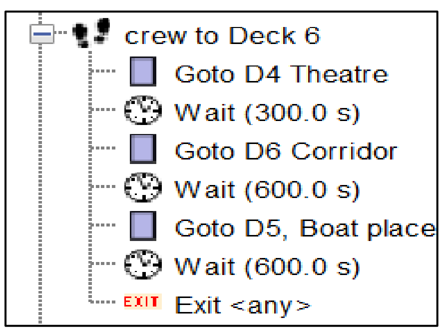

Figure 9: Crew - Pathfinder Set up (Author-generated)

This behavior structure provides a realistic sequence of crew management, passenger guidance, inspection of the decks, and organizing systematic evacuation which corresponds to a realistic maritime emergency order of operations. This simulation setup directly supports the study's goal of identifying evacuation bottlenecks and performance limitations under Arctic emergency scenarios.

4.6 Simulation Parameters and General Assumptions

To maintain realism and uniformity across all simulated evacuation scenarios, a common set of assumptions was applied. These parameters align with standard cruise ship operations during normal nighttime sailing in Arctic regions, excluding any exceptional or extreme operational disruptions unless specifically modeled.

In these scenarios, it is presumed that the vessel remains fully accessible for evacuation. Movement throughout the ship is unrestricted as all decks, corridors, staircases, and exits remain open and clear. Communication systems such as emergency alarms, PA announcements, and other relevant communications are available and operating without any delays or technical malfunctions. The shipboard environment replicates standard night conditions wherein lights and visibility are at average levels. No other external hindrances are experienced unless stated in the scope of specific scenario parameters.

These baseline assumptions provide a controlled environment within which human behavior, movement patterns, and spatial dynamics can be accurately modeled. They are essential for isolating the impact of internal architectural features and demographic characteristics on evacuation performance.

4.7 Compliance with IMO MSC.1/Circ.1533 Guidelines

The evacuation simulation model has been developed as per the International Maritime Organization's MSC.1/Circ.1533: Revised Guidelines on Evacuation Analysis for New and Existing Passenger Ships issued in 2016. These guidelines serve as best international benchmarks for estimation and modeling onboard passenger vessels.

The following are some of the simulation's key features:

- **Pre-Movement (Reaction) Times**
  An assigned reaction time was calculated according to IMO guidelines. Among trained crew members, response times range from 1 to 5 seconds. Passengers, however, display longer response times of anywhere from 60-120 seconds, depending on age and condition. These ranges reflect real-world behavioral variability and ensure credible pre-movement modeling (IMO, 2016. -a).
- **Muster and Assembly Analysis**
  The evacuation sequence was subdivided into two principal phases: (1) assembly at muster stations and (2) boarding into lifeboats. The model makes sure that all passengers arrive at muster stations within the 30-minute benchmark set by SOLAS performance criteria (IMO, 2016. -a).
- **Route Capacity and Bottleneck Modeling**
  The escape routes, staircases, and corridors were evaluated concerning their capacity for movement. The model implements appropriate crowd flow behavior as noted in the Circular, including congestion accumulation and clearance rates. The dynamic steering

engine of Pathfinder was applied to group movement and negotiation of space without the presence of spacing constraints.

The simulation follows these guidelines to MSC.1/Circ.1533 to ensure methodological precision, enhances evacuation performance results credibility, accuracy, and applicability, and aligns with frameworks recognized globally (IMO, 2016. -a).

Building on the established simulation model, the following sections examine its application in evaluating evacuation performance under varying Arctic conditions.

Chapter 5: Risk Assessment

The Arctic's remote, harsh environment poses novel challenges for the operation of cruise ships. Emergency response efforts in this area are complicated by severe weather conditions, sparse land infrastructure, and inefficient communication systems. Growing cruise ship tourism in the Arctic poses significant risks if sufficient proactive measures, such as planning and protection, are not established. A systematic assessment of risks is essential to ensure passenger safety and environmental protection. This chapter provides a strategy to analyze the various types of hazards that could obstruct emergency responses on Arctic cruise ships. Risk assessment starts with defining major categories of risks and then a risk matrix is constructed to rank certain risk categories based on likelihood and impact.

5.1 Risk Identification

This part describes the primary risk that influences the efficiency of emergency response in Arctic cruise vessels. The risks can be grouped into five major categories:

5.1.1 Crew-Related Human Risks

Within the context of an Arctic cruise ship's emergency response, there are several crucial human risks concerning anthropogenic behavior regarding action and task execution in activity domains that have been identified.

One critical problem has to do with delay of alarm triggering, which is associated to crew hesitation. The reasons for such delays in alarm setting are always aimed at reducing panic among the passengers. However, this hesitation may lead to very serious delays in initiating evacuation procedures (Andreadakis et al., 2024).

This issue is made worse by the distinct lack of training, particularly on lower-ranking crews who tend to receive only basic orientation training while the officers undergo a detailed one. This difference in training results in a lack of crew integration and preparedness in responding to emergencies.

Another factor includes lack of leadership during emergencies where poor decision-making and miscommunication results in some needed actions not being undertaken on time. Some other members are overconfident with regards to their abilities which leads them to neglecting set safety measures and protocols which support smooth coordination during emergency situations.

Emergency responses are affected by poor muster station management. Confusion at assembly points often hampers the smooth embarkation of lifeboats, particularly when there is a loss of communication between the crew and the bridge, or the crew and passengers. This type of breakdown in communication can lead to disorderly and ineffective evacuations (Andreadakis et al., 2024).

Human error plays a significant role as well. Crew fatigue, miscalculations, and poor decision-making pose problems that are made worse by the extreme cold paired with the high level of physical exertion. Heavy protective clothing, such as thick gloves and heavy gear, can hinder effective handling of firefighting equipment and speed during critical moments.

Slips, trips, and falls are greater problems when placed in the context of a wet or icy deck. These events greatly impair the ability to respond to an emergency and raise the risk of injury amongst active crew members.

Under institutional variables such as discrimination and job insecurity, lack of trust may prevent crew from openly expressing concerns or reporting safety issues. It is this silence that allows hazards to persist and reduce the overall responsiveness of emergency situations (Dalaklis & Baxevani, 2018).

5.1.2 Passenger-Related Human Risks

The behavior of cruise passengers is problematic because it interferes with the efficiency of emergency response systems on-board Arctic cruise ships.

The most critical problem is denial and delayed reaction in which passengers tend to ignore or minimize the significance of warning signals. This response dramatically slows down processes during the most important primary phases of an emergency.

On the opposite side of the spectrum, panic and overreacting can cause severe delays and physical crowding around muster points or exits which disrupts crew activities and greatly exacerbates the danger for all passengers. One such factor contributing to this response is inadequate knowledge of safety protocols since a substantial number of passengers do not actively participate in safety drills (Andreadakis et al., 2024).

Evacuation procedures become more challenging in Arctic environments due to cold weather impairment. Extremely low temperatures have the potential to reduce a passenger's range of movement and cognitive function, increasing the likelihood of confusion, slower physical movement, and injury sustained (Malik et al., 2024).

5.1.3 Ship-Related Risks

The cruise ships structural and mechanical integrity greatly impacts the efficiency of its emergency response mechanisms, particularly under the harsh and volatile conditions of the Arctic. Life-saving efforts and evacuation strategies can be critically impacted due to ship design and equipment inadequacy under cold weather stress.

A notable vulnerability arises from both structural and stability inadequacies, which can greatly endanger safe evacuation. Poorly designed corridors, stairwells, and exits tend to create overcrowding during emergencies, which hinder the movement of passengers and crew. Such spatial organizational inefficiencies tend to increase evacuation time while also increasing the chances of injuries or procedural breakdowns (Andreadakis et al., 2024).

Flooding, along with other catastrophic onboard incidents like fire and collision, can render lifeboat evacuation unsafe or impossible. In many cases, rising water levels can obstruct access to lifeboat stations and hinder the lowering of lifeboats (Andreadakis et al., 2024).

In Arctic conditions, additional complexities derive from equipment failures caused by low temperatures. Sub-Zero conditions disable firefighting systems which include hoses, nozzles, valves, and liquid extinguishing agents during the critical timeframe, which severely diminishes a vessel's onboard emergency readiness (International Maritime Organization [IMO], 2014).

Lifeboat deployment issues also remain a problem of interest. Factors like Ice accumulation, malfunctioning lowering mechanisms, and improper passenger distribution, among other things, can lead to delays, overcrowding, or even situations where the lifeboats cannot be launched when necessary (Andreadakis et al., 2024). Even when lifeboats are deployed, mechanical malfunctions such as engine failure and loss of steering control significantly decrease the utility of the lifeboats in rescue missions (Hansen et al., 2016).

The failure of core operational systems like propulsion, electrical supply, and fuel management can initiate primary failure chains which in turn affect lighting, alarms, and communication systems. Because the crew is disabled from responding to pervasive situational awareness or coordination challenges during high-stress scenarios, these systems pose even more of a disruption (Malik et al., 2024)

Lastly, hull damage from grounding or ice impacts can cause rapid flooding, block internal pathways and overpower the onboard containment systems. This damage can worsen rapidly even under stable conditions with ice and weather, obstructing critical escape routes and increasing the time needed for responding to emergency situations (Johannsdottir et al., 2021).

5.1.4 Navigation and Operational Risks

Navigational and operational risks greatly affect the efficiency of emergency response systems in Arctic cruises. A primary issue is the lack of appropriate navigational charts because several regions in the Arctic are poorly mapped. This absence of charting places vessels at risk of uncharted dangers such as shallow waters and ice formations, which significantly increases the chances of an accident occurring in these poorly charted, high-risk areas (Cruise Committee, 2022; Lloyd’s & Chatham House, 2012).

Moreover, narrow passages in the Arctic, such as fjords which are very narrow and severely at risk of grounding. These regions require sophisticated navigation. Any minor miscalculation could delay critical response actions or even prevent timely evacuations (Johannsdottir et al., 2021).

Limited emergency infrastructure in the Arctic, including a lack of auxiliary vessels and long response times, significantly complicates rescue efforts. During emergencies, ships may need to manage crises independently for protracted periods, which can hinder evacuation and response actions (Hansen et al., 2016).

Finally, navigating satellites with little to no meteorological data often leads to unreliable navigation, which significantly complicates predicting weather and ice conditions. Further, this unpredictability raises the chances of navigational inaccuracies, potentially delaying emergency responses or misdirecting evacuation efforts (Lloyd's & Chatham House, 2012)

5.1.5 Communications Risks

Effective electronic communication is critical for coordinating emergency responses. However, some factors in Arctic cruise operations contribute to significant communication risks that hinder emergency response efficiency.

One of the primary issues is magnetic and solar interference, which can disrupt vital communication systems. Additionally, satellite limitations in the Arctic region, particularly above 70°-72° North, result in weak GPS signals that impair accurate navigation and tracking, complicating emergency response efforts (Lloyd's & Chatham House, 2012)

In the region, satellite networks have a low data transfer capacity (limited bandwidth) which limits the ability to send critical data during emergencies, negatively affecting important updates (Lloyd's & Chatham House, 2012)

Poor satellite coverage, in addition to radio blackouts, leads to communication breakdowns that cripple the ship's interactions with external rescue vessels or other ships (Hansen et al., 2016). This unreliable communication adds to the difficulty of coordinating the evacuation and other emergency processes.

Furthermore, the region's inaccessibility, coupled with fierce weather, darkness, and other conditions, can lead to prolonged delays in response and communication, increasing the time needed to respond to emergencies (Andreadakis et al., 2024)

Such poor telecommunication systems also make it difficult to provide timely updates crucial for effective decision-making like the weather information, ice conditions, or the ship's emergency status. All of these reasons may reduce the effectiveness of evacuation and rescue operations (Lloyd's & Chatham House, 2012)

In conclusion, the Arctic's unique environmental, operational, and human-related risks present significant challenges to the efficiency of emergency response systems aboard cruise ships. From crew behavior and passenger reactions to ship vulnerabilities and unpredictable weather, these risks can delay response times and complicate evacuations. Understanding and addressing these risks is essential for improving emergency response systems in the Arctic. The next section will examine these risks in more detail through a risk matrix to further evaluate their impact on emergency response efficiency.

5.2 Risk Matrix

To effectively prioritize and manage the wide range of risks identified in Arctic cruise operations, a structured evaluation method is essential. While the previous discussion provided a qualitative assessment of human, technical, and shep related hazards, the following section applies a quantitative approach using a risk matrix. This allows for the systematic comparison of risk severity and likelihood, helping to distinguish between critical threats that require immediate intervention and lower-priority issues that can be monitored over time. By assigning risk scores based on established probability and consequence criteria, the matrix supports informed decision-making and targeted mitigation planning tailored to Arctic cruise ship emergencies.

Figure 10 presents the Risk Classification Matrix used to evaluate and prioritize hazards in Arctic maritime operations. In this study, only the highest-risk factors categorized in the red zone of the risk matrix, namely Collision (25), Technical Failures (20), and Fire (15) were prioritized for further analysis. These risks present the most severe consequences in Arctic cruise operations and demand immediate mitigation. By focusing simulation efforts on these critical scenarios, particularly collisions, the study aims to develop strategies that reduce their likelihood and impact through improved evacuation modeling and enhanced preparedness planning.

Consequence/Probability		Impact →				
		Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Catastrophic (5)
Likelihood ↑	Very Likely (5)	Deck Equipment Wear & Tear (5)	Slips, Trips, and Falls (10)	Failure in Communication (15)	Severe Weather (hurricanes, storms, high seas) (20)	Collision (25)
	Likely (4)	Routine Maintenance Tasks (4)	Minor Documentation Errors (8)	Grounding (12)	Equipment Failure(16)	Technical Failures (Engine Failure) (20)
	Possible (3)	Unsafe Speed (3)	Inappropriate use of technology/equipment	Contact (9)	Poor Judgment /Visibility(12)	Fire(15)
	Unlikely (2)	Poor Design (2)	Rule Violations (4)	Cybersecurity Breach (6)	Inadequate Crew Training(8)	Virus Outbreak (10)
	Very Unlikely (1)	Lack of manufacturer guidance (1)	rms or Equipment Test F	Navigation Chart Errors (3)	Operational Errors (4)	Explosion (5)

Figure 10: Risk Classification Matrix for Arctic Maritime Operations (Author-generated)
Note. Table developed by the author based on insights from Andreadakis et al. (2024); Arctic Council (2009); Tang et al. (2013), and Bailey et al. (2010).

The risks specified and captured in the matrix arise from a mixed approach combining extensive literature study and guided brainstorming sessions with the domain experts. Insights were gained from scholarly literature and shipping industry safety documents, and practical hazards deriving from the actual maritime operations were also brought in during the brainstorming stage. For instance, researchers highlighted fire and evacuation-related risks because of their consequences on life-saving operations (Andreadakis et al., 2024). Weather and environmental risks are included in the Arctic report (Arctic Council, 2009), which is most pertinent to maritime activities in high-latitude or Arctic regions. The authors of the study concluded communication breakdowns, misplaced technological applications, and the gap between perceived risks and actual incidents contrary to the expectations as lagging some of the main obstructing factors to operational efficiency (Bailey et al., 2010; Tang et al., 2013)

This chapter achieves the objective of conducting systematic risk assessment for Arctic cruise operations. By identifying critical Hazards across human, technical, and ship domains, and evaluating their severity through a structured risk matrix, the study provides a comprehensive understanding of vulnerabilities that impact emergency response efficiency. These insights form a foundational step for transitioning into simulation-based analysis, where collision scenarios identified as critical threats are examined through Pathfinder to evaluate evacuation efficiency and support improved safety planning in Arctic cruise operations.

Chapter 6: Results

In alignment with the study's objective of improving evacuation planning through simulation, the following analysis models a realistic Arctic emergency using Pathfinder software. Collision, identified as a critical risk in the risk matrix, was selected as the primary scenario trigger specifically, a hull breach from an iceberg impact. Two evacuation scenarios were simulated using Pathfinder: a standard evacuation with all routes accessible (S1), and a blocked starboard-side scenario (S2) representing partial structural failure or obstruction during an Arctic emergency. By comparing these standard and restricted egress scenarios, the simulation identifies evacuation bottlenecks, travel delays, and coordination challenges, offering valuable insights for enhancing emergency preparedness aboard Arctic cruise vessels

6.1 Arctic Emergency Scenario

In this scenario, a cruise ship with 200 passengers and 100 crew members is navigating through the remote, ice-infested region of the Arctic Ocean close to Svalbard. The ship is equipped with emergency systems such as lifeboats, survival suits, and operational communication systems in compliance with the Polar Code regulations. Despite this preparedness, the ship collides with an uncharted iceberg, causing catastrophic damage on the vessel's starboard side and breaching the hull.

The vessel starts flooding with water on the lower decks which results in the ship listing heavily and compromising its structural stability. As a result, the risk of capsizing is increased. The captain evaluates the threat and declares a full-scale emergency which leads to the initiation of the evacuation plan. Considering the isolation of the ship, there is no immediate search and rescue support available, and the ship's crew is solely responsible for conducting a coordinated evacuation

The environmental context heightens the urgency of the situation. Arctic conditions involve extreme cold which may lead to hypothermia and the psychological stress of a rapidly deteriorating ship structure which threatens survival. The crew must coordinate the transfer of all individuals to lifeboats in a highly systematic and efficient manner to mitigate further loss of life. This scenario emphasis the importance of well-rehearsed emergency plans, crew preparedness, and robust onboard coordination in Arctic cruise operations.

6.2 Scenario-Specific Assumptions

The simulation of the iceberg collision scenario includes a set of tailored considerations which describe the specifics of this highly Arctic incident. These considerations are critical for understanding behavior and timing of evacuation within the context of the scenario, unlike the general model framing boundaries presented in Chapter 8.

The incident occurs during the night when most passengers are asleep, resulting in slowed individual response times and delayed initial mobilization.

Approximately one third of the crew is also off duty or asleep at the time of impact; only the awake crew respond immediately which creates an initial manpower limitation in managing the emergency.

Progressive flooding is occurring on the lower decks, primarily on the starboard side due to hull breach which contributes to increased instability and listing of the vessel.

The ship, if performed efficiently, still has some time to lose fueling flood doors before the reserve subjective uncontested structural integrity collapses but does allow window for full unobstructed evacuation.

No search and rescue assets (SAR) are immediately available due to the vessels' remote arctic position making sovereign evacuation the sole prerogative of ship crew.

There is an increased risk of hypothermia due to exposure and time of survival in lifeboats, which heightens the urgency for evacuation.

These aspects inform the operational boundaries and behavioral dynamics modeled in the simulated evacuation activities. They evaluate how limited personnel, compromised stability, and harsh time-sensitive cold exposure risks affect decision making, efficiency, and performance during emergencies in Arctic cruise scenarios.

6.3 Evacuation Strategy

The evacuation procedure on board follows a structured, multi-phase strategy that ensures the safety of both crew and passengers. The Figure below illustrates the core phases Assembly, Evacuation, and Rescue beginning from the initial incident detection to the final rescue. Responsibilities are clearly divided: the crew handles coordination and life-saving apparatus, while passengers are guided to safety through detailed procedures. The evacuation strategy illustrated below was described by a command-and-control officer of a cruise vessel during an interview conducted for this study.

6.3.1 Emegency Response Phase

This phase is initiated immediately after the detection of an emergency onboard. The ship's two-phase alarm system is implemented to ensure a controlled and well-coordinated evacuation. The process begins with crew activation, followed by passenger mobilization, guided entirely by trained staff and officers.

Upon the first alarm, all crew members report immediately to the muster station at the theatre on Deck 4. Here, the Staff Captain explains the situation and outlines the evacuation protocol. This ensures that the crew is fully prepared to assist passengers once the general alarm is set. Figure 11 illustrates the crew response timeline, showing the structured sequence from initial alarm to full crew mobilization and briefing at the muster station

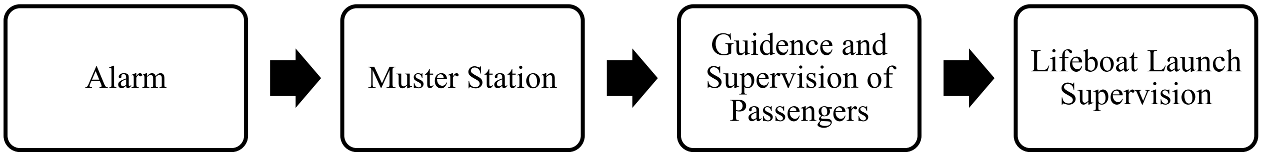

Figure 11: Crew Timeline (Author-generated)

After the crew is briefed and deployed, the second alarm is triggered for passengers. All passengers are instructed to return to their cabins to dress appropriately (including donning thermal clothing due to the Arctic environment), and then proceed to the theatre on Deck 4, which serves as the primary muster station for all. Figure 12 shows standardized evacuation flow from alarm activation to muster station assembly, guiding passengers through designated routes.

Figure 12: Passenger Timeline (Author-generated)

6.3.2 Evacuation Phase

The evacuation phase starts as soon as the ship's Captain gives the order to abandon ship. Passengers who are already at the muster points wait to be directed to their respective boarding areas. The crew set up Life Saving Appliances (LSAs) such as the lifeboats and prepare them for immediate use. To ensure quick and easy access, and speed of retrieval, passengers are assigned to specific lifeboats according to passenger profiles to balance access and speed: elderly and middle-aged passengers are assigned to Deck 4's boats, while younger participants and crew members head to Deck 5.

Boarding is conducted under supervision to minimize congestion and maximize efficiency. Once lifeboats are filled and cleared, deployment begins. If sea conditions or ship stability warrant, alternatives such as air evacuation via helicopter may be initiated at the discretion of the Staff Captain.

6.3.3 Rescue Phase

The final phase commences after the lifeboat launching is done. While lifeboats do give some degree of protection, they are not equipped to exposure particularly to Arctic or subarctic conditions for long periods of time, air and sea-based SAR (Search and Rescue) units are dispatched as quickly as possible to prevent hypothermia and fatigue.

The rescue may involve helicopters and other vessels; other vessels might also involve bringing lifeboats to the rescue depending on asset availability and distance from the region. The rescue operation tends to prioritize the most vulnerable individuals, people which especially in advanced stage medical condition or show indicators of cold exposure. This stage transitions evacuees from lifeboats to fully secure environments, ensuring medical attention, warmth, and shelter.

Figure 13 provides a clear timeline of these phases, emphasizing the importance of command decisions, structured crew response, and integrated rescue operations in successfully managing large-scale shipboard evacuations.

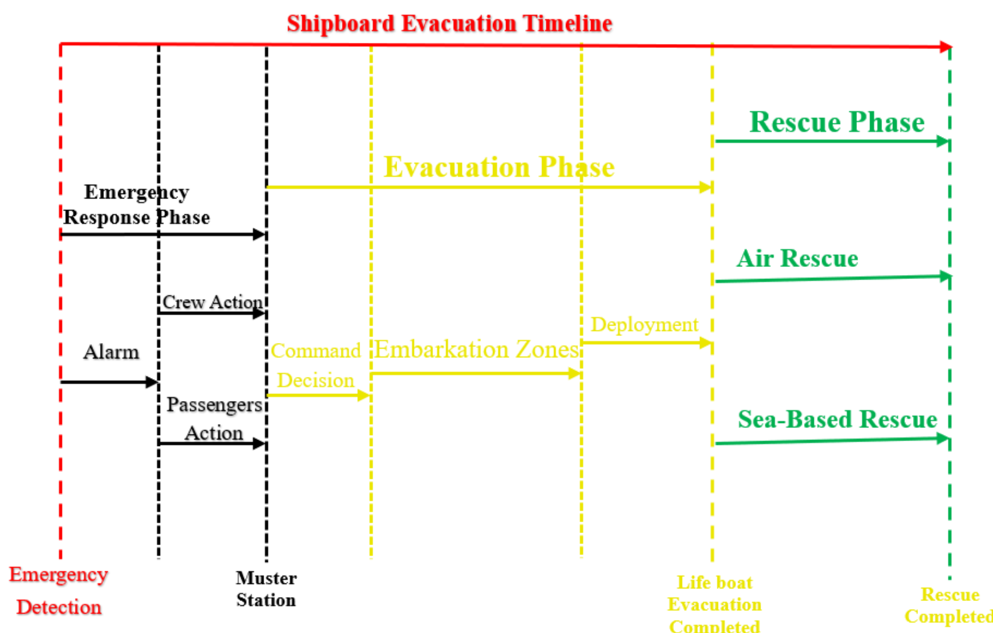

Figure 13: Timeline of Evacuation Phases (Author-generated)

The following symbols are used in the diagram to represent each stage of the evacuation process and its key phases:

Red Arrow: Overall Evacuation Timeline

Black Arrows: Emergency Phase (Alarm, Assembly)

Yellow Arrows: Evacuation Phase (Embarkation, Deployment)

Green Arrows: Rescue Phase (Air and Sea based Evacuation)

Dotted Lines: Phase boundaries

6.4 Evacuation Simulation Results & Arctic SAR Coordination

This section integrates the outcomes from agent-based evacuation modeling along with an extensive review of Arctic Search and Rescue (SAR) resources to evaluate the polar cruise ship emergency readiness. The first part explains the analyses of two evacuation scenarios Standard

Access and Starboard Blocked, estimating the evacuation time, travel distances, coordination at the muster stations, and other activities proportional to the restricted egress route using the Pathfinder simulation. The second part is concerned with Multinational Arctic SAR response plans as a case study applying the theory developed in part one having broadened the scope to the context of actual environments validating previously formulated models. In such regions at high latitude, remote and harsh climate, efficient rescue is severely dependent on airborne evacuation armaments (e.g., helicopters outfitted with winch systems for swift personnel extraction) and maritime assets (e.g., ice-strengthened patrol vessels for prolonged supportive position and sheltering survivors). Integrating all these layers, dealing with internal evacuation processes, performance onboard and external rescue planning and coordination, lowering the mortality rate during an Arctic maritime emergency.

Part 1: Pathfinder Simulation Results

6.4.1 Evacuation Performance Analysis

This report presents a comparative analysis of two evacuation scenarios onboard a cruise ship using agent-based modeling:

1. Standard Access Scenario 1 (S1): All evacuation routes are available.
2. Starboard Blocked Scenario 2 (S2): The starboard side evacuation routes are restricted.

6.4.2 Key Metrics Comparison

The goal is to evaluate how partial access obstruction impacts evacuation performance, travel distance, and muster station timelines. A detailed summary of the Pathfinder evacuation simulation results for both the standard access (S1) and starboard blocked (S2) scenarios is provided in Appendix 5.

6.4.2.1 Completion Time Analysis

The average completion time rose from 1633.8 seconds in the standard access scenario to 1653.4 seconds in the starboard blocked scenario, representing a 1.2% increase due to rerouting. Notably, the standard deviation of completion times with a 273.3 second average dropped to 246.2 seconds, which is a 9.9% improvement in average consistency. Moreover, total evacuation time rose from 2109.6 seconds to 2186.4 seconds, which is an increase of 3.6% in overall evacuation time indicating the restricted egress route.

6.4.2.2 Travel Distance Analysis

The mean travel distance grew from 169.7 meters to 216.2 meters in the starboard blocked condition which showed an increase of 27.4% that coincides with longer travel detours that were needed to access exits. Likewise, the standard deviation, which is a measure of the individual variability within a dataset's average, increased from 49.3 meters to 61.4 meters, indicating an increase of 24.5% in the individual variability of evacuation paths. This highlights how the limitation of access forced evacuees to reroute through more restrictive access into and cross through decks leading to outside areas using narrower or heavily congested corridors which increased overall travel effort, added a heightened level of complexity, and system complexity. The figure 14 provides information that a measurable increase in evacuation time and distance increases under the starboard blocked condition, demonstrating the operational impact of restricted egress pathways,increases in travel distance, variability, and overall system strain.

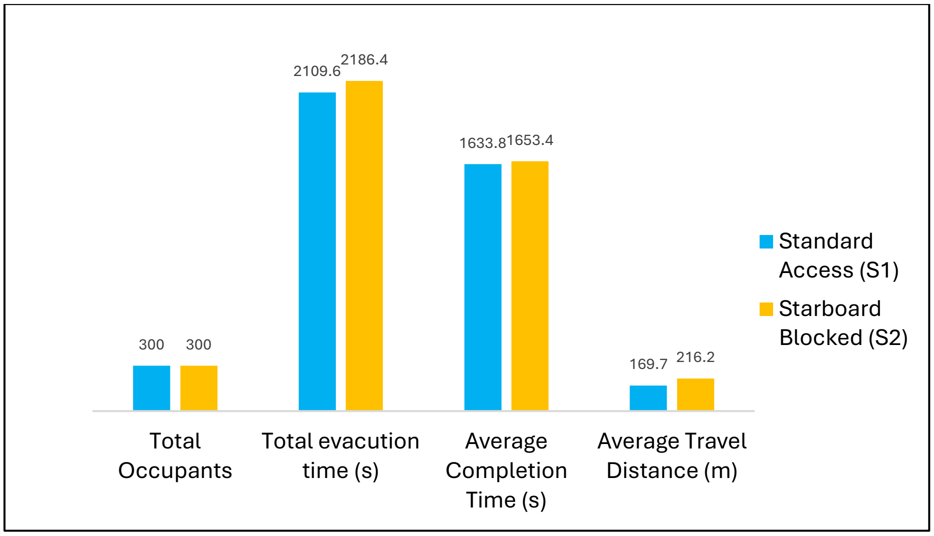

Figure 14: Evacuation Metrics between Standard Access (S1) and Starboard Blocked (S2) Scenarios (Author-generated)

6.4.2.3 Occupant Flow to Muster Station

The figure 15 for both Standard Access (S1) and Starboard Blocked (S2) scenarios show the time-dependent variation in the number of occupants present in the Theatre muster station.

In Standard Access (S1), occupants began arriving at the muster station earlier, with a smoother and more continuous accumulation pattern, peaking slightly above 160 occupants around the 1000-second mark. The decline in occupancy indicates an organized transfer to lifeboats, with the room vacated before 2000 seconds.

In contrast, Starboard Blocked (S2), which includes the Starboard Blocked condition, displays a more erratic accumulation pattern, with initial buildup showing more oscillations due to congestion and rerouting challenges. Although the peak number of occupants remains comparable, their residence time in the D4 Theatre extends longer, and evacuation from the room is slightly delayed compared to S1.

This comparison emphasizes how access restrictions in S2 led to less efficient and more variable occupant movement, highlighting the critical role of uninterrupted egress in maintaining orderly evacuation flows and minimizing time spent in critical muster locations.

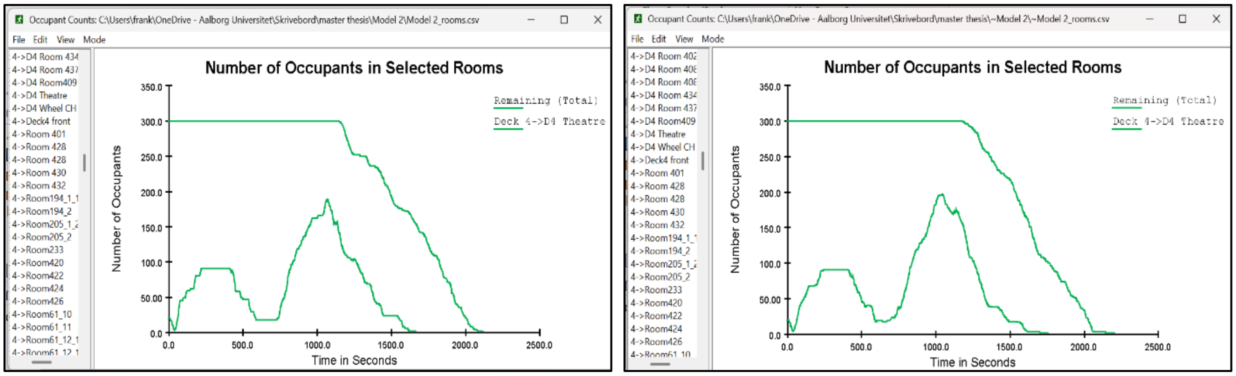

Figure 15: Standard Access and Starboard Blocked (Author-generated)

6.4.2.4 Crew Arrival Time at Muster Stations

Under the standard access scenario, crew members arrived at the muster stations in 223.1 seconds. This time worsened to 248.4 seconds in the starboard blocked scenario which represents an increased delay of 11.3%, over 25 second difference. Such a delay may critically affect the efficiency of the initial phases of emergency response coordination and the management of crowd control, especially during the initial phases when leadership presence is essential. Figures 16 and 17 illustrate the differences in crew arrival times at muster stations under the standard access and starboard blocked scenarios, respectively, highlighting the operational impact of restricted egress routes

Figure 16: Standard Access (Author-generated)

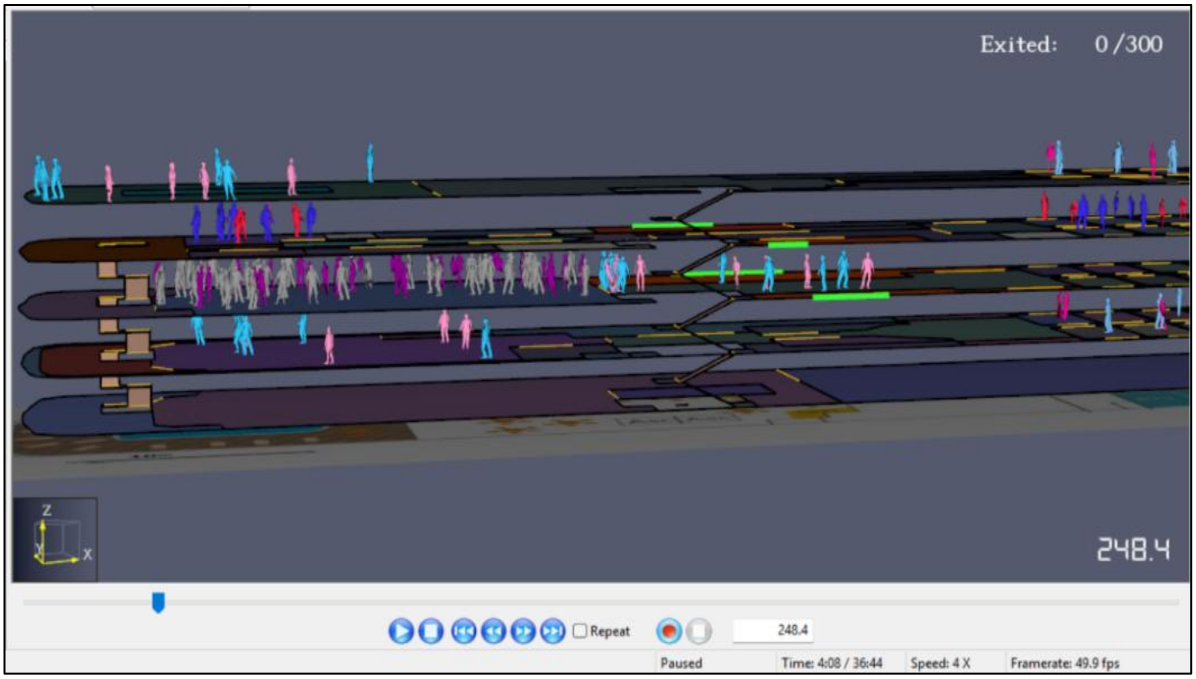

Figure 17: Starboard Blocked (Author-generated)

6.4.2.5 Passenger Muster Station Arrival Time

In the Standard Access scenario, passengers reached muster stations in 1071.9 seconds. This further heightened under the Starboard Blocked conditions to 1143.2 seconds, resulting in a delay of roughly 71.3 seconds or 6.7% increase. This delay underscores the additional travel burden and route changes required due to restricted egress which creates additional bottlenecks that complicate the assembly process and impact the schedule of subsequent evacuation phases.

In conclusion, although all participants were evacuated in both cases, the Starboard Blocked condition case presented some measurable challenges such as moderate increases in evacuation delays, increased vertical distance, and crew participation engagement being severely diminished. This exemplifies why it is important to have multiple pathways and egress evacuation planning that allow for additional access and interchangeable routes. Such planning is fundamental in providing dynamic routing measures needed to execute successful separation maneuvers during real-world emergency situations.

Although all individuals were evacuated in both scenarios, the differences in time, path complexity, and congestion patterns illustrate how evacuation design directly impacts performance. These comparative findings are discussed in the following chapter.

6.4.3 Real-World Verification of Evacuation Modeling

To evaluate the reliability of the evacuation model beyond regulatory benchmarks, simulation results were compared with real-world data from a documented passenger ship evacuation. In that event, approximately 350 passengers and crew were evacuated in 45 minutes, under hazardous weather conditions (40–45 knot winds and rough seas), utilizing lifeboats, helicopter airlift, and support from other vessels (The Maritime Executive, 2016).

Simulations in this study were conducted assuming normal conditions and estimating a total time of 35 minutes for all individuals to reach the lifeboats, not considering the time it took to launch the boats. This means that the average assembly time placed in the simulation was much closer to the actual operation which included launch, transfer delays, and environmental constraints.

Key behavioral and logistical elements observed in the real evacuation including rapid crew response, effective safety protocols, and leadership aligned with assumptions used in the simulation (e.g. crew preparedness and defined muster protocols). This consistency between modeled outcomes and actual performance underlines the model's credibility and suggests that it reasonably reflects real evacuation dynamics, especially for the assembly phase.

Part 2: Arctic SAR Coordination Framework

With the internal evacuation simulation complete, the second part of this analysis assesses external Search and Rescue (SAR) response times and coordination in Arctic emergencies.

6.4.4 Accident Location and SAR Coordination Zone

The simulated accident site is in the central Arctic region, positioned roughly approximately the same distance from several surrounding Arctic nations. The nearest SAR ports include Tromsø, Norway (~1,250 km), Longyearbyen, Svalbard (~750 km), Akureyri, Iceland (~1,150 km), and Nuuk, Greenland (~1,600 km). These distances reinforce the logistical complexity and need for tri-national coordination in Arctic emergency scenarios. Figure 18 shows the accident site and the nearest SAR ports in each country which are responsible for emergency response in high-risk zones.

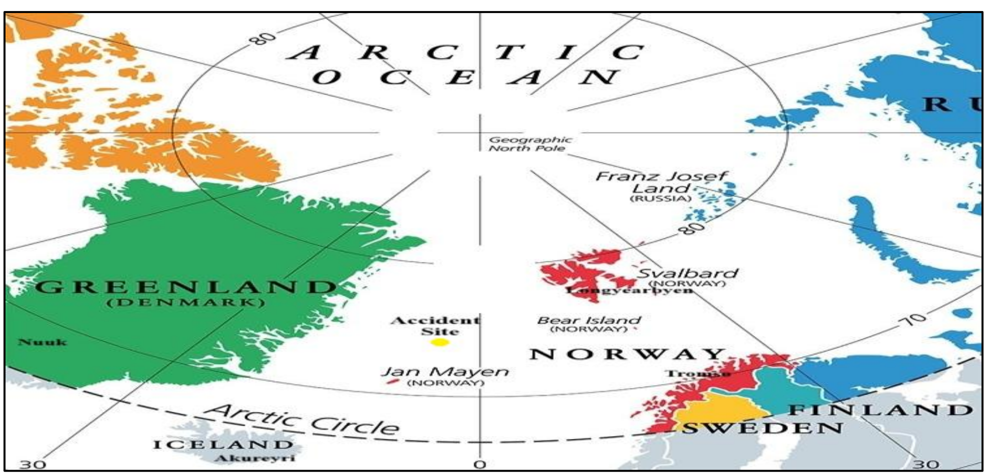

Figure 18: Accident Site in the Arctic Region and nearby ports

source: Adapted from Allen (2024).

6.4.5 Multinational SAR Capabilities Overview

After passengers are evacuated and organized into lifeboats, there is an immediate need to begin external search and rescue (SAR) operationsIn the extreme Arctic setting, rescue survival time is constrained by the intense cold, isolation, and slow access to medical assistance. Urgent SAR intervention must be deployed immediately as these factors, alongside exposure to the elements, can lead to hypothermia, severe psychological stress, and strained resources. The accident site is located within a cluster of Greenland, Iceland, and Svalbard which makes multi-national coordination extremely crucial.

Greenland, Iceland, and Norway are positioned ideally for an Arctic response. Greenland's proximity to the remote parts of the Arctic comes with limited infrastructure. Iceland acts as a central point with its organized SAR structure and modern aerial fleet. It's supported by an efficient Joint Rescue Coordination Center (JRCC.). Norway provides SAR services from Svalbard and mainland at Arctic Norway and takes leadership in regional coordination under the Arctic SAR Agreement 2011. The collaboration forms a multi-layered Arctic rescue network critical to managing emergencies in extreme conditions.

The Master (Captain) of the ship has the first obligation with regards to contacting the appropriate shore-based SAR services. Communication is done using VHF radios, satellite phones, Digital Selective Calling, or an EPIRB (Emergency Position Indicating Radio Beacon). Distress calls are received by the nearest JRCC located in Iceland, Norway, or Greenland depending on the location of the vessel. JRCC gets active in coordinating the response, which involves air and maritime evacuation if required. In cases of large-scale emergencies, immediate contact is made with the bordering SAR authorities for support. There is no question that a dependable and swift communication system between responders on shore and the vessel aids timely and effective rescue operations. The procedures were verified through the expert interviews as part of the research project with maritime professionals, command personnel from SAR and regulatory authorities.

6.4.6 National SAR Capacity Analysis

In this analysis, we focus on the Search and Rescue (SAR) operations of each Arctic coastal state separately Norway (Svalbard and mainland), Iceland, and Greenland (Denmark). Each nation’s air and naval SAR assets are evaluated to ascertain how efficiently they would deal with a worst-case scenario, say, the evacuation of 300 individuals stranded in the Arctic Ocean. This involves estimating the aircraft's cruising speed, vessel range and capacity, and total evacuation time in both best-case and worst-case scenarios. The number of vessels and helicopters selected for analysis was determined based on the researcher’s judgment and perspective on their relevance to the study objectives. After analyzing the range and constraints of each nation’s individual resources and capacities, only then do we assess the combined, multi-national SAR capability, which becomes crucial for evaluation in scenarios of extreme weather, mechanical failure, or resource depletion.

6.4.6.1 Norway: National SAR Capacity

The entire post-evacuation rescue operation relies on Norwegian SAR assets, both air and naval units would be engaged to transport all 300 evacuees from lifeboats, or a distressed vessel located approximately 1,250 km from mainland Norway.

Norway's air evacuation capability includes six AW101 "SAR Queen" helicopters, capable of reaching Arctic accident sites 1,250 km away in approximately 4.5 hours at a cruise speed of 278 km/h (Leonardo S.p.A., n.d.). Each helicopter can carry 50 standing passengers per trip. In this scenario, four helicopters are available to evacuate 300 people. Since each sortie carries 50 passengers, six total evacuation trips are needed. With four helicopters, the evacuation can be completed in two waves: the first wave evacuates 200 passengers using all four helicopters, and the second wave uses two of those helicopters again to evacuate the remaining 100 passengers.

Each round trip, including flight, hoisting, return, and turnaround, takes approximately 10.92 hours. After the first wave, the two helicopters doing the second trip begin their next flight after a short 15-minute turnaround. The second wave ends about 11.17 hours after the mission starts, plus another 10.92 hours for the second-round trip. As a result, the total time to evacuate all 300 passengers comes to approximately 22.09 hours.

This calculation demonstrates that even with high-capacity helicopters, air evacuation alone is a time-intensive process, especially under Arctic conditions and cannot be relied upon as the sole rescue method for large-scale emergencies.

Norway's maritime evacuation capability includes a fleet of three Jan Mayen-class offshore patrol vessels, Jan Mayen (W310), Bjørnøya (W311), and Hopen (W312), designed to support large-scale Arctic SAR operations. Each of these contemporary vessels can carry 100 passengers, which means that when all three vessels are activated, they can evacuate a total of 300 people at once. These ships have a diesel electric driven propulsion plant which enables them to attain a maximum speed of 22 knots or 25 mph (Wikipedia contributors, n.d. -c).

If these Jan Mayan class vessels were fully militarized, it would take less than 30.5 hours for them to reach the site of the supposed accident 1,250 km away. This would be possible only if all three vessels were deployed at once. These vessels have an automated boarding system that allows them to transport up to 300 passengers along with the crew in one single intermodal boundless trip without the hassle of using multiple trips.

Furthermore, Norway possesses two additional vessels, the NoCGV Svalbard and the Kronprins Haakon. These ships may not be fully equipped to handle an entire passenger evacuation scenario but can play crucial roles in the coordination and rapid response during emergencies. The ships function better in the realm of medicine and logistics; command and control and communications as opposed to overwhelming numbers of evacuees.

Effective Arctic evacuation requires both air and sea support. Helicopters offer faster response but limited capacity per trip, while naval vessels can evacuate all passengers at once but take longer to arrive. Norway's combined use of both ensures a balanced and reliable rescue strategy in large-scale emergencies.

6.4.6.2 Svalbard: Regional SAR Capacity

As part of Norway's Arctic territory, Svalbard contributes a forward-operating SAR capability critical for rapid response in polar emergencies. Its asset though limited in scale are strategically positioned to act as a first-line rescue response while reinforcements from mainland Norway are mobilized. This section evaluates Svalbard's capacity to respond independently to a full-scale evacuation scenario involving 300 cruise ship passengers.

Svalbard's air evacuation capability is provided by two Super Puma helicopters stationed in Longyearbyen, specially configured for Arctic search and rescue (SAR) operations. These aircraft are equipped with advanced navigation systems, infrared sensors, and hoist mechanisms to enable rescue in poor visibility and ice-obscured conditions. Each helicopter can reach the accident site, located approximately 750 km away, in about 3.04 hours at a cruise speed of 247 km/h (Airbus, n.d.).

The total time per sortie includes 3.04 hours to reach the site, approximately 38 minutes (0.63 hours) for hoisting 19 passengers, a 3.04-hour return flight, and a 15-minute turnaround, resulting in a full cycle duration of roughly 7.84 hours. Given that each helicopter carries 19 passengers per trip, a total of 16 evacuation trips are needed to evacuate 300 individuals. With both helicopters operating simultaneously, each completing 8 evacuation trips, the entire air evacuation operation can be completed in approximately 62.72 hours under ideal conditions.

This scenario highlights both the advantages and limitations of aerial evacuations in the Arctic: while helicopters offer relatively fast access, the limited capacity and number of evacuation trips required contribute to significant overall operation time.

Svalbard's maritime evacuation capability is centered on the Polarsyssel, a dedicated Arctic patrol vessel that supports year-round search and rescue (SAR) operations. Equipped with a helicopter deck, two rescue boats, and a medical bay, it is Ice Class 1B certified, enabling safe operation in broken or thin ice conditions. The vessel requires approximately 27 hours to reach the accident site, with a capacity of 35 passengers per trip (Stange, 2014).

For simplicity, the vessel's operation is considered cyclical: after picking up 35 passengers, it returns to shore and redeploys. This results in a round-trip evacuation time of 54 hours (27 hours each way). Based on this evacuation rate, nine round trips would be needed to evacuate all 300 passengers. Thus, evacuating all 300 passengers using the Polarsyssel alone would take approximately 486 hours, or about 20.25 days, based on nine round trips at 54 hours per cycle.

While this vessel is not suited for rapid mass evacuation, it plays a vital role in on-site stabilization, search coordination, and survivor support, especially when helicopter resources are limited or delayed by Arctic conditions.

Arctic evacuations require a balanced approach. Super Puma helicopters offer quicker response times but are limited in capacity and number. The Polarsyssel provides slower, low-capacity transport but is crucial for support and stability in harsh conditions. Together, they highlight the need for a flexible, multi-layered rescue strategy in remote Arctic operations.

6.4.6.3 Iceland: National SAR Capacity

Iceland has a relatively moderate and flexible Search and Rescue (SAR) capability, which is established on systems of air and sea integration. Iceland's rescue forces, situated in the North Atlantic, can Arctic maritime incidents with a reasonable combination of speed, endurance, coordination support, and operational support. This portion analyzes Iceland's capacity to single-handedly manage a large-scale simulation of a cruise ship evacuation within an all-encompassing scenario.

Iceland's air evacuation capability is provided by three Airbus H225 Super Puma helicopters operated by the Icelandic Coast Guard (ICG), specially outfitted for maritime SAR operations. These helicopters can perform winch rescues from lifeboats or ship decks, which is critical in the Arctic. However, according to information provided by senior officers from the national Coast Guard authority, only two of these helicopters are typically available at any given time for operational deployment.

Each helicopter can cruise at a speed of 263 km/h, reaching the site of an accident located roughly 1,150 kilometers away in approximately 4.4 hours (Airbus, n.d.). The additional time needed to evacuate 19 passengers is 38 minutes of hoisting time. The flight back to midland, such as Akureyri, adds another 4.4 hours so with an estimated 15 minutes for passenger drop-off and operational reset, that's additional time as well.

This brings the total to 581 minutes (9.7 hours) round-trip time per sortie. If we consider a scenario to evacuate 300 passengers, each of the two helicopters must undertake 8 trips in parallel. Under ideal conditions, total evacuation time is estimated at 77.6 hours. While these helicopters offer reliable mid-range rescue capabilities, their capacity and high round-trip time renders them ineffective for rapid mass rescue evacuation scenarios.

Iceland's maritime evacuation capability is supported by two SAR vessels, ICGV Þór and ICGV Freyja, both well equipped to manage large-scale operations in Arctic conditions. These vessels would take roughly 32.68 hours (cruise speed 19 knots) to travel to the accident site, which is 1,150 km away. ICGV Þór can carry 48 persons, crew included (Landhelgisgæsla Íslands, n.d.), and Freyja can accommodate 35 individuals (Wikipedia contributors, n.d.-a). As a rough estimate, the combined fleet would need approximately 9 trips to evacuate all 300 passengers based on these figures.

Both ships are equipped with lifesaving equipment, onboard accommodation, and medical facilities which enable efficient stabilization of evacuees during the post-rescue phase prior to transport or recovery. The estimated total time for sea-based evacuation using Icelandic vessels is approximately 327 hours. Considering additional time for passenger boarding, alighting, refueling, and operational resets between trips, total evacuation time increases to approximately 350 hours or roughly 14.6 days. This estimate illustrates the time and logistical complexity associated with using maritime resources for large scale evacuation scenarios in the Arctic.

Iceland's air and sea rescue assets each play critical roles in Arctic evacuation efforts. The Airbus H225 Super Puma helicopters offer reliable mid-range rescue capabilities but are limited by small capacity and long round-trip times. In contrast, the ICGV Þór and Freyja provide essential support and stability but require significantly more time to complete full-scale evacuations. Together, they underscore the need for a combined approach, where both speed and endurance are balanced to manage the unique challenges of Arctic SAR operations effectively.

6.4.6.4 Greenland (Denmark): National SAR Capacity

Greenland serves as an autonomous territory under the Kingdom of Denmark. H225 helicopters and a fleet of ice-strengthened patrol vessels form air and maritime SAR capabilities, respectively. Greenland offers strong maritime support for advanced SAR operations at remote locations. This section evaluates Greenland's national capacity to respond to a cruise ship evacuation independently.

Greenland's air evacuation capability relies on Airbus H225 helicopters operated by Air Greenland, which serve as the region's primary search and rescue (SAR) asset (Airbus, 2019). The mid-range cruise speed of the heavy configuration H225 is 263 km/h; thus, an aircraft should reach a simulated accident site about 1600km away in roughly 6.1 hours (Airbus, n.d.). Each sortie can accommodate 19 personnel, of which 300 would require evacuation would require evacuating a total of 16 evacuation trips.

Each round trip by the Air Greenland Airbus H225 helicopter consists of several key components. The flight to the accident site takes approximately 6.1 hours (366 minutes), followed by 38 minutes of hoisting time to lift 19 passengers. The return flight to the mainland requires another 6.1 hours, and an additional 15 minutes is needed for passenger drop-off and operational reset.

This results in a total round-trip time of approximately 785 minutes, or about 13.1 hours per sortie. Therefore, under ideal conditions, evacuating 300 passengers using a single Air Greenland H225 helicopter, a total of 16 trips are required. The total estimated evacuation time is about 209.6 hours, or nearly 8.7 days. This highlights the significant time investment and operational limitations of relying on a single aerial asset for large-scale evacuations in remote Arctic regions.

Although the H225 is Arctic-ready, Greenland's limited fleet—just two units—along with challenges like crew fatigue, range, and harsh weather, constrains large-scale evacuations. The absence of forward-looking infrared and Night Vision Goggles systems (to be implemented by 2026) further limits low-visibility operations. Fixed-wing assets such as the Challenger 604 and C-130J Hercules are available to support aerial reconnaissance, coordination, and logistics, though they cannot replace helicopters for extraction missions (U.S. Air Force, n.d.).

Greenland's sea-based SAR capability is anchored by four Thetis-class and three Knud Rasmussen-class offshore patrol vessels, specifically designed for Arctic missions. These vessels feature ice-reinforced hulls, onboard medical bays, helicopter support, and 60-day operational endurance without resupply.

At the time of an incident, it is assumed that two Knud Rasmussen-class vessels and one Thetis-class vessels are available for immediate deployment. Vessels of the Knud Rasmussen class with a cruise speed of approximately 17 knots (Wikipedia contributors, n.d. -d), would take 50.82 hours to reach the accident site 1,600 km away. In comparison, Thetis-class cruising at 15 knots would reach the site in 57.6 hours (Wikipedia contributors, n.d. -b). Together the three available vessels Thetis and Knud Rasmussen can evacuate 186 passengers per trip (2 x 43 from Knud Rassmussen + 100 from Thetis). To evacuate all 300 passengers, two full rotations are required to be made. Assuming each round trip takes approximately 115.2 hours based on the longest vessel's travel time, total evacuation time is estimated at 230.4 hours or roughly 9.6 days.

These ships are a crucial part of Greenland's maritime SAR response and, although slower than aerial assets, provide dependable support and shelter for extended evacuation and stabilization during extreme Arctic conditions.

Greenland's SAR capacity, though limited in air resources, offers strong maritime support through ice-capable patrol vessels. While helicopter evacuation is constrained by fleet size and weather, sea-based assets provide reliable but slower evacuation and stabilization. This underscores the need for enhanced aerial capability and continued multinational coordination to ensure an effective Arctic emergency response.

Figure 19 illustrates the air- and sea-based evacuation capacities of Arctic coastal nations, highlighting their individual response timelines and capabilities in supporting cruise ship emergencies.

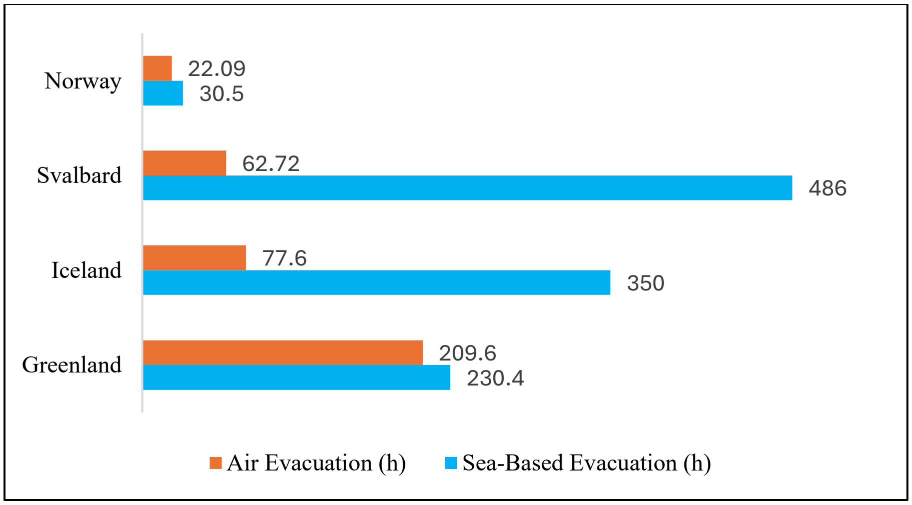

Figure19: Summary of Evacuation Times by Region (Author-generated)

6.5 Combined Maritime SAR Scenario

For this scenario, consider that the same cruise ship emergency occurs in the Arctic Region and terrible weather conditions make air evacuation impossible. Operations must depend exclusively on maritime search and rescue resources from Svalbard, Iceland, Greenland, and mainland Norway. Each country has its own ship mobilization plan to maximize the number of passengers evacuated to 300. As pointed out by a expert in an interview conducted for this research, helicopters availability is often limited or delayed in Arctic emergencies, thus the need for a reliable maritime evacuation plan is underscored.

6.5.1 Coordinated Evacuation Strategy

The evacuation of 300 passengers unfolds in cumulative phases:

Phase 1: Initial Stabilization – Svalbard

Polarsyssel, Svalbard's Arctic patrol vessel, arrives at the location in roughly 27 hours and initiates the operation by rescuing 35 passengers.This aids in establishing on-scene command, stabilizing survivors, coping with the incoming forces, and coordinating the multinational fleet.

Phase 2: Mid-Phase Reinforcement –Norway Respond

Following the initial stabilization by Polarsyssel, Norwegian SAR assets arrive in Phase 2 as the primary evacuation forceThe Jan Mayen-class patrol vessels—Jan Mayen (W310), Bjørnøya (W311), and Hopen (W312) take an approximate time frame of 30.5 hours to reach the incident location. They are a part of the Task force which can evacuate the entire 300 passengers in one single trip. Their swift deployment gives important support and very greatly boosts aid in the evacuation process.

Phase 3: Operation Completion – Iceland and Greenlandic Vessels on Strategic Standby

The evacuation has been completed in a single operational wave, with all 300 passengers evacuated ,35 by Polarsyssel (Phase 1) and 265 by Norwegian vessels. Throughout the course of the operation, Iceland's search-and-rescue resources, alongside Greenland's Knud Rasmussen class patrol vessels set to arrive at 50.82 hours and the Thetis-class boat arriving at 57.6 hours, remain on strategic standby. No activity of these assets is required, but full support and aid is available greatly enhancing the region's multi-layered emergency response framework. Figure 20 illustrates the Arctic SAR response structure, focusing on sea-based assets and their projected timelines. This operation exemplifies how well-coordinated multinational collaboration can ensure a timely and effective response, even under the demanding conditions of the Arctic.

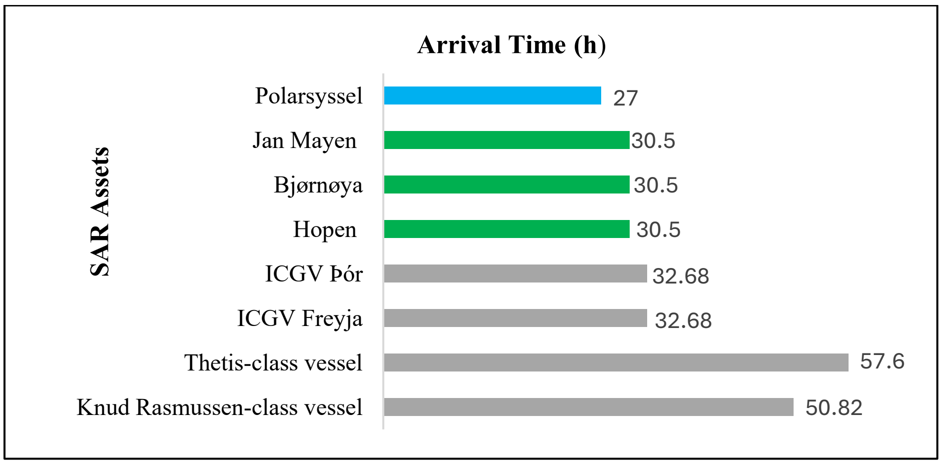

Figure 20: Arctic SAR Response (Sea-Based Assets Only) (Author-generated)

The color-coded legend below identifies the roles of different nations and phases in the evacuation timeline:

Blue Phase 1: Svalbard Response

Green Phase 2: Norway Response

Gray Phase 3: Iceland and Greenlandic Standby Vessels

In summary, the simulation and SAR analysis highlight how restricted evacuation routes and delayed rescue responses can severely affect safety in Arctic cruise emergencies. Ensuring clear egress, strong onboard coordination, and timely multinational SAR support is essential for effective emergency preparedness in these challenging environments.

Chapter 7: Discussion

7.1 Discussion of Evacuation Simulation Results and SAR Preparedness

Building on the simulation and SAR analysis presented in Chapter 6, this chapter discusses their broader implications for Arctic cruise safety, evaluates alignment with regulatory benchmarks, and proposes system-level recommendations.

The study explains the complexity of conducting large-scale cruise ship evacuations in the Arctic and emphasizes the urgent need for integrated, regionally coordinated search and rescue (SAR) strategies. The simulation results showed that restricted egress pathways and delayed crew mobilization adversely affected passenger movement smoothness and evacuation efficiency. Specifically, Blocked exits contributed to an increased total evacuation time of 3.6 %, with a total evacuation time change from 2109.6s to 2186.4s, and an average travel distance increase of 27 % from 169.7 m to 216.2 m. Additionally, crew delays extended initial response time by over 11%, compromising early-stage coordination.

These evacuation times exceed internationally recognized optimal safety limits. The SOLAS Convention states that all passengers are boarded on lifeboats within 30 minutes (1800 seconds) of sounding the abandon ship signal. (International Maritime Organization [IMO], 2016). In both scenarios, evacuation time exceeds this limit and emphasizes the gap of compliance. This is even more problematic in Arctic region where even slight delays expose one to the risk of Hypothermia, confusion, and disorganization during the most critical stages of an emergency.

Evidence from the real world further supports these claims. The actual evacuation of an Arctic cruise with over 350 passengers and crew under dangerous weather conditions took roughly 45 minutes. This is in comparison to the modeled estimate, which was under more optimal circumstances. This alignment supports the credibility of the simulation while also exposing how fragile real-world timelines can become when subject to ice, wind, and low visibility.

Further validation is drawn from the SAR capability analysis of Arctic nations. Only Norway meets the Polar Code requirement of the five-day (120-hour) survival limit for air evacuation (22.09 hours) and sea-based evacuation (30.5 hours). Although Svalbard's air evacuation time of 62.72 hours is acceptable, its sea-based evacuation time of 486 hours makes it untenable under the survival limit.

In contrast, Iceland (sea-evacuation) and Greenland are nowhere close to the 120-hour window. Iceland's air evacuation requires 77.6 hours is reasonable while the sea-based response is estimated to take 350 hours. Greenland's figures are 209.6 hours for air evacuation and 230.4 hours for sea based and both these figures exceed the survival timeframe set by the Polar Code (International Maritime Organization [IMO], 2016).

These findings show a critical preparedness gap: only Norway has SAR capabilities that fully align with Polar Code survival expectations without external assistance. For other regions, timely evacuation depends heavily on pre-positioned resources, resilient onboard systems, and coordinated multinational support.

Given these extended timelines, cruise ships operating in remote Arctic zones must be largely self-reliant during the first 24 to 48 hours of an emergency. Initial stabilization and survivability will depend on onboard preparedness specifically, trained crew, accessible egress pathways, and clearly defined joint action plans. Although Arctic nations possess capable SAR platforms, existing systems often lack effective integration with ship-level operations. Vulnerable passengers, particularly those with medical or mobility impairments, remain underrepresented in current planning and protocols.

While multinational exercises like SAREX show promise, significant challenges remain. Real-time interoperability, forward-deployed SAR assets, and Arctic-specific crew training are still limited. Furthermore, mandatory passenger briefings and scenario-based protocols are inconsistently implemented across cruise operators. These gaps demonstrate that while Arctic SAR capacity appears robust in theory, it may not scale effectively in a real large-scale cruise emergency. Therefore, targeted improvements in evacuation preparedness, pre-coordinated SAR deployments, and inclusive rescue planning are essential to ensure passenger safety in one of the world's most extreme and unforgiving environments.

7.2 Strategic Recommendations for Arctic Cruise Safety

This study proposes a series of recommendations based on functional system mapping using the Functional Resonance Analysis Method (FRAM) to strengthen Arctic cruise safety and regional emergency preparedness. This approach captures the interdependence of key actions required to ensure effective passenger evacuation, onboard survivability, and multinational SAR coordination. By modeling safety operations through eight interconnected functions, it becomes possible to visualize and address both onboard and external weaknesses before an Arctic emergency occurs.

The recommendations outlined below are derived from the simulation results, operational gaps identified through case analysis, and SAR coordination limitations. Each function in the FRAM model is defined using standard categories: Input (I), Output (O), Precondition (P), Resource (R), Control (C), and Time (T). Collectively, these functions offer a roadmap to improving response outcomes and ensuring survivability in extreme polar environments.

The FRAM model presented here is a core part of the author's proposed recommendations. It illustrates that the success of external SAR efforts depends fundamentally on the early-stage actions taken onboard. Functions 1 and 2—passenger preparedness and crew-specific Arctic training—form the foundational layer for improved survival assumptions (Function 3). These assumptions then guide operational strategies, including dual-vessel operation and forward deployment of SAR assets (Functions 4–5). Subsequent functions focus on enhancing communication and coordination through JRCC engagement, multinational cooperation, and standardization (Functions 6–8). The function-based recommendations are summarized below:

- Arctic cruise passengers should be equipped with clear, structured pre-departure briefings that address cold exposure, lifeboat expectations, and survival protocols. This function ensures passengers are mentally and physically prepared to follow instructions, thereby reducing panic during evacuation. This is especially critical given that cruise passengers are often elderly and lack survival training, making them more vulnerable in extreme environments. A clear example of these challenges is the Viking Sky incident in Norway (2019), where an engine failure during rough seas forced a helicopter evacuation (Johannsdottir et al., 2021). Elderly passengers had to be airlifted one by one, significantly delaying the process and increasing operational risk. Input for this function includes Arctic-specific risk briefings, and outputs are informed, better-prepared passengers. The process should be managed by cruise safety officers before departure. To make it effective and enforceable, this can be operationalized by integrating mandatory Arctic safety briefings into pre-boarding procedures and verifying passenger participation through digital checklists.
- Frontline crew involved in evacuation must receive certified cold-weather evacuation training. Simulation feedback indicates that lower-ranking staff often lack preparedness, increasing the risk of disorganized mustering. Operators should conduct realistic cold-weather evacuation drills that go beyond standard muster routines to improve Arctic cruise safety. Training should include survival gear use, staged disembarkation in harsh conditions, and procedures for assisting injured or mobility-impaired passengers. Importantly, real-world Arctic experience is essential. Practical exposure to the region's extreme weather, terrain, and logistical challenges significantly enhances a crew member's readiness and ability to respond effectively during an actual emergency. With trained Arctic-ready crew as the output, this function becomes foundational for managing evacuations under time constraints. Effective implementation would involve incorporating Arctic-specific modules into annual crew training programs and conducting seasonal cold-weather evacuation drills to enhance preparedness.
- Based on empirical data and simulation findings, Arctic survival timelines in policy documents such as the Polar Code must be revised from five days to a more realistic 48-hour window. This change better aligns equipment needs, lifeboat capacity, and SAR timing assumptions, enabling more effective emergency response planning. This may be implemented by submitting formal policy recommendations to the IMO and Arctic Council safety subcommittees for review and potential amendment of existing survival time guidelines.
- Cruise ships transiting remote Arctic regions should adopt a paired-sailing protocol. Operating in mutual support significantly enhances initial rescue potential before SAR units arrive. This strategy is based on the revised survival time assumption and requires route planning coordination between cruise operators and regulatory authorities.

Implementation could involve integrating dual-vessel routing into voyage planning systems and mandating regulatory approval for solo transits through high-risk Arctic zones.

- To shorten response times, air and sea rescue assets should be pre-positioned seasonally in critical Arctic gateways (e.g., Akureyri, Longyearbyen, Banak). This function supports immediate intervention following distress signals and is based on anticipated mutual support limitations in high-risk areas. This can be achieved by coordinating with national SAR agencies to develop seasonal deployment plans for air and sea rescue assets, timed to coincide with peak Arctic cruise activity
- Cruise lines must file their emergency plans and voyage data with the nearest JRCCs prior to departure. Coordinated communication between ships and response centers ensures faster mobilization and reduces confusion during complex, multinational incidents. A practical step would be to establish a standardized pre-voyage reporting protocol, enabling cruise operators to electronically submit voyage data to the relevant JRCCs before departure.
- National limitations in SAR capacity call for increased cooperation among Greenland, Iceland, and Norway. This includes joint drills, pooled equipment, and shared protocols that enable a unified approach during real-time operations. Implementation may involve conducting joint SAR drills and establishing formal cooperation agreements through the Arctic Coast Guard Forum to strengthen regional response capacity.
- All Arctic SAR partners must use compatible language protocols and rescue technologies. This standardization reduces delays due to technical or linguistic mismatches and ensures smooth coordination across borders. This can be implemented by developing a standardized SAR communication guidebook and ensuring its distribution across all participating agencies and vessels to promote seamless cross-border coordination.

Figure 21 provides a visual representation of this integrated FRAM framework. Implementing these eight FRAM-based functions as a cohesive system can significantly enhance Arctic cruise safety, reduce passenger vulnerability, and facilitate a faster, more efficient international SAR response. This model offers a proactive, scenario-informed strategy for Arctic emergency preparedness that aligns operational capabilities with real-world constraints.

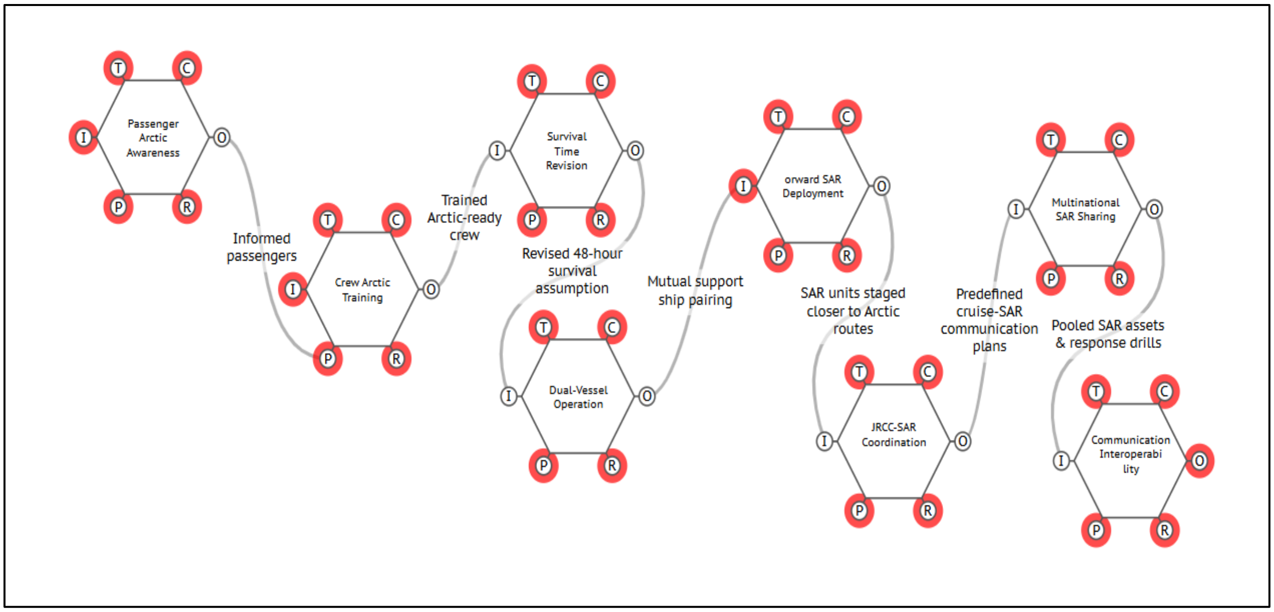

Figure 21: FRAM Model of Recommendation (Author-generated)

7.3 Future Research Directions

Future research could delve deeper into the specific approaches adopted by polar cruise and expedition operators in the development of their emergency preparedness plans. Particular attention should be given to safety practices, contingency protocols, and the extent of compliance with the Polar Code. By employing document analysis and conducting interviews with key industry stakeholders, future studies could uncover the practical challenges faced by operators and identify any gaps between regulatory expectations and real-world implementation. This line of inquiry would contribute valuable insights into the effectiveness of current regulatory frameworks and help inform the evolution of safety strategies in the Arctic cruise industry.

It could also prove valuable to assess the training and joint exercises of the Arctic Search and Rescue (SAR) actors related to mass-rescue operations in the High Arctic. While events such as SAREX 2012, the first major multinational SAR exercise in Greenland, have demonstrated the potential in developing coordination responses to emergencies, future studies should assess scope, frequency, and effectiveness of such training across Arctic nations.

Incorporate profiles of passengers with mobility restrictions into evacuation simulations to improve accuracy and identify accessibility gaps. This research supports inclusive design and compliance with international regulations, offering high value despite the minimal resources required

Future work should incorporate data from real Arctic maritime incidents to improve simulation. Although this study utilized authentic specifications for SAR assets, a lack of detailed incident records limited scenario accuracy. Collecting empirical data will better validate models and improve preparedness planning.

Chapter 8: Conclusion

The objective of this research is to evaluate in detail the efficiency of emergency evacuation and rescue systems applied to Arctic cruise ships. The study provides a comprehensive assessment of Arctic cruise ship evacuation preparedness using a multifaceted approach incorporating ship-based simulation, occupant modeling, SAR capability evaluation, and functional system analysis. By simulating an extreme risks iceberg collision scenario within a remote Arctic region, this study demonstrated the operational problems associated with constrained egress options, severe environmental conditions, and extended rescue timelines.

The key findings from the Pathfinder simulation indicate that even minor disruptions, such as blockage at the starboard (right side) access, which significantly escalated evacuation times (3.6%) alongside increases in travel distance (27.4%) and delayed passenger and crew arrivals at muster stations. These measurable impacts stress the need for better distributed evacuation routes and emphasize the need to fully mobilize the crew early on, conduct room-to-room surveillance, and employ behavioral modeling tailored to realistic risk scenarios.

The analysis of SAR capabilities throughout Norway, Iceland, Greenland, and Svalbard revealed contradictions concerning the response times. Only Norway fulfilled the Polar Code's 120-hour (five days) requirement for both air and sea-based evacuation. Iceland and Greenland, however, exceeded this window by several days, with full maritime evacuations estimated at 14.6 and 9.6 days, respectively. This highlights the importance of multinational collaboration, pre-positioning SAR units, and interoperable communication networks as described in the Arctic SAR Agreement 2011.

Importantly, the simulation's evacuation duration also surpassed the SOLAS benchmark of 30 minutes for lifeboat readiness, Reinforcing concerns regarding the adequacy of onboard preparedness in polar conditions. This highlights the Arctic-specific risk posed by delays, which increase vulnerability to hypothermia, disorganization, and evacuation bottlenecks, especially for passengers with mobility limitations or medical conditions.

The simulation's compliance with benchmark evacuations, such as the Le Boréal incident, adds validation of its methodological credibility and the importance of organized, tiered evacuation procedures (e.g., staged evacuation of passengers, followed by crew disembarkation). Although it underlines the passengers' risk of enduring extended exposure to subfreezing temperatures, particularly when air evacuation is not feasible.

The FRAM-based system analysis proposed eight interconnected functions that define a robust Arctic response, from mandatory passenger safety briefings and cold-weather crew training, dual-vessel operations and standardized SAR coordination. These functions were informed directly by simulation's timing data and the real-world evacuation case studies, including the Le Boréal incidents. Functional Resonance Analysis Method (FRAM) offers visualization of interdependent operations to the stakeholders which allows proactive solutions to be made for operational bottlenecks.

As the author, this research expanded my comprehension of the complex issues involved in Arctic cruise ship evacuation, particularly how human behavior, vessel design, and extreme environmental conditions intersect in emergency scenarios. From this project, I learned practically how risk assessment tools (risk matrix) and system-based analysis methods like FRAM are used. These tools helped me recognize how small disruptions can trigger wider system failures. The process also enhanced my ability to evaluate preparedness strategies, assess functional dependencies, and appreciate the importance of coordinated international response efforts in remote maritime emergencies. Overall, this project strengthened my skills in simulation modeling, risk analysis, and safety evaluation within a real-world maritime context.

Overall, this study further supports the claim that Arctic cruise ship evacuation can be successfully achieved, by preparedness, international cooperation, and operational flexibility, not solely by a vessel's design or technology. These are foundational concepts that need to be included in training as well as policy to maintain maritime safety resilience in one of the world's harshest environments.

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Appendix 1: SOLAS Safety Requirements for Arctic Ship Operations

With Reference to Polar-Specific Adaptations

The International Convention for the Safety of Life at Sea (SOLAS) forms the cornerstone of maritime safety regulation worldwide. For cruise ships operating in polar regions, SOLAS sets essential safety standards in areas such as fire protection, life-saving appliances, navigation, communication, and crew training. While the Polar Code, adopted by the International Maritime Organization (IMO), provides specific operational guidelines for polar waters, it is implemented as an extension of SOLAS. Therefore, this appendix outlines the key SOLAS provisions relevant to Arctic cruise operations, with reference to their application in polar contexts.

1. Fire Safety Systems

(SOLAS Chapter II-2)

- **System Functionality**: Fire safety systems must operate effectively in all conditions, including extreme cold.
- **Equipment Protection**: Firefighting equipment should be accessible and shielded from ice or snow accumulation.
- **Crew Access**: Design must allow safe use of equipment while wearing heavy cold-weather gear.
- **Heated Storage**: Fire pumps and extinguishers may require heated compartments to remain functional.
- **Drainage Capability**: Fire hoses must be drainable to prevent freezing.
- **Temperature-Resistant Materials**: Equipment must be constructed from materials suitable for sub-zero conditions.

2. Life-Saving Appliances and Arrangements

(SOLAS Chapter III)

- **Accessible Escape Routes**: Must remain usable despite snow or ice.
- **Arctic-Ready Survival Craft**: Lifeboats and rafts must function reliably in freezing temperatures.
- **Thermal Protection**: Immersion suits or thermal protective aids are mandatory for all personnel.

- **Illumination Equipment**: Searchlights are required for lifeboats to ensure visibility during polar darkness.
- **Survival Provisions**: Lifesaving equipment must include adequate rations and supplies for extended rescues.
- **Independent Power**: Life-saving systems should function without reliance on the ship's main power source.
- **Rapid Evacuation Standard**: SOLAS requires that all passengers and crew be able to abandon ship and board survival craft within 30 minutes of the abandon-ship order being given.

3. Navigation Safety

(SOLAS Chapter V)

- **Ice Information Access**: Ships must have updated nautical charts and ice data.
- **Resilient Navigation Equipment**: All systems must perform reliably in harsh polar climates.
- **Redundancy**: Dual heading systems, echo sounders, and protected antennas are recommended.
- **High-Latitude Functionality**: Equipment such as GNSS compasses may be required for operations above 80° latitude.
- **Ice Detection**: Lighting systems must enable visual detection of ice ahead.

4. Communication Systems

(SOLAS Chapter IV)

- **Ship-to-Ship/Ship-to-Shore Communication**: Systems must remain fully functional despite polar conditions.
- **Convoy Signaling**: Ships traveling in convoys with icebreakers require audible and visual signaling equipment.
- **Search and Rescue (SAR) Coordination**: Reliable communication with SAR units, aircraft, and medical assistance is critical.
- **Lifeboat Communication Gear**: All survival craft must carry location and distress signaling equipment that operates independently.

5. Training and Certification of Personnel

(SOLAS Chapter I & STCW Convention)

- **Mandatory Training**: Masters, chief mates, and navigational officers must complete basic and/or advanced training for polar operations under the STCW Convention.
- **Supplementary Crew**: Other personnel may assist but cannot replace certified officers in safety responsibilities.
- **Familiarity with Procedures**: All crew members must be trained in the use of emergency systems, as specified in the ship's Polar Water Operational Manual (PWOM), where applicable.

6. Additional Training Based on Ice Conditions

(Per STCW and Referenced by Polar Code Implementation Guidelines)

Ice Conditions	Tankers	Passenger Ships
Ice-Free	Not applicable	Not applicable
Ice-Influenced Waters	Advanced training for master and chief mate; basic training for officers in charge of a navigational watch	Same as tankers

Appendix 2: Summary of Polar Code Safety Requirements for Ship Operations in Polar Waters

The International Code for Ships Operating in Polar Waters (Polar Code) was adopted by the IMO Maritime Safety Committee. It applies to ships operating in Arctic and Antarctic regions, with the primary objective of ensuring safe ship operations and the protection of the polar environment by addressing risks unique to these water risks not fully covered by other maritime instruments.

2.1. Equipment and Onboard Systems

- Bridge Windows
  Ships must be equipped with means to remove ice, freezing rain, snow, spray, mist, and condensation from bridge windows.
- Lifeboats
  All lifeboats must be partially or fully enclosed to ensure occupant protection in extreme conditions.
- Thermal Protection Clothing I
  Adequate thermal protection must be provided for all persons on board.
- Thermal Protection Clothing II
  Passenger ships must carry an immersion suit or thermal protective aid for each individual onboard.
- Ice Removal Equipment
  Vessels must carry specialized ice removal equipment, such as:
  - Electrical or pneumatic devices
  - Manual tools like axes and wooden clubs
- Fire Safety Measures
  Firefighting equipment must remain operable in freezing temperatures, and:
  - Be protected against ice formation
  - Be usable by personnel in bulky cold-weather clothing

2.2. Ship Design, Construction, and Stability

- Ship Categories
  Ships are classified based on ice conditions:
  - Category A: Designed for medium first-year ice
  - Category B: Designed for thin first-year ice

    - Category C: Operates in open waters or milder ice conditions

- Intact Stability
  Ships must maintain sufficient intact stability, accounting for:
    - Ice accretion
    - Stability calculations that include icing allowances
- Materials
  Hull and structural materials must be suitable for the ship's polar service temperature.
- Structural Strength
  Ice-strengthened ships must withstand global and local ice loads, ensuring structural resilience during operations in ice-covered waters.

2.3. Navigation, Certification, and Operational Readiness

- Ice Navigation Information
  Ships must be equipped to receive real-time ice condition updates relevant to their route.
- Certification and Documentation
  Vessels must carry:
    - A Polar Ship Certificate
    - A Polar Water Operational Manual (PWOM) detailing operational and safety procedures
- Training Requirements
    - Masters, Chief Mates, and Navigational Watch Officers must complete:
        - Basic training for operations in open polar waters
        - Advanced training for navigating ice-covered areas

Appendix 3: Arctic Coast Guard Forum (ACGF) and National SAR Structures

3.1 Arctic Coast Guard Forum (ACGF)

The Arctic Coast Guard Forum (ACGF) is an independent, informal, and operationally-driven body, not bound by treaty, with the objective of promoting safe, secure, and environmentally responsible maritime activity in the Arctic. Its members include all eight Arctic nations: Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the United States.

The forum is guided by rotating chairmanship every two years, aligning with the Arctic Council's leadership. Norway holds the current chairmanship (2023–2025).

Organizational Structure

- ACGF Chair: Leads the forum and represents strategic direction.
- Secretariat: Ensures operational coordination and continuity.
- Working Groups: Address priority issues and report to the Secretariat.

Strategic Goals

- Strengthen multilateral coordination and maritime agreements.
- Address regional maritime challenges through joint coast guard agency action.
- Collaborate with the Arctic Council via information exchange.
- Promote safe and sustainable Arctic maritime activity.
- Ensure transparency and stability in Arctic maritime operations.
- Enhance emergency response protocols and navigation safety.
- Advance marine environmental protection.
- Support the wellbeing of Arctic communities, including Indigenous peoples.
- Integrate science to support operational Coast Guard functions.
- Share best practices and technologies for sustainable maritime operations.

(Source: Arctic Coast Guard Forum, n.d.)

3.2 National SAR and Coast Guard Structures

3.2.1 Denmark – Arctic Command

Headquarters:Nuuk,Greenland
Liaison Units: Thorshavn (Faroe Islands), Pituffik Space Base, Kangerlussuaq, Station North, Daneborg, Mestersvig, and Air Base Aalborg

Main Responsibilities:

- Surveillance and sovereignty enforcement in Greenland and the Faroe Islands.
- Maritime and aeronautical search and rescue (SAR).
- Pollution response and fishery inspection.
- Military defense of the Arctic territories.
- Support for civil society and scientific research.

Area Of Responsibility

Spans from the Faroe Islands to the Greenland Sea, Arctic Ocean, Denmark Strait, and Baffin Bay.

3.2.2 Iceland – Icelandic Coast Guard (ICG)

Headquarters:Reykjavik
Operations & Rescue Coordination Centre: Reykjavik and Keflavik

Main Duties:

- Maritime and aeronautical search and rescue (SAR)
- Marine pollution surveillance and response
- Fisheries enforcement and marine environment protection
- Law enforcement support, diving operations, and hydrographic surveys
- Emergency medical transport and nautical charting
- Operation of the Iceland Air Defence System

Governance:
Operates under the Ministry of Justice

3.2.3 Norway – Norwegian Coast Guard

OrganizationalAffiliation:
Part of the Norwegian Armed Forces

Headquarters: Sortland, Northern Norway

Core Functions:

- SAR (Search and Rescue)
- Fisheries inspection and sovereignty enforcement

- Environmental protection and oil spill response
- Maritime security operations and interagency coordination
- Supporting civilian authorities and international cooperation

Collaboration:
Works in coordination with police, customs, the Norwegian Coastal Administration, Directorate of Fisheries, meteorological and marine research institutes, and the Governor of Svalbard (Arctic Coast Guard Forum, n.d.).

Appendix 4: Model Ship Design

4.1 Expedition ship Overview

Expedition ships are specialized vessels built for supporting drives which include remote locations such as the Arctic. Ships are generally classified into three types: Luxury Expedition Ships, which provide premium amenities to customers while still being able to access places like the Arctic; Expedition Ships, which focus on the operational comfort for long journeys through difficult environments; and Icebreakers, super specialized ships built with strong hulls to sail and crush ice in the Arctic and Antarctic regions Icebreakers. All these vessels allow safe and efficient travel to some of the remote, icy, and pristine parts of the globe.

4.1.1 Model Ship

The model ship in this report is from Expedition Ships that serves as the basis for evacuation simulation in Pathfinder, where its structure and features are used to simulate emergency response scenarios in polar exploration environments. Designed for navigating ice-laden waters in both the Arctic and Antarctic, this expedition vessel combines robust engineering with cutting-edge technology to ensure safe and efficient operations in extreme conditions.

The ship can accommodate between 200 and 300 guests, supported by a dedicated crew of approximately 100 to 150 members. Its construction enables it to endure the most polar Ice Class 1C certified regions: it is perfect for exploration in harsh and distant territories. The ship's power comes from an electric or diesel-electric propulsion system, enabling the vessel to cruise at a steady 14 knots, ensuring both reliability and safety in isolated areas.

The ship carries four Arctic-rated lifeboats, capable of safely evacuating all occupants. These lifeboats are fully enclosed, insulated against extreme cold, and equipped with heating, emergency rations, thermal blankets, and communication devices such as radios. Because of the propulsion systems and reinforced frames, they can safely navigate away from ice threats, ensuring their safety and survival until help arrives. A particular characteristic of this model ship is the deployment of Zodiac inflatable boats which allows small scale surveying of coastal regions unreachable by bigger ships.

4.1.2 Deck-by-Deck Layout

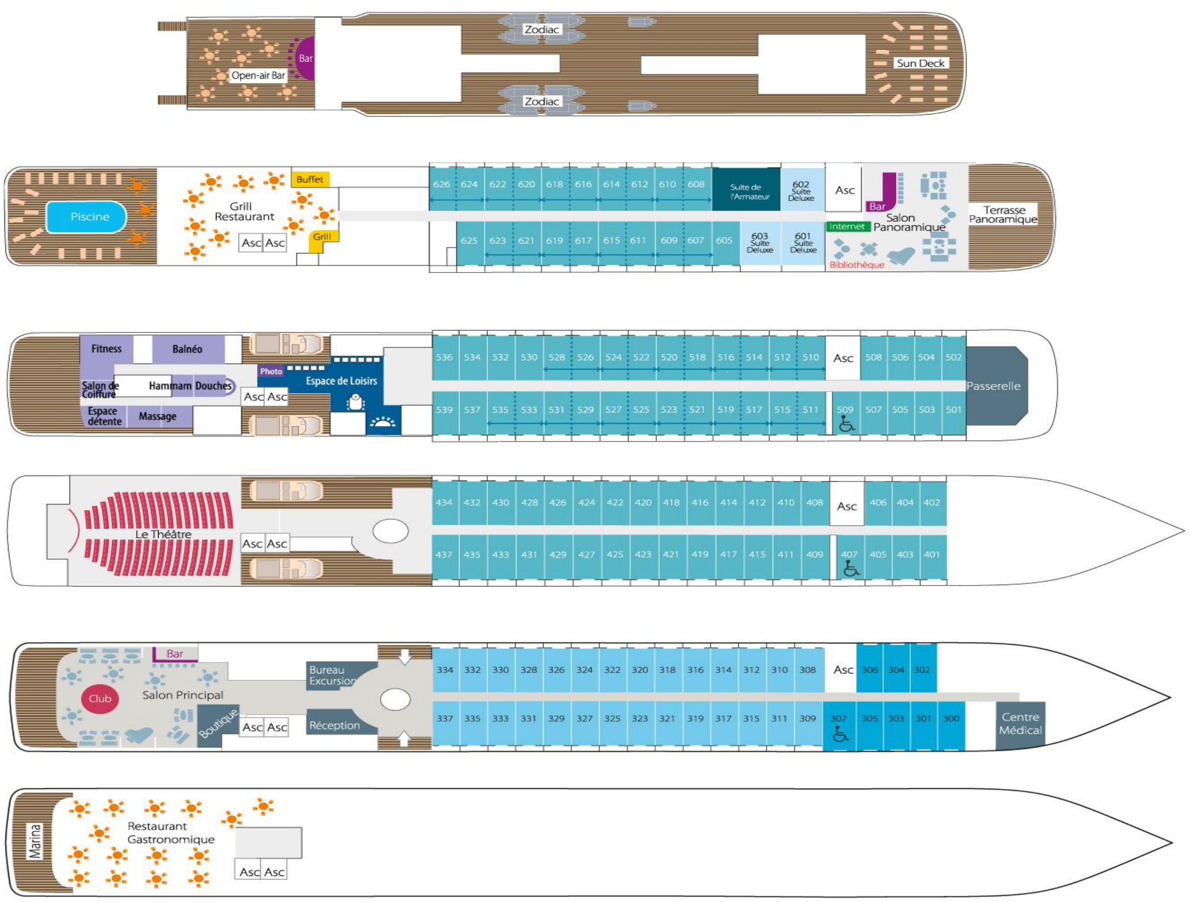
Deck 2 is primarily dedicated to dining areas, featuring a variety of restaurants and buffet zones. This deck is designed to offer diverse dining experiences for guests, providing spacious seating arrangements and efficient service areas. The layout ensures smooth flow for passengers during mealtimes, with ample space for socializing and enjoying a range of culinary options.

Deck 3 combines passenger cabins with public amenities that enhance the guest experience. This deck features a bar, boutique, and excursion office, providing a social hub for passengers to gather, relax, and plan activities. The mix of private cabins and public spaces allows for a dynamic atmosphere, catering to both relaxation and engagement with onboard services.

Deck 4 is a central area that includes both accommodation and entertainment facilities, with the highlight being a large theater designed for performances and presentations. This deck also serves as a key location for lifeboat access, offering embarkation points for passengers in the event of an emergency. The central positioning of the theater and its proximity to evacuation points make it a versatile and functional space for both entertainment and safety purposes. Dedicated to relaxation and rejuvenation.

Deck 5 is home to fitness centers, massage rooms, and spa services. This deck provides passengers with opportunities to unwind, offering a range of wellness treatments to enhance their experience. The design of this deck allows for a tranquil atmosphere, encouraging guests to take part in leisurely activities while enjoying the calming views of the surrounding environment.

Deck 6 features premium suites and exclusive outdoor observation points, offering guests a more luxurious and private experience. The spacious cabins provide a high level of comfort, while the observation areas allow passengers to enjoy panoramic views of the polar landscapes. With direct access to open spaces, this deck is ideal for those seeking a quieter, more refined experience, allowing them to observe the pristine surroundings in privacy and comfort.



Deck Plan

4.3 Ship Crew Organization

Modern seafaring involves a variety of activities, and every ship has a distinct organizational structure in order to facilitate proper management. Every ship possesses a captain, better known as the master, who is in command of every department such as the deck, engineering, and electro-technical departments, and the steward's department. The captain, also referred to as the Master, oversees all departments. He is the sole authority on the vessel and in charge of everything related to the operation of the ship on behalf of the ship owner. Curiously, the Captain does not legally count as a crew member.

4.3.1 Deck Department

Under the bridge, four persons region ensure safe navigation: Captain who masters the whole controls, Officer of the Watch (OOW), who keeps the navigational watch, First Pilot, who provides conning and steering expert guidance, and Helmsman who obeys helmet orders to steer the vessel. Assisting them is the Deck Department headed by Chief Mate (second in command) who oversees navigation, cargo, and stability. The First mate oversees navigation while the Second Mate manages voyage scheduling, while the Third mate supervises safety equipment and watches. Under supervision, Deck Cadets learn the ropes, while the Boatswain, Able Seamen, and Ordinary Seamen carry out mooring, cargo, and maintenance works. Seamless coordination among this team is vital, especially while operating in confined or high-risk waters (Transport Accident Investigation Commission, 2017).

4.3.2 Engineering Department

The Engineering Department, led by the Chief Engineer, ensures the ship's propulsion and mechanical systems operate safely and efficiently. The second engineer operates the main engine maintains while the third oversees auxiliary systems and fuel, the forth supplies both. Engine Cadets train under supervision, while Motormen, Oilers, and Wipers perform essential machinery upkeep and assist with daily engine room operations.

4.3.3 Electro-Technical Department

Maintaining the electrical and electronic systems of the ship is handled in this department. The Electro-Technical Officer (ETO) is responsible to the Chief Engineer and is trained in the ship's intricate technical systems.

4.3.4 Steward's Department

The Steward's Department manages comfort and welfare of every person on board. Chief Steward has responsibility of catering and accommodation, and the Chief Cook manages the meal preparation and galley hygiene.

4.4 Cruise Ship Evacuation Command Structure

A cruise ship evacuation follows a hierarchical communication and response structure to ensure the safety and orderly movement of passengers during emergencies. The Cruise Ship Evacuation Command Structure was outlined by a command-and-control officer of a cruise vessel during an interview conducted for this study. The process is carefully designed to maximize efficiency and minimize confusion in critical situations as given in the figure below. At the peak hierarchy, the captain oversees the situation, being assisted by the Staff Captain if available. Under them, there is Command Control, who supports the captain in communication and action control for the ship. The vessel is divided into various zones, the evacuation is being managed from different levels by Zone Commanders who are in charge of separate sections. Each Zone Commander has an Evacuation Team Leader who reports to them and is accountable for the execution of the evacuation plan within their jurisdiction. The evacuation personnel, most of whom are from Steward's Department are assigned to facilitate the movement of passengers.

This structured approach ensures a systematic flow of information and actions from the highest command level down to ground-level staff, resulting in a highly coordinated and efficient evacuation process. It prioritizes passenger safety while maintaining control and order throughout the vessel. This pattern of evacuation is in compliance with the primary maritime policy rules designated by the guidelines of SOLAS (Safety Of Life At Sea) Regulations.

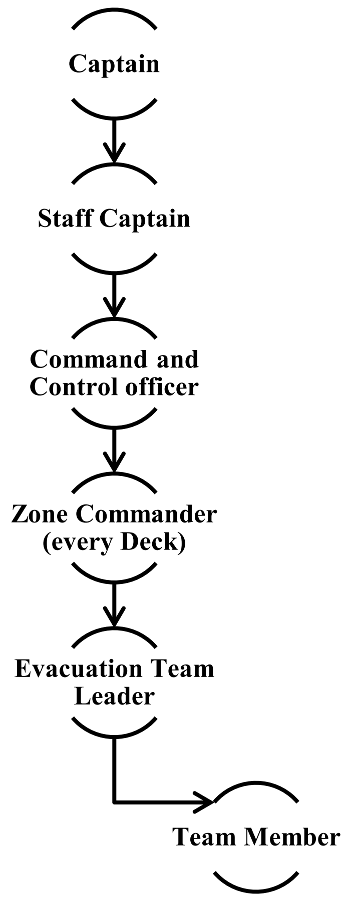


Figure: Evacuation Command Structure (Author-generated)

This section provides the ship's structure and crew organization, highlighting their role in ensuring safe operations in polar environments. It sets the stage for the next section, which introduces the digital ship model developed in Pathfinder for evacuation simulation.

Appendix 5: Pathfinder Simulation Results

5.1 Standard Access (S1)

Simulation: Model 2

Scenario: Standard Access

Version: 2024.2.1209

Mode: Steering

Total Occupants: 300

Completion Times for All Occupants (s):

Min: 1147.6 "00258"

Max: 2116.1 "00077"

Average: 1633.8

StdDev: 273.3

Completion Times by Behavior (s):

Behavior	Count	Min	Min_Name	Max	Max_Name	Avg	StdDev
Crew in Management	18	1995.8	"00058"	2116.1	"00077"	2033.5	33.1
D4 Boat 1 Right	29	1391.6	"00365"	1487.9	"00132"	1445.5	27.0
D4 Boat 2 Lft	50	1571.1	"00183"	1806.8	"00174"	1682.0	56.1
D4 corridor to boat 3 -	20	1147.6	"00258"	1225.2	"00257"	1185.4	24.5
D4 corridor to boat 3 - Copy	20	1174.8	"00290"	1348.5	"00225"	1275.1	66.2
D5 Boat 3 right	10	1427.2	"00285"	1492.8	"00282"	1462.0	24.2
D5 Boat 4 Lft	50	1489.5	"00301"	1950.2	"00322"	1721.2	153.8
D6 corridor to boat 1	20	1186.2	"00147"	1357.3	"00160"	1220.5	45.6
Evacuation crew to Deck 3	8	1821.9	"00050"	1985.5	"00046"	1957.2	51.3
Evacuation crew to Deck 4	8	1762.3	"00056"	1825.7	"00094"	1807.5	22.0
Evacuation crew to Deck 5	8	1916.8	"00089"	1929.9	"00092"	1924.2	4.2
Evacuation crew to Deck 6	8	1897.0	"00103"	1906.8	"00104"	1902.3	3.3

bridge crew	10	1286.9	"00070"	1568.9	"00069"	1432.3	105.5
crew on D4 boats Left	9	1853.6	"00022"	2080.4	"00020"	1948.3	69.4
crew on D4 boats Right	12	1815.7	"00035"	2073.7	"00018"	1928.2	78.8
crew on D5 boaT Right	10	1807.8	"00112"	1984.8	"00110"	1883.2	56.1
crew on D5 boats Left	10	1716.2	"00045"	1958.1	"00041"	1866.0	78.9
all behaviors	300	1147.6	"00258"	2116.1	"00077"	1633.8	273.3

Travel Distances for All Occupants (m):

Min: 94.4 "00068"

Max: 327.1 "00103"

Average: 169.7

StdDev: 49.3

5.2 Starboard Blocked (S2)

Simulation: Model 2

Scenario: Starboard Blocked

Version: 2024.2.1209

Mode: Steering

Total Occupants: 300

Completion Times for All Occupants (s):

Min: 1166.8 "00262"

Max: 2215.6 "00077"

Average: 1653.4

StdDev: 246.2

Completion Times by Behavior (s):

Behavior	Count	Min	Min_Name	Max	Max_Name	Avg	StdDev

Crew in Management	18	1993.6	"00058"	2215.6	"00077"	2054.2	61.7
D4 Boat 1 Right	29	1368.0	"00357"	1713.0	"00141"	1547.0	121.7
D4 Boat 2 Lft	50	1506.3	"00202"	1831.4	"00185"	1637.5	75.2
D4 corridor to boat 3 -	20	1166.8	"00262"	1354.6	"00260"	1244.3	54.9
D4 corridor to boat 3 - Copy	20	1243.2	"00294"	1611.2	"00217"	1406.9	109.0
D5 Boat 3 right	10	1413.7	"00283"	1689.8	"00278"	1527.9	113.1
D5 Boat 4 Lft	50	1426.0	"00315"	1953.9	"00349"	1671.5	151.9
D6 corridor to boat 1	20	1292.3	"00155"	1404.3	"00160"	1347.1	27.0
Evacuation crew to Deck 3	8	1833.0	"00050"	1885.6	"00052"	1866.7	18.8
Evacuation crew to Deck 4	8	1777.0	"00056"	1959.9	"00096"	1875.9	79.9
Evacuation crew to Deck 5	8	2048.3	"00087"	2064.2	"00089"	2056.7	5.4
Evacuation crew to Deck 6	8	2009.1	"00105"	2022.7	"00102"	2016.1	4.4
bridge crew	10	1288.3	"00070"	1570.6	"00069"	1434.6	107.1
crew on D4 boats Left	9	1744.3	"00024"	1997.2	"00020"	1847.1	80.9
crew on D4 boats Right	12	1722.5	"00033"	1961.1	"00018"	1846.6	77.1
crew on D5 boaT Right	10	1738.2	"00118"	2011.7	"00115"	1886.6	88.5
crew on D5 boats Left	10	1708.4	"00045"	1999.7	"00041"	1895.5	89.7
all behaviors	300	1166.8	"00262"	2215.6	"00077"	1653.4	246.2

Travel Distances for All Occupants (m):

Min:	95.7 "00068"
Max:	421.3 "00088"
Average:	216.2
StdDev:	61.4

•

Appendix 6: Arctic SAR Evacuation Calculations

6.1: Norway SAR Evacuation Calculation Details

A. Norway Air Evacuation

Four AW101 "SAR Queen" helicopters operated by Norwegian SAR services are available for air evacuation at the time of the incident.

Distance to accident site: 1,250 km

Cruise speed: 278 km/h

Time to site (one way): 1,250 / 278 ≈ 4.5 hours

Hoisting time per sortie: ~1 hour

Return trip: 4.5 hours

Turnaround time after drop-off: ~0.92 hours

Total time per sortie:

4.5 (to site) + 1 (hoist) + 4.5 (return) + 0.92 (reset) = 10.92 hours

Each helicopter capacity: 50 standing passengers

Total passengers to evacuate: 300

Number of evacuation trips needed: 300 / 50 = 6 total evacuation trips

Evacuation trips per helicopter (4 available):

• First wave: 4 helicopters evacuate 200 passengers in 4 evacuation trips

• Second wave: 2 helicopters perform 2 additional evacuation trips to evacuate the remaining 100 passengers

Flight Duration Summary:

• Wave 1 (All 4 helicopters): 1 round trip each = 10.92 hours

• Wave 2 (2 helicopters):

- Wait time before redeployment: 0.25 hours
- Second round trip: 10.92 hours
- Total Wave 2 time: 11.17 + 10.92 = 22.09 hours

B. Norway Sea Evacuation

This part details the calculation process used to estimate the total maritime evacuation time for 300 passengers using Norway's Jan Mayen-class offshore patrol vessels.

Vessel Details:
- Class: Jan Mayen-class (Jan Mayen W310, Bjørnøya W311, Hopen W312)
- Passenger Capacity per Vessel: 100 passengers
- Total Number of Vessels Deployed: 3
- Total Passenger Capacity: 3 × 100 = 300 passengers
- Maximum Speed: 22 knots (approximately 25 mph or 40.74 km/h)

1. Calculate time to reach site:
   - Time = Distance / Speed
   - Time = 1,250 km / 40.744 km/h ≈ 30.68 hours

Rounded, this is reported as "less than 30.5 hours" for clarity and simplicity in the report.

2. Total Evacuation Time:
   - Since all three vessels operate simultaneously and each can carry 100 passengers, a single coordinated voyage is sufficient to evacuate all 300 passengers.
   - Thus, total evacuation time = time to reach site = approximately 30.5 hours.

Assumptions:
- All vessels are fully operational and dispatched at the same time.
- Weather and sea conditions allow travel at maximum speed.
- No turnaround trips are required.
- Passengers are ready for immediate boarding upon arrival.

6.2: Svalbard SAR Evacuation Calculation Details

A. Svalbard Air Evacuation

Two Super Puma helicopters based in Longyearbyen are available for air evacuation.

Distance to accident site: 750 km
Cruise speed: 247 km/h
Time to site (one way): 750 / 247 ≈ 3.04 hours
Hoisting time per sortie: 38 minutes (0.63 hours)
Return trip: 3.04 hours
Turnaround time after drop-off: 15 minutes (0.25 hours)

Total time per sortie: 3.04 (to site) + 0.63 (hoist) + 3.04 (return) + 0.25 (reset) = 6.96 + 0.63 = 7.84 hours

Each helicopter can carry 19 passengers per trip.
To evacuate 300 passengers: 300 / 19 ≈ 15.8 → 16 total evacuation trips required
Each helicopter completes 8 evacuation trips.
Assuming continuous rotation and ideal conditions, total evacuation time ≈ 8 trips × 7.84 hours = 62.72 hours

B. Svalbard Sea Evacuation

The Polarsyssel is used for maritime evacuation operations.

Distance to accident site: 750 km
Cruise speed: 27.78 km/h (15 knots)
Time to site (one way): 750 / 27.78 ≈ 27 hours

Round-trip time: 27 hours (to site) + 27 hours (return) = 54 hours
Capacity per trip: 35 passengers
Total passengers: 300
Number of round trips needed: 300 / 35 ≈ 8.57 → 9 round trips

Total evacuation time: 9 × 54 = 486 hours ≈ 20.25 days

6.3: **Iceland SAR Evacuation Calculation Details**

A. Iceland Air Evacuation

Two Airbus H225 Super Puma helicopters operated by the Icelandic Coast Guard (ICG) are available for air evacuation at the time of the incident.

- Distance to accident site: 1,150 km
- Cruise speed: 263 km/h
- Time to site (one way): 1,150 / 263 ≈ 4.37 hours
- Hoisting time per sortie: 38 minutes ≈ 0.63 hours
- Return trip: 4.37 hours
- Turnaround time after drop-off: 15 minutes ≈ 0.25 hours

Total time per sortie:
4.37 (to site) + 0.63 (hoist) + 4.37 (return) + 0.25 (reset) = 9.62 hours

- Each helicopter capacity: 19 passengers

- Total passengers to evacuate: 300
- Number of evacuation trips needed: 300 / 19 ≈ 15.8 → 16 total evacuation trips
- Evacuation trips per helicopter (2 available): 16 / 2 = 8 evacuation trips each

Total evacuation time (ideal conditions):
8 evacuation trips × 9.7 hours (rounded) = 77.6 hours

B. Iceland Sea Evacuation

The ICGV Þór and ICGV Freyja are the primary maritime assets for evacuation.

- Distance to accident site: 1,150 km
- Cruise speed: 19 knots ≈ 35.19 km/h
- Time to site (one way): 1,150 / 35.19 ≈ 32.68 hours
- Round-trip time: 2 × 32.68 = 65.36 hours

Passenger capacity per trip:

- ICGV Þór: 48 persons (including crew)
- ICGV Freyja: 35 persons
- Combined capacity per trip: 48 + 35 = 83 passengers
- Total passengers to evacuate: 300
- Number of round trips required: 300 / 83 ≈ 3.61 → 4 full round trips
- Total sea evacuation time: 4 × 65.36 = 261.44 hours

Estimated evacuation duration with loading/unloading and reset time:
≈ 327–350 hours ≈ 13.6–14.6 days

6.4: Greenland SAR Evacuation Calculation Details

A. Greenland Air Evacuation

Two Airbus H225 helicopters operated by Air Greenland are available for air evacuation.

Distance to accident site: 1,600 km

Cruise speed: 263 km/h

Time to site (one way): 1,600 / 263 ≈ 6.1 hours

Hoisting time per sortie: 38 minutes ≈ 0.63 hours

Return trip: 6.1 hours

Turnaround time after drop-off: 15 minutes ≈ 0.25 hours

Total time per sortie: 6.1 (to site) + 0.63 (hoist) + 6.1 (return) + 0.25 (reset) = 13.08 hours ≈ 13.1 hours

Each helicopter capacity: 19 passengers

Total passengers to evacuate: 300

Number of evacuation trips needed: 300 / 19 ≈ 15.8 → 16 total evacuation trips

Evacuation trips per helicopter (2 available): 16 / 2 = 8 evacuation trips each

Total evacuation time (ideal conditions): 8 evacuation trips × 13.1 hours = 104.8 hours per helicopter

Considering only one helicopter operational: 16 evacuation trips × 13.1 hours = 209.6 hours (8.7 days)

B. Greenland Sea Evacuation

Three vessels available: 2 x Knud Rasmussen-class, 1 x Thetis-class

Cruise speed: Knud Rasmussen = 17 knots (≈ 31.48 km/h), Thetis = 15 knots (≈ 27.78 km/h)

Distance to accident site: 1,600 km

Time to site: Knud Rasmussen ≈ 50.82 hours, Thetis ≈ 57.6 hours

Combined capacity per trip: 2 x 43 + 100 = 186 passengers

Trips needed to evacuate 300 passengers: 2 full rotations

Each round trip time (based on longest ship - Thetis): 57.6 × 2 = 115.2 hours

Total evacuation time: 2 × 115.2 = 230.4 hours (≈ 9.6 days)