ESTIMATING MAXIMUM EXPECTED TIME OF RESCUE: FOCUSING ON HELICOPTER RESCUE TO MARINE INCIDENTS IN THE CANADIAN ARCTIC

by

Isabella de Almeida Fernandes

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

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ABSTRACT

This research explores the impact of various factors on helicopter operability and response times during Search and Rescue (SAR) operations in the Canadian Arctic marine environment. Using the Helicopter SAR Operations Model (HESARO) to simulate scenarios—such as the number of people in distress, incident locations, and seasonal variations—and the Royal Canadian Armed Forces Helicopter Environmental Operability Model (RHEO) to assess challenges faced by Cormorant helicopters in adverse weather, the study evaluates the Maximum Expected Time of Rescue for Helicopter Operations (METR-HT). The HESARO model, built as a Discrete Event Simulation (DES), realistically simulates the sequence of SAR events (e.g., helicopter takeoff, refueling, search, and rescue) at specific time intervals. This event-based approach enables the assessment of SAR operations under predefined conditions. To account for variability and uncertainty, the model integrates Monte Carlo Simulation (MCS), introducing randomness into key factors such as weather, takeoff preparation, and hoist time for Persons in Distress (PID). Through multiple simulation runs, the model captures a broad range of possible SAR outcomes, enhancing its ability to reflect the unpredictability of real-world operations. The results highlight significant spatial and temporal variations in response times, with northern zones showing extended durations, particularly during winter months when METR-HT exceeds 26 hours. In contrast, southern Arctic zones demonstrate faster response times, with durations falling below 15 hours in summer. These findings emphasize the need for seasonal preparedness in Arctic SAR operations. The insights derived from this study have implications for improving the IMO Polar Code, advising ship operators on safety protocols, and supporting strategic planning by the Canadian Coast Guard and Armed Forces as maritime traffic and incident risks continue to rise in the Arctic.

Key words: Search and Rescue, Maximum Expected Time of Rescue, helicopter operations, Canadian Arctic

LIST OF ABBREVIATIONS USED

AIRSS	ARCTIC ICE REGIME SHIPPING SYSTEM
CAF	CANADIAN ARMED FORCES
CCG	CANADIAN COAST GUARD
DND	DEPARTMENT OF NATIONAL DEFENCE
IMO	INTERNATIONAL MARITIME ORGANIZATION
JRCCS	JOINT RESCUE COORDINATION CENTERS
METR	MAXIMUM EXPECTED TIME OF RESCUE
NWP	NORTHWEST PASSAGE
PID	PERSONS IN DISTRESS
POB	PEOPLE ON BOARD
SAR	SEARCH AND RESCUE
SOLAS	SAFETY OF LIFE AT SEA
SME	SUBJECT MATTER EXPERT
REB	RESEARCH ETHICS BOARD

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1. INTRODUCTION

Global warming represents a fundamental and urgent issue that is extensively explored and debated worldwide. One of its most significant impacts is climate change, which has a strong effect in the Arctic region. Temperatures in the Arctic have increased at a rate nearly four times the global average (Bintanja & van der Linden, 2013). This warming has led to a dramatic reduction in Arctic Sea ice extent, which is shrinking by approximately 12.2% per decade due to warmer summer temperatures (Lindsey & Scott, 2022).

According to WWF Arctic (2024), this loss of sea ice is occurring alongside a global surge in demand for resources, new shipping routes, and economic opportunities. The reduction in sea ice has facilitated the exploration and use of new shipping routes such as the Northwest Passage, which connects the Atlantic and Pacific Oceans. Such developments have led to a rise in shipping traffic in the Canadian Arctic, driven by both commercial and tourism activities (Mudryk et al. 2021).

However, the increase in shipping activity has several adverse consequences. Fu et al. (2021) emphasize that Arctic shipping not only introduces risks to local ecosystems, such as threats to marine mammals from increased underwater noise and vessel strikes, but also poses broader environmental hazards like oil spills, emissions of sulfur and nitrogen oxides, and black carbon emissions that contribute to climate change. This last one is due to carbon residues that, when deposited on ice and snow, reduce their reflectivity (albedo). Furthermore, the growing human presence in the Arctic, driven by increased shipping, underscores the need for robust Search and Rescue (SAR) operations to respond effectively to maritime incidents that could result in severe environmental impacts and loss of life.

1.1 CONTEXT

1.1.1 Search and Rescue in the Arctic

As these risks increase, special efforts from government organizations are required. In particular, when considering disasters in cold climates, the coordination of response to disasters becomes even more challenging and essential. Lauta et al. (2018) identifies cold disasters (disasters occurring in cold environments) as particularly challenging due to three main factors. The first one is the increased challenge to survive due to low temperatures and extreme weather.

Mak et al. (2011) highlights that this survivability depended on many factors, such as the level of protection evacuees have against the cold as well as the air quality inside lifeboats and life rafts. The second factor is that due to these low temperatures and extreme weather, there is also a sparser population in the region that results in limited physical and social infrastructure. This lack of infrastructure affects the ability to deliver aid, mobilize resources, and coordinate effective communication during disaster response, making it more difficult and slower to reach affected areas quickly and efficiently. Lastly, cold disasters often involve complex institutional arrangements and occasionally disputed jurisdictions. This can lead to ambiguities related to the mandates, obligations, and limitations - such as jurisdictional authority or the capacity to respond effectively- of various countries and authorities, which often need to be clarified while the disaster is ongoing.

In the Canadian Arctic, the incidents are responded to and coordinated by multiple organizations. The National SAR Manual presents federal SAR policy and outlines the federal SAR organization and interdepartmental structure to provide successful SAR (DND, 2014). The Canadian Coast Guard (CCG), in collaboration with the Royal Canadian Air Force (RCAF), operates a coordinated SAR system that delivers on-water and aerial response to maritime incidents. The RCAF has been mandated by the government to provide dedicated aircraft and crews for maritime SAR operations. The SAR system includes the operation of three Joint Rescue Coordination Centres (JRCCs) that are funded, established, and operated by the CCG and RCAF. In Canada, there are three JRCCs, see Figure 1, which are JRCC Victoria in British Columbia, JRCC Trenton in Ontario, and JRCC Halifax in Nova Scotia. JRCC Halifax oversees SAR incidents in the eastern region and coordinates SAR alerts and emergency responses. Additionally, there is a Marine Rescue Sub-centre (MRSC) based in Quebec City and one in St. John's. The role of the MRSC is to alleviate the workload of the JRCC in regions with heavy marine traffic. In this way, these three regions divide responsibility for SAR operations across Canada and they can be observed in Figure 1 below.

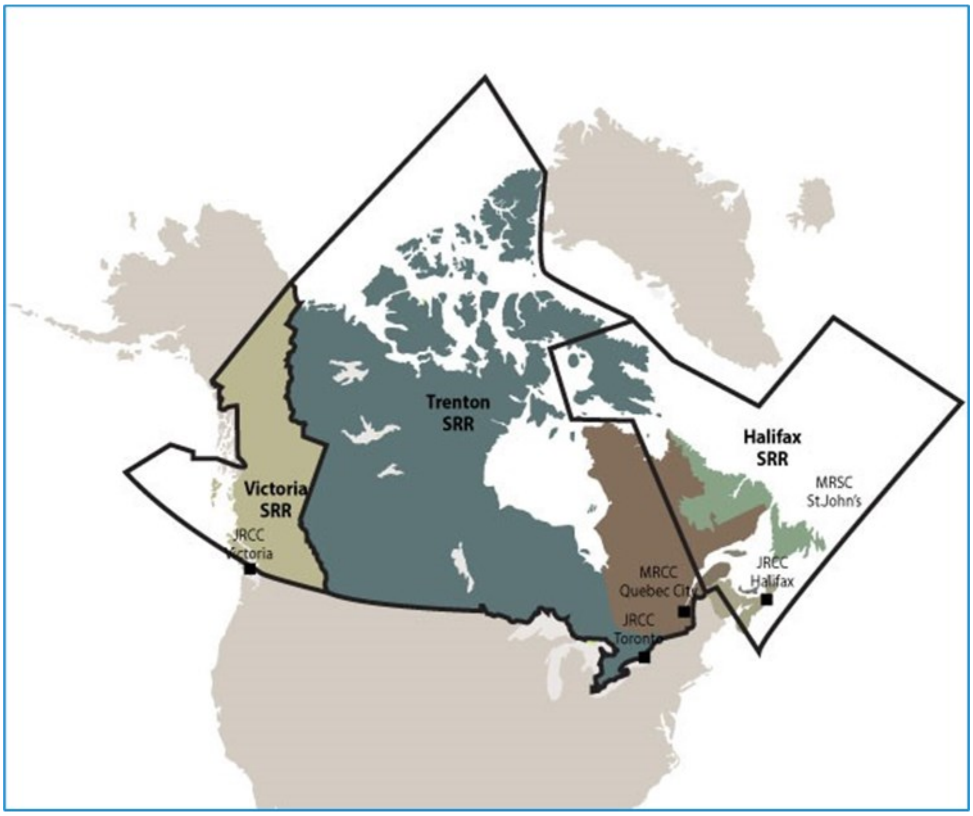

Figure 1: Map of Canada showing 3 Search and Rescue regions. (Canadian Coast Guard, 2019)

Figure 1 represents how the responsibility is shared between the three JRCCs in the Canadian Arctic. JRCC Victoria is responsible for the primary SAR response in the Yukon Territory, while JRCC Trenton oversees the Northwest Territories and Nunavut, including northern Baffin Island. JRCC Halifax handles SAR operations for the southern half of Baffin Island. (Department of National Defence, 2018).

However, challenges persist in implementing SAR effectively in Canada, particularly in remote and Arctic regions. Research highlights deficits in SAR risk governance, such as limited organizational capacity, dispersed responsibilities, and inadequate stakeholder engagement. These governance challenges complicate SAR response efforts in vast maritime areas with varying risk profiles and changing climatic conditions (Cucinelli et al., 2023).

1.1.2 Challenges in Arctic Search and Rescue

SAR operations in the Arctic face unique challenges depending on the type of response asset. For instance, marine response face sea ice concentrations, which significantly impacts routes and increases response times (Choi et al., 2015). Mostaghimi (2024) estimated these increases as well as Stoddard et al. (2024) who calculated the ice risk-adjusted Estimated Time of Arrival for polar class ships. In contrast, air response is most affected by adverse weather conditions. According to Zacharová and Čerňan (2023), critical factors such as wind, visibility, turbulence, icing, and storms are the greatest factors to helicopter operations. In addition to directly affecting flight safety and transit times, extreme conditions can also cause airport closures or disrupt fuel supply chains, further delaying SAR air assets from reaching incident sites. A notable example occurred in November 2023, when a snowstorm with winds exceeding 100 km/h in Arviat prevented planes from landing or taking-off for over 24 hours (Antunes, 2023). Additionally, Ohi and Kim (2020) affirm that visibility and crosswind speeds are key factors influencing flight disruptions. These challenges are worsened by the Arctic's vast, rapidly changing environments, where varying weather conditions across its extensive areas can complicate timely and effective rescue responses.

Given these intensified risks and the extra challenging environment for SAR, the International Maritime Organization (IMO) created the International Code for Ships Operating in Polar Waters, known as the Polar Code, which addresses not only SAR but also ship design and operations to increase safety of ships in polar waters as well as equipment and environmental protection in these remote locations. One of the specifications in the Polar Code is that the equipment and supplies necessary for survival in a maritime emergency must remain operational to anticipate survivability of people on board for the Maximum Expected Time of Rescue (METR), which must be at least five days (IMO, 2024).

Gudmestad and Solberg (2019) suggest that survivors would likely not endure five days under the current equipment regulations. The definition of "sufficient" equipment in these regulations is unclear (Power et al., 2019). Moreover, the Polar Code does not adequately address all potential health risks, particularly mental health, physical mobility, and dehydration. There is also evidence of insufficient understanding and implementation of the Polar Code. Furthermore, various sources indicate that completing a rescue in 5 days is insufficient to reach some remote locations, especially under challenging environmental conditions, due to the limited infrastructure, and the fact that response assets in Canada are concentrated in the South. (Mostaghimi, 2024; Solberg, 2017).

The limited infrastructure and extreme conditions prevalent in the Arctic render the five-day stipulation outlined in the Polar Code impractical for many SAR operations, as corroborated by the findings of Mahoney & Python (2023) and Mostaghimi (2024).

1.1.3 Modeling and Analysis of Search and Rescue

Several studies have explored the modeling and analysis of SAR operations, focusing on predicting times to improve strategic planning. Previous research has addressed aspects such as optimizing response times, determining the optimal location of SAR vessels (Akbari et al., 2018), enhancing communication systems, and assessing the impact of environmental conditions on operational efficiency. Forouzangohar (2022) contributed by developing a location-allocation model that not only improves SAR vessel coverage along Canada's East Coast but also integrates transit time estimation mechanisms, balancing cost, coverage, and resource allocation. These studies provide valuable insights into SAR challenges and solutions in Arctic environments.

Stoddard et al. (2024), for instance, focused on determining the fastest route between two locations in the Arctic by ship, accounting for ice risk. Similarly, Mostaghimi (2024) estimated travel time based on various incident locations throughout the Canadian Arctic, while also evaluating key factors that contribute to efficient SAR operations for marine resources, with a focus on estimating the Maximum Expected Time of Rescue (METR) using marine assets. While both studies focus on marine resources, Zarrin Mehr et al. (2023) investigated SAR response by air. Zarrin Mehr's work explored how factors such as distance, the number of helicopters, and operational conditions affect the overall success and duration of SAR operations when using the Cormorant CH-149 helicopters.

1.1.4 Research Contributions

This research contributes to the field by analyzing how weather conditions impact helicopter operability in the Canadian Arctic, with a specific focus on the Cormorant SAR helicopter for marine incidents. The study examines key factors affecting helicopter operability and uses simulation techniques to estimate the Maximum Expected Time of Rescue – Helicopter Operations (METR-HT) under various weather conditions. By exploring different scenarios across locations and times of the year, this research aims to enhance SAR strategic planning and improve operational effectiveness in the Arctic.

1.2 RESEARCH OBJECTIVES AND QUESTIONS

The primary aim of this research is to investigate how weather conditions influence the operability of helicopters in SAR operations impacts on response time for ship incidents in the Canadian Arctic, and to determine the METR for helicopter response. The study addresses these key objectives by evaluating helicopter performance under various weather conditions, identifying the factors that affect METR-HT, and simulating strategic scenarios across different locations and times of the year. The research is guided by the following specific objectives and research questions:

- To evaluate the impact of weather conditions on the operability of RCAF helicopters used in Search and Rescue operations in the Canadian Arctic.
- To determine the Maximum Expected Time of Rescue (METR) for helicopter-based rescues.
- To simulate strategic scenarios to identify METR for helicopter operations, considering varying weather conditions through incident locations and times of the year.

Research Questions:

Q1: How does the weather impact helicopter operability in the Canadian Arctic?

- Q1.1: What specific weather factors affect the operability of the Cormorant helicopter, and in what ways?
- Q1.2: How do these weather factors vary across different locations and times of the year in the Canadian Arctic?

Q2: What is the METR for helicopter operations in the Canadian Arctic?

- Q2.1: What factors influence the METR for helicopter times?
- Q2.3: How do varying weather conditions impact METR-HT in different locations in the Canadian Arctic?

1.3 THESIS OUTLINE

This thesis is organized into six chapters. Chapter 2 provides a comprehensive overview of existing research on Arctic shipping and SAR operations. It also examines previous studies related to helicopter operability and the METR. Chapter 3 details the research methods, data collection procedures, and analysis techniques used in this study. It explains the simulation models applied to the SAR scenarios, how they are determined and their relevance to understanding METR. In Chapter 4, the findings of the research are presented, highlighting the effects of weather conditions on helicopter operability and METR. This chapter provides an analysis of how varying weather conditions influence response time. Chapter 5 interprets the results in the context of the existing literature, exploring the implications for SAR operations and strategic planning in the Arctic as well as suggesting directions for future research. Finally, Chapter 6 summarizes the key findings and contributions of the research.

2. LITERATURE REVIEW

During a ship incident event, especially when located in Polar Waters, surviving in the harsh environment conditions is challenging. Because of this, multiple efforts from SAR organizations are made to ensure prompt response and that ships are equipped with appropriate survival equipment. This reality is equally important for northern Canadian maritime areas. Consequently, this literature review aims to understand relevant aspects of SAR for marine incidents, their types and frequency. Anticipating the modeling required to answer the research questions, the aeronautical response system and its organization are described as well, and earlier model developments to gain insights in aeronautical SAR operations are reviewed. The overall aim is to provide a basis of understanding the importance of METR investigations in the Canadian Arctic, and to review previous related work.

This chapter presents a thematic literature review to outline and provide a basis for understanding key aspects of SAR in the Canadian Arctic, focused primarily on helicopter response for building the model and performing the analyses to answer the research questions outlined in the introduction. The literature review starts by giving an overview of ship activities in the Canadian Arctic in order to understand the extent and nature of maritime activity in these waters. Insights from existing literature on historical ship accidents in this region are discussed, highlighting the types and frequency of incidents that necessitate helicopter SAR operations. Patterns and common factors identified in emergencies that may impact the METR are discussed, drawing from existing research. In addition, in section 2.2, an overview of the Canadian SAR system, its structure, operations, and challenges are presented. Then, in section 2.3, a review of simulation models for maritime SAR operations in the Canadian Arctic is provided, describing existing models with similar aims to the current work. These themes together set the scope and provide an information basis to develop and construct the proposed model to investigate the METR.

2.1 ARCTIC MARITIME SAFETY AND SHIP ACCIDENTS

2.1.1 Overview of Ship Activity in the Canadian Arctic

Arctic shipping has experienced significant changes due to climate change, which has led to a reduction in sea ice cover and opened new shipping routes. In the period of 2013 to

2023, maritime traffic in the Canadian Arctic was increased by 37% as reported by PAME (2020). According to the same source, the number of unique ships entering the Polar Code area was 784 in September 2013, whereas in the same month in 2023, this number increased to 1,122. This rise in activity brings new challenges to maritime safety and highlights the need for an effective SAR system.

Maritime activity in the North is vital for the communities that rely on it, with approximately 95% of supplies to this region being transported by sea (Transport Canada, 2018). As the Northwest Passage (NWP) becomes more accessible due to climate change, predictions indicate that shipping activity will continue to rise. This increase is not only driven by the accessibility of new routes but also by the expansion of project proposals in the Canadian Arctic (Drewniak & Dalaklis, 2018). Besides supplying communities, further maritime activities in the Arctic consist of fishing, supporting industrial operations, exporting resources, research, and tourism (Eguíluz et al., 2016).

However, the decrease in sea ice, while facilitating more shipping activity, also raises the risks involved. The Arctic remains a harsh environment where ice conditions, including the southern shift of pack ice and the presence of drifting old ice (OI), continue to pose significant threats to maritime safety (Drewniak et al., 2021). These conditions can create choke points in narrow channels, presenting considerable navigation hazards. Additionally, vessels navigating these treacherous waters pose risks to the fragile Arctic ecosystem and the traditional socio-cultural environments (Fu et al., 2021). This evolving situation underscores the importance of robust SAR capabilities to address the heightened risks associated with Arctic shipping (Wilson et al., 2004).

While some studies, like Sheehan et al. (2021), have projected that the shipping season could extend to 2.5 months by 2030 due to reduced ice coverage, this view is now challenged by more recent findings. For instance, Cook et al. (2024) argue that despite the overall decline in sea ice, the presence of multi-year ice (MYI) and the formation of ice choke points in key areas of the NWP may reduce the length of the shipping season. Their analysis of shipping routes from 2007 to 2021 suggests that some regions, particularly along the northern route, have seen a significant reduction in navigable weeks due to these persistent ice hazards. This contrasting evidence highlights the complexity and variability of Arctic ice conditions and suggests that predictions of an extended shipping season may be overly optimistic, especially for certain sections of the NWP. Allianz Global Corporate & Specialty (2020) [10] points out that although the consistency of accident investigation reports is currently lacking, these reports play a crucial role in enhancing safety and preventing future accidents by providing insights from past incidents. Considering this, the next subsection will present results of work focusing on historical incidents in the Canadian Arctic.

2.1.2 Analysis of Historical Ship Accidents in Canadian Waters

Historical data on ship accidents in Canadian waters shows common patterns. Transportation Safety Board of Canada (2023) shows that in 2022 there were 197 shipping accidents, with most of them concerning fishing vessels (30%) and cargo vessels (23%). In addition, the main accident types were collision, grounding and fire/explosion which represented 32%, 25% and 17% respectively. Comparably, in the period 2010 to 2019, the lead cause is machinery damage/failure in ships in Arctic waters, often aggravated by harsh weather conditions and limited navigational aids (Allianz Global Corporate & Specialty, 2020).

Another study from past incidents is the one by Stoddard and Pelot (2020). Using a spatiotemporal analysis of maritime SAR incidents from 2005 to 2013, a seasonal pattern is elucidated, with a higher number of cases in summer months. Furthermore, this study analyzed the severity of incidents across Canadian waters. The results emphasize the important role of historical data to support SAR decision-making and highlight the importance for ongoing improvements in safety protocols for ships and rescue capabilities for SAR services. Although Stoddard and Pelot (2020) focused on the Atlantic region, their findings on the seasonal pattern of incidents, with higher occurrences in the summer months, may still offer relevant insights for this research. The multi-year analysis highlights increased maritime activity in the summer, which could similarly impact SAR operations in the Arctic. Additionally, the presence of incidents during the winter months underscores the importance of testing scenarios year-round, as weather and operational challenges persist throughout the entire year.

When analyzing historical ship incidents, it is crucial for the purposes of the current work to gain insights into cases involving aerial response. The Canadian Armed Forces responds to more than 9,000 SAR calls per year countrywide, with around 1,000 requiring the deployment of SAR air assets (Frost, 2021). The author also notes a rise in the number of these calls involving aerial response based on data from 2015 to 2019. He also shows an increasing tendency in aeronautical response operations due to climate change and the related increased shipping activity in the north.

Ng (2014) highlights the importance of helicopter assets in SAR operations, given their capability to provide rapid response and aerial viewing when searching. Additionally, helicopters can perform vertical landings, eliminating the need for a runway or landing infrastructure, unlike most fixed-wing aircraft that require horizontal landing space. This makes helicopters particularly versatile for operations in remote areas and for responding to incidents at sea, where they can hover and perform rescues without needing landing infrastructure. In contrast, Solberg et al. (2017) cite some limitations of helicopters, including their restricted flight times due to limited fuel capacity, which is worsened by the scarcity of refueling infrastructure in northern regions. Other challenges include crew rest requirements, technical issues, weather restrictions, limited range, and visibility concerns. The limited capacity to rescue numerous individuals is another critical factor, particularly as cruise ship traffic in the Arctic increases.

Despite these limitations, helicopters remain highly effective for responding to incidents involving smaller vessels, where their quick deployment can significantly reduce loss of life. Furthermore, in cruise ship scenarios, helicopters can provide vital support, such as delivering supplies or coordinating the operation. This support is evidenced from the research vessel Akademik Ioffe incident in 2018, when CCG vessels were deployed for the rescue and CC-130H Hercules aircraft (a fixed wing SAR Unit) and CH-149 Cormorant helicopters were tasked. The Hercules arrived on scene 8 hours after the first distress message was broadcasted and stood by in the ship's location, circling around it. The Bell 429 helicopter (a SAR Unit from the CCG vessel Amundsen) was deployed to oversee the evacuation (Transportation Safety Board of Canada, 2018).

In addition, helicopters can provide direct operational support by rescuing people in major scenarios as well. An example of such as case is the Viking Sky cruise ship incident, which happened near the Norwegian coast in 2019 with 1,373 persons on board. The large-scale SAR operation involved multiple agencies, with helicopters serving as the primary asset for hoisting people in distress from the ship (DSB, 2020). The rescue operation was a success even with high waves and adverse weather: the operation was completed after 18 hours with 475 people rescued from the cruise ship, including 466 passengers and 9 crew members. The remaining passengers stayed on the ship, as the situation improved when the vessel regained some propulsion power and was able to maneuver.

In conclusion, helicopters can offer a highly effective SAR response due to their numerous advantages, even in harsh conditions and remote areas. As highlighted by Karatas et al. (2017), if allocated strategically they are the most effective vehicles for responding to maritime incidents thanks to their capabilities such as air search, rapid personnel and equipment transport, reduced patient transport time, specialized equipment for various incidents, and reliable operation in challenging environments.

2.2 OVERVIEW OF CANADIAN SAR OPERATIONS AND CHALLENGES

SAR in Canada is a collaborative effort involving various agencies, reflecting the vast size of the country and its diverse terrain and weather conditions. The National Search and Rescue Program (NSARP) involves national, provincial, and municipal governments, alongside other SAR organizations, to deliver SAR services nationwide (Government of Canada, 2018). When the distress involves ships, there are two main entities responsible to provide response to maritime SAR, the Canadian Coast Guard and the Canadian Armed Forces. This section will introduce these two organizations as well as the challenges faced and gaps in the context of the Canadian Arctic.

2.2.1 Structure and Operations of Canadian SAR

According to Funston (2014), SAR operations in the Arctic are uniquely challenging due to the vast and remote area they cover and the unforgiving environment. SAR missions include air, ground and marine, with different organizations dividing the responsibility for these operations.

The regulatory context for Maritime SAR in Canada is shaped by a complex interplay of international and national laws and agreements. As Cucinelli et al. (2023) note, Canada is a signatory to several international conventions, including the UN Convention on the Law of the Sea, SOLAS, and the SAR Convention. These conventions establish general principles and requirements for SAR operations.

At the national level, Canadian legislation, such as the Canada Shipping Act, Marine Liability Act, Emergency Management Act, and Oceans Act, provides the legal framework for implementing these international obligations. Additionally, the Canadian Aeronautical and Maritime Search and Rescue manual (CAMSAR) outlines specific guidelines and standards for coordinating and operationalizing SAR response.

Cucinelli et al. (2023) also gives context on the agencies and actors involved in Maritime SAR in Canada. These responsible authorities form a complex network of organizations working together to ensure a coordinated and effective response to maritime emergencies. As introduced in Section 1.1.1, the Canadian Coast Guard (CCG) as the primary agency to coordinate maritime SAR has the task to provide specialized on-water response resources. The Royal Canadian Air Force (RCAF) provides aerial SAR capabilities. The RCAF has been mandated by the government to provide dedicated aircraft and crews for maritime SAR operations.

Additionally, federal vessels and aircraft are tasked by Joint Rescue Coordination Centres (JRCC) with SAR response duties based on their capabilities (CCG, 2017). The JRCCs are staffed by the Department of National Defence (DND) and CCG, overseeing the entire process of SAR operations, from initial planning to final execution (Government of Canada, 2019). DND also plays a key role in developing national SAR policies and working collaboratively with the CCG on marine SAR.

Transport Canada (TC) serves as the lead regulatory authority for overseeing and regulating transportation systems in Canada, setting shipping legislation and safety standards and supporting aeronautical SAR prevention. Other federal partners, such as Parks Canada, Environment and Climate Change Canada, and Public Safety and Emergency Preparedness Canada, also contribute to SAR efforts. Additionally, provincial, territorial, and municipal governments may provide technical support and scientific advice.

To better understand how these agencies are divided DND (n.d.) published an info brief containing all the government SAR response agencies, presented in the Figure 2 below.

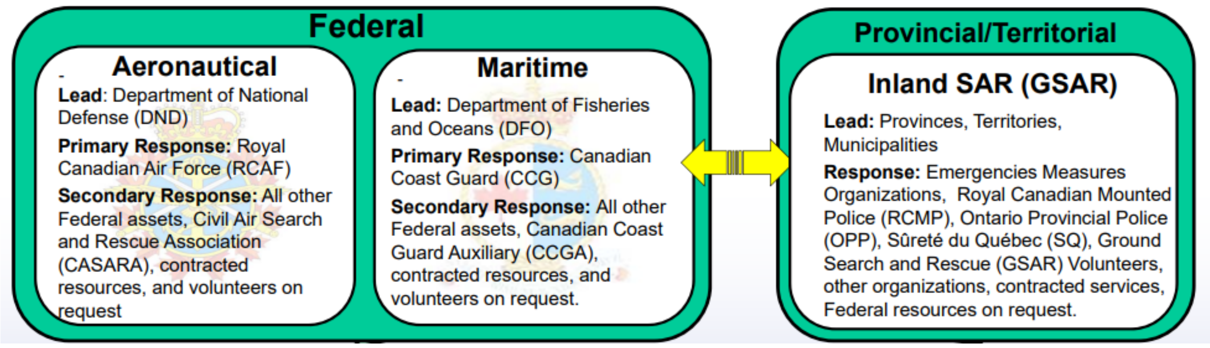

Figure 2: All of Government SAR Response Agencies (DND, n.d.)

The current work focuses on the aeronautical, more specifically, the Royal Canadian Air Force (RCAF), which provides the primary air response. This organization has resources to support each JRCC and the assets are listed below in Table 1 (Canada, Department of National Defence, 2022).

Table 1: SAR aircrafts operated by the Royal Canadian Air Force (Canada, Department of National Defence, 2022)

Aircraft	Type
CH-146 Griffon	Rotary
CH-149 Cormorant	Rotary
CC-130H Hercules	Fixed Wing
CC-295 Kingfisher	Fixed Wing

The table shows all four types of air assets from the RCAF as well as if this is a rotary (helicopter) or a fixed wing asset. In addition, each of them has a specific number of crew required to operate and the number of SAR Technicians (SAR Techs) needed who are experts trained to provide advanced medical treatment and rescue in remote or inaccessible areas. Figure 3 complements the information from Table 1 including the location where each asset is based.

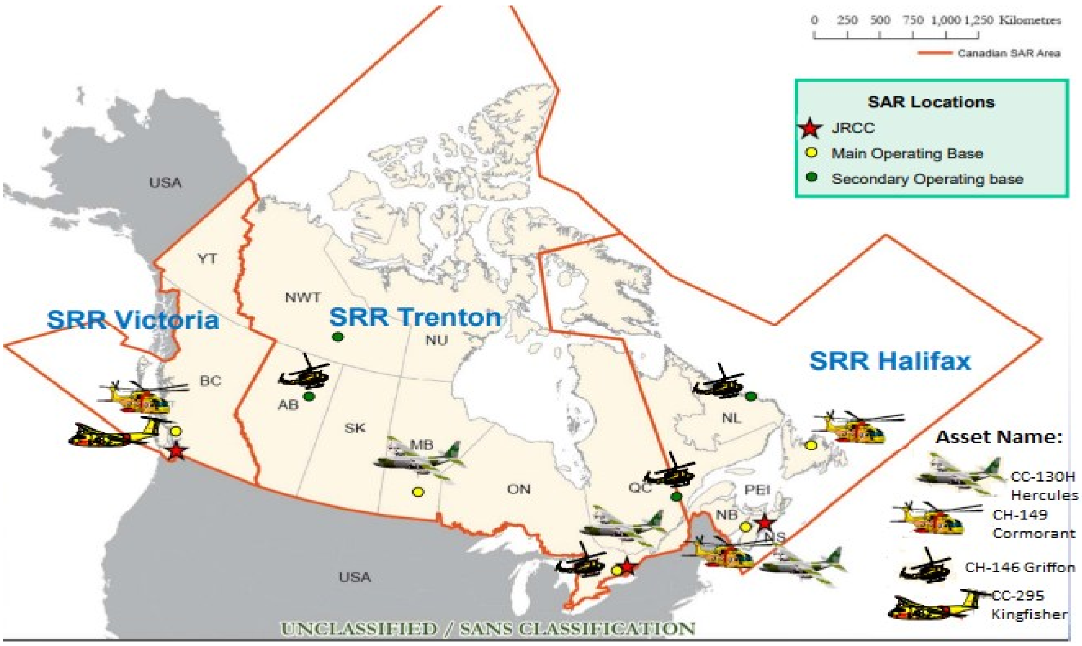

Figure 3: Location of primary and secondary Air SAR assets (adapted from DND, n.d.)

Each asset is adequate for specific kind of mission. For example, the Hercules is a capable aircraft that can quickly transport emergency supplies and SAR personnel to remote locations. The Cormorant is a powerful helicopter equipped with three engines, allowing for extended search missions. SAR Techs can be lowered from the helicopter to rescue individuals in remote areas or from ships. It has a large cargo area with capacity for up to 12 people. The helicopter is essential in this context since it can access some remote areas which vessels cannot or cannot easily reach, especially when challenges such as heavy waves and sea ice are encountered (The Standing Senate Committee on Fisheries and Oceans, 2018).

According to Harila (2019) SAR operations include 5 stages, the notification of an emergency, the first measurements, the preparation of the SAR operation, the deployment of emergency resources and lastly, the conclusion of the SAR operation. Kennedy et al. (2013) also describes the relevant phases of SAR operations, although dividing only in 4 phases. The phases are shown in Figure 4, the stages of a SAR operation include initial communications, travel to location, search period and rescue activities.

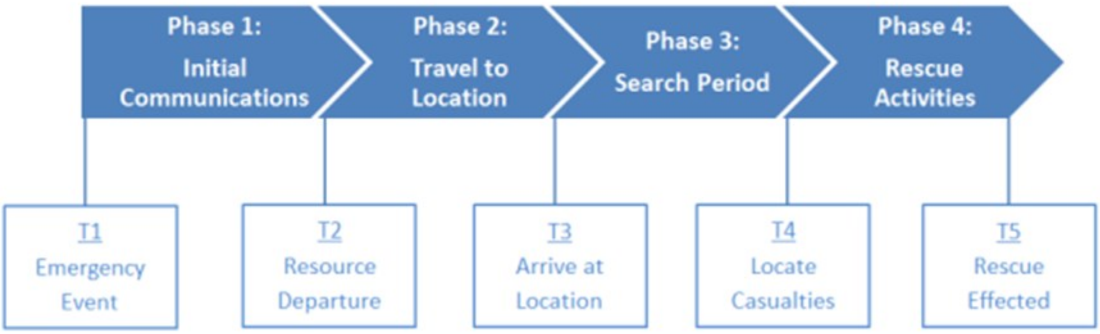

Figure 4: Exposure timeline and relevant phases of SAR operations (Kennedy et al., 2013)

Kennedy et al. (2013) highlights these 4 phases that are in the process of exposure time that they calculate in their work. Each phase includes their start points and end. Phase 1 starts with the emergency event and ends with the resource departure. Phase 2 starts with the resource departure and ends with the arrival at the incident location. Phase 3 starts with the arrival at location and ends with the location of people in distress. Lastly, Phase 4 is the time between locating people in distress and it is completed when people are successfully located in a rescue resource. The author affirms that the factors influencing total exposure time might affect only one phase, multiple or all phases shown in Figure 4.

Lastly, Zarrin Mehr et al. (2023) divide the SAR process into several distinct phases. Unlike previous models, the authors introduce additional steps, resulting in a total of nine phases. Phase one involves confirming the distress notification. Phase two focuses on decision-making based on the location, weather conditions, and available resources. Phase three is the preparation of the helicopter, while phase four covers the flying stage. Phase five involves the search, and phase six addresses the rescue. Phases seven and eight pertain to the weather's impact and the coordination of multiple helicopters, if necessary. Lastly, phase nine involves disembarking the survivors.

2.2.2 Challenges in Arctic SAR

Arctic SAR operations face numerous challenges. These include difficult and dangerous operating conditions, limited support infrastructure, and unreliable communications. Coordination and cooperation issues further complicate efforts, especially since primary SAR assets are located in southern Canada, resulting in vast distances to cover. Additionally, there are fewer vessels of opportunity and aircraft available for quick response, the land-ice interface presents unique obstacles, and extreme weather conditions often exacerbate these difficulties. Russell (2011) notes that the harsh Arctic environment significantly complicates SAR efforts, with the changing environment requiring additional response capabilities in the area to enhance the SAR effectiveness.

Ikonen and Andreassen (2019) identify several gaps regarding Arctic SAR, such as lack of coordination, inadequate contingency planning, poorly charted areas, outdated technology, and unreliable communication systems. A finding from the authors through an exercise in Iceland is that ship crews typically do not want to call in an incident to the JRCC right away and will try to correct it alone, whereas response authorities want to know about a possible need to rescue as soon as possible so they can prepare. This is important because if industry is late alerting the response authorities, then the whole response is delayed, putting lives at risk. The Norway Coast Guard noted that if they are notified right away, they can move helicopters or have response assets on standby in the region to facilitate a rapid response if the situation worsens.

Fuston (2014) analyses the gaps in response initiatives in Canada’s North. The author mentions infrastructure, training, communications, monitoring and notification, response equipment, governance issues, and insurance.

The remoteness of the Arctic poses a significant challenge for SAR. Bouchard (2020) highlights the need for improvements in airport infrastructure, including increasing the number of airports up north and better positioning SAR technicians, all of whom are currently located in southern regions. The author also mentions the importance of investments in weather monitoring capabilities, given the less predictable weather conditions, as well as improved lighting systems for the airports runways, as these are critical for operational safety in low visibility conditions.

In addition to these operational challenges, governance deficits further complicate SAR efforts in the Arctic. Cucinelli et al. (2023) identify key deficits in organizational capacity, such as the shortage of resources and personnel, particularly in remote northern regions, which affects response times. Furthermore, the dispersed responsibilities among various agencies hinder coordination, delaying critical decisions. Different perceptions of risk between SAR authorities and local communities also create challenges, emphasizing the need for better usage of Indigenous knowledge for SAR operations.

2.2.3 Helicopter operability

As discussed in Section 2.1.2, helicopters face various challenges in Arctic SAR operations, primarily due to weather conditions and range restrictions. Kennedy et al. (2013) identifies additional factors that impact operations and consequently, total rescue time. The authors include distance from airport, distance from shore, type of response resource, physical state of response resources and crews, communication effectiveness and capability, preparation of response crew, state of evacuees. Kennedy et al. (2013) also note that for marine response the training and experience of the vessel's captain and crew significantly influence SAR operations, especially in harsh environments. It is argued that these factors can significantly influence the total response time for marine incidents in the Arctic. When focusing on the weather conditions, various factors impact helicopter operability, in particular the assets' performance such as reduced range, decreased speed, or even flight cancellations to ensure safety. According to Ferrari (2019), these critical weather factors include visibility, temperature, wind and precipitation. This highlights the importance of considering those conditions when calculating helicopter times.

These weather conditions vary considerably based on the location and time of the year. Karatas et al. (2017) conducted a study in the Aegean Sea region to determine an allocation plan of SAR helicopters considering proximity to potential incident locations. The authors show how the weather varies across different stations and the importance of considering them when calculating helicopter response times. According to these authors, three weather factors impacting helicopter operability are thunderstorm, heavy precipitation and fog, which should all be accounted for in the vicinity of station. For the calculation of probability distributions of these 3 weather conditions, the study used historical weather data in the vicinity of 9 different stations along the coastline of the Aegean Sea. In addition to considering weather conditions, this work also accounts for probability distributions of helicopter failure rates. System failures in SAR vehicles can significantly impact operations. Despite scheduled maintenance, unexpected failures can occur, particularly during peak seasons. To consider this, Karatas et al. (2017) used historical data to determine probability distributions that were used as inputs in their work.

Several studies consider the weather impact on the expected time of arrival (ETA) for marine assets, highlighting the importance of considering weather when estimating transit time. Whereas for helicopter operations it is likely that other factors influence transit and rescue operation times, these studies confirm the importance of including weather conditions in SAR vessel operations modeling and analysis. For example, Simonsen et al. (2015) studied how to generate an optimum route for ships based on weather forecasts. The model considers the impacts in fuel consumption and how weather routing impacts finding minimum time of arrival using storm avoidance.

Additionally, Mostaghimi (2024) developed a simulation model to estimate the Maximum Expected Time of Rescue – Vessel Transit (METR-VT), accounting for varying conditions such as ice coverage, time of year, bathymetry, and ice-going capabilities of vessels. This methodology aligns with the importance of accounting for the factors influencing helicopter SAR operations, particularly when considering weather and environmental conditions that affect response times in the Arctic. Incorporating such variables improves the accuracy of SAR modeling and strategic planning for Arctic operations.

Siljander et al. (2015) applied GIS-based tools to evaluate SAR response times, considering environmental conditions like wave height and the capabilities of SAR units in the Gulf of Finland. Their work highlights how prevailing wave conditions and harsh environmental factors can significantly affect SAR response times, especially in remote regions such as the northwest Atlantic and Arctic. This supports the importance of including environmental factors like adverse weather when estimating response times for strategic SAR planning. New methods are required to better estimate the impact of these conditions on total SAR time.

Although these works show the importance of considering weather factors when calculating total response times, they primarily focus on marine-based SAR operations. In contrast, very few studies have addressed the impacts of weather conditions on aerial responses in SAR, particularly within the Canadian Arctic. Some of these works are presented in Section 2.3, but even those studies have significant limitations, such as not considering historical weather data for operating conditions or considering only summer months. This gap in literature highlights the need for further research in this area.

The present work aims to fill this void by focusing specifically on how weather conditions influence helicopter operability and response times in Arctic SAR operations. As discussed in Section 2.2.3, the unpredictable and harsh weather conditions in the Arctic play a crucial role in limiting helicopter performance and increasing total times. By incorporating detailed weather data and helicopter performance metrics, this study will contribute to more accurate SAR response models and strategic planning for Arctic rescue operations, addressing the limitations left by previous studies and providing insights into the complex realities of Arctic SAR for air responses.

2.3 EXISTING WORKS FOR SAR OPERATIONS IN THE CANADIAN ARCTIC

Several models have been developed to simulate SAR operations, each with its own strengths and limitations. Zarrin Mehr et al. (2023) employs Discrete Event Simulation and Monte Carlo Simulation to predict SAR outcomes, implemented in Matlab code. Earlier, Piercey et al. (2019) proposed a deterministic approach to estimate exposure times in Polar regions, based on a set of closed-form formulas implemented using Python programming. This latter approach is more focused on integrating SAR operational data into a straightforward predictive model, rather than simulation techniques such as Monte Carlo.

This distinction reflects the differing focuses of the two works: Zarrin Mehr's model is aimed at exploring various scenarios through stochastic processes that can support strategic decisions, while Piercey et al.'s work is deterministic, providing a practical calculation method to estimate exposure times based on user-defined SAR variables and operational constraints.

2.3.1 Rescue Time Simulation

Zarrin Mehr et al. (2023) investigated the factors that influence SAR operations when using helicopter assets, focusing on the Cormorant CH-149 helicopter type. The study examined which factors have the greatest impact on SAR operations and analyzed how distance, PID, refueling location and the number of helicopters affect the total time of the operation. The author also validated his model to ensure its predictions were consistent and accurate.

To achieve those objectives, Zarrin Mehr developed a macro-scale SAR model and implemented this in a MATLAB code to simulate helicopter SAR operations on Canada's East Coast. Using a Discrete Event Simulation approach, Zarrin Mehr introduced stochastic elements to account for operational uncertainties, to gain insights to the variability associated with SAR operations. The model considers essential elements of the SAR operations, including the incident location, number of people in distress, helicopter base and refueling locations, helicopter specifications, the number of helicopters operating in the area, and the season. While Zarrin Mehr et al. (2023) adopts a generic approach to differentiate helicopter operability in summer and winter conditions, focusing primarily on factors like distance and the number of helicopters, the current research specifically addresses the detailed representation of weather conditions and their impact on helicopter SAR response operations. This current work aims to provide a more refined understanding of how varying weather conditions influence total times.

Zarrin Mehr et al. (2023) research also emphasizes the importance of model validation through real-world case studies. The model's plausibility was demonstrated by successfully replicating the timeline of the Viking Sky incident, with the simulation results aligning closely with actual rescue operations, showing a high degree of accuracy. Additionally, the research extends its applicability to Arctic scenarios, indicating a significant reduction in rescue times when helicopter bases are relocated closer to incident sites, particularly for smaller survivor groups. This validation process points to the usefulness of the model and its potential to inform strategic decisions in SAR operations under varying conditions.

Kennedy et al. (2013) developed a set of interlinked deterministic formulas to calculate the exposure time at any location in the Arctic. Their approach considers the different phases of the SAR process given a marine incident, the response resources, the key factors influencing the duration of exposure time, and the incident location. For this, emergency scenarios were selected, a survey and workshop for expert opinion and lastly, data analysis for constructing an exposure time map was performed. The authors state that there are 15 factors that influence exposure time: the distance between emergency site and airport, distance between emergency site and shore, wind and waves, air temperature and precipitation (the combination of low air temperatures and precipitation can lead to icing conditions, which significantly impact SAR operations), ice condition, type of response resource, physical state of response resource and crew, communication effectiveness, preparation of response crews, communication capability, state of evacuees, visibility, bathymetry, training of captain and crew and the accuracy of environmental models (for example for drift predictions and weather conditions). For the scenarios, Kennedy et al. (2013) selected 8 locations and weather scenarios These scenarios were chosen based on general low and high conditions rather than a detailed historical evaluation for each location.

Figure 5 below shows the results obtained, where the 'low range' corresponds to scenarios involving helicopter response, and the 'high range' corresponds to scenarios involving marine response.

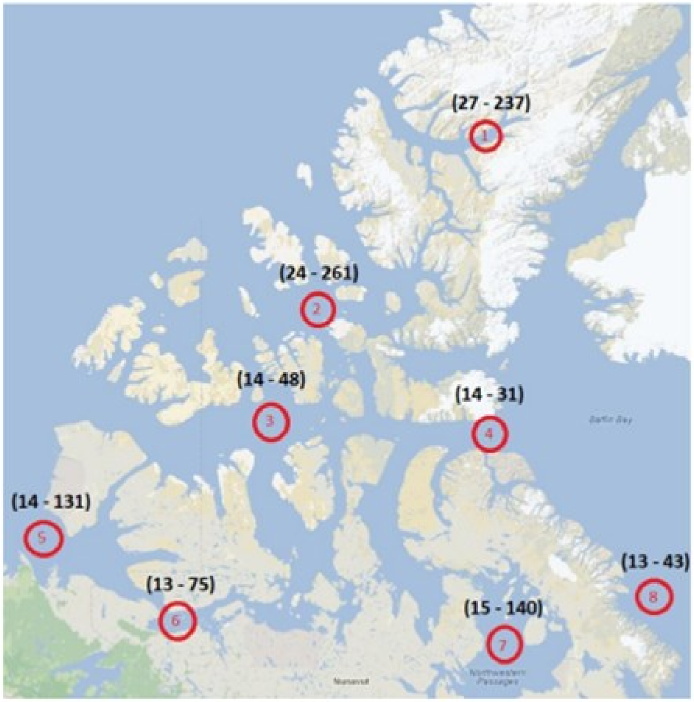

Figure 5: Results of the model by Kennedy et al. (2013) showing merged exposure time ranges based on air and marine Canadian resources.

In the model, the time of the year considered is mid-August, not accounting for other periods when incidents could occur too. In addition, the results account only for low and high environmental conditions, not considering conditions that could occur in between. The authors emphasize that the marine-based exposure time ranges are highly dependent on the specific time of year. They recommend further research to define exposure time ranges for the shoulder seasons of the operational period to better understand how varying environmental conditions throughout the year impact response and transit times in the Arctic. In contrast, the present work extends this analysis by accounting not only for shoulder seasons but also for the extreme winter conditions in the Canadian Arctic, providing a more comprehensive view of response times across all seasons.

Piercey et al. (2019) developed a comprehensive methodology for estimating exposure time in Polar regions, building on earlier work by Kennedy et al. (2013). Their approach considers several key variables critical to SAR operations: rescue craft speed, capacity, and range; proximity of bases and ports to the route; the number of individuals awaiting rescue; and the number of survival crafts deployed. Additional factors are related to SAR response time, which are communication delays, and task force deployment time. The methodology is particularly significant in the context of the International Maritime Organization's Polar Code, which requires that life-saving appliances be functional for at least five days, the default minimum value for the Maximum Expected Time of Rescue in Polar regions according to the Code. The study's findings suggest that as new and more remote routes open in these areas, exposure times may exceed this five-day benchmark, potentially leaving evacuees vulnerable beyond the functional limits of their life-saving equipment. This work underscores the need for enhanced SAR capabilities and preparedness in Polar regions as maritime activity continues to expand into these challenging environments.

Hunter and Rempel (2021) conducted a case study simulating the evacuation of a cruise ship with 2,000 passengers along the Northwest Passage in August. Their analysis utilized a mixed-integer programming capacitated vehicle routing model to assess transportation and logistics challenges. The study established a Discrete Global Grid (DGG) system to partition the Canadian Arctic into hexagonal cells, allowing for a granular analysis of potential evacuation routes. However, it should be noted that the study assumed optimal conditions, such as the continuous availability of SAR resources and the absence of weather delays. This represents a best-case scenario and therefore likely does not fully capture the complexities of real-world evacuations. Recognizing the need for medical care and repatriation to southern Canada, these authors considered the distance to Forward Operating Locations (FOLs) as a crucial factor in evacuation planning. Additionally, they estimated community response capacity based on population size to assess potential supplementary support. By categorizing cells based on factors such as proximity to communities and traffic density, the model provides insights into potential fatalities and response times. This case study demonstrates the value of modeling tools in evaluating SAR capabilities and informing decision-making in the context of large-scale evacuations in the Arctic, while acknowledging the need for further research to address the potential limitations of assuming ideal conditions. In particular, the lack of accounting for weather conditions, whereby these are found to significantly influence the operability of response assets as described in Section 2.2.3, is a limitation which should be addressed in follow-up research.

2.3.2 Evaluation of Simulation Models

The current body of research on SAR operations has produced several models addressing various factors that influence rescue operations. A detailed comparison of these models is presented in Table 2: Comparison of previous related studies, which highlights their objectives and the factors they include in their model, such as geographical context, environmental conditions, and types of SAR assets (air or marine).

Table 2: Comparison of previous related studies

Paper	Objective	Canadian Arctic	Historical Environmental Conditions	Air Response
Mostaghimi (2024)	Estimate METR vor vessels response	☒	☒	☐
Mehr (2023)	Investigate factors impacting total SAR time	☒	☐	☒
Karatas & Gunal (2017)	Allocation plan of SAR helicopters	☐	☒	☒
Mahoney & Python (2023)	Evaluate SAR exposure times	☐	☒	☒
Proposed study	Estimate METR for helicopter response	☒	☒	☒

Note: topic is considered ☒; topic is NOT considered ☐

As presented in Section 2.2.3, Karatas et al. (2017) employ a hybrid methodology combining optimization and simulation for allocating SAR helicopters in the Aegean Sea, showing that integrating both methods leads to more efficient resource utilization. However, this model is tailored to the Aegean Sea, a region that is significantly less harsh and remote compared to the Canadian Arctic. The distances in the Aegean Sea are much shorter, and the region does not experience the extreme environmental conditions or the vast, remote areas that are typical in the Arctic. As a result, while the model may be effective for short-distance, relatively mild environments, its applicability to the Arctic's vast, harsh landscapes is limited.

While existing studies, like those by Karatas et al., offer valuable insights into SAR operations, the gap between their focus areas and the unique challenges of Arctic environments leaves an opportunity for further research. This study addresses those challenges by focusing on helicopter-based SAR operations in the Canadian Arctic, which includes long distances, remote locations, and extreme weather conditions.

Mahoney & Python (2023) also focus on SAR exposure times but limit their study to the United States (US) Arctic. Additionally, while Mostaghimi (2024) provides a model for estimating METR for vessels, it does not cover helicopter SAR operations, which are a crucial component of SAR responses in remote Arctic regions. Moreover, Zarrin Mehr et al. (2023) examines factors impacting SAR times of air response but includes a limited number of cases in the Arctic region and lacks accounting for historical weather conditions.

In summary, as shown in Table 1, none of the existing models fully address all critical aspects necessary for comprehensive Arctic SAR modeling, particularly for air-based SAR operations in the Canadian Arctic. The gaps in the literature – including the omission of seasonal variability, the limited focus on Arctic regions, and the absence of integrated air response modeling – are precisely where this study contributes. By developing a model that incorporates these elements, this study aims to enhance SAR planning and response efficiency in Arctic regions.

3. METHODOLOGY

The research methodology for this study incorporates both qualitative and quantitative approaches. Semi-structured interviews were conducted for preliminary data gathering, followed by data collection from Environment and Climate Change Canada (n.d.), which provided historical weather data sourced from weather stations located at airports across Canada used in this current work. These datasets were processed and analyzed through the development of two quantitative models: the Helicopter Environmental Operability Model (section 3.2.4) and the Helicopter Search and Rescue Operations Model (Section 3.2.3), to explore helicopter total times of CH-149 Cormorant helicopters in Canadian Arctic SAR operations, with a focus on weather impacts supported by statistical analysis. This study aims to establish the METR for helicopter operations to help decision makers with updates to the IMO Polar Code which specifies the ship's operating locations and times, as well as the survival equipment on board.

This chapter presents the method developed, explaining the conceptual approach and its key components. It also outlines the data sources used, and the assumptions made during its application. Figure 6 provides a flow chart illustrating the logical steps of the methodology, helping to clarify the process of addressing the research questions.

3.1 INTERVIEWS

The interviews were divided into two distinct phases, the first one focused on getting initial information around the theme and the second one focused on getting insights for the modelling development and validation. It is important to mention that for both phases of the interviews, an ethics application was submitted to Dalhousie University's Research Ethics Board (REB) (file # 2021-5883). This application included all the questions that were used in the interviews, interview protocols, processes to anonymize data, ensuring that the study met ethical guidelines and standards.

In addition to these elements, the REB application also required detailed information about the recruitment process for interview participants, including how individuals would be approached, the criteria for inclusion, and steps taken to ensure voluntary participation. The application outlined how informed consent would be obtained, ensuring that participants were fully aware of the nature of the research, their rights, and the option to withdraw at any time without consequence. Furthermore, it specified the procedures for data storage and security, detailing how interview recordings and transcripts would be securely stored to protect participant confidentiality.

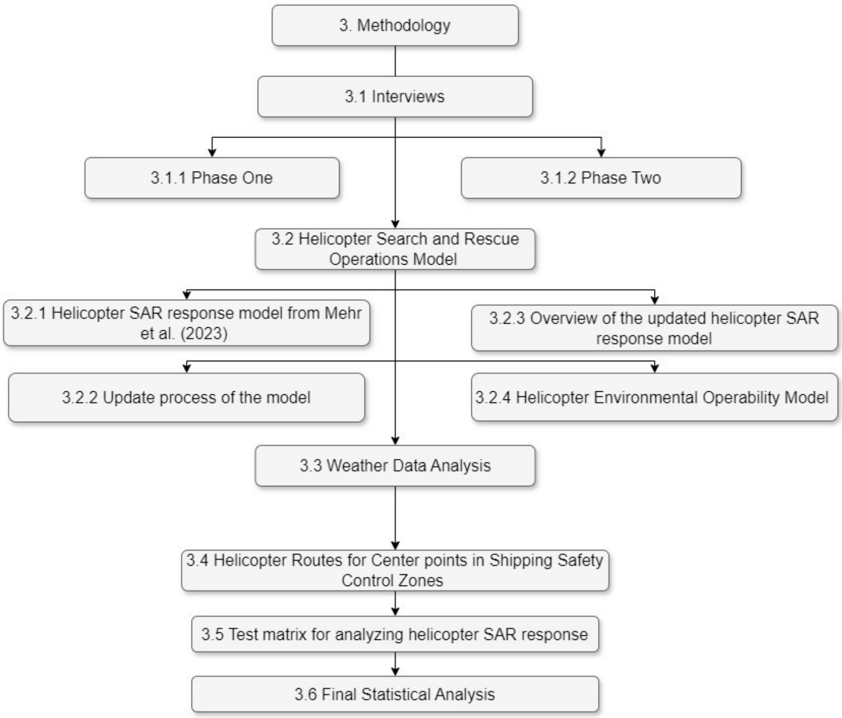

Figure 6: Flow chart showing structure of Chapter 3

The REB also required a risk assessment, which involved evaluating any potential risks to participants (such as emotional distress or discomfort) and explaining how these risks would be mitigated. Finally, the application included a plan for how results would be communicated to participants, ensuring transparency and the opportunity for participants to receive summaries of the research findings if desired.

3.1.1 Phase One

The first phase aimed to gather general information related to the research theme, including Cormorant specifications and limitations, and factors influencing the METR. In addition, it aimed to reach consensus on how the model should look (i.e., what is included or excluded and why), prioritize factors of influence, identify which government, local or international resources are available to respond to incidents in the North and what their capacities and capabilities are. Understand the decision-making process at different phases of the SAR mission and verify findings from the literature review, and identify relevant databases.

With those objectives, the model development was supported by real world information, making it more reliable.

The workshop was focused on Arctic maritime and aeronautical SAR planners, responders, and managers, marine shipping consultants, and international partners. This phase consisted of a three-day workshop that lasted for around four hours and a half each. The workshop was held online due to restrictions during the Covid-19 pandemic, taking place in February 2022 using the Zoom platform. All the sessions were recorded using the platform tools and the attendees were informed of being recorded in accordance with REB. In the beginning of the session, a link leading to a folder was provided with documents that would facilitate the discussion, such as the slide presentation, consent form, "Zoom: best practices" document, acronyms, a definitions document, and lastly, a document presenting the project in more details.

Each day of the workshop focused on distinct parts of the research, with the first day of interviews targeting SAR planners, the second focusing on aeronautical responders including DND, air fleet pilots/operators, SAR techs, CASARA and lastly, the third session with marine responders such as CCG, CCGA, classification societies, and mariners.

The first day of workshop had the goal to gain a better understanding of what parameters and variables should be accounted for in the model, what influences rescue time and how decisions during the SAR response process are made. During the session, polls were administered so the group could gather everyone's opinions based on their experiences and expertise. The polls included questions about the Expected Time of Rescue under different conditions and how the time of year influences SAR operations. In the first poll, participants were asked whether they believed the time of year affects rescue operations, providing a simple yes/no response. Additional polls were designed to explore the relationship between the number of Persons on Board (POB) and the time required for rescue.

In addition to brainstorming about the presentation of results, the design of the METR model, and identifying the key factors influencing METR—such as divisions of time, space, and people—discussions also focused on the project assumptions and how they shape the model. These assumptions, including the criteria for selecting a place of safety and defining operational parameters, were integral to the design of the METR framework. For example, the assumption of where a rescue operation concludes—defined as a place of safety where survivors' immediate needs, such as food, shelter, and medical care, are addressed (IAMSAR, 2019)—directly informs how the model calculates rescue times and outcomes. In the third part of the discussions, the group posed situational questions, using hypothetical locations and timeframes, to leverage the expertise of attendees in fully understanding the model's underlying challenges and refining its accuracy.

The second day directed attention to which factors influence rescue time and how decisions are made around taking and utilization of resources. The second day of the workshop started with questions focused on what are the factors that influence the SAR times when an aeronautical asset is operating. The first half of the morning was focused on distress notification and the transit time, followed by the second half that aimed at the on-scene times up to the time when the last person is rescued and return to a place of safety. On that day, discussion about how weather, sea conditions, and the number of people on board influence SAR time, and for these hypothetical questions assuming an incident with different POB and weather conditions were made.

Four interviewees participated in the workshop’s second day, three of whom are members of the Canadian Armed Forces and the fourth one being a representative from IMP Group (Industrial Marine Products), specifically from its Aerospace and Defense sector. In addition, researchers on METR and SAR were also present, totaling 18 people.

Prior to conducting the interviews, a detailed plan for extracting and analyzing information from the discussions was established as part of the REB approval process. After the interviews were completed, the transcription automatically generated by the Zoom platform was carefully cross-checked against the original recordings to ensure accuracy and correct any errors. The transcription was then organized into a consistent format in an Excel spreadsheet, segmenting and labeling key themes, concepts, and categories. Following the guidance of Miles et al. (2014), this followed the content analysis methodology, systematically displaying the data, allowing for the extraction of critical insights on how weather conditions impact helicopter operability in SAR operations. This process facilitated clear conclusions and informed the development of the RCAF Helicopter Environmental Operability Model (RHEO) – Section 3.2.4 and the Helicopter SAR Operations Model (HESARO) – Section 3.2.3, aligning with the research goals.

3.1.2 Phase Two

The second phase of the interviews happened in the last stage of the RHEO and the HESARO models development. The goal was to validate values that were obtained from the first phase and that were being used in the simulation such as helicopter range, helicopter maximum speed and tank capacity parameters, as well as variables concerning times, such as wait times, weather factors impacting speed, and take off preparation times. The objective was to make sure that no misunderstandings had occurred in the first phase. In addition, the focus was on collecting data and validating the refueling stops most frequently used in Canada for routes to the Arctic. This process involved cross-checking the stops initially identified through SkyVector (n.d.) with actual data, along with validating the output of the HESARO and the RHEO models. This phase was divided into two subphases, an online interview for more open discussion and afterwards, some validations through email for questions that were more direct.

Regarding the first subphase, it took place online in the same way as the first phase of interviews in February of 2024 using the Zoom platform. Two SAR helicopter pilots and one SAR Tech with experience in the Arctic participated in this session. This interview lasted one and a half hours and began with a review of the recording consent, an introduction of the attendees, and an outline of the project context, followed by an update on the stage of model development at the time of the interview. Those stages consisted of literature review, interviews, workshops, modelling design (RHEO model) and assumptions and some preliminary runs of the Helicopter SAR response model from Zarrin Mehr et al. (2023). After this first introduction, those preliminary results were presented in which, three incident locations (in Zones 4, 8 and 13 presented in Section 3.4) were tested in the Canadian Arctic using the model developed by Zarrin Mehr et al. (2023).

The goal with selecting the three incident locations was to validate if the total time (which includes checking distress notification, takeoff preparation, transit time, refueling, searching and rescue time) is aligned with realistic values for SAR operations for those scenarios. In addition, refueling stops, base where the helicopter takes off and the temporary base (where people in distress will be placed) were the focus for validation as well. For each of the three selected locations, 4 different scenarios were selected. These included varying the number of people in distress (12 or 24 people) and the season (summer or winter).

The second part of this interview was to prepare questions to support the model development. For this, the focus was to validate assumptions, reconfirm values from the first workshop and validation of the weather model. The questions are described in sequence below.

The first question related to the validation of refueling stops. As mentioned previously, in this Phase 3 incident locations were tested and the goal with the first question was whether the refueling stops selected for those locations made sense to the SAR experts and if it was consistent with reality. The second question was similar to the first, but now validating the bases nearby the incident location selected as a temporary base for dropping off rescued people. The third question focused on the validation of important numbers that represent the SAR system, including helicopter capacity, pickup time, typical times such as distress notification and helicopter preparation time, helicopter range, fuel tank capacity and maximum speed. The fourth question was to validate the developed weather model and its numbers that represent the thresholds for helicopter operation (described in section 3.2.3). The fifth question focused on the delay factor associated with unfavorable conditions in terms of impact on helicopter range. The focus on this question was to obtain numbers to implement in the model. The sixth question related to visible moisture, checking any other condition besides fog, rain, drizzle, cloud cover, snow and ice which leads to freezing surfaces in the presence of low temperatures. The seventh question was similar to the fifth but focused on understanding the speed reduction associated with each weather parameter. The eighth question was to check whether any additional weather factors impact the SAR operation besides the previous four that were obtained from the first phase of interviews. Lastly, the nineth question is related to crew change and readiness level depending on the time of the day or season.

After the interview session, a follow-up email was sent to one of the available pilots to validate the refueling stops. The main objectives were to determine whether certain airports are preferred over others for SAR operations, identify any airports that are avoided or non-preferred, and confirm that all listed airports provide A-1 fuel, which is used in the Cormorant.

3.2 HELICOPTER SEARCH AND RESCUE OPERATIONS MODEL

The simulation model applied in this research is based on the work developed by Mehr et al. (2023). The model used by Zarrin Mehr et al. (2023) is a Discrete Event Simulation (DES) that, as explained by Babulak and Wang (2010), involves creating models that mimic real-world systems, using stochastic computational and mathematical methods. It simulates the dynamic behavior of these systems by tracking events as they occur in sequence and produces comprehensive reports on performance outcomes. Zarrin Mehr et al. (2023) employs Monte Carlo methods to represent uncertainty and randomness in the helicopter (SAR) process. Harrison (2010) explains that Monte Carlo simulation applies random sampling and statistical techniques to approximate mathematical functions and replicate the behavior of complex systems.

To account for these uncertainties, the model incorporates probability distributions for selected variables such as takeoff preparation time, search time and hoist time. Zarrin Mehr's et al. (2023) work focused on incidents along the east coast of Canada, using Gander Airport, Newfoundland as the Canadian Forces Base from which the Cormorant helicopter takes off. The SAR system simulation begins with the distress notification and concludes when the last person in distress is rescued and brought to a place of safety. The model operates on a time-step logic, updating at each stage of the simulation.

Zarrin Mehr et al. (2023) also tested two scenarios in the Canadian Arctic, demonstrating that the model can be applied beyond the east coast. In this current research, based on the interviews discussed in Section 3.1, additional locations were selected for testing to cover the entire Arctic region (Section 3.4 in Table 7), including more remote locations and other Canadian Forces Bases besides Gander (e.g., CFB Comox). In addition, a description of the development and methodology used for the RCAF Helicopter Environmental Operability Model (RHEO) can be found in Section 3.2.4 as well as the Helicopter SAR Operations Model (HESARO).

3.2.1 Helicopter Search and Rescue response model from Zarrin Mehr et al. (2023)

To simulate the SAR operation for helicopters response, Zarrin Mehr et al. (2023) used the flow chart in Figure 7 below to represent the steps of the process.

The process starts with the distress notification, and depending on multiple factors represented in the flow chart, the helicopter will be deployed. After this step, the preparation to take off occurs, followed by the flying model, searching model and rescue model. These last three happen depending on factors such as sufficient fuel, possibility of performing the rescue and finding PID. The process is concluded when all the survivors are picked up.

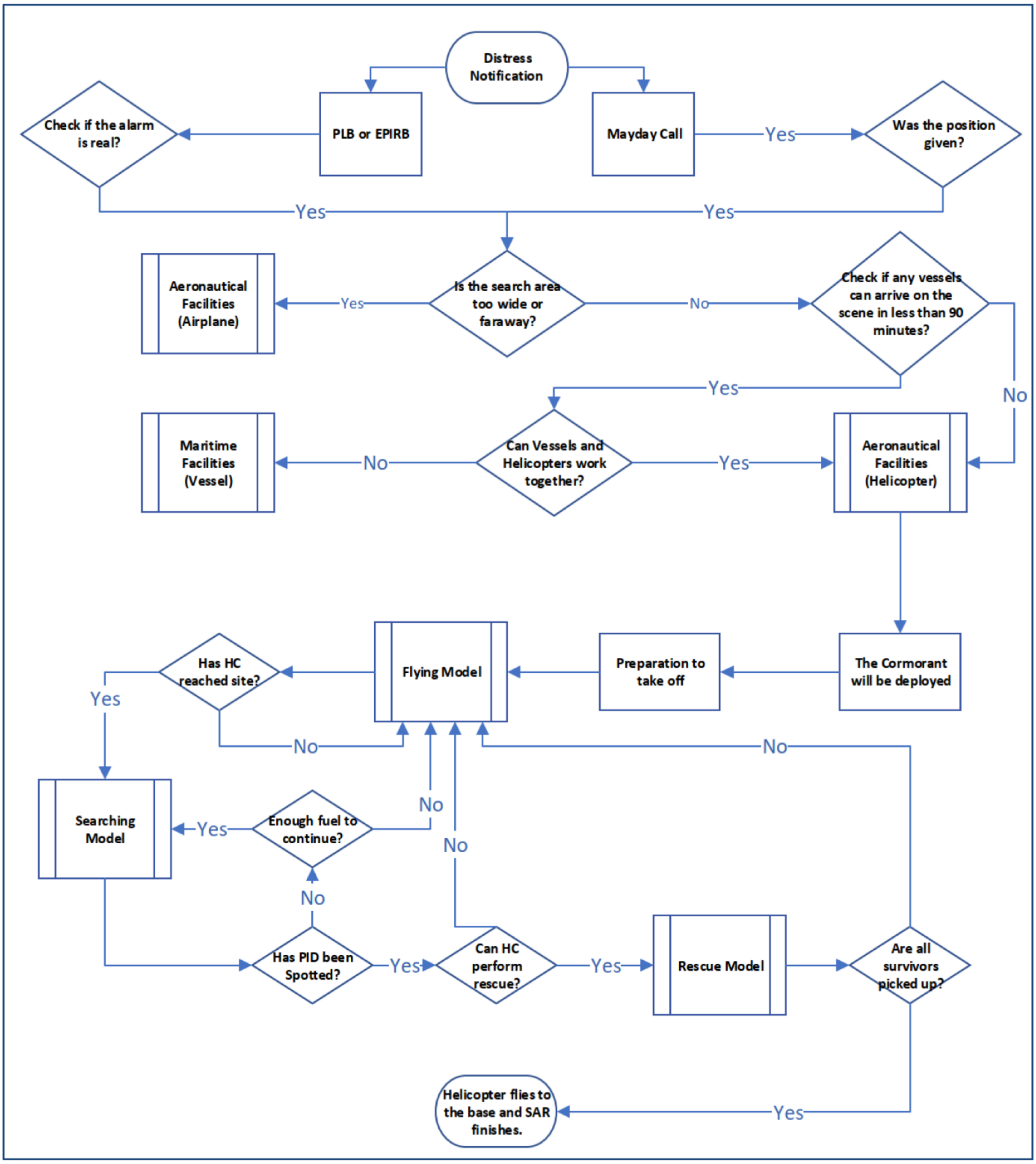

Figure 7: Simplified SAR Operation Flow Chart for Helicopters (Zarrin Mehr, 2023)

The weather impacts applied in Meh et al. (2023) original model employs a time-stepping approach sampling from probability distributions in a Monte Carlo approach to account for changes in the SAR process. The weather factor conditions (which are coefficient factor variables that are integrated into the model through a matrix of size 1001x2, representing time steps from minute 0 to minute 10,000 (the maximum simulation time defined). The second column of this matrix consists of weather factors, that were applied uniformly across time steps and so weather impacts were assessed at fixed time intervals. Each weather factor is multiplied by the helicopter maximum speed to account for changes caused by different weather conditions. These factors vary based on whether the simulation is set in summer or winter, with distinct distributions for each season.

For example, in the summer scenario, a random number is generated from a normal distribution with a mean of 1 (representing 'Very Good' weather) and a standard deviation of 0.01 (the difference between 'Very Good' and 'Good'). Conversely, in winter, the distribution has a mean of 0.97 ('Bad') and a standard deviation of 0.01 (the difference between 'Bad' and 'Very Bad').

Besides the weather variables, it is important to introduce other variables from Zarrin Mehr et al. (2023) that impact the response times in his model. These variables are searching time, hoisting time and take off preparation time. To account for uncertainty in the preparation phase, Zarrin Mehr et al. (2023) introduced a randomization process. This process first generates a random value to determine whether the incident occurs during normal working hours (weekdays, 8 hours/day) or outside of these hours. If the incident occurs during working hours, the preparation time is drawn from a normal distribution with an average of 30 minutes and limited to 45 minutes. For incidents outside of these hours, the preparation time is longer, following a distribution with an average of 90 minutes and a maximum of 120 minutes.

For the search time, Zarrin Mehr et al. (2023) used a normal distribution with a mean of 30 minutes and a standard deviation of 10 minutes to sample the variable randomly. The same was done for hoist time of PID but this one with mean of 5 minutes and standard deviation of 2 minutes.

The parameters used in the model were the helicopter capacity, helicopter range, helicopter speed, fuel tank capacity, fuel critical level and maximum speed, as summarized in Table 3.

In section 3.2.2, a table with a summary of these parameters and variables described earlier is presented as well as what changes were applied in the development of the HESARO model.

Table 3: Parameters regarding helicopter specifications for the Search and Rescue response model from Zarrin Mehr et al. (2023)

Parameters	Zarrin Mehr et al. (2023)	Unit
Passenger capacity	15	people
Helicopter Range	1185	km
Fuel tank capacity	3416	kg
Fuel critical level	133	kg
Refueling time	30	minutes
Maximum Speed	277	km/h

3.2.2 Update to the model process

The development of the simulation model followed a meticulous process that began with a comprehensive review and testing of Zarrin Mehr et al. (2023) original Helicopter Search and Rescue response model. The primary aim was to understand the underlying logic and evaluate its applicability to various polar region locations. This initial phase involved several testing sessions where input modifications were made based on the validations from the first and second phases of interviews.

During these sessions, specific parameters such as incident locations, refueling stops, air bases, and the operational specifications of the Cormorant helicopter were updated. These modifications were essential to tailor the model to the unique requirements of SAR operations in the Arctic region. The changes made in the parameters are highlighted in the table below.

Table 4: Parameters updated from Search and Rescue response model from Zarrin Mehr et al. (2023)

Parameters	Zarrin Mehr et al. (2023)	Present work	Unit
Passenger capacity	15	12	people
Helicopter Range	1185	1143	km
Fuel tank capacity	3416	4000	kg
Fuel critical level	133	600	kg
Refueling time	30	30	minutes
Maximum Speed	277	241	km/h
Distress check time	15	3	minutes

For the first parameter in Table 5, it was informed by the pilots that the seated capacity for the Cormorant HC-149 is 12 people, so this number should be considered. It was mentioned that emergency cases have occurred where 20 people had to be transported, but the conservative approach was chosen.

For the helicopter range, the unit used by pilots is in nautical miles, which is 617 nm. To use in the HESARO model, this number was converted and the number used was 1143 km.

The third row of Table 4 addresses the Cormorant helicopter's fuel capacity. The helicopter can hold up to 4,200 kg of fuel, although it was suggested using 4,000 kg as the limit for planning when gravity refueling is used, as this method doesn't allow tanks to be filled past the nozzle opening. Due to limited refueling options and infrastructure in the Arctic, 4,000 kg was selected for the model. Fuel consumption and capacity in the model are calculated in minutes. For example, 4,000 kg of fuel with a burn rate of 800 kg per hour provides 5 hours or 300 minutes of flight time.

Pilots typically plan to land with at least 400 kg remaining as a safety margin for flights in the southern regions, so it was recommended to use a higher number for the Arctic (600kg as shown in the fourth row of the table). As introduced before, on average, the helicopter consumes about 800 kg of fuel per hour, which gives it approximately 4.75 hours of airborne time.

Lastly, the Cormorant's optimal speed is 130 knots in calm conditions (last row in Table 5) and the average refueling time for these assets is 30 minutes.

Besides the specifications described, the variables associated with different phases of the SAR process are also essential for model construction and the calculations of total time. Four separate times were validated in the second phase of interviews. They are distress check time, take off preparation time, search time and pick up time. They are summarized in Table 6 below.

From the interviews, the SME affirmed that the Search Time and Hoist Time were valid and align with realistic times. About the takeoff preparation, the updated posture time for Canada at the time of the interviews were of 120 minutes. It was informed that for helicopters that number is often less than that, but no details were given. In this way, the chosen approach was using a triangular distribution with minimum values of 45 minutes, mode 75 minutes and maximum of 120 minutes. This approach takes into account that it usually takes less than 120 minutes until take off after distress notification, but also that sometimes that upper limit is reached. According to Kissell & Poserina (2017), the triangular distribution is used when the relationship between variables is understood, but there is not enough data for a full statistical analysis. It is often applied in simulations where little is known about the data-generating process, and it is sometimes called a "lack of knowledge" distribution for this reason.

Table 5: Variables updated from Search and Rescue response model from Zarrin Mehr et al. (2023)

Variables	Zarrin Mehr et al. (2023)	Present work
Search Time	Normally distributed with a mean of 30 minutes and a standard deviation of 10 minutes.	Normally distributed with a mean of 30 minutes and a standard deviation of 10 minutes.
Hoist time	Normally distributed with a mean of 5 and standard deviation of 2 minutes	Normally distributed with a mean of 5 and standard deviation of 2 minutes
Take off preparation time	Normally distributed with a mean of 150 minutes and standard deviation of 30 minutes (detailed in Section 3.2.1)	Triangular distribution with lower limit of 45, upper limit 120, and mode 75 minutes

For the distress notification, if it is by radio it takes up to 3 minutes. Although, it is possible to have exceptions where it could take an hour to get notified. In terms of modelling, the time considered was 3 minutes.

The second phase of development focused on improving the simulation of weather impacts. This began with an in-depth review of the original code, ensuring that any modifications followed a consistent structure and minimized coding errors. The updated weather model (see section 3.2.4) accounts for the spatial and temporal variability of weather conditions, a critical factor for accurately simulating SAR operations in the challenging Arctic environment.

Incorporating SME's feedback, the update also introduced weather checks at take-off and landing, emphasizing conditions at these key points. While helicopters can adjust routes or altitudes mid-flight, weather at air bases and refueling stops remains a primary concern. As a result, the weather impact matrix from Zarrin Mehr et al. (2023) (described in section 3.2.1) was adapted to reflect conditions at specific stop locations, rather than fixed time intervals.

Practically, the model now generates weather conditions for each stop location along the route. If adverse weather is encountered at a refueling stop, the delay factor influences the helicopter's speed for the entire leg to the next stop. This spatial approach better simulates the operational realities of SAR missions in the Arctic. A detailed explanation of the changes made can be found in section 3.2.4.

3.2.3 Overview of the Helicopter Search and Rescue Operations Model

In adapting Zarrin Mehr's model for this work, several significant modifications were made as presented in Table 4 and Table 5. In addition, the modifications related to weather will be presented in Section 3.2.4. These modifications resulted the Helicopter SAR Operations Model (HESARO) aimed at better representing the unique conditions and challenges of the Arctic region. These changes are illustrated in a flowchart in Figure 8 later in this section and are categorized into adjustments to the weather model.

As mentioned in section 3.2.1, the original weather model in Zarrin Mehr's simulation classified conditions as Very Good, Good, Bad, and Very Bad. To enhance the model's applicability to the Arctic environment, these conditions were redefined to Favorable, Unfavorable, and No-go. This change reflects the critical decision points for helicopter SAR operations, particularly regarding take-off and landing, where weather plays a crucial role.

The HESARO model is structured as a Discrete Event Simulation (DES), where the sequence of SAR operations (such as helicopter takeoff, refueling, search, and rescue) is simulated at specific intervals. This sequence is presented in Figure 8. Each event within the SAR operation is modeled based on predefined conditions, capturing the sequence of activities that unfold as the SAR operation progresses. However, Arctic SAR operations require a more dynamic approach due to variable weather conditions and extensive distances, which are better addressed through the integration of Monte Carlo Simulation (MCS).

In this DES framework, MCS introduces randomness by sampling key influencing variables, such as weather conditions, takeoff preparation time, and hoist time for PID. This combination of DES and MCS allows the model to simulate numerous SAR scenarios, capturing the inherent unpredictability of real-world operations. For instance, weather conditions along the helicopter's route—at takeoff, refueling stations, and temporary base—are subject to stochastic variability, ensuring that each simulated rescue operation reflects different possible outcomes. This randomness is crucial for accurately representing the variability encountered in Arctic conditions.

Weather conditions are now associated with specific locations along the helicopter route through a route-based matrix. For each leg of the journey, the matrix adjusts helicopter speed and fuel consumption according to the sampled weather conditions at each stop. For example, if the helicopter departs from Gander and stops at Goose Bay and Iqaluit before reaching Pond Inlet, the weather at each stop directly influences the travel time for that leg. If adverse weather is encountered at Goose Bay, a delay factor is sampled from the Monte Carlo Simulation, adjusting the helicopter's speed from Goose Bay to Iqaluit. Such adjustments are essential to ensure that the model accurately reflects operational challenges faced during Arctic SAR missions.

Historical weather data is essential to fully leverage the enhanced model, providing a realistic basis for the stochastic variables sampled during MCS.

In conclusion, the modifications address key weather challenges in Arctic SAR operations, improving the model's applicability and accuracy. The next section (3.2.4) will investigate the specifics of the RCAF Helicopter Environmental Operability Model (RHEO), introduced in the flow chart below in Figure 8, providing a comprehensive understanding of its implementation and impact on the simulation.

The diagram outlines the logic flow of the HESARO model, distinguishing between deterministic and probabilistic elements. The simulation starts with the distress notification and ends when the last person in distress is disembarked at the temporary base (closest airport to the incident location).

Distress Notification (Deterministic): The process begins with the notification of a distress event (top left of the diagram) which usually takes 3 minutes as shown in Table 4 in Section 3.2.2.

Preparation for Takeoff (Probabilistic): Once resources are deployed, the helicopter undergoes preparation for takeoff. The model uses a triangular distribution as shown in Table 5.

Weather Check (Probabilistic): Before takeoff, the model evaluates the weather conditions. If the weather is No-go, the model transitions to Wait for Better Weather (2^{nd} orange dot). The helicopter cannot take off until the weather improves. If the weather changes to favorable or unfavorable conditions, the helicopter proceeds to the flying model.

Flying Model (Deterministic and Probabilistic): The helicopter takes to the air, transiting to the Last Known Position (LKP).

- Probabilistic: If unfavorable conditions are met, the model adjusts fuel consumption and speed of the helicopter.

- Deterministic: If fuel is insufficient to get to LKP, the helicopter must stop for refueling.

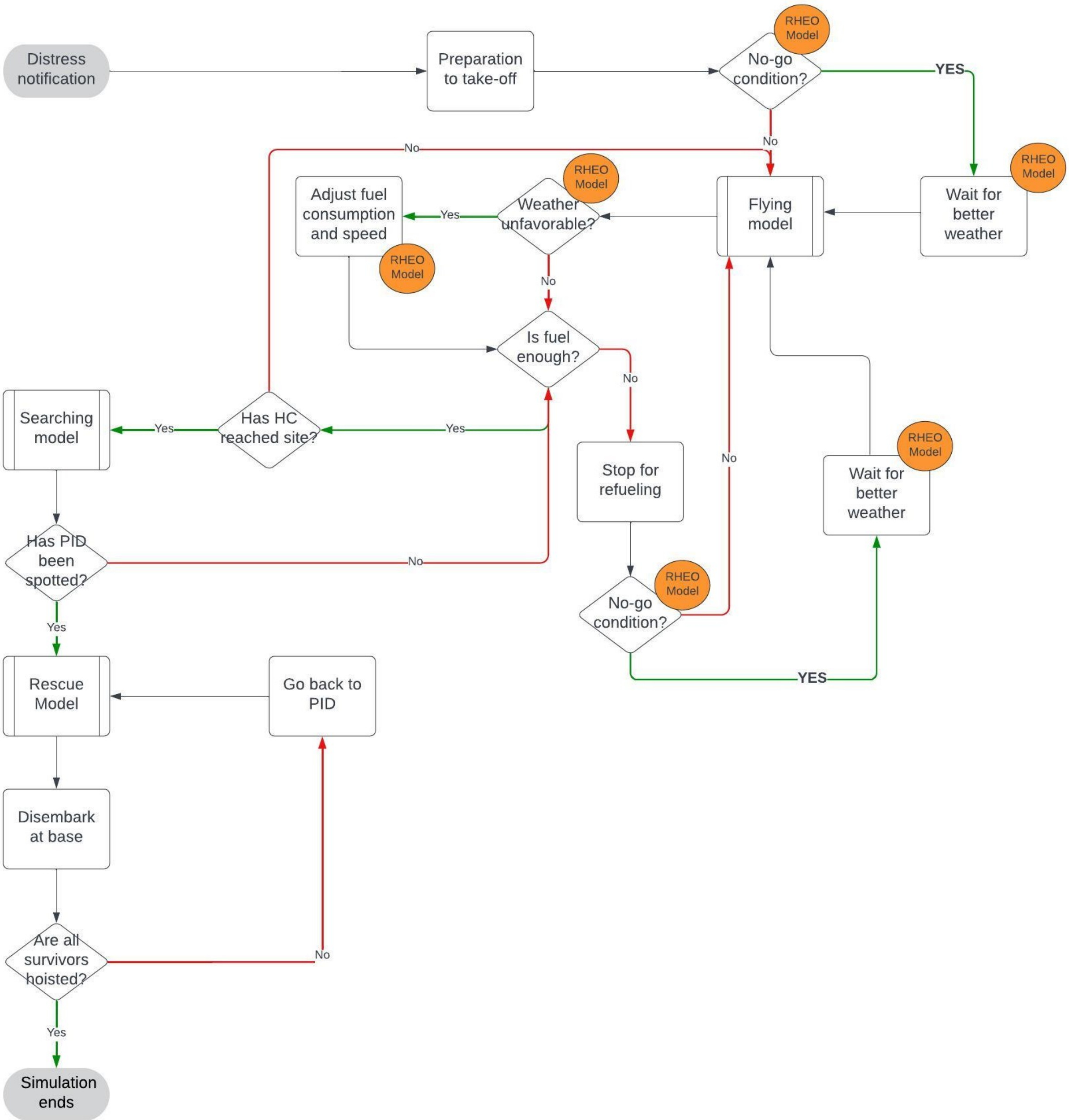

Figure 8: Flow chart showing Helicopter Search and Rescue Operations Model indicating weather modifications in orange

Fuel Check and Refueling (Deterministic and Probabilistic):

- Deterministic: If fuel is insufficient, the helicopter stops for refueling.

- Probabilistic: After refueling, the model checks weather conditions again, which are probabilistically determined. If it's a No-go condition, the helicopter waits for better weather.

Arriving at Incident Site (Deterministic): Once fuel and weather conditions are favorable/unfavorable, the helicopter resumes its flight to the incident location. The model checks whether the helicopter has reached the site. If it has, the search operation begins, if it has not, it goes back to flying model.

Search Model (Probabilistic): Upon arrival at the incident site, which is the LKP, the helicopter conducts a search to locate the Persons in Distress (PID). In the same way as Zarrin Mehr et al. (2023), the model does not include the simulation of various search patterns or replicate specific real-world search operations. Instead, the model selects a search time for each run at random from a normal distribution (MCS). If the PID is successfully spotted, the model moves to the rescue phase. If not, the helicopter will continue searching while fuel is still sufficient.

Rescue Model (Deterministic and Deterministic):

- Probabilistic: Once the PID has been located, the helicopter begins rescuing the individuals and the hoist time is normally distributed as show in Table 5.
- Deterministic: The model checks if all survivors have been hoisted into the helicopter.

Return to Base (Deterministic): After the rescue, the helicopter returns to the temporary base with the survivors. If all the survivors are successfully rescued and disembarked at the base, the simulation ends.

Recurrent Weather Checks (Probabilistic): Throughout the entire process, the model continuously checks for weather changes and adapts accordingly. No-go conditions and refueling are key decision points that may alter the course of the mission.

The modifications made are indicated by the orange dots in Figure 8. A more accurate classification of weather conditions (Favorable, Unfavorable, No-go) was introduced to replace the original categories (Very Good, Good, Bad, Very Bad). This enhances decision-making accuracy regarding mission viability and delays through linking the three different weather conditions levels to different weather delay factors based on weather conditions (presented in Section 3.2.4) at landing/take-off points. At this point (1), the helicopter is still at the base and if a No-go condition is encountered it will wait for better weather (2). The wait time due to No-go conditions is sampled based on the explanation in section 3.3. After the wait time, if Favorable or Unfavorable conditions are encountered, the helicopter is ready to fly (flying model starts). A check for Unfavorable weather conditions was added (3), allowing for adjustments in fuel consumption and speed if unfavorable weather (4), with those adjustments detailed in Section 3.2.4). When stopping at refueling stations, the weather in that location will be checked influencing whether the mission can proceed or needs to wait due to No-go conditions (6). This includes the logic for waiting periods at refueling stops due to No-go conditions, accounting for delays and adjusting the timeline based on sampled weather conditions at intermediate stops.

3.2.4 Royal Canadian Armed Force Helicopter Environmental Operability Model

The Royal Canadian Armed Force Helicopter Environmental Operability (RHEO) model was developed based on insights from the first phase of the interviews (Section 3.1.1) and validated during the second phase (Section 3.1.2). The second day of the workshop served to identify key weather parameters influencing helicopter operability, namely visibility, precipitation (specifically freezing precipitation and thunderstorms), air temperature, and wind. It was determined that weather impacts on the Cormorant helicopter fall into two categories: those preventing the helicopter from landing or taking off, and those affecting its speed, fuel consumption, and consequently, its range. To address the weather impacts as outlined in research question Q2.3, these impacts were categorized into three types: Favorable, Unfavorable, and No-go.

The next step was to extract information from the same interview to complete what was referred to as the RHEO that accounts for Favorable, Unfavorable and No-go weather conditions. Of the four weather parameters considered, only two—temperature and wind—were categorized as leading to ‘Unfavorable' conditions. In these cases, the helicopter could still fly, but its speed and/or fuel consumption would be negatively impacted. Precipitation and visibility were not classified under 'Unfavorable' because they directly determine whether flight is possible or not. These two factors either result in a 'Favorable' or 'No-go' decision, with no intermediate impact on operability as in the case of temperature and wind. Table 8 in Section 4.1 shows the validated threshold values for these conditions.

Lastly, it was important to understand how those Unfavorable and No-go conditions impact the METR-HT. Unfavorable weather conditions related to air temperature occur when the temperature falls below 5°C in the presence of visible moisture. In this case, the pilots turn on the anti-icing systems and for that, it is also required to turn on the auxiliary power unit to drive those, resulting in more fuel being burnt. The typical fuel burn rate increases by 15 to 20%. In the model, if the weather is unfavorable due to temperature, the fuel burnt is adjusted then to 20%, choosing the conservative approach. The speed can also be affected by low temperatures and air density, although the helicopter can still fly at its maximum speed, more fuel would be burnt in this situation. Alternatively, pilots usually choose to reduce the speed by 10% to mitigate those effects, and hence this reduction was applied in the model too.

On the other hand, unfavorable weather due to wind happens with presence of headwind, which is the wind that faces the helicopter in the opposite direction to which it is flying. Therefore, the impact of wind on the helicopter operation is due to both wind speed and wind direction and this impact will depend on the aircraft direction. To calculate the helicopter's direction and factor in wind components, the SkyVector (n.d.) website, an online aeronautical chart service for flight planning, was used. For each incident location, the direction from the SAR bases (either Gander, Comox or Greenwood), depending on the scenario) to the incident site was entered as the route origin. This step was crucial to account for wind direction along the flight path, as the wind's influence on the helicopter's speed and fuel consumption varies depending on whether it is a headwind, tailwind, or crosswind. Furthermore, the calculated wind components were named as crosswind, headwind, and tailwind respectively. The wind vector then was broken down into those component vectors using the formulas below.

$$HC = WS \times cos(\theta) \qquad (1)$$

$$CC = WS \times sin(\theta) \qquad (2)$$

HC - stands for Headwind Component

CC - stands for Crosswind Component

WS - is the wind speed (i.e., the magnitude of the wind vector)

θ - is the angle difference between the helicopter direction and the wind direction

Wind direction refers to the geographic (true) direction from which the wind originates, rather than the magnetic direction. It is averaged over the two-minute period leading up to the observation time and is reported in tens of degrees. For example, a reading of 9 corresponds to 90 degrees, indicating an east wind, while 36 represents 360 degrees, indicating wind from the geographic North Pole. A value of zero indicates calm conditions with no wind (Environment and Climate Change Canada. (n.d.)).

The input of the formula was the windspeed that was obtained from historical data as introduced in the beginning of Chapter 3. The historical data were extracted from Environment and Climate Change Canada. (n.d.). which provides hourly data observations. The theta is the angle difference between the wind direction, determined also from the historical data and the aircraft direction, calculated using SkyVector (n.d.).

The impact of headwind on the helicopter airspeed is directdly subtracted, for instance if the helicopter is flying at 130 knots (which is the maximum speed used in the HESARO model) and faces a headwind of 20 knots, the resulting speed is 110 knots. In this logic, to calculate the delay factor for wind (which is the speed reduction factor) the formula below was used.

$$WDF = 1 - \left(\frac{HC}{MS \times 0.539957}\right) \qquad (3)$$

WDF - Wind Delay Factor

HC - stands for Headwind Component

MS – maximum Cormorant airspeed without compromising fuel consumption

For the No-go conditions, the numbers for wind and air temperature were straightforward, as observed in Table 8 presenting the RHEO in Chapter 4. It is similar, for precipitation, but instead of number thresholds, the presence of thunderstorms or freezing precipitation were considered No-go (taken from the column 'weather' in the historical data (as explained in Section 3.3). Lastly, for the visibility parameter, a decision on what threshold number should be used had to be made, since that one is dependent on every case and every location where the helicopter is going to land. From the interviews, it was learned that pilots distinguish between two types of visibility operations, the Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). VFR involves pilots navigating primarily by visual reference to the ground, using their sight and maps. In contrast, IFR is more restrictive and procedural, requiring pilots to rely on aircraft instrumentation to maintain controlled parameters of altitude, flight path, departure, and arrival instructions.

VFR operations require clear skies, which can be particularly challenging to model accurately given the uncertain conditions of the Canadian Arctic. Therefore, for the current work, it was decided to use IFR thresholds for visibility in the model, adopting the conservative choice. According to subject matter experts, IFR weather criteria are the most critical Go/No-Go consideration for Arctic operations. This is especially true for aircraft such as the CH149 Cormorant, which needs to fly in a straight line to its effective radius—the maximum safe distance the helicopter can travel while ensuring it has enough fuel to return safely to the base or a refueling point. The effective radius takes into account fuel consumption, weather conditions, and the need to avoid obstacles. To ensure safe operations, the Cormorant typically climbs to an altitude that allows for IFR clearance if necessary, staying within this range to account for unpredictable conditions.

The VFR minimums are a 300-foot ceiling and ½ mile visibility. For IFR, the minimums are set at 400 feet above the lowest useable published approach minimum for the intended airport, and the forecast visibility at the destination must be at least 1 mile greater than the lowest published visibility for the intended approach. Since different airports have varying minimum visibility requirements (e.g., Eureka at 1½ miles, Alert at ½ mile, and Iqaluit at 3/8 mile), a conservative approach was adopted in this research. The minimum visibility threshold was set at 2 miles (3.2 kilometers) for all locations (assuming an average of 1 mile published for all airports).

3.3 WEATHER DATA ANALYSIS

To investigate the spatial and temporal variability of weather conditions in the Canadian Arctic, historical weather data for various locations of refueling stops and air bases were gathered. A Python script utilizing Selenium and WebDriver was developed to automate the download of weather data from Environment and Climate Change Canada's website (n.d.). Data for 43 locations (observed in figure 10, Section 4.1.1) spanning seven years (2013–2019) were collected, with the dataset providing hourly weather observations.

The raw data fields extracted include temperature (°C), wind direction, wind speed (km/h), visibility (km), and a descriptive 'weather' field that captures conditions like thunderstorms, freezing precipitation, or fog. Additionally, geographic and time-related columns such as station name, longitude, latitude, year, month, and day were also included to differentiate the specific location and time of each observation. These fields were critical for mapping the weather conditions to the specific incident locations and SAR base operations.

To streamline the analysis process, a flow chart was developed to illustrate each step of the data analysis. This approach ensures a systematic and transparent methodology, facilitating the thorough examination of weather patterns across different times and locations.

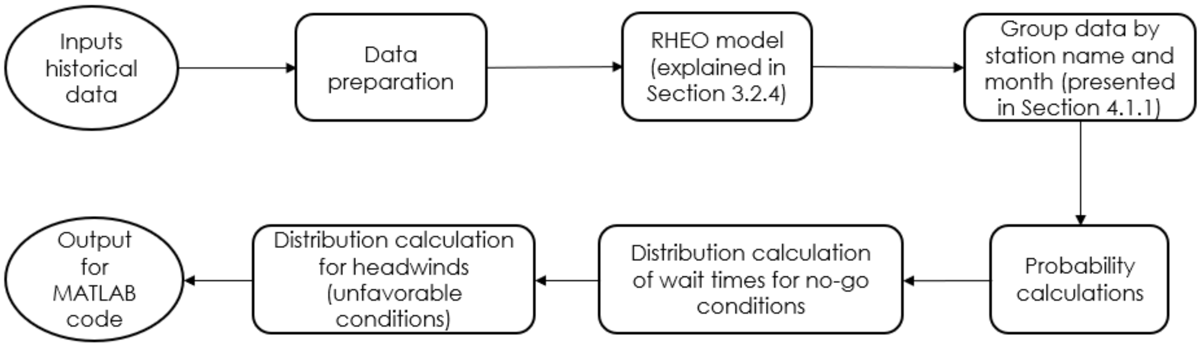

Figure 9: Flow chart for data analysis presented in this Section 3.3

The flow chart presented in Figure 8 shows that the code starts by receiving all the data downloaded for all locations and all months and then consolidates this information into one comprehensive dataframe, which combines all the weather data into a structured format for further analysis. The dataset is structured such that each row of this dataframe represents an hour, with corresponding weather conditions for the following columns. For the data preparation (first action symbol of the flow chart), the rows with missing data are filtered out, and the RHEO model, defined in Section 3.2.4, is applied to categorize the weather data into favorable, unfavorable, and No-go conditions (second action symbol of the flow chart in Figure 8). The RHEO model was used to assess each weather variable—temperature, visibility, wind, and precipitation—against the predefined thresholds. Based on this assessment, four new columns were added to the original dataframe, with each column indicating whether the respective variable (temperature, visibility, wind, or precipitation) was categorized as favorable, unfavorable, or No-go for each hour.

Python's pandas library was employed to efficiently manipulate and analyze the data (third action symbol of the flow chart in figure 8). The dataset was filtered based on the RHEO model, and the frequency of each weather category was calculated for each station-month combination. Subsequently (fourth action symbol of the flow chart), the probability of occurrence for each category was determined by dividing the category of the RHEO model count by the total number of observations for that station-month. This probabilistic representation allowed for a quantitative assessment of weather conditions in terms of the favorability, unfavourability, or No-go condition, facilitating comparisons across different locations and time periods.

As outlined before, delays arise from two primary factors: (1) the wait time during No-go conditions until it is safe to resume flights, and (2) the impact of unfavorable weather conditions on helicopter speed and fuel consumption. These are described in the following subsections (3.3.1 and 3.3.2).

3.3.1 Wait times due to No-go conditions

The next step (fifth action symbol of the flow chart in Figure 8) was the analysis of duration for No-go conditions. The accurate estimation of delays due to weather conditions is a critical component in the operational modeling of helicopter activities for the complete temporal analysis, since it supports the result of total times accounting for realistic conditions in the METR estimation. The data preparation for durations was conducted using Python with the primary objective of quantifying the potential wait times. This was achieved by identifying sequences of consecutive rows that indicated the same weather condition, specifically focusing on periods where No-go conditions were sustained over time. For instance, if the dataset indicated a "No-go" condition starting at 09:00 and ending at 12:00 on February 13th of a certain year, this period was represented by three consecutive rows labeled "No-go" condition. The duration for this condition was thus recorded as three hours. A custom script was developed to iterate through the dataset, detecting transitions between different weather conditions and calculating the duration of each identified period. The script specifically captures the start and end times of each period of consecutive conditions in a certain weather category according to the RHEO model, computes the duration of each of these periods in hours, and stores these values for subsequent probabilistic analysis.

For the analysis, the computed durations were aggregated to derive insights that would serve as inputs in the Matlab model. These insights were obtained from the statistical analysis of the categorical No-go and Unfavorable weather conditions. For each month and location, calculations were performed for key statistics, including the mean, median, minimum, maximum, standard deviation, and quartiles. This methodological approach enabled the quantification of the impact of weather on helicopter operations, specifically through the lens of operational delays due to adverse weather conditions. The insights gained from this analysis were vital for defining the time intervals (bins) used in the simulation in the MATLAB code, allowing us to categorize the duration of No-go and unfavorable conditions more effectively.

3.3.2 Delay factor for unfavorable wind

Unlike air temperature, which has a constant delay factor for helicopter speed in the HESARO model, wind is more variable. To quantify the impact of wind on delays in the simulation, a function was developed to calculate wind delay factors based on the analysis discussed in Section 3.2.4, using formula (3) presented in that Section.

In this step, a new dataset was created by filtering for headwind components greater than 0 knots. The data were then grouped by station name and month for further analysis. Similar to the 'No-go' step, a descriptive analysis was conducted to understand the distribution of headwind components. Based on this analysis, a function was developed to process each row of the data frame. This function divides the data into time intervals (bins) according to specific percentiles and standard deviation values, allowing for a more detailed understanding of the data distribution.

Finally (last symbol of the flowchart in Figure 8), the data described was downloaded as csv files for each zone of the Shipping Safety Control Zones (SSCZ) (shown in Figure 10, Section 3.4) to be used as input in the MATLAB code.

3.3.3 Royal Canadian Armed Force Helicopter Environmental Operability Model: MATLAB implementation

The probability data calculated as explained in Section 3.3.2 served as the foundation for the weather delay factor generation process implemented within the MATLAB code. The function to sample weather delay factors takes station names and months as inputs. The code then generates random numbers between 0 and 1 from a uniform random distribution to simulate random weather events. By comparing these random numbers with the cumulative probabilities for each RHEO category of weather condition, the code assigns a specific weather condition (favorable, unfavorable, or No-go) to each parameter using a helper function to sample the weather condition. Thus, one condition is generated for each of the four weather parameters assigning Favorable, Unfavorable or No-go to wind; Favorable, Unfavorable or No-go to visibility; Favorable, Unfavorable or No-go to temperature; and Favorable, Unfavorable or No-go to precipitation. Based on those 4 conditions, a decision, for each refueling stop is made, which is a general condition (shown in Figure 9 below with a hypothetical example) of weather.

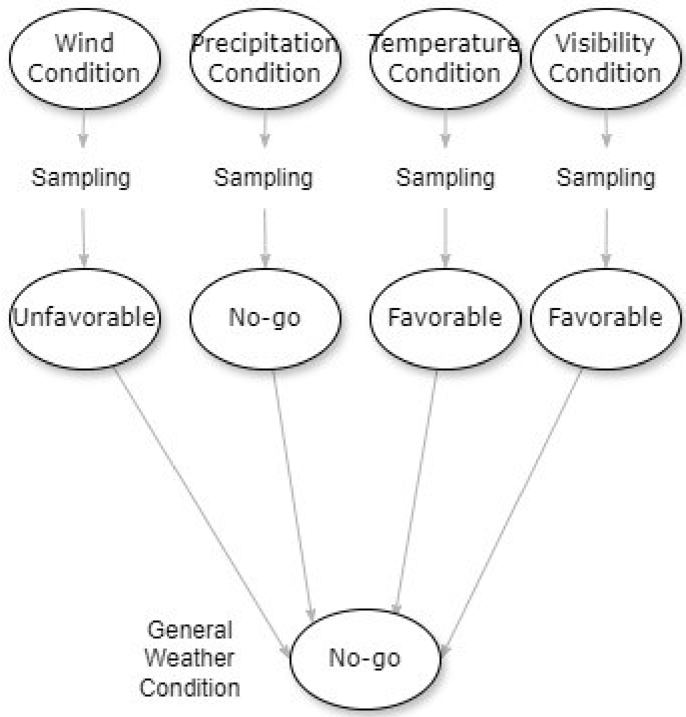

Figure 10: Flowchart showing a hypothetical example with the logical process of defining the weather condition for each refueling stop

In Figure 10, it can be seen that for each of the four parameters (wind, precipitation, temperature, visibility), if any of them are categorized as "No-go," the overall condition for that location is automatically set to "No-go." This reflects the critical importance of any single severe condition on helicopter operability. If none of the parameters is "No-go," but at least one is categorized as "Unfavorable," the general condition is set to "Unfavorable." Finally, if all parameters are "Favorable," the overall condition is "Favorable," meaning the helicopter will proceed without weather delays.

In cases where more than one factor is labeled as "Unfavorable," the model evaluates which parameter has the greatest impact on the helicopter's performance and applies the delay corresponding to that factor. The same logic is applied when multiple "No-go" conditions are present. The reason for that is that METR means “Maximum Expected” which means that some reasonable choice needs to be made between “maximum” and “average”. Thus, a reasonably conservative choice is needed, as opposed to a totally conservative approach. As noted by

Mostaghimi (2024), it is important to adopt a conservative yet reasonable approach to ensure safety and reliability in calculating METR, without overly inflating expected delays.

To determine the delay due to unfavorable weather conditions, a function to sample delay factors was implemented to process the wind data. For each fuel station, the function extracts the relevant wind speed discretized that varies for each month. A headwind component is sampled from these bins, and the wind delay factor is computed using the given formula (1) from Section 3.2.4. This factor quantifies the speed reduction due to headwinds and it is applied to the maximum speed of the helicopter in knots converted to kilometers per hour (presented in Table 5 in Section 3.2.2). The function outputs an array containing the station name, headwind component, and the calculated speed delay factor due to wind conditions for each station.

Lastly, No-go conditions necessitate halting helicopter operations until weather conditions improve. To estimate the duration of these delays, the function to generate wait times processes the local weather data for each station and condition. It identifies the relevant third quartile of No-go value for each condition (e.g., Wind_No-go, Precipitation_No-go). The third quartile value represents the upper quartile value of the No-go duration, providing a conservative estimate of the wait time required for conditions to improve sufficiently to resume operations. Lastly, for the output generation, the function compiles an array of locations and corresponding wait times, providing a detailed overview of expected delays under No-go conditions.

In the simulation, weather conditions are generated for each refueling station and bases. This allows for different legs to encounter varying weather conditions. If Unfavorable weather conditions occur on multiple legs, the RHEO model applies different weather delay factors for each affected leg. As a result, the helicopter's speed can be adjusted differently on each leg based on the specific weather conditions encountered, leading to varying impacts on travel time across the route.

This methodology enabled a comprehensive analysis of delays due to both unfavorable and No-go conditions, thereby allowing a representative impact on helicopter operation. The integration of historical data and statistical analysis ensures that the model reflects realistic scenarios, contributing to more accurate decision-making processes.

3.4 HELICOPTER ROUTES FOR CENTER POINTS IN SHIPPING SAFETY CONTROL ZONES

The approach to dividing the Canadian Arctic into representative zones for testing incident locations was guided by the Shipping Safety Control Zones to create a foundation for determining incident points. Transport Canada established the Arctic Shipping Safety and Pollution Regulations (ASSPR), which regulate navigation in ice-covered waters in compliance with the Polar Code. This framework divides the Canadian Arctic into sixteen Shipping Safety Control Zones (SSCZs), as illustrated in Figure 10, adapted from Canadian Coast Guard (2012).

For the selection of incident locations, one site was chosen for each zone, primarily based on its geographical center. This approach was only modified when the center point fell on land. In those cases, the nearest offshore point to the center was selected. Furthermore, when the center of one zone was too close to a neighboring zone's center, a more strategic location was determined based on expert input, considering the aim of having representation of different enough scenarios (based on maritime routes, distances and weather patterns). The zones can be observed in Figure 10, in which the blue stars represent the selected incident locations.

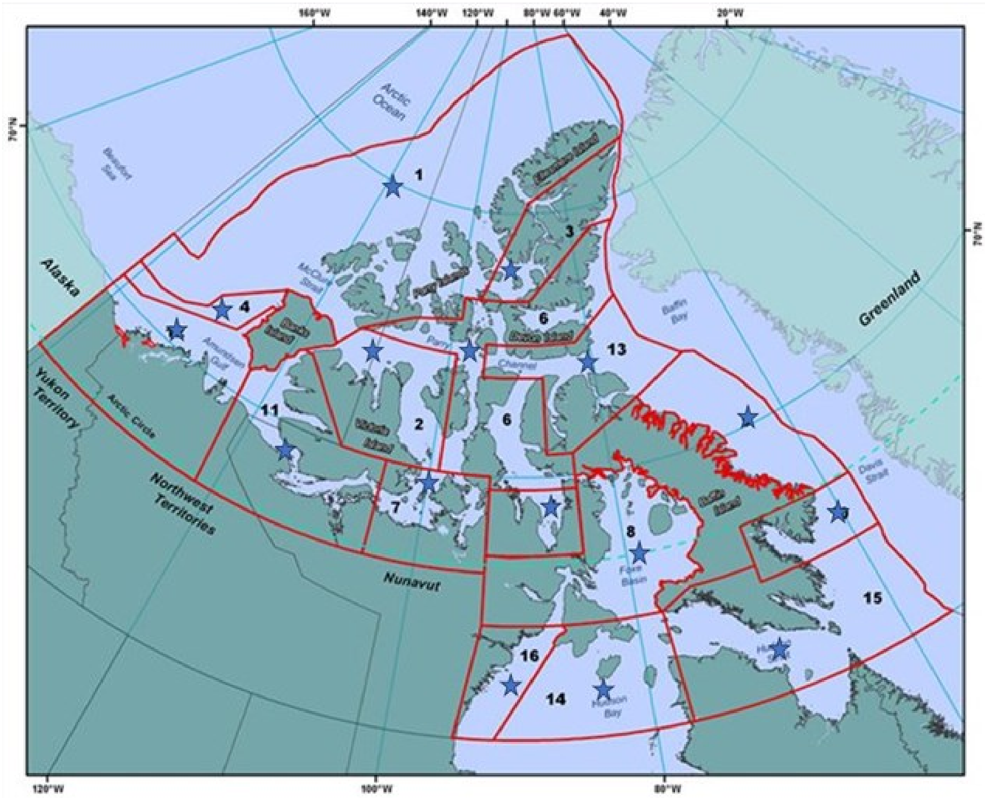

Figure 11: Shipping Safety Control Zones with incident locations represented by blue stars

Although the SSCZs cover vast areas, they do not fully encompass Hudson Bay and James Bay, as illustrated in Figure 11. To achieve complete coverage of the entire Canadian Arctic marine region, an additional zone (Zone 17) was manually added to cover the area of interest. The incident location for this zone, along with the other 16 zones originally from the SSCZ, is provided in Table 7.

Table 6: Latitude and longitude of incident locations for each of the 17 Zones; (see also Figure 10)

Zones	**Latitude**	**Longitude**
1	80.2	-116.5
2	73.9	-110.1
3	78.0	-92.1
4	72.5	-128.7
5	68.7	-87.1
6	74.5	-97.0
7	69.3	-99.7
8	66.5	-77.9
9	70.4	-65.1
10	65.7	-61.0
11	69.2	-116.0
12	70.2	-132.0
13	74.1	-81.3
14	61.3	-83.0
15	61.8	-69.6
16	62.0	-91.9
17	56.54	-81

Subject-matter experts (SME) provided essential insights for selecting refueling stop locations (as mentioned in section 3.1.2), all of which are Canadian airports with Jet A-1 fuel availability, which is a type of aviation fuel used in Cormorant helicopters. The refueling stops across Canada used in the model are shown in Figure 12 in Section 4.1.1.

The refueling stops were pre-selected for each zone using SkyVector (n.d.) and validated through interviews with pilots and subject matter experts (SMEs). These refueling stations are considered as potential stops only if they are located between the base and the incident location or close to it. Based on these pre-determined refueling stations, the model generates the route by calculating the shortest straight-line distance. The model dynamically checks the closest available station based on the helicopter's fuel levels and selects it if refueling is needed.

As for the selection of the base from which the helicopter departs, this decision was made based on expert input. SMEs indicated that for incidents located in the north, towards Baffin Island or east of Resolute Bay, helicopters would typically depart from Gander. For incidents west of Hudson Bay, the responding helicopter would depart from Comox. These base assignments were pre-determined in the model to reflect real-world operational decisions.

3.5 TEST MATRIX FOR ANALYZING HELICOPTER SAR RESPONSE

In order to analyze and compare the SAR response times across locations and seasons effectively, a comprehensive test matrix was developed. This matrix was designed to test the key factors known to influence the Maximum Expected Time of Rescue (METR). Based on the literature review and insights gained from interviews, the most critical parameters identified for testing include the number of Persons in Distress (PID), weather conditions, and geographic location of an incident.

The decision to test various PIDs was influenced by the helicopter's capacity, which is 12 people (excluding crew).

Weather conditions are a significant variable affecting SAR operations. To account for weather variations throughout the year, a probabilistic model was developed (section 3.3). This model considers monthly changes in weather to provide a more accurate representation of the conditions faced during SAR missions throughout the year. The decision to use monthly data rather than seasonal averages was made to capture the substantial variations that can occur within a single season. This approach ensures that the model reflects realistic and granular weather variations, enhancing the reliability of the simulation results.

The choice of locations for testing was based on the SSCZ (Search and Rescue Shipping Coordination Zones) outlined in Section 3.4, which considers ship activity in the Canadian Arctic. By selecting central locations within these zones, the test matrix aims to evaluate the SAR response across different regions, each with its own unique challenges and conditions. This geographic diversity in testing ensures that the model is robust and applicable to various operational contexts within the Arctic.

A series of test scenarios were designed to cover a range of conditions for each of the parameters identified. These scenarios included cases where the PID was set to 12, with each scenario tested under the specific weather conditions of each month. A probabilistic model was used to simulate realistic weather patterns for these monthly variations. Additionally, the scenarios were adjusted based on geographic location, and testing points positioned in the SSCZ (Figure 10) to assess SAR response throughout the Canadian Arctic. The result test matrix is presented below.

Table 7: Test matrix with all scenarios tested in using the HESARO model

Scenario ID	PID	Month	Geographic Location (SSCZ)
1	12	January	SSCZ Zone 1
2	12	February	SSCZ Zone 1
3	12	March	SSCZ Zone 1
…	12	…	SSCZ Zone 1
12	12	December	SSCZ Zone 1
13	12	January	SSCZ Zone 2
…	12	…	SSCZ Zone 2
24	12	December	SSCZ Zone 2
…	12	…	…
204	12	December	SSCZ Zone 17

Note that the matrix includes 12 monthly tests for each of the 17 SSCZ zones, resulting in a total of 204 test scenarios. By systematically varying these parameters, the test matrix provides a comprehensive framework for analyzing the factors that influence SAR response times. The results from these tests were used to compare and analyze the METR, providing valuable insights into the effectiveness and efficiency of helicopter SAR operations in different conditions.

The structured approach outlined in this section ensures that all critical factors affecting SAR response times are thoroughly tested and analyzed. The results from these tests form the basis for the subsequent analysis and discussion, helping to explore how weather factors vary with spatiotemporal variations (Q1.2) as well as how different factors influence the METR for helicopter times (Q2.1). This detailed testing framework gives insights into how the model behaves under different conditions, ensuring its reliability for realistic SAR responses in the challenging conditions of the Arctic.

3.6 FINAL STATISTICAL ANALYSIS

For the final statistical analysis, various descriptive analyses were conducted on the results for each month and location. This included analyzing several key factors influencing helicopter SAR times. One aspect of the analysis focused on the percentage of No-go conditions. This analysis showed how often No-go conditions occurred across the different scenarios presented in the test matrix in table 9. Additionally, the 3rd quartile of the duration of No-go conditions was analyzed. This represents the time below which 75% of the No-go condition durations fall, giving insight into how long No-go conditions typically last once they occur.

Finally, a probability distribution analysis of the weather delay factors (resulted from unfavorable conditions) affecting helicopter speed was conducted for a selected set of six scenarios. These weather delay factors are dependent on variables like wind speed and direction as well as temperature as described in section 3.2.4, which can impact helicopter arrival time. The combination of these analyses provides a comprehensive understanding of how weather conditions influence the operational capacity of SAR helicopters across the Canadian Arctic.

4. RESULTS

As described in Section 3.2.4, the RHEO model was developed to better understand helicopter operability in the Canadian Arctic. This includes analyzing the four weather factors (wind, precipitation, visibility and temperature) that impact its operations dividing each into three different conditions: Favorable, Unfavorable and No-go. The last two are the ones leading to a higher METR for helicopter rescue. To better understand these effects, Section 4.1 presents an analysis of the conditions and weather factors separately for different locations across Canada (including helicopter bases and refueling stops), and for the 12 months of the year. The probabilities of Favorable, Unfavorable and No-go conditions were applied to the simulation model as described in Section 3.2. To give detailed insights into the HESARO model, various results for two scenarios were selected for analysis, and described in detail in Section 4.2. In this section, total helicopter SAR times are presented, as well as their distribution as a function of distance and weather impacts are included (from unfavorable and No-go conditions). Other model elements are also analyzed, such as the search time distribution. Furthermore, in Section 4.3, the results of the HESARO model are presented, with all scenarios of the test matrix presented in Table 7 (Section 3.5), as well as a comparison of the model's performance with different numbers of PID. As a validation of these results, the final values of SAR total times (discretized using the third quartile) were compared to those obtained from Helicopter Search and Rescue response model from Zarrin Mehr et al. (2023) original model for the same 17 zones.

4.1 RESULTS FROM ROYAL CANADIAN ARMED FORCE HELICOPTER ENVIRONMENTAL OPERABILITY MODEL

The development process of the HESARO model was described in Section 3.2.3. In addition, the RHEO model was described in Section 3.2.4 which was essential to account for weather delays in the HESARO model. The base for the RHEO model is presented in the table below, showing the thresholds for the probability analysis conducted.

Table 8: RHEO model – thresholds for each weather factor

System limits	Favorable	Unfavorable	No-go
Wind (knots)	None or tailwind	headwind	55 knots
Air temperature (C)	>=0	5°C + visible moisture	-43°C
Visibility (miles)	>2miles	-	<=2 miles for landing and take off
Precipitation	None	-	Freezing precipitation/thunderstorms

Table 9 details the thresholds for each weather condition (Favorable, Unfavorable, and No-go) for the weather factors that impact Cormorant Helicopter operability and, consequently, the METR-HT. In Section 4.1.1, the probability results from applying these thresholds to historical data are presented.

4.1.1 Frequency and Analysis of No-go Conditions

In this section, the probabilities of encountering No-go conditions are presented for the four different weather factors, based on data from weather stations (airports) that serve as refueling stops for helicopter SAR operations in the Canadian Arctic and used for the scenarios tested in this work. This analysis illustrates how these probabilities vary across different stations and throughout the months of the year. The stations used in the model are represented in Figure 12.

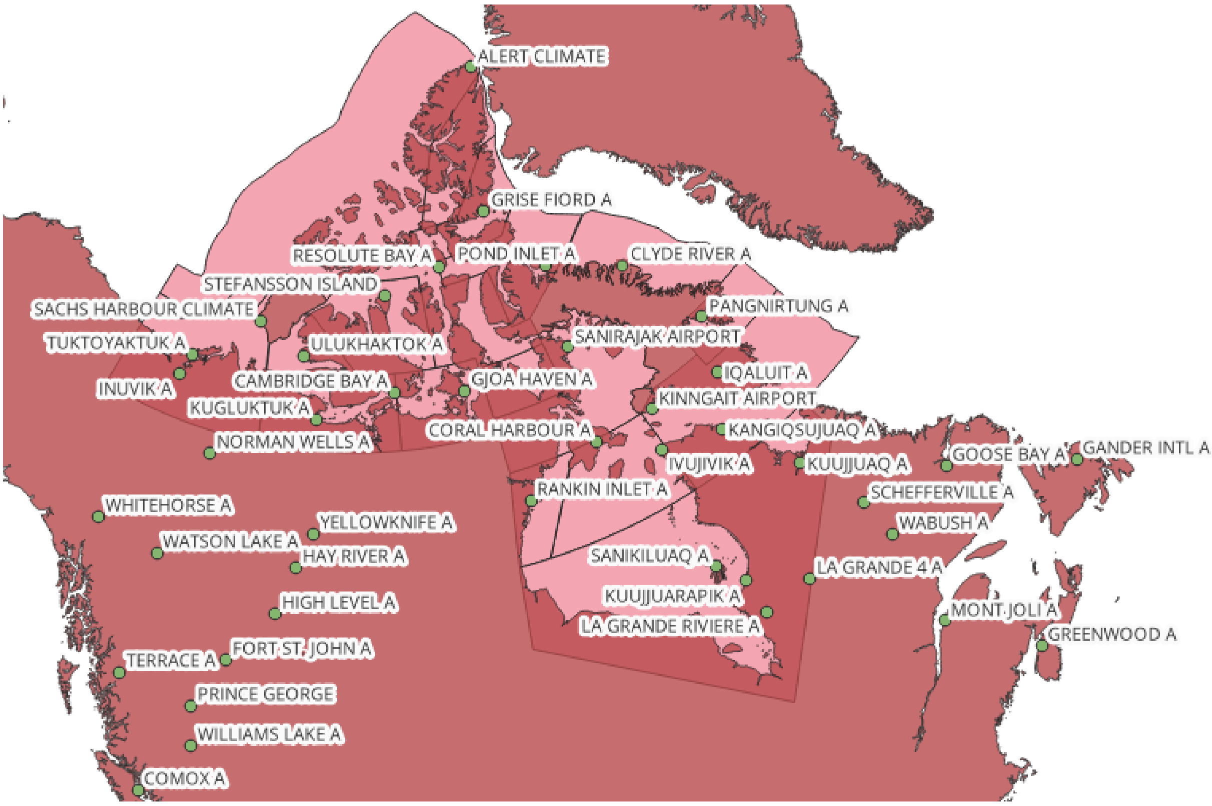

Figure 12: Map of Canada with AIRSS zones and stations used in this work

Figure 12 displays the airports used as refueling stops and bases in the model, providing context for interpreting the outputs discussed later in this section.

In Figure 13, the probabilities of No-go conditions due to temperature are presented, showing how these probabilities vary throughout different months of the year and different stations. The thresholds to define No-go conditions due to temperature are presented in Section 4.1, Table 8.

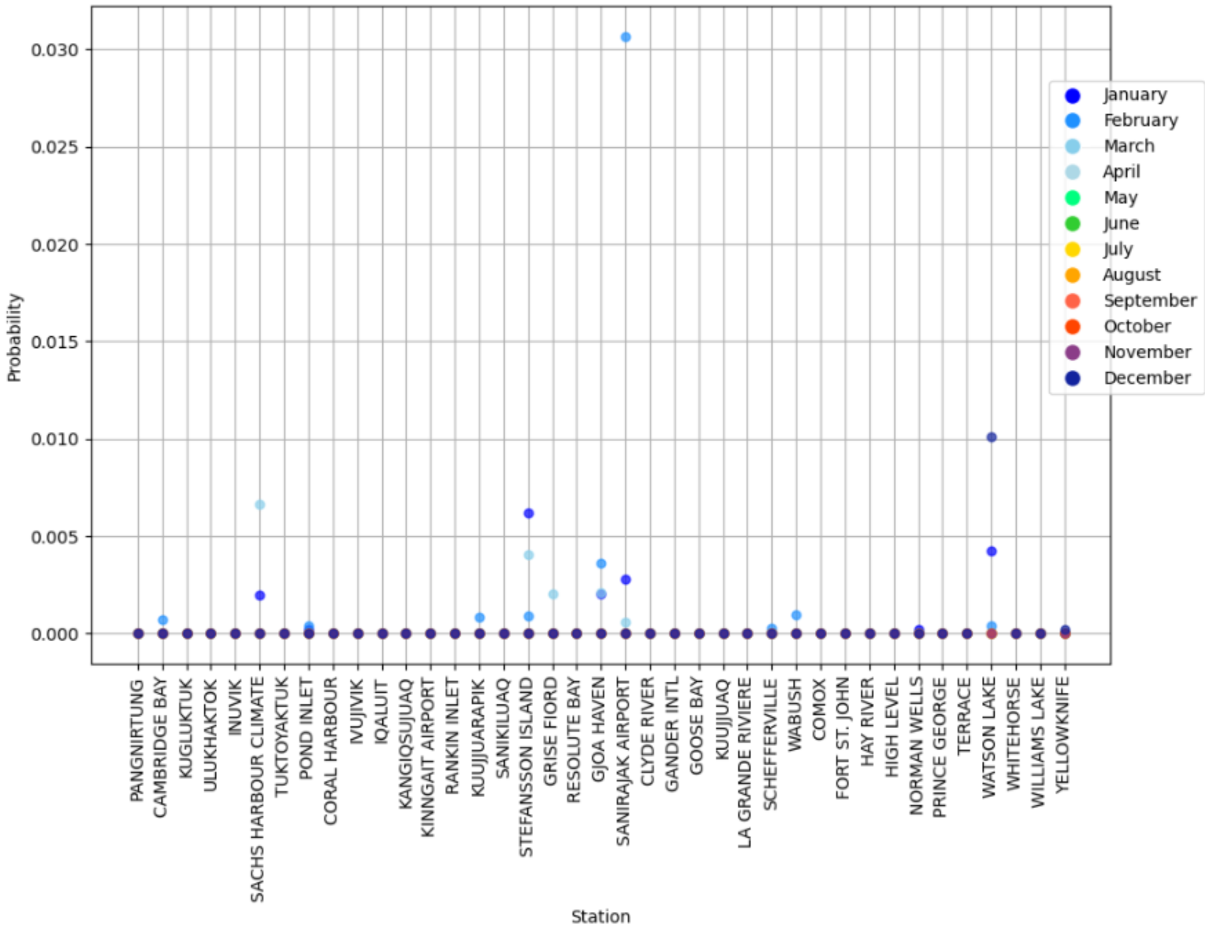

Figure 13: Probability of encountering temperature-related No-go conditions at the weather stations in the Canadian Arctic

In Figure 13, it can be seen that the probability of No-go conditions due to temperature is very low, with the majority of cases close to zero. This is because the threshold for temperature is very low, -43 degrees for helicopter operations (Section 4.1, Table 8). The graph shows that the highest probability of encountering a No-go condition due to temperatures below -43°C is for Sanirajak Airport, amounting to 3% for the month of February. Other locations show probabilities between 0 and 1%, with most of these occurring in the months of January, February and March. Temperature-related No-go conditions also occur in December, for example at Watson Lake, showing a 1% probability of No-go in that month.

Figure 14 shows the probabilities of No-go for the precipitation weather factor, obtained according to the procedure described in section 3.3 using the RHEO model of section 3.2.4. The thresholds to define No-go conditions due to precipitation are presented in Section 4.1, Table 8.

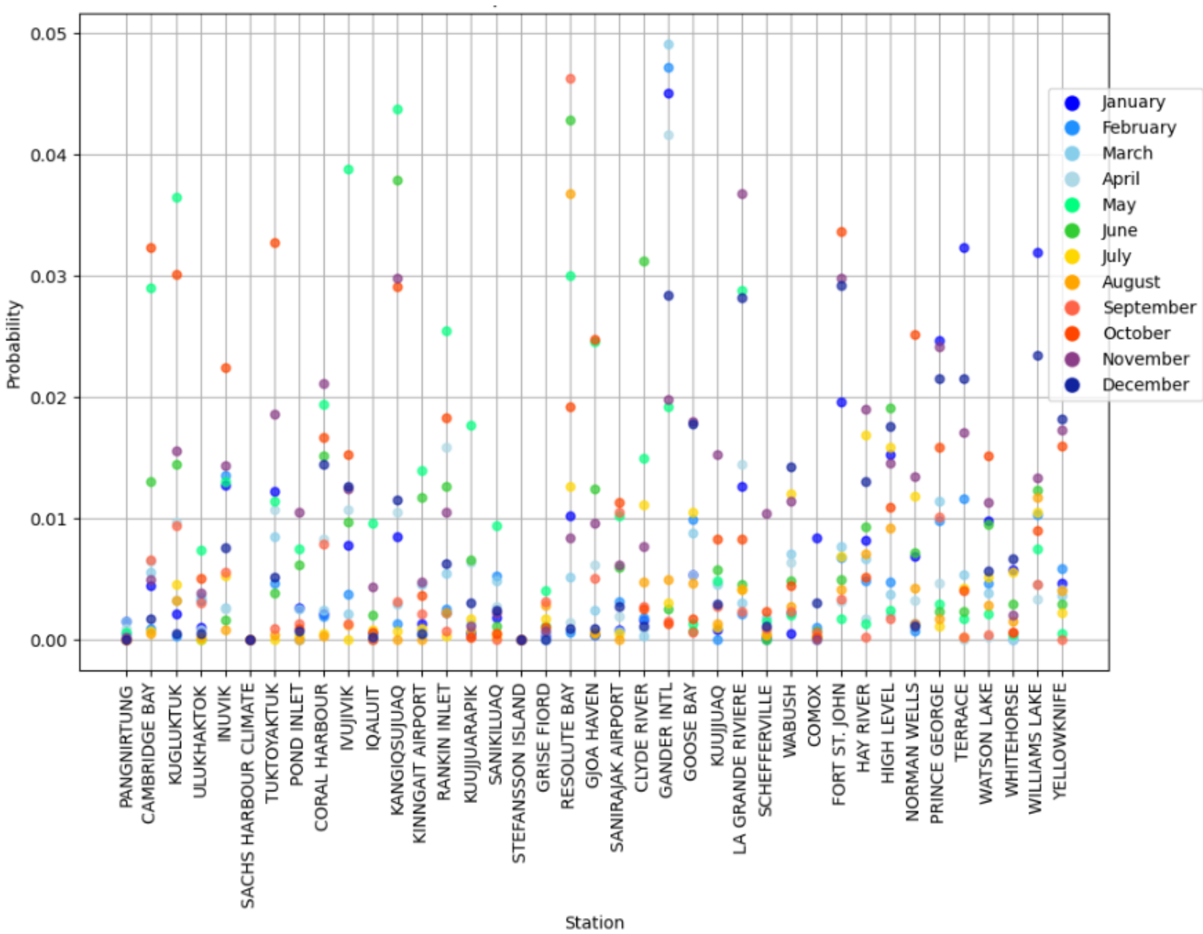

Figure 14: Probability of encountering precipitation-related No-go conditions at the weather stations in the Canadian Arctic

In Figure 14, it can be seen that the probability of No-go conditions due to precipitation is significantly higher across the year and in different stations, compared to those obtained for the temperature weather factor. In section 3.2.3, this threshold is described, based on the rationale that cases of No-go conditions due to precipitation happen when there is freezing precipitation and/or thunderstorms.

In Figure 14, the stations are placed together by their respective zones. In Table 7, the stations are grouped according to the SSCZ zones of Figure 11. The graph in Figure 14 indicates that the probability of precipitation-related to No-go conditions is higher during the summer months for airports like Kugluktuk, Ivujivik and Kangiqsujuaq, i.e. from June to September. On the other hand, higher probabilities are encountered for February and other winter months for airports like Terrace Airport and Williams Lake Airport. The airports on the right side of

Figure 14 are characterized by stations located in the West of Canada. This can be observed in Table 9, which lists the airports located in each zone.

Table 9: Distribution of stations by SSCZ zone

Station Name	**Zone**
ALERT CLIMATE	1
STEFANSSON ISLAND	2
GRISE FIORD	6
RESOLUTE BAY	6
GJOA HAVEN	7
SANIRAJAK AIRPORT	8
CLYDE RIVER	9
PANGNIRTUNG	10
CAMBRIDGE BAY	11
KUGLUKTUK	11
ULUKHAKTOK	11
INUVIK	12
SACHS HARBOUR CLIMATE	12
TUKTOYAKTUK	12
POND INLET	13
CORAL HARBOUR	14
IVUJIVIK	14
KINNGAIT AIRPORT	15
IQALUIT	15
KANGIQSUJUAQ	15
RANKIN INLET	16
KUUJJUARAPIK	17
SANIKILUAQ	17

Not all zones have stations in them, which is why some of them are not shown in the table. In addition, stations in southern Canada (outside of the Canadian Arctic) were also used as refueling stops since the RCAF SAR bases are in southern locations. Table 10 shows the southern stations used in the HESARO model, which are divided between locations in the East (E) and West (W) of Canada.

Table 10: Distribution of stations located in southern Canada

Station Name	Zone
GANDER INTL	E
GOOSE BAY	E
KUUJJUAQ	E
LA GRANDE RIVIERE	E
SCHEFFERVILLE	E
WABUSH	E
GREENWOOD	E
LA GRANDE 4	E
MONT JOLI	E
COMOX	W
FORT ST. JOHN	W
HAY RIVER	W
HIGH LEVEL	W
NORMAN WELLS	W
PRINCE GEORGE	W
TERRACE	W
WATSON LAKE	W
WHITEHORSE	W
WILLIAMS LAKE	W
YELLOWKNIFE	W

In Table 10, it is shown that 9 stations were used around the East side and 11 used in the West. Stations located out of the SSCZ Zones, meaning that they are in Southern Canada and to the west of Hudson Bay are classified as West (W), while those to the east of Hudson Bay are classified as East (E). Hudson Bay is a large body of water to the South of Zone 14 showed in Figure 11 in Section 3.4.

Figure 15 shows the probabilities of an RCAF helicopter encountering wind-related No-go conditions, analyzed as per the procedure in Section 3.3.2 according to the criteria of the RHEO model in section 3.2.4 and thresholds presented in Section 4.1, Table 8.

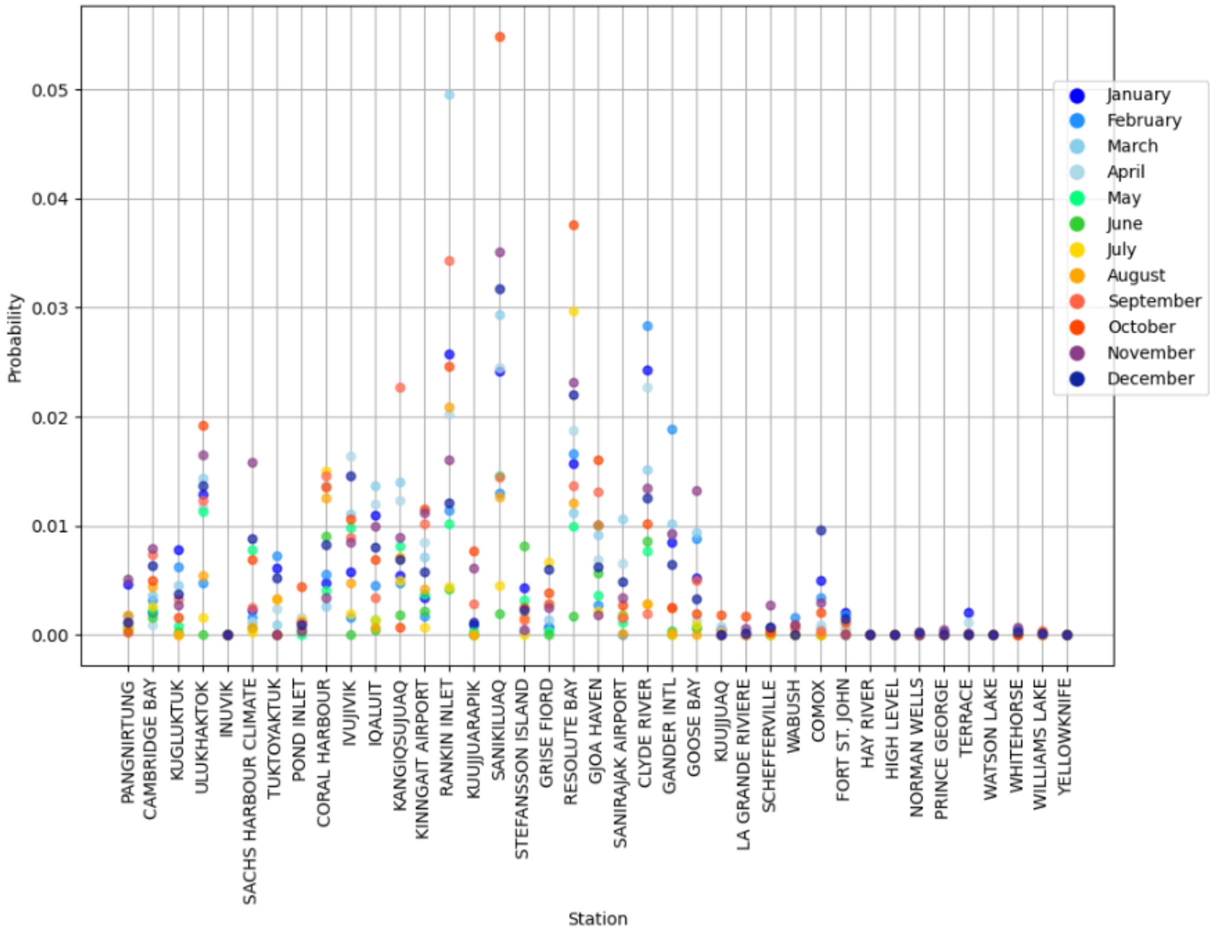

Figure 15: Probability of encountering wind-related No-go conditions at the weather stations in the Canadian Arctic

For this weather factor, the higher probabilities for No-go conditions are for stations like Rankin Inlet, Sanikiluaq, Resolute Bay and Clyde River (Zones 16, 17, 6 and 9 in Table 9) and for the months of October and April. The probabilities of No-go condition for wind are all relatively low, with a ca. 5% probability at Sanikiluaq being the maximum one. The reason for this is that the threshold for wind is high (as presented in Table 8). Helicopters can operate in winds up to 55 knots, and higher wind conditions are relatively rare in most of the Canadian Arctic. Compared to Temperature, the highest probability was 1% in Watson Lake Airport and around 0.7% in Sachs Harbour and Stefansson Island.

Figure 16 shows the probabilities of an RCAF helicopter encountering visibility-related No-go conditions, analyzed as per the procedure in Section 3.3.2 according to the criteria of the RHEO model in section 3.2.4 and thresholds presented in Section 4.1, Table 8.

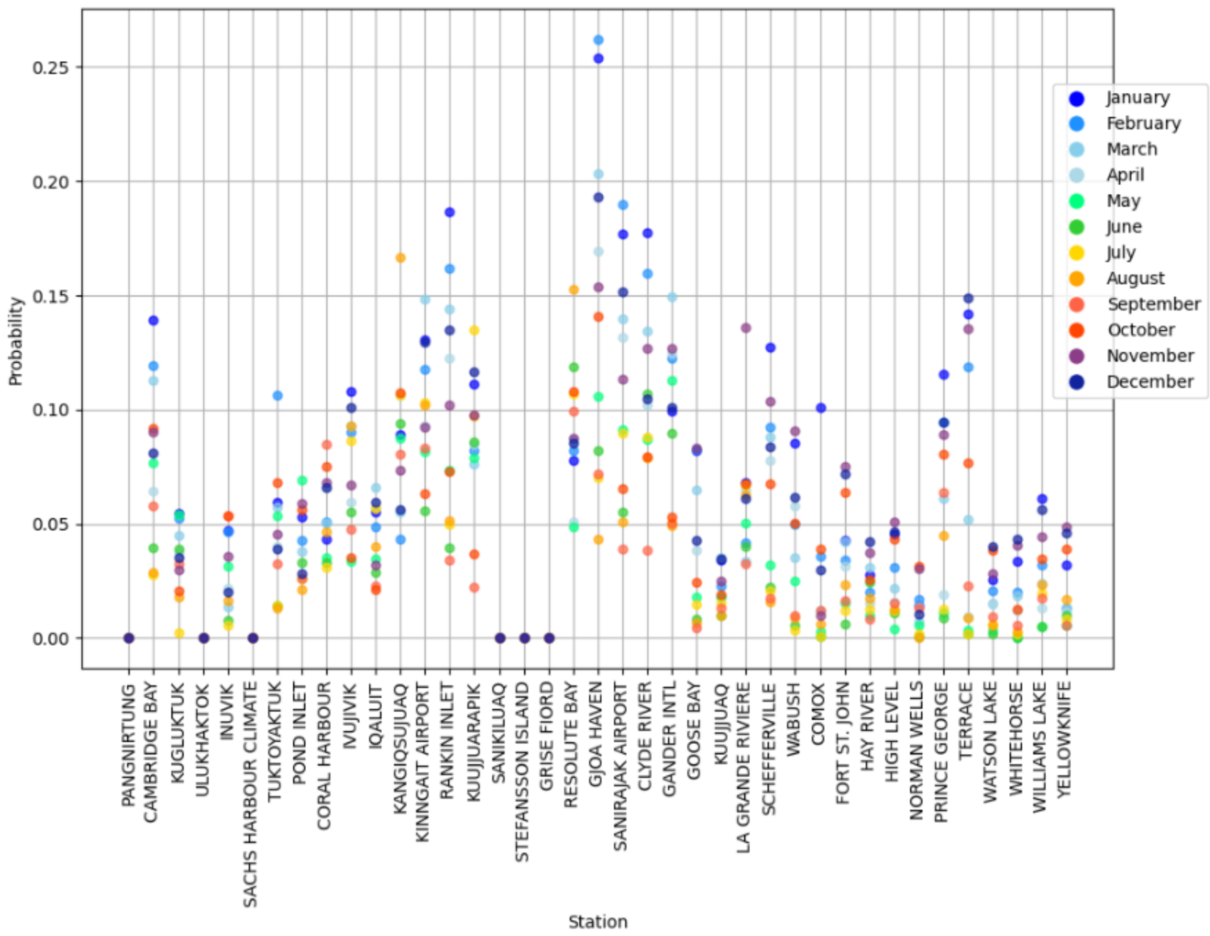

Figure 16: Probability of encountering No-go-related Visibility conditions at the weather stations in the Canadian Arctic

Figure 16 shows that probabilities of No-go conditions due to visibility are higher when compared to the other three conditions, which happen often in winter months, especially January and February. While Temperature Conditions shows the highest probability 1% for No-go, Wind 5%, Visibility can get up to 25% (as seen in Gjoa Haven Airport) and the majority between 10 and 20% especially in January and February.

For a deeper analysis of No-go conditions, beyond assessing the probabilities of occurrence, it is essential to evaluate their duration when they do occur. This is because wait times due to No-go conditions have a direct impact on the Maximum Expected Time of Rescue for Helicopter Operations (METR-HT). For the results of METR-HT in this work, the third quartile of those durations were selected. To illustrate this, two locations, Gjoa Haven and Sanirajak, were selected for analysis, as both exhibited non-zero probabilities of temperature No-go conditions during the winter months (January, February, and March). The following graph (Figure 17) presents the analysis for temperature conditions at Gjoa Haven, followed by three additional graphs detailing Precipitation, Wind, and Visibility conditions.

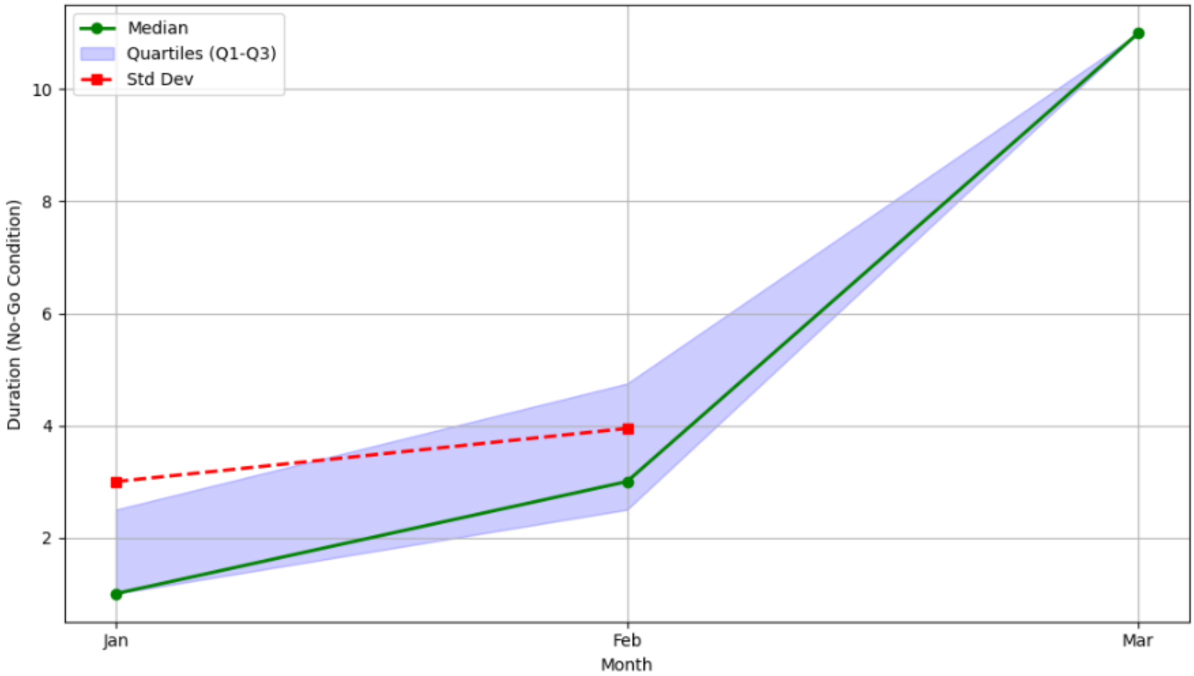

Figure 17: Comparison of descriptive statistics for No-go condition durations due to temperature for Gjoa Haven in January, February and March

Figure 17 shows that the duration of No-go condition due to Temperature in Gjoa Haven has a Median of less than one hour for January. In comparison, around three hours in February and eleven hours in March. It is also possible to conclude that March had only one occurrence, given that Standard Deviation (SD) is zero for that month and first and third quartiles are also at 11. The analysis for Precipitation for the same location was also done and it is presented below.

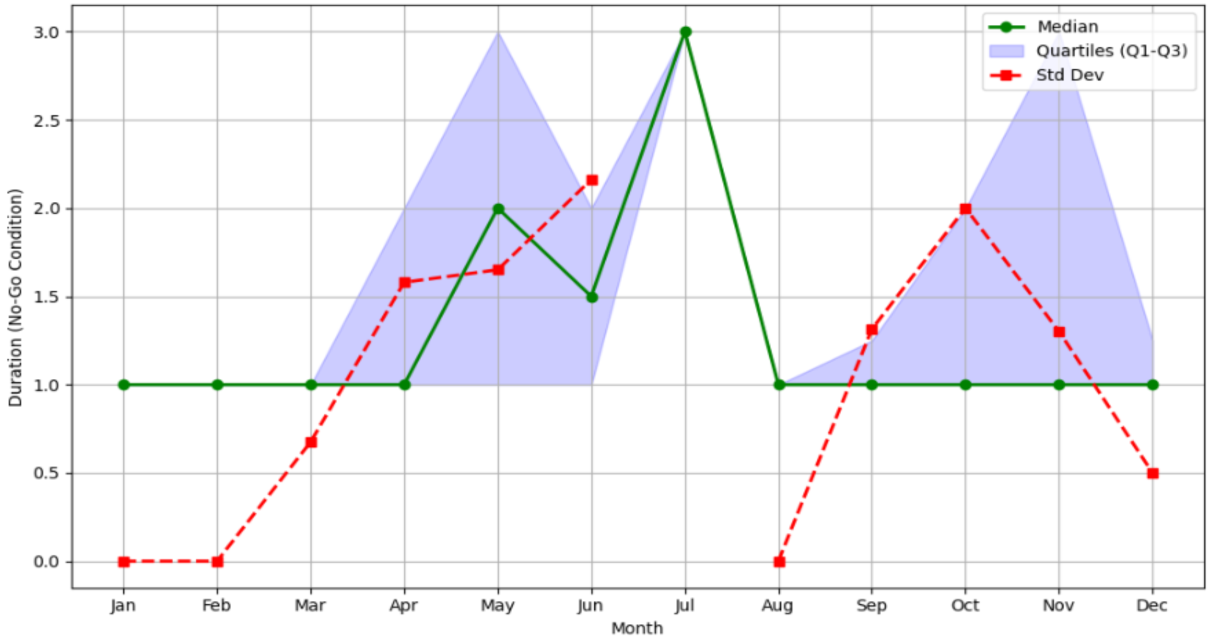

Figure 18: Comparison of descriptive statistics for No-go condition durations due to precipitation for Gjoa Haven from January to December

Figure 18 shows that higher durations due to precipitation occur in May, October and November.

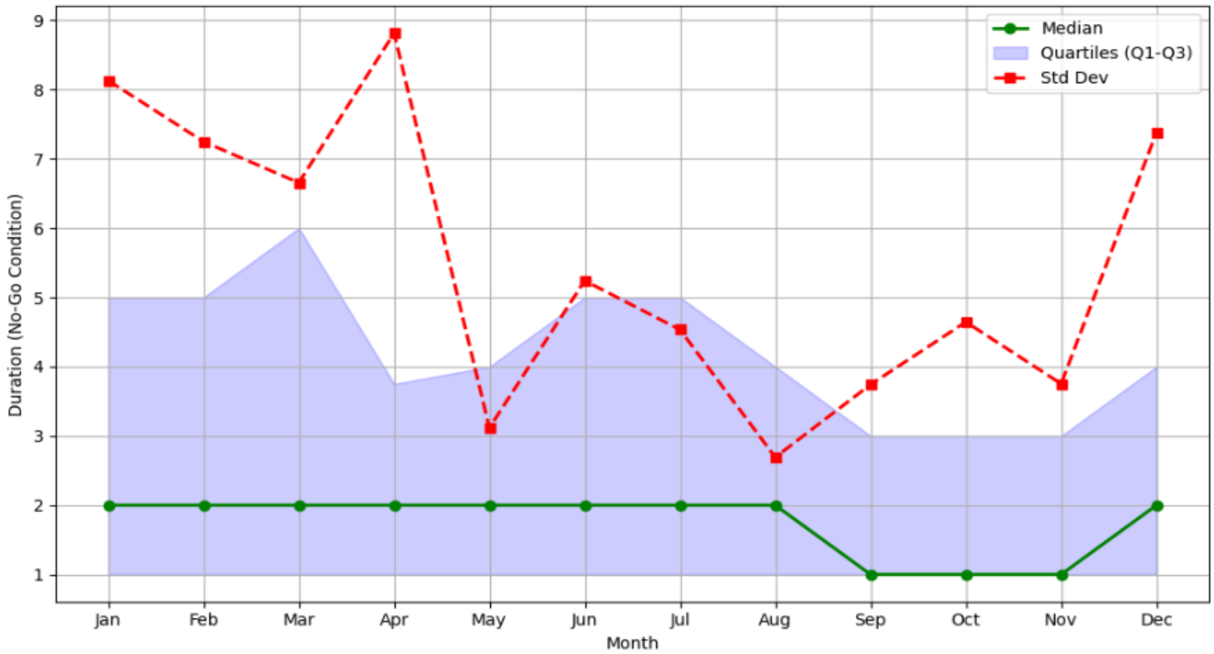

Figure 19: Comparison of descriptive statistics for No-go condition durations due to visibility for Gjoa Haven from January to December

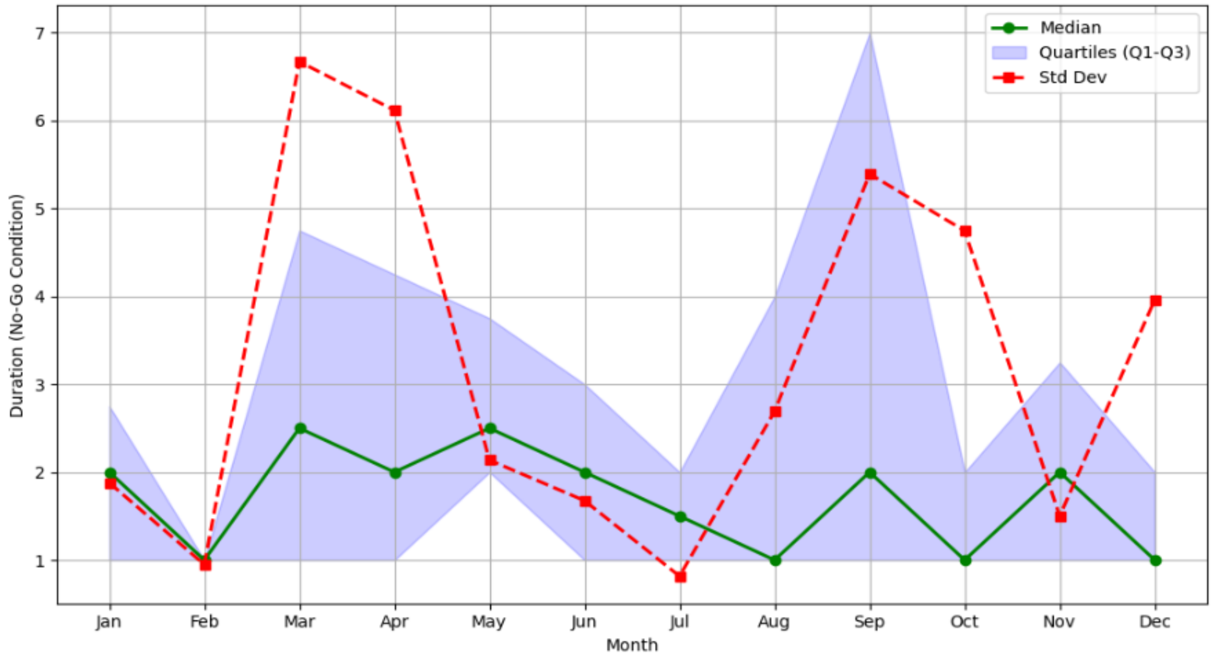

Figure 20: Comparison of descriptive statistics for No-go condition durations due to wind for Gjoa Haven from January to December

The following graph (Figure 25) presents the analysis for temperature conditions at Sanirajak Airport, followed by three graphs also detailing Precipitation, Wind, and Visibility conditions in Figure 26, Figure 27 and Figure 28.

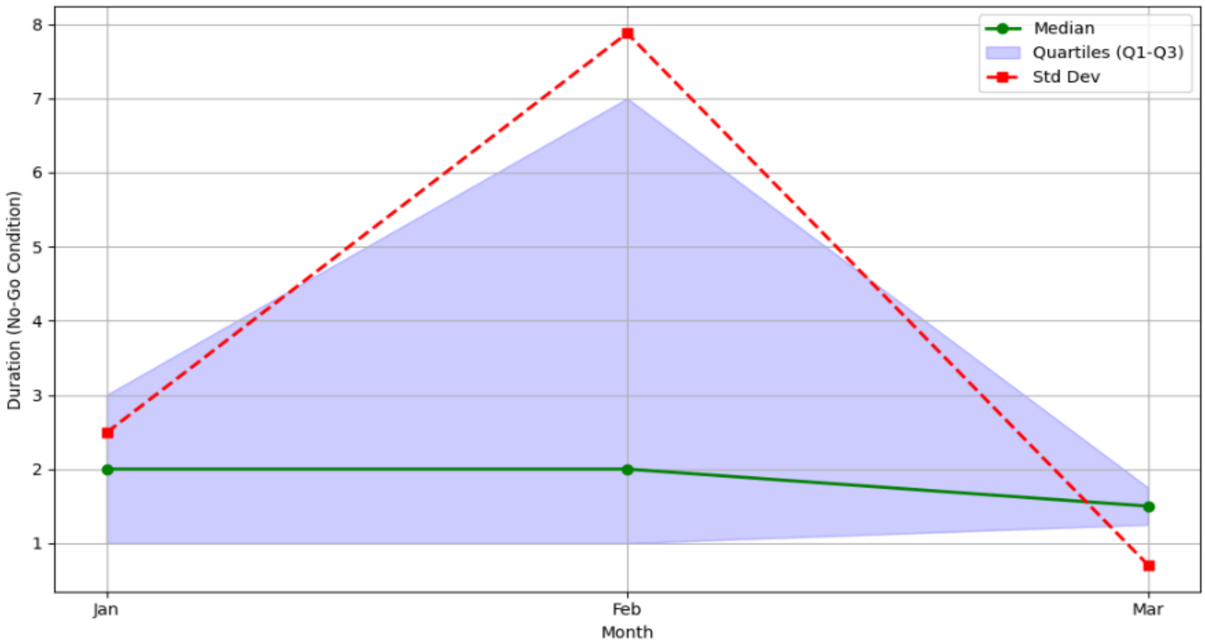

Figure 21: Comparison of descriptive statistics for No-go condition durations due to temperature for Sanirajak Airport in January, February and March

Figure 21 shows that the duration of No-go condition due to Temperature in Sanirajak Airport has a Median of 2 hours for January. It is also possible to conclude that March had only one occurrence, given that Standard Deviation (SD) is zero for that month and first and third quartiles are also at 11. The analysis for Precipitation for the same location was also done and it is presented below.

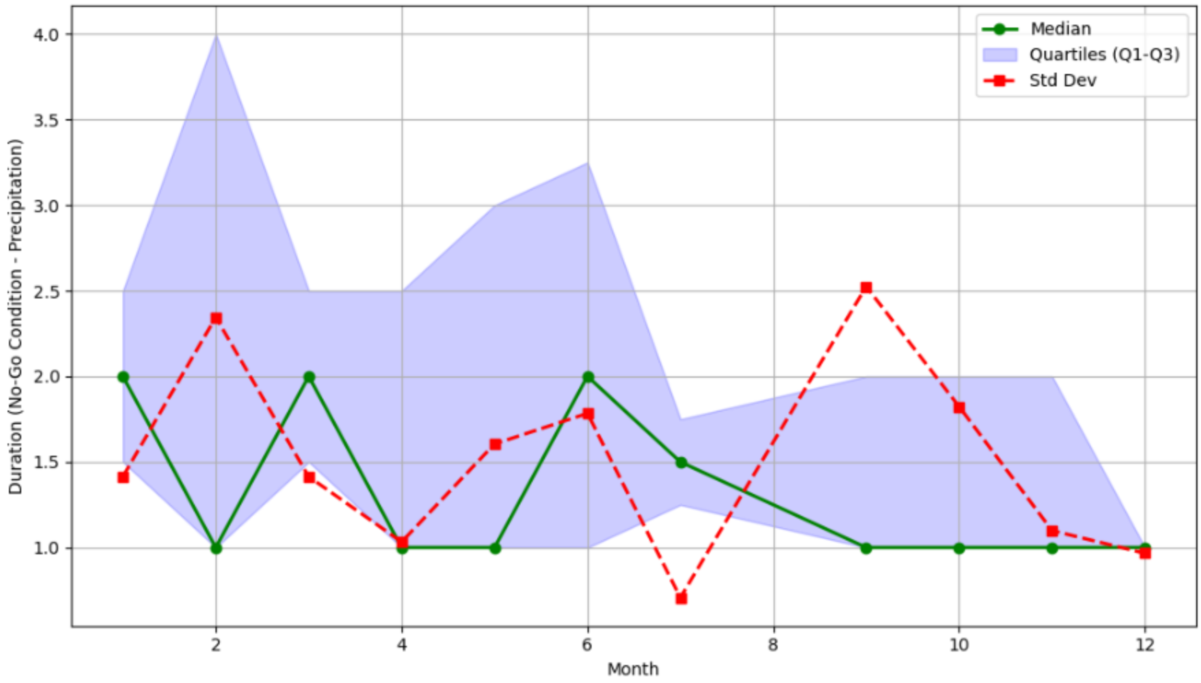

Figure 22: Comparison of descriptive statistics for No-go condition durations due to precipitation for Sanirajak Airport from January to December

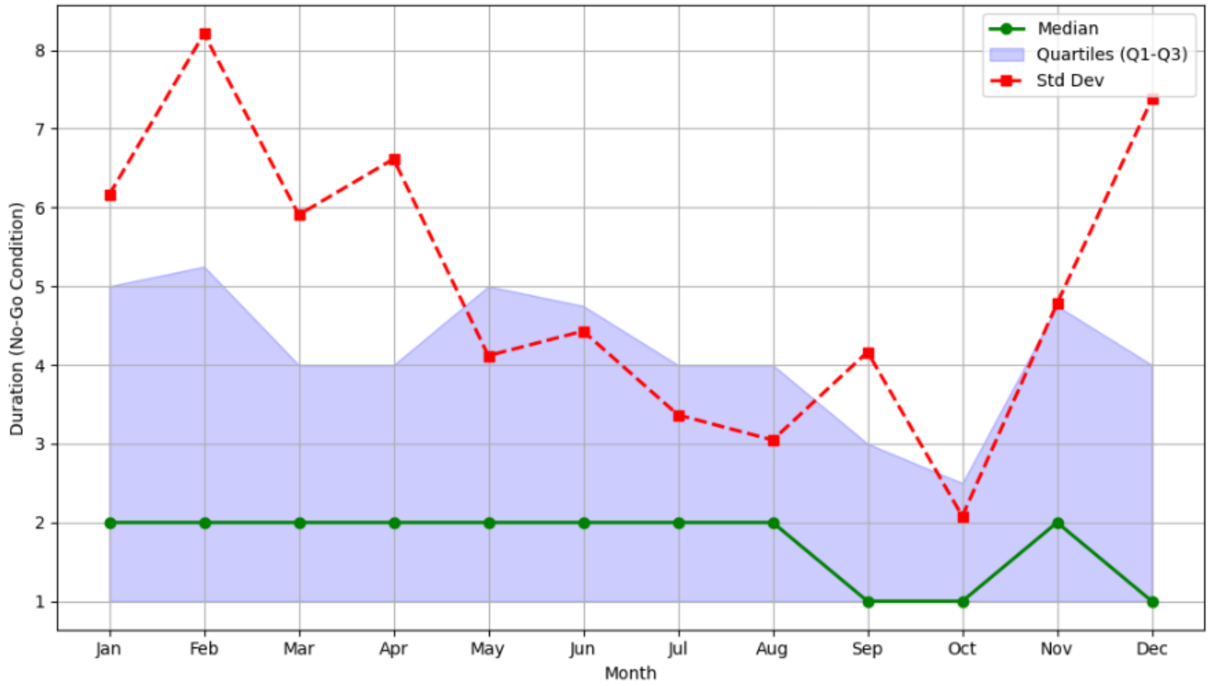

Figure 23: Comparison of descriptive statistics for No-go condition durations due to visibility for Sanirajak Airport from January to December

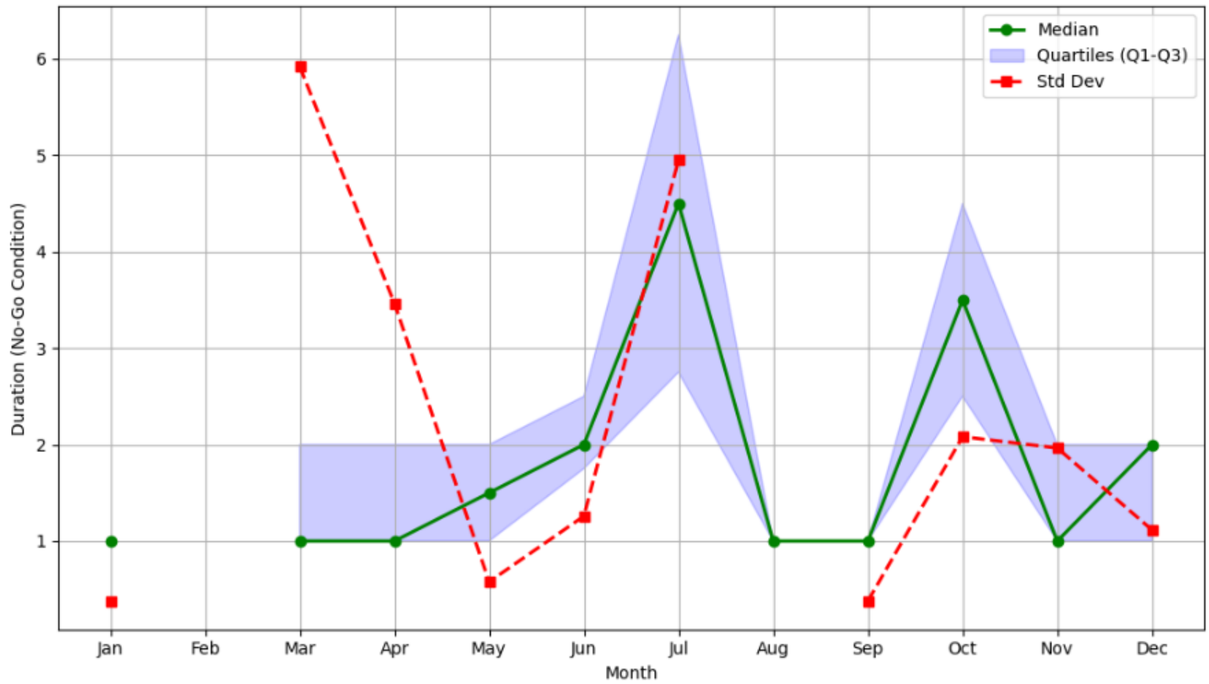

Figure 24: Comparison of descriptive statistics for No-go condition durations due to wind for Sanirajak Airport from January to December

Sanirajak experiences the highest durations in July and October, with the third quartile at 6 hours in July and around 4 hours in October. In contrast, Gjoa Haven shows the highest durations for No-go conditions due to wind in March, April, and September, with values around 4 hours and 6 hours, respectively (see Figure 24).

4.1.2 Frequency and Analysis of Unfavorable Conditions

This section presents graphs showing the probabilities of unfavorable conditions for RCAF helicopter operations due to temperature and wind, making use of the procedure described in section 3.2.4 and the RHEO model described in section 3.3.3. These probabilities are higher than No-go conditions. As introduced in section 3.2.4, unlike for No-go conditions, in unfavorable conditions helicopter operations can proceed, but with adverse effects on the helicopter transit speed, its fuel consumption and its range. Figure 25 shows the probabilities for temperature-related unfavorable conditions for the different stations and over the course of the year.

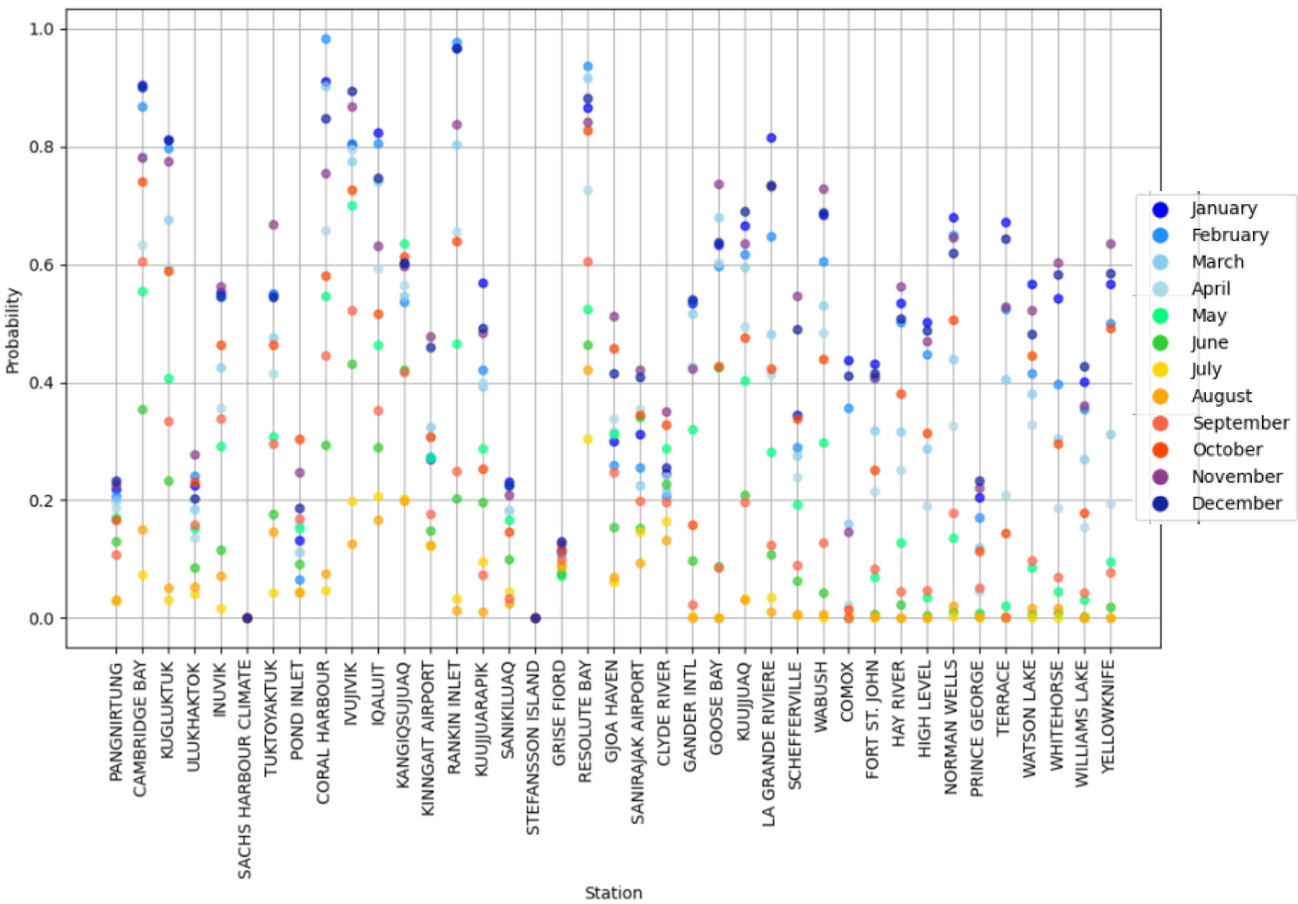

Figure 25: Probability of Unfavorable-related Temperature conditions at the weather stations in the Canadian Arctic

In Figure 25, the seasonal patterns are more consistent than for No-go conditions (Figure 14), with the higher probabilities generally associated with the winter months and the lower ones in months like July, August and September. That is why yellow/orange colors are observed on the bottom part of the graph and blue on the top. Several stations, such as Coral Harbour, Rankin Inlet and Resolute Bay, show temperature-related probabilities of unfavorable conditions close to 100% for December, January and February. Other stations frequently have the probabilities as close to 80% for the same months.

Figure 26 shows the probabilities for wind-related unfavorable conditions for the different stations and over the course of the year.

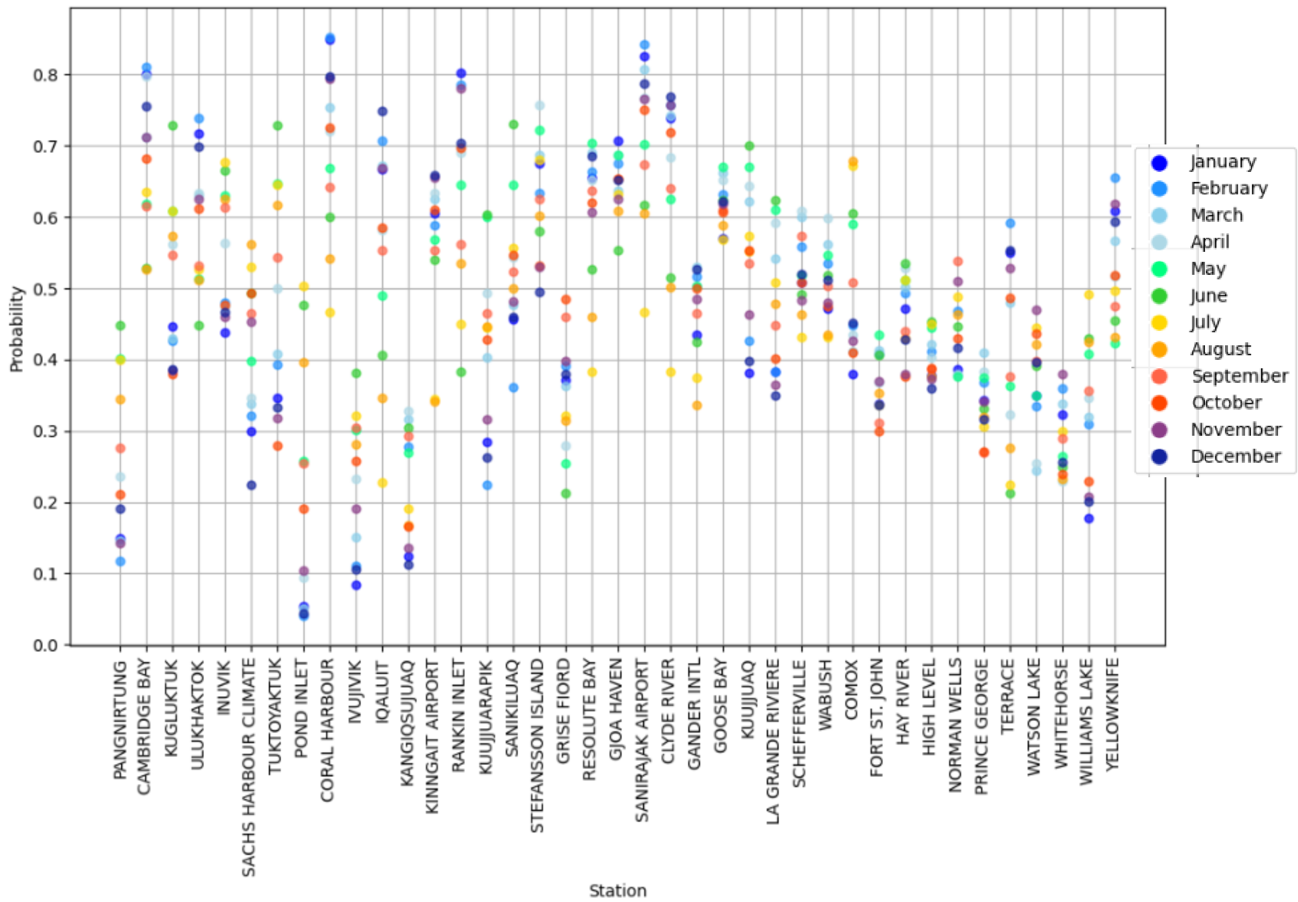

Figure 26: Probability of Unfavorable-related Wind conditions at the weather stations in the Canadian Arctic

Figure 26, similarly to Figure 25, shows relatively high probabilities of wind-related unfavorable conditions for the winter months in most stations. Notably, there are high probabilities also in summer months for many stations such as Kuujjuaq (E), Tuktoyaktuk (Zone 12) and Sanikiluaq (Zone 17). This is due to variations in wind direction, which are more influenced by the geographical location of the stations than by the time of year.

4.2 DETAILED INSIGHTS INTO HELICOPTER SAR RESPONSE FOR SELECTED SCENARIOS: ANALYSIS RESULTS

To enable more in-depth insights into how helicopter SAR response operations proceed according to the model, and to provide a basis for understanding the finally resulting response times, it is important to understand the model logic (Chapter 3), the inputs (Section 4.1, 3.2.2 and 3.2.4) and finally the model outputs.

In this section, some SAR response scenarios are selected, for which detailed insights in the model representation of the helicopter SAR operations are presented. For this, Zone 12 and Zone 13 were selected, facilitating the reader's understanding of how the helicopter SAR response times and the final METR-HT were obtained. The scenarios were selected to be sufficiently distinct, providing insights into how weather factors, location, and time of year impact the results. These two zones are defined based on their geographical positioning, representing the eastern and western extremes of the Canadian Arctic region (Figure 11). This distinction highlights the differing environmental and operational conditions between the east and west of the Canadian Arctic. In this way, different air bases from which RCAF helicopters respond are considered. Consequently, these scenarios also represent different refueling stops and therefore different operational conditions, due to the differences in distances between refueling stations and different weather conditions.

4.2.1 Detailed Results for Scenarios at Zone 13

For the tested scenarios in Zone 13 (Scenario ID from 145 to 156 in Table 7 in Section 3.5), the helicopter is deployed from Gander Airport, with the community of Pond Inlet serving as a temporary base to transport people in distress. The selected refueling stops are Goose Bay, Kuujjuaq, Iqaluit, Pangnirtung and Clyde River. The route used in the model is shown in Figure 27, which shows the RCAF SAR base (Gander Airport), refueling stations, temporary base (Pond Inlet), and the incident location, represented as Last Known Position (LKP).

Figure 27 shows the potential refueling stops. It also shows the representation of each leg of the route, indicated by the numbers in Figure 27. In aviation, a leg means the single direction between two points flown or in terms of modeling, they represent the arcs within the network (Kannon et al., 2015). It is noted that the 8th leg overlaps with the 6th and 7th legs. The 6th leg represents the helicopter going from Pond Inlet to LKP, followed by the 7th leg that is when the helicopter is searching between LKP and PID and finally, after the rescue, the 8th leg is the path from the PID location back to Pond Inlet.

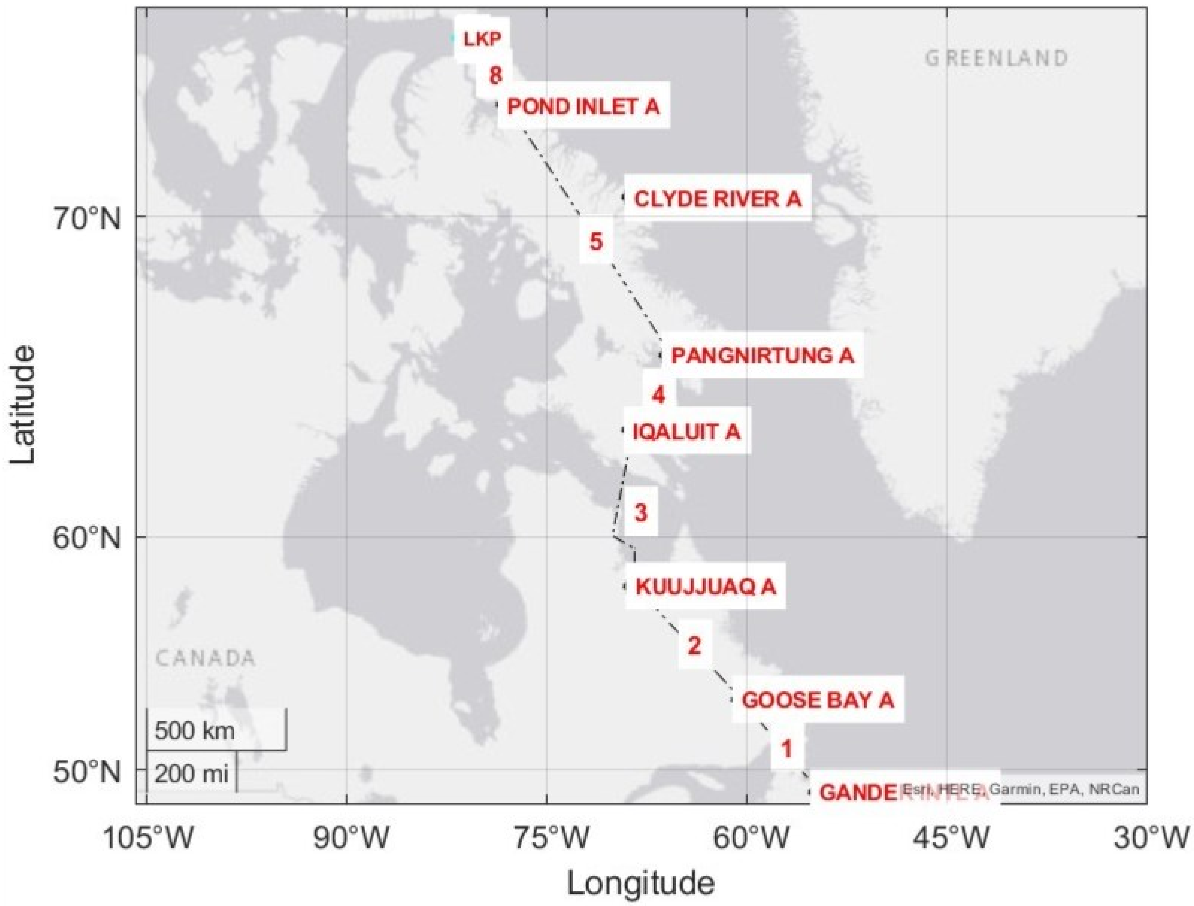

Figure 27: Helicopter route for scenarios with incident location in zone 13 (Scenario 145 to 156)

Table 11: Time and route distribution for each month in zone 13 with PID 12

Scenario ID	Month	Cannot rescue	8 Legs	9 Legs	11 Legs	3rd Quartile of Total SAR Time	Time (hours)
145	January	790	6241	2815	154	9	24.8
146	February	908	6803	2218	71	8	24.7
147	March	855	6514	2495	136	9	25.6
148	April	679	6371	2747	203	9	24.4
149	May	573	6655	2588	184	9	24.2
150	June	269	7794	1834	103	8	21.9
151	July	0	9263	680	57	8	21.3
152	August	0	9237	701	62	8	21.0
153	September	278	7124	2371	227	9	21.7
154	October	691	5332	3580	397	9	22.6
155	November	889	5298	3529	284	9	24.6
156	December	968	5658	3162	212	9	24.3

Note: Leg means the single direction between two points flown or in terms of modeling, they represent the arcs within the network

Table 11 shows the simulation results for scenario 1, i.e. for an incident with 12 PID located in zone 13 (incident location with latitude 74.1 and longitude -81.3, see also Figure 11), for all months of the year. The simulation with 10,000 iterations each month indicates that in the majority of the cases, the entire SAR operation is completed in 8 legs, as shown in the example of Figure 27. In addition, 14% of the iterations for the navigational season (months of June, July, August and September) and 27% for the winter (December, January and February) required 9 legs. For example, to obtain the 27% for the winter, the calculation was (3162+2815+2218)/30000, where 30,000 represents the total iterations (10,000 for each month). For those cases, the additional leg compared to the route shown in Figure 27 is characterized by the refueling stop at Clyde River Airport.

Furthermore, when analyzing the numbers in Table 11 for SAR operation cases, on average, 1.7% of the iterations for the navigational season and 1.6% for the winter required 11 legs. These percentages were calculated based on the total number of iterations resulted for 11 legs in column 6 performed across June, July, August and September or December, January and February for winter months. For all cases using 11 legs, the extra legs when compared to the route represented in Figure 27 are also associated with a refueling stop at Clyde River Airport. In addition, as the search takes a long time in these cases, the amount of fuel would not suffice to locate the PID, hoist them into the helicopter, and bring the rescued people back to the temporary base at Pond Inlet. In that way, the helicopter goes back to the refueling stop to fill up again. In those conditions, the 7th leg is from Pond Inlet to LKP, the 8th is searching and flying to PID, the 9th is flying back to Pond Inlet to refuel, the 10th is flying back to PID and rescuing people, and the 11th is flying back to Pond Inlet and completing the SAR operation.

In Table 11, the third column shows the number of iterations of the Monte Carlo simulation in which the helicopter could not complete the rescue, those cases are explained in detail in Section 4.3.1. In addition, in Table 11, the third column shows that for the months of July and August, all simulation runs results in operations which were completed. In contrast, the number of incomplete rescues increases significantly from November to March.

The simulation results also provide insights in the different phases of the responding SAR helicopter process from the time when a distress call is received, until all PID are dropped off at the temporary base. The sequence of the operational status of a responding helicopter over time for the month of September with 12 PID in Zone 13 is shown in Figure 28.

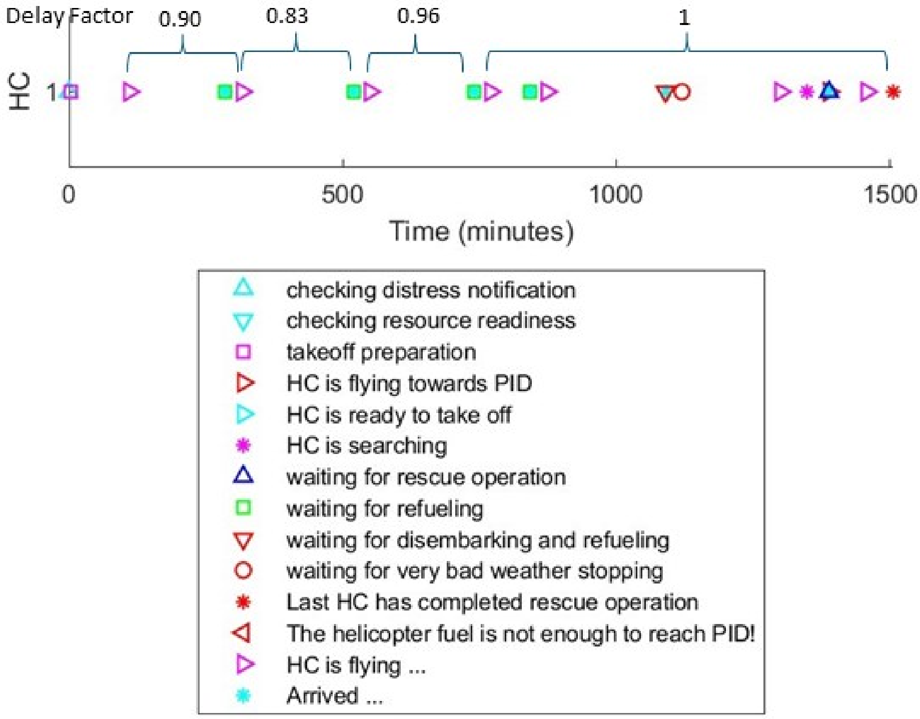

Figure 28: Timeline showing the sequence of the operational status of the responding helicopter over time, example case for a rescue in zone 13 with 12 PID in September

Figure 28 shows when each of the steps of the SAR operation occurs according to the simulation, starting with checking distress notification, followed by the takeoff preparation. The pink triangle pointing to the right shows when the helicopter starts flying. The operation continues until it needs to stop for refueling (green square) and this is repeated four times. In this example the helicopter stopped due to No-go conditions and proceeded when the conditions changed, so the search started (pink star). The same logic continues until the helicopter completes the rescue operation. Figure 28 also shows what was the weather factor for each leg of the helicopter. This shows that the first three legs were affected by unfavorable weather conditions.

Another result which can provide insights into the simulation model's functionality is shown in Figure 29. This shows the distance traveled by the responding SAR helicopter from the RCAF base to the temporary base as a function of the time.

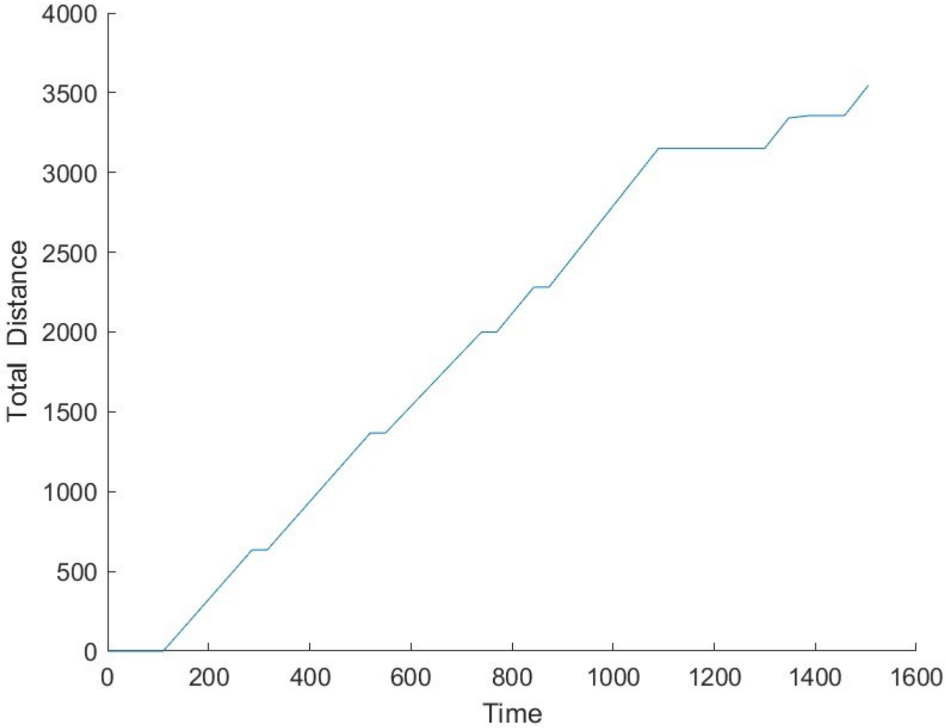

Figure 29: Total distance (in km) covered by the SAR helicopter over time (in minutes) in zone 13 with12 PID in September (sample result from 1 of 10,000 iterations)

The figure illustrates the total distance covered by the SAR helicopter over time. The diagonal segments of the line represent the periods during which the helicopter is moving, progressively covering more distance until the SAR operation is complete, which in this case results in a total of over 3500km traveled in over 1500 minutes (25 hours). The horizontal segments in the graph indicate the time spent by the helicopter at refueling stops, during which no distance is added. Each leg is linear, which means that the helicopter travels at a constant speed between each refueling stop. In addition, one larger segment can be seen close to minute 1,100, during which the helicopter stopped for a longer period. This corresponds to a No-go condition which lasted 180 minutes in this example case.

The next output represents the search time in Figure 30 below, which occurs from the moment at which the SAR helicopter arrives at the LKP location, until the PIDs are located.

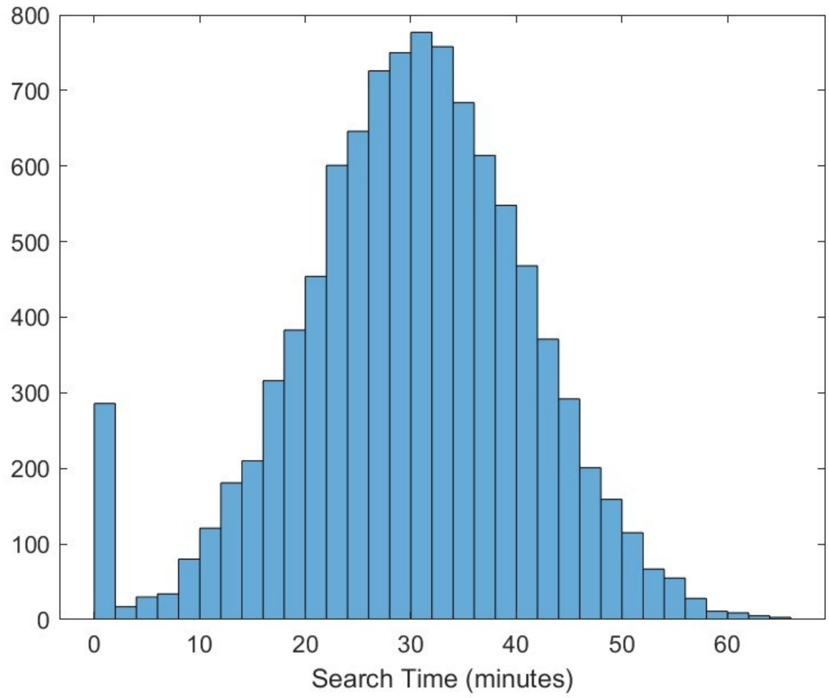

Figure 30: Search time distribution for zone 13 in September with PID 12

The histogram shows the distribution of search times, measured in minutes, for SAR helicopter operations. The data shows a roughly normal distribution, peaking around 30 minutes, which indicates that the most frequent search time is approximately 30 minutes. A significant bar at the zero mark indicates the number of instances where the helicopter was unable to conduct a rescue, leading to no search phase being initiated.

Figure 31 shows the distribution of the total SAR operation times, i.e. the time at which all PID are dropped off at the temporary base.

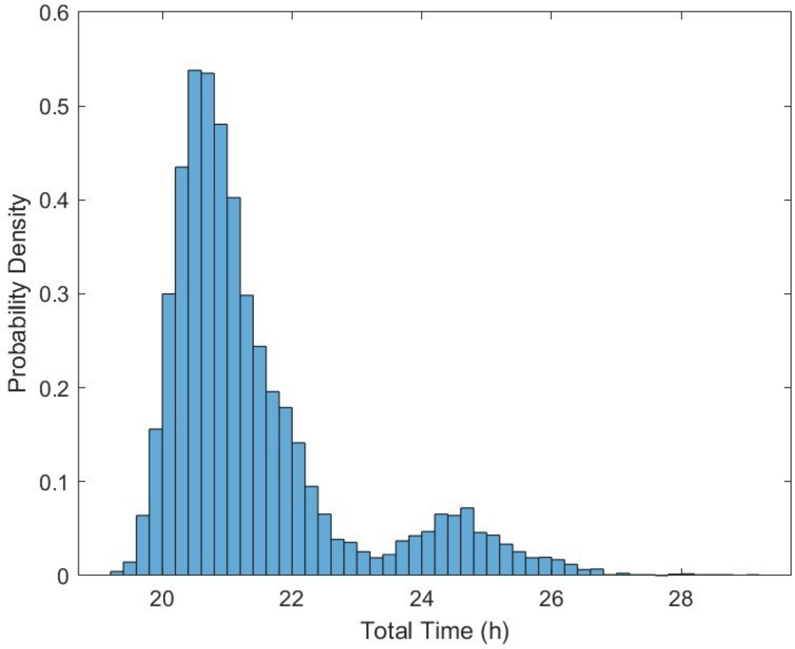

Figure 31: Total time distribution for zone 13 in September PID 12

This histogram represents the probability density distribution of the total SAR operation times (in hours) for a response to 12 PID in zone 13 occurring September. The histogram shows a bimodal distribution, with two distinct peaks. The first and higher peak occurs around 21 hours, indicating that the most common total time for the operation is in this range. The second, smaller peak is between 24 and 25 hours.

The second peak in Figure 31 indicates the operations which were more severely affected from No-go and Unfavorable conditions, influencing the total SAR operation duration. As seen in Figure 40 in Section 4.3.1, for September, 8,388 of 10,000 cases did not present a No-go condition, representing approximately 84% of the cases. This explains the shape of the distribution in Figure 30. For the other 16%, the average wait time due to No-go conditions was 3 hours (see Table 12), which also aligns with the second peak of total times distribution. Table 10 shows the average wait time for the other months when helicopters perform SAR operations in zone 13.

Table 12: Average wait time per month due to No-go conditions per leg in zone 13

Month	Average Wait Time (hours)
1	4.6
2	4.8
3	4.6
4	4.2
5	4.4
6	4.0
7	3.5
8	3.8
9	3.0
10	3.1
11	3.9
12	3.9

Table 12 shows that waiting times due to No-go conditions are higher in the first months of the year and start to decrease in June onward until November when they increase again.

4.2.2 Detailed Results for Scenarios at Zone 12

For the tested scenarios in zone 12 (Scenario ID from 133 to 144 in Table 7 in Section 3.5), the RCAF SAR helicopter is deployed from the base in Comox on the west side of Canada, with Tuktoyaktuk Airport serving as a temporary base for transferring people in distress. The potential refueling stops are Terrace Airport, Watson Lake Airport, Norman Wells Airport and Inuvik Airport. The route given by the model is depicted in Figure 32, and in the same way as in Figure 27 for zone 13, it shows the SAR base, refueling stations, temporary base, and LKP.

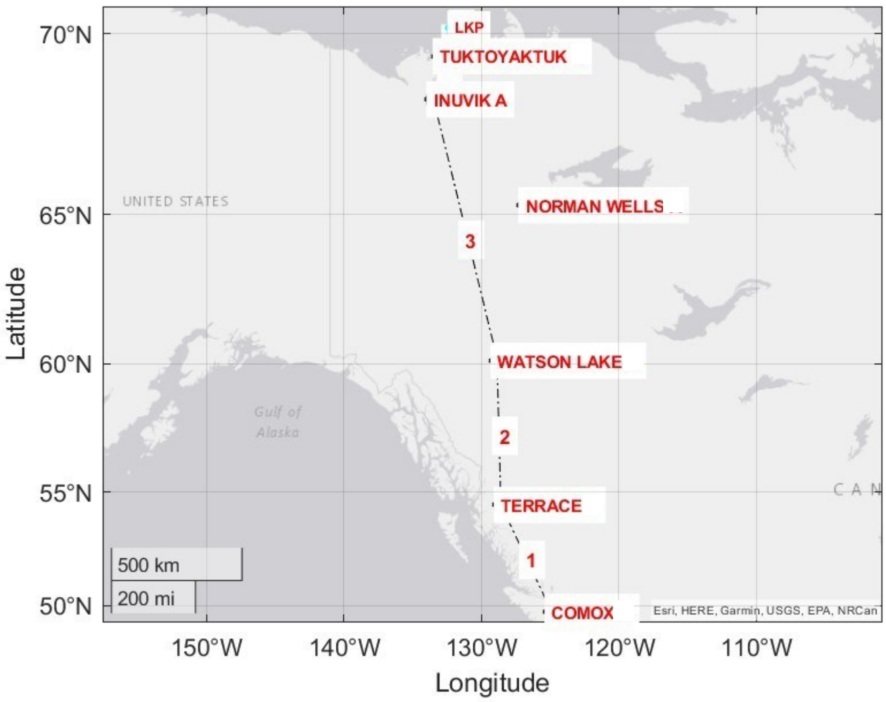

Figure 32: Helicopter route for incident location in zone 12

Figure 32 shows the potential refueling stops. It also shows the representation of each leg of the route. As shown in Table 13 later in this Section, cases in which a responding helicopter uses 6 and 7 legs were the most common occurrences. In the route depicted in Figure 32, from the 4th leg onward, the route is overlapped by the labels for the airports and LKP. For better visualization, Figure 33 and Figure 34 provide a zoomed-in view of the route, clearly showing the details when 6 and 7 legs are required.

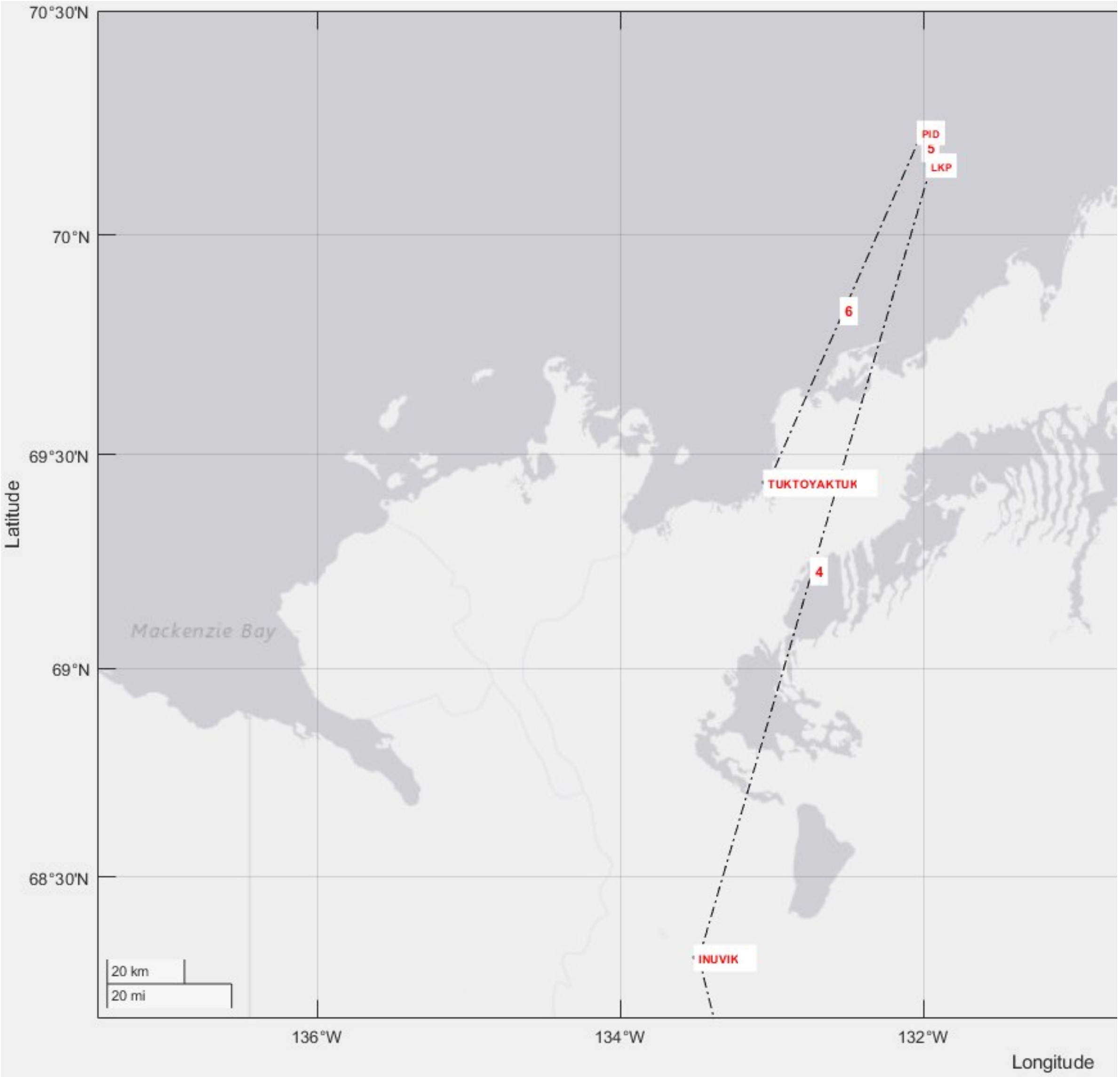

Figure 33: Detailed route from leg 4 to 6 for a case of a responding SAR helicopter to an incident in zone 12, response to 12 PID in September

Figure 33 is a representation of a case in which the responding SAR helicopter uses 6 legs, where the 4th leg represents the helicopter's voyage from Inuvik to LKP, the 5th leg corresponds to the search period, during which the helicopter flies from LKP to the PID location, while the 6th leg is the path from PID back to Tuktoyaktuk Airport (temporary base in this case).

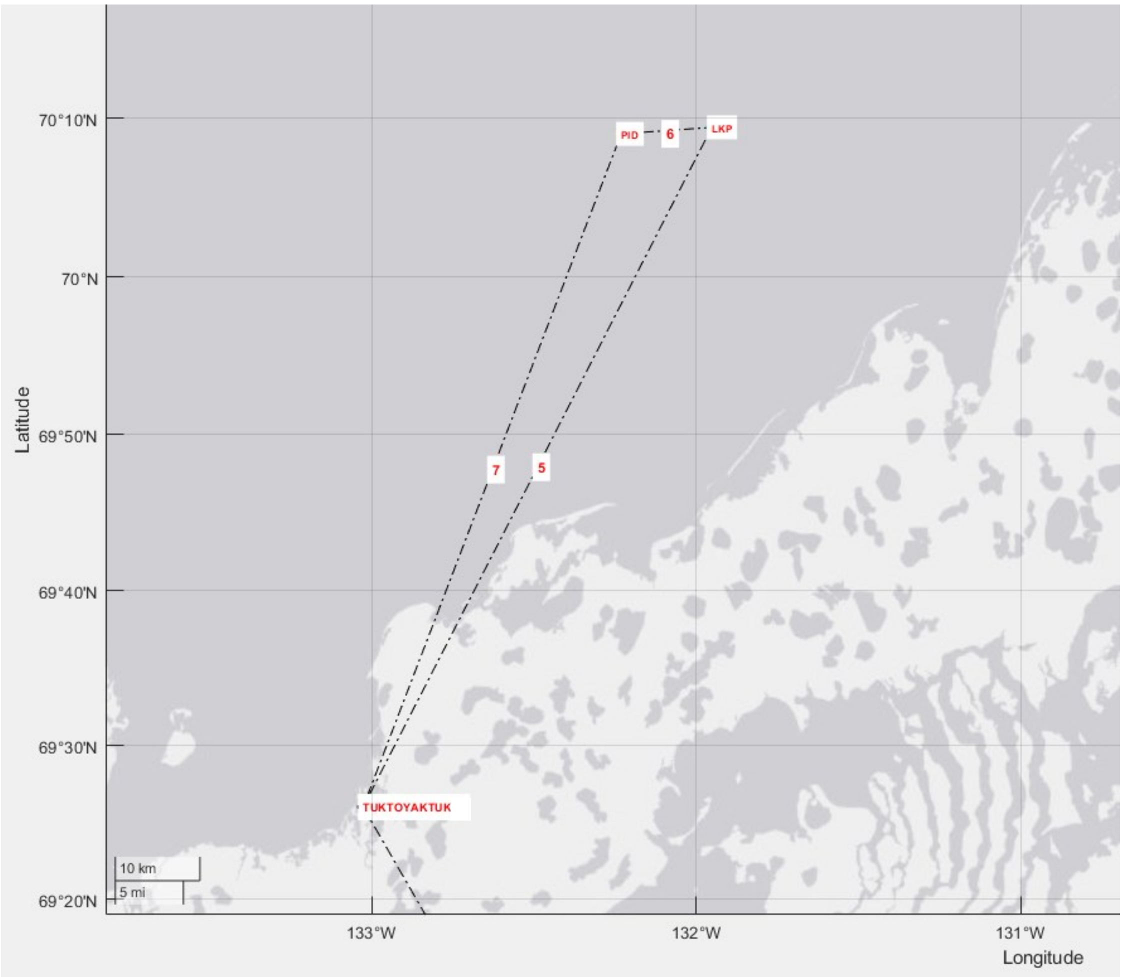

Figure 34: Detailed route from leg 5 to 7 for a case of a responding SAR helicopter to an incident in zone 12, response to 12 PID in September

In Figure 34, an example case of an operation involving 7 legs is presented. Differently from the whole route previously presented, the helicopter used Norman Wells Airport as one of the refueling stops, followed by a refueling stop in Tuktoyaktuk (5th leg – from Tuktoyaktuk to LKP). The 6th leg corresponds to the transit from LKP to PID and the 7th leg represents the flight back to Tuktoyaktuk (temporary base), after the PID are rescued from the incident scene.

Table 13 shows the frequency of cases for 6, 7 and 8 legs as well as the number of cases when helicopter cannot complete the rescue, for a Monte Carlo simulation of scenario 2 with 10,000 iterations.

Table 13: Time and route distribution for each month in zone 12 with PID 12

Scenario ID	Month	Cannot rescue	6 Legs	7 Legs	8 Legs	3rd Quartile of Total SAR Time	Time (Hours)
133	January	759	1931	7310	0	7	18.5
134	February	584	2704	6712	0	7	17.3
135	March	0	3603	6396	1	7	16.5
136	April	0	4351	5647	2	7	16.2
137	May	0	6877	3121	2	7	15.8
138	June	0	8946	1052	2	6	15.4
139	July	0	9839	160	1	6	15.3
140	August	0	9149	851	0	6	15.4
141	September	0	5927	4073	0	7	15.9
142	October	0	2955	7044	1	7	17.1
143	November	0	2094	7905	1	7	17.3
144	December	691	2378	6931	0	7	17.3
Note: Leg means the single direction between two points flown or in terms of modeling, they represent the arcs within the network							

In Table 13 the simulation result for an incident with 12 PID located in zone 12 (incident location with latitude 70.16 and longitude -131.95, see also Figure 11), for all months of the year. The simulation with 10,000 iterations each month indicates that in the majority of the cases, the entire SAR operation is completed in 7 legs in the winter months and 6 legs for the summer months as shown in the example of Figure 32, Figure 33 and Figure 34. In addition, only 6.91% (obtained from 691/1000), 7.59% and 5.84% of the iterations resulted in conditions when the helicopter could not complete the rescue only for December, January and February consecutively.

Furthermore, only 1 or 2 cases out of the 10,000 iterations resulted in a flight pattern requiring 8 legs to complete the helicopter SAR operation, depending on the month. For those cases, the legs are characterized as follows: the 1st is the voyage from Comox to Terrace Airport, the 2nd Terrace to Watson Lake, the 3rd from Watson Lake to Inuvik, the 4th Inuvik to LKP, whereas the 5th leg corresponds to the travel from the LKP to the location of the PID, i.e. the 5th leg emulates the search period. The rescue operation starts but the helicopter goes back to the refueling stop due to insufficient fuel, which explains the extra legs 6 to 8. Thus, the 6th leg represents the helicopter going back to Tuktoyaktuk for disembarking PID (if any were already rescued) and refueling, the 7th leg is from Tuktoyaktuk back to the PID location and finally, the 8th leg is the voyage back to the temporary base.

Similarly to zone 13, the simulation results also provide insights in the different phases of the responding SAR helicopter process from the time when a distress call is received, until all PID are dropped off at the temporary base. The sequence of the operational status of a responding helicopter over time for the month of September with 12 PID in Zone 13 is shown in Figure 35.

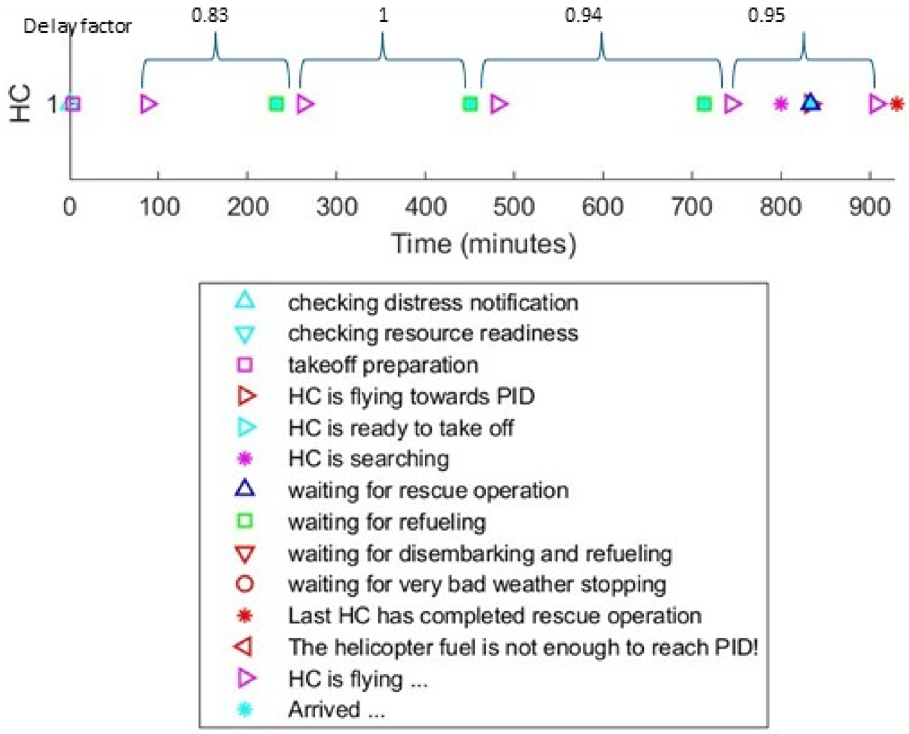

Figure 35: Timeline showing the sequence of the operational status of the responding helicopter over time, example case for a rescue in zone 12 with 12 PID in September

Figure 35 shows when each of the actions of the helicopter SAR operation occurs in the simulation, starting with checking distress notification, which is followed by the takeoff preparation. The pink triangle pointing to the right shows when the helicopter starts flying, which in this case occurs a bit before the 100th minute. The same logic continues until the helicopter completes the rescue operation.

Another result which can provide insights into the simulation model's functionality is shown in Figure 36, similarly to Figure 29 for zone 13. This shows the distance traveled by the responding SAR helicopter from the RCAF base to the temporary base in function of the time. This graph is represented below in Figure 36.

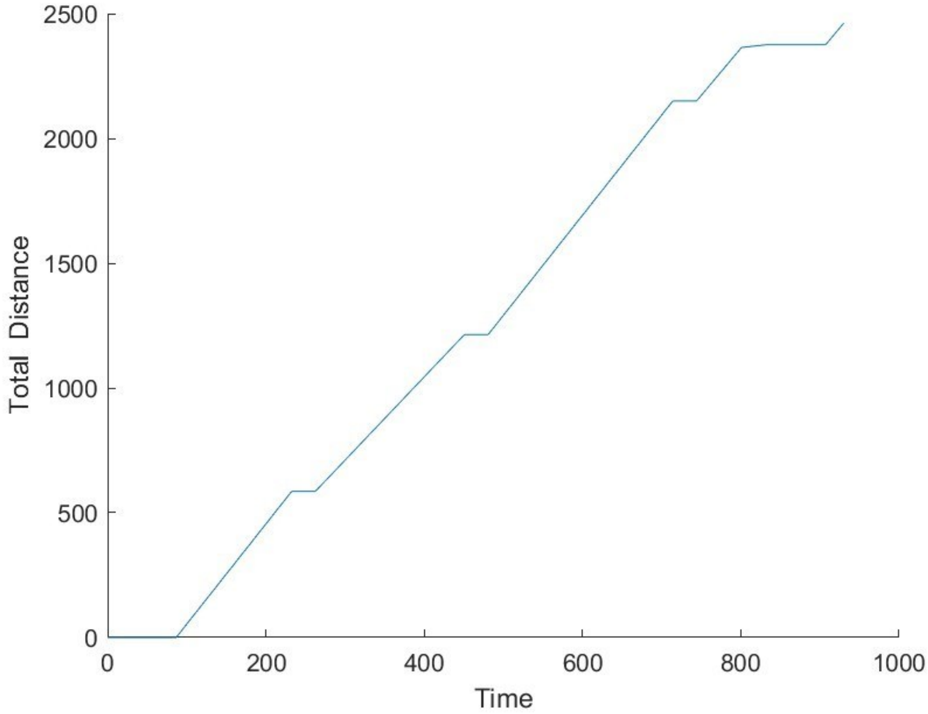

Figure 36: Total distance (in km) in function of the total time (in minutes) in zone 12 with 12 PID in September (sample result from 1 of 10,000 iterations)

The figure illustrates the total distance covered by the SAR helicopter over time. The diagonal segments of the line represent the periods during which the helicopter is moving, progressively covering more distance until the SAR operation is complete, which in this case results in a total of over 2,500 km traveled in over 900 minutes (15 hours). The horizontal segments in the graph indicate the time spent by the helicopter at refueling stops, during which no distance is added. The trend in each leg is linear, which means that the helicopter travels at a constant speed between each refueling stop. The smaller segments associated with a non-moving helicopter (constant total distance over a time period) are associated with the time spent at a refueling station.

The next output represents the search time in Figure 37, which occurs from the moment at which the SAR helicopter arrives at the LKP location, until the PID are located.

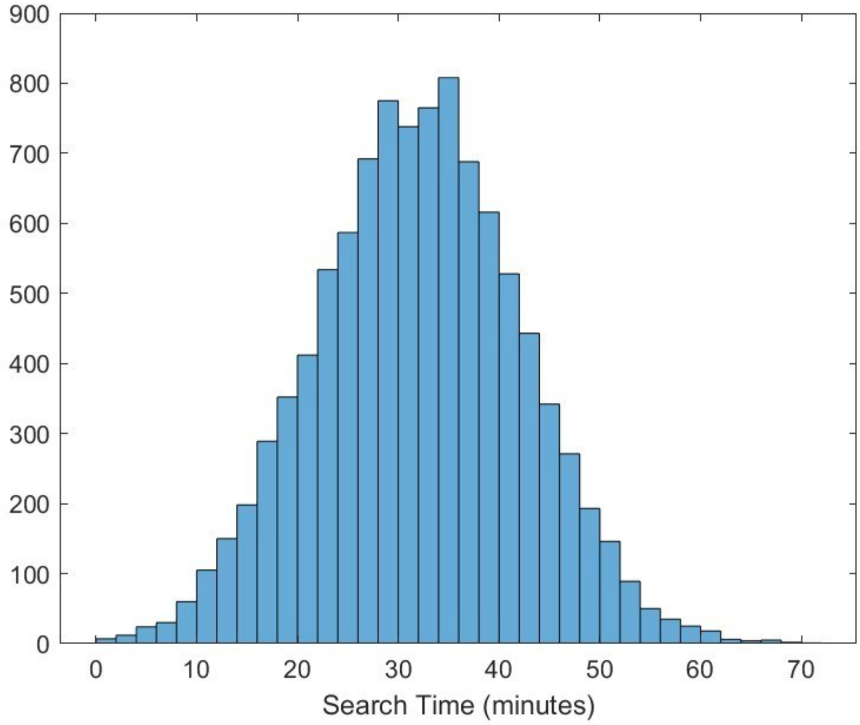

Figure 37: Search time distribution for zone 12 in September with PID 12

The histogram shows the distribution of search times, measured in minutes, for RCAF SAR helicopter rescue operations. The y-axis represents the frequency of occurrences. The results show a roughly normal distribution, peaking after 30 minutes, which indicates that the most frequent search time is between 30 and 40 minutes.

Figure 38 shows the distribution of the total SAR operation times, i.e. the time at which all PID are dropped off at the temporary base.

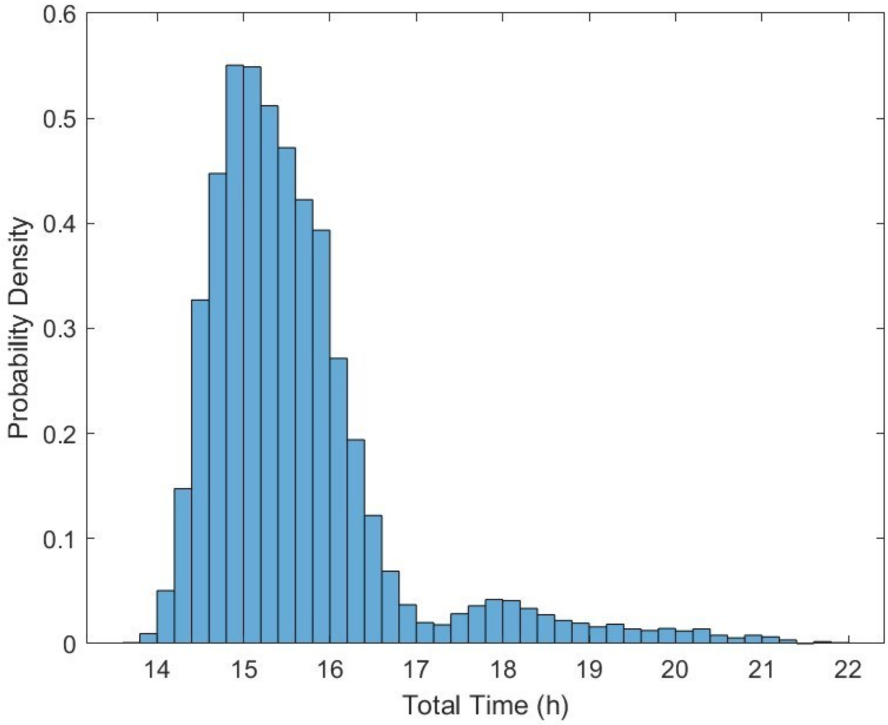

Figure 38: Total time distribution for zone 12 in September PID 12

This histogram represents the probability density distribution of the total SAR operation times (in hours) for zone 12 in September related to SAR helicopter operations. The histogram shows again a bimodal distribution, with two distinct peaks. The first and larger peak occurs around 15 hours, indicating that the most common total time for the operation is around this number. The second, smaller peak is around 18 hours.

The second peak in Figure 38 indicates the operations which were more severely affected from No-go and Unfavorable conditions, influencing the total SAR operation duration. As seen in Figure 16, for September, 8,561 of 10,000 cases did not present a No-go condition, representing approximately 86% of the cases. This explains the shape of the distribution in Figure 38. For the other 14%, the average wait time due to No-go conditions was 2.9 hours (see Table 14), which also aligns with the second peak of total times distribution. Table 14 shows the average wait time for the other months when helicopters perform SAR operations in zone 12.

Table 14: Average wait time per month due to No-go conditions in zone 12

Month	Average Wait Time (hours)
1	5.1
2	3.5
3	3.1
4	2.5
5	3.2
6	2.0
7	2.4
8	2.9
9	2.9
10	3.9
11	3.8
12	4.3

Table 14 shows that waiting times due to No-go conditions are higher in January and December and start to decrease from February onward until November. The smaller numbers are from June to September.

4.3 RESULTS FROM THE HELICOPTER SAR OPERATIONS MODEL

The simulation results of third quartile for total SAR operation times across all 17 zones, PID 12 and all months of the year are outlined in the test matrix described in Section 3.5, with the corresponding heat map displayed in Figure 39.

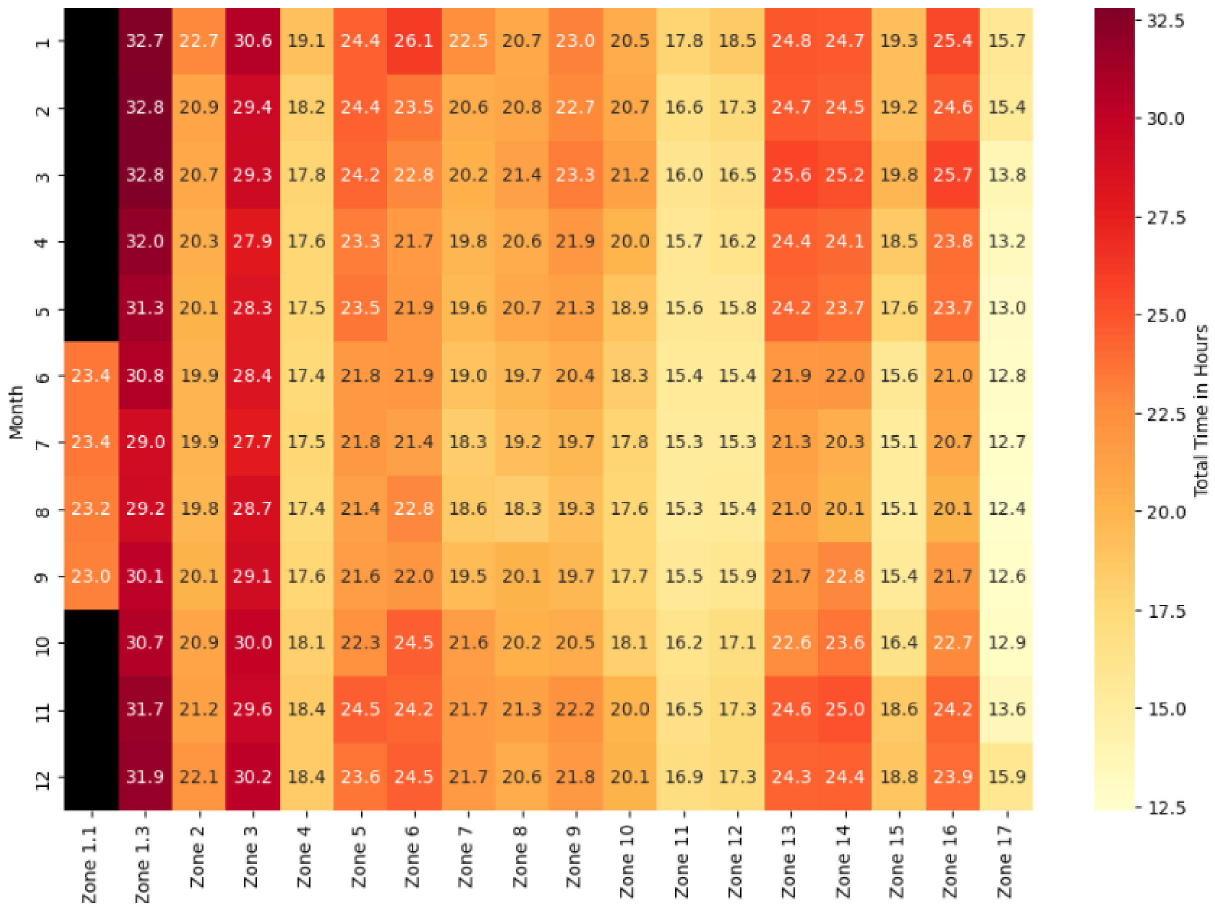

Figure 39: Heatmap showing third quartile for helicopter SAR times operations with 12 PID

The heatmap shows the third quartile of the total SAR response time for zones 1 to 17 introduced in Figure 11. It is noted that for zone 1, two locations were selected because of its large size and because different routes are needed for each of these, resulting in significantly different rescue times. This can be further observed in Figure 40 that shows the map of Canada with maximum and minimums of these times for each zone. Note that zones 1.3 and 3 show the highest total times (in darker color), followed by zone 1.1 for which the simulation indicates that rescue operations can only be completed during the summer months.

It is also possible to observe that Zones 1.3 and 3 show the highest third quartile for helicopter total SAR times (in darker colors). This is primarily because these zones represent some of the most remote areas in the Canadian Arctic, as highlighted in Figure 10 in Section 3.4. The remoteness of these zones increases the likelihood of encountering Unfavorable and No-go conditions.

Zone 1.1 shows that outside of the summer months, SAR operations are not possible. This is due to the high incidence of Unfavorable weather conditions from October to May, combined with the significant distances to the nearest refueling points.

Zones 12, 5, 6, 13, 14 and 16 also show high numbers for METR-HT. All zones exhibit lower total SAR times (in lighter colors) during the summer months, particularly in June, July, August, and September. To complete this analysis, a map showing the minimum and maximum values of METR-HT over the course of a year for the different zones is presented in Figure 40. This map confirms that more remote locations are associated with higher values of METR-HT, as can be expected.

In Figure 40, it can be observed that Zone 1 has multiple incident locations. This is because, for the original incident location shown in Figure 11, the helicopter was unable to complete the rescue. As a result, two additional locations were selected: 1.1 in the southern part of Zone 1, 1.2 (the original location), and 1.3 in the northern part of Zone 1. Interestingly, although 1.3 is farther north than 1.2, rescue conditions are more favorable due to a different route being used. In this case, the helicopter approaches from the east (Gander Airport) instead of from Comox, which is the approach used for Zone 1.1.

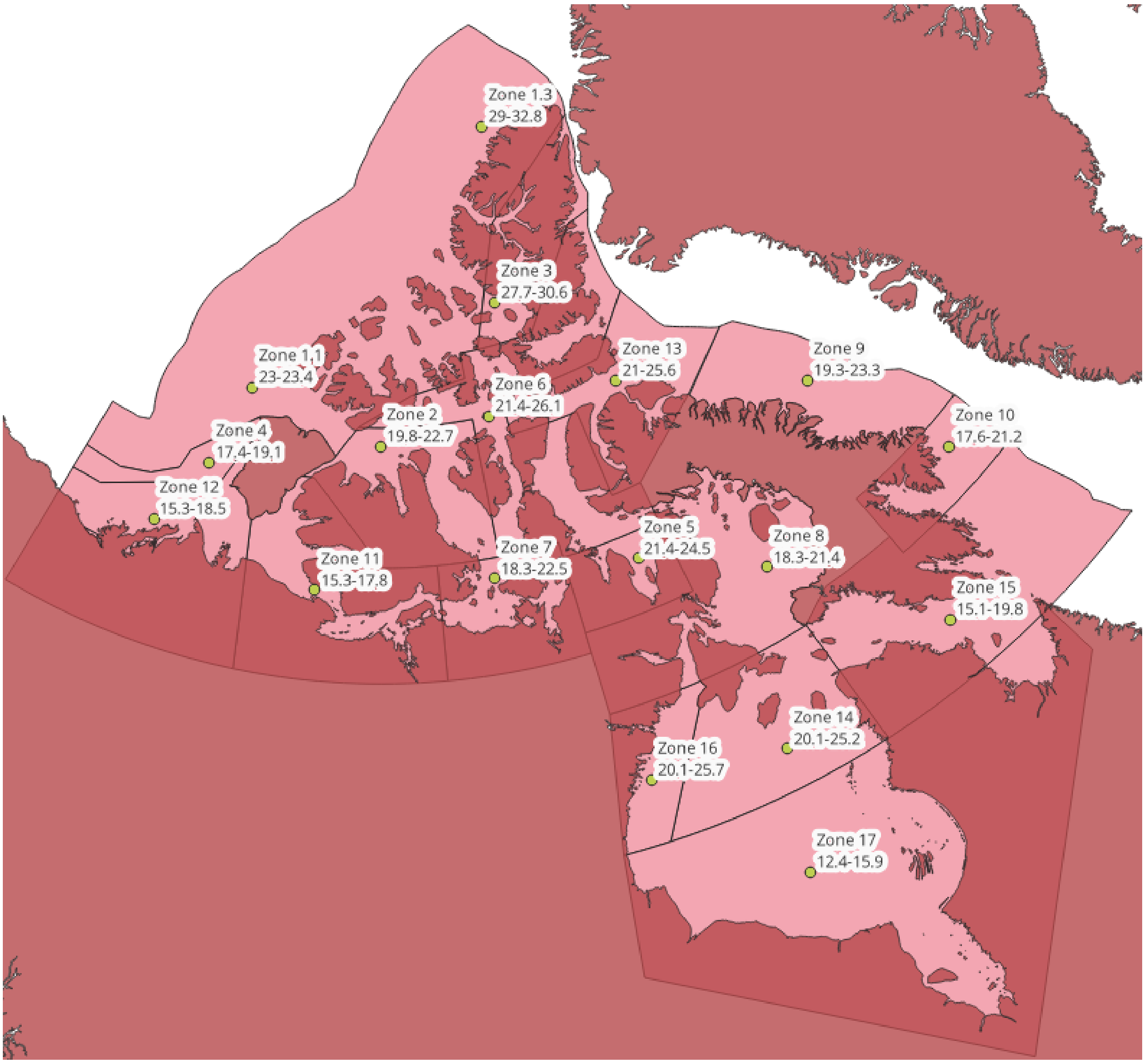

Figure 40: Map of Canada divided into AIRSS zones with min and max values of third quartiles over the course of a year for helicopter SAR operations, cases with 12 PID

4.3.1 Influence of weather conditions on helicopter SAR operations

To further understand the impacts of both No-go and unfavorable conditions on the duration of helicopter SAR operations according to the RHEO model, graphs showing the frequency and duration of No-go conditions for each month and zone are presented as well as the number of occurrences when the helicopter could not complete the rescue due to unfavorable conditions.

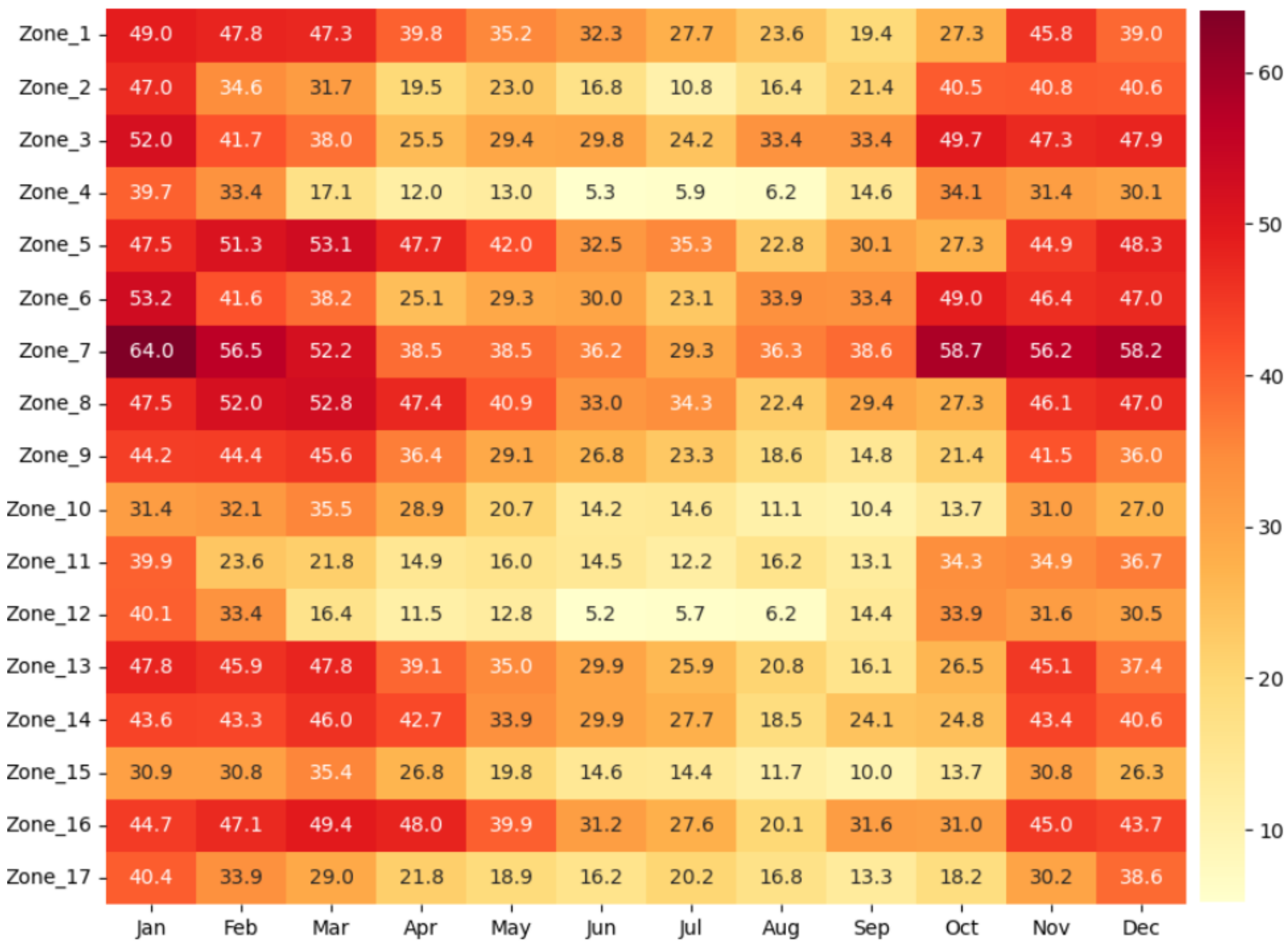

Figure 41: Heatmap showing the percentage of SAR operations in each zone and month where at least one No-go condition was encountered

The heatmap helps to understand areas with higher occurrences of No-go for helicopter SAR operations throughout the year across the Canadian Arctic, showing the percentage of cases in which at least one No-go condition is encountered. In general, it is possible to observe darker areas on both extreme sides of the heatmap, indicating higher occurrences in winter months. When comparing the different zones, it is seen that zones 2, 4, 10, 11, 12, 15 and 17 experience lower effects from No-go conditions. To gain deeper insights into the effects of these No-go conditions on the METR-HT, a heatmap with the durations of No-go conditions when they occur is presented below.

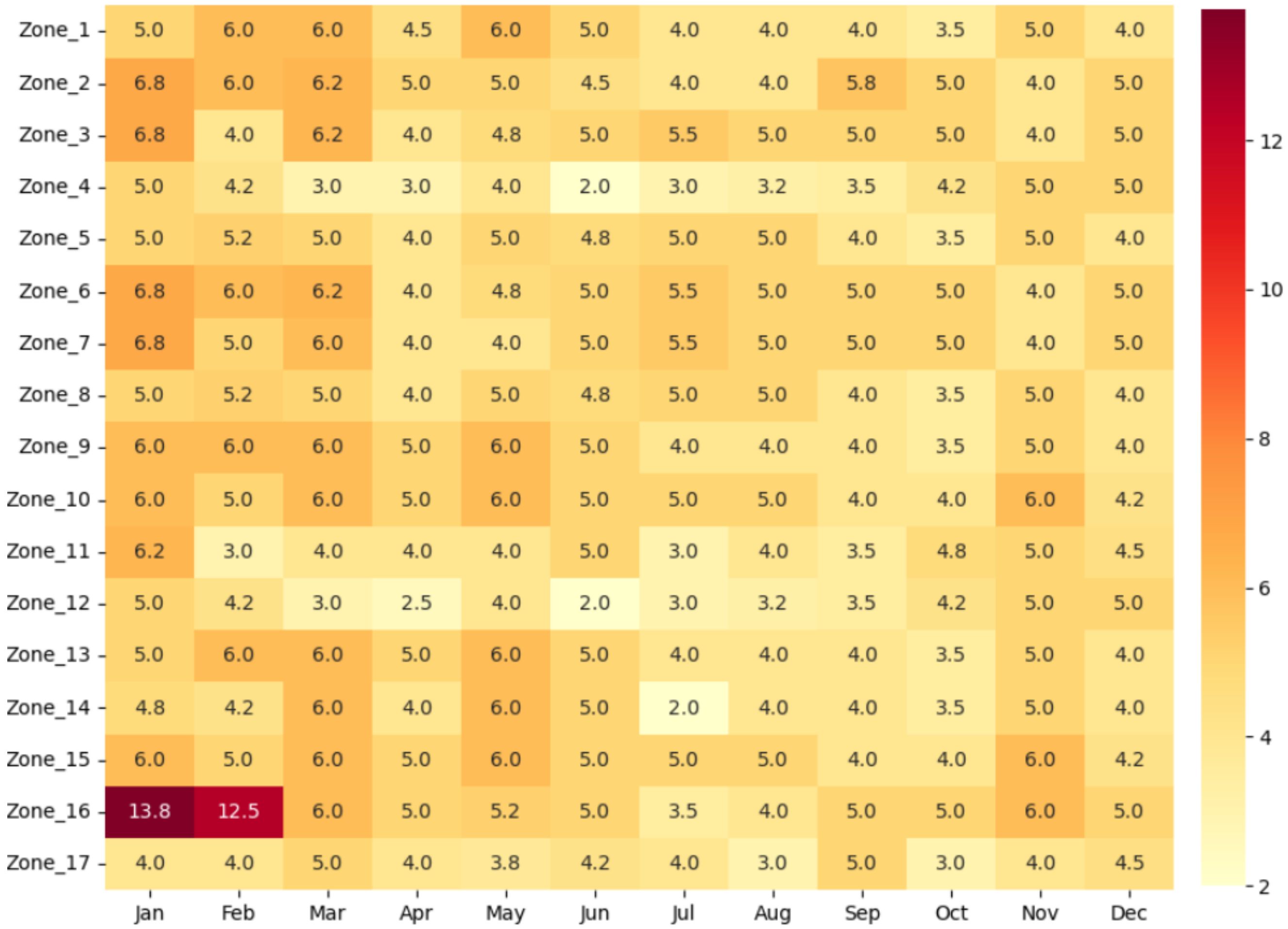

Figure 42: Heatmap showing average durations (hours) of a No-go condition occurring during a given helicopter SAR operation, for each zone and month

Similarly to observations made for Figure 28, these results show that longer wait periods due to No-go conditions occur in the winter months, with some zones seeing extended delays through until May. Lighter areas in zone 4, 12 and 17 indicates that these zones are less impacted by waiting time delays due to No-go conditions. Lastly, zone 16 show a very high wait time for the months of January and February, which can delay trips for more than half day on average.

When considering unfavorable conditions, a clear way to understand their impact is by examining cases where the helicopter is unable to complete the rescue. The heatmap below show these occurrences depending again on location and months of the year.

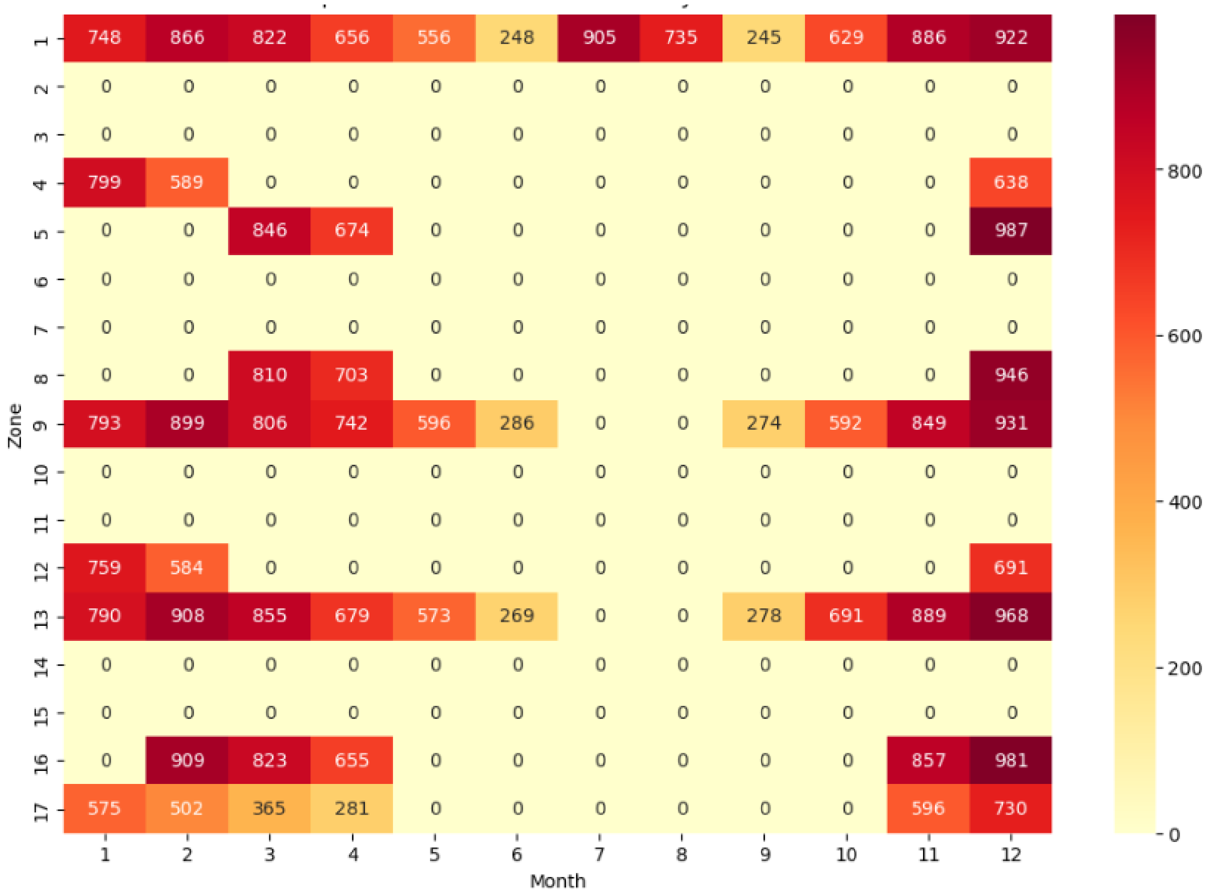

Figure 43: Heatmap showing number of incomplete rescue operations for each zone and month out of 10,000 iterations

The heatmap illustrates the number of occurrences, out of 10,000 model iterations, where the helicopter was unable to complete the rescue. This happens when the distance to the next refueling stop exceeds the helicopter's range, which is often reduced due to unfavorable weather conditions. While these occurrences are relatively rare – since refueling stops are typically spaced closely enough to accommodate the helicopter's range even in unfavorable conditions – exceptions do occur, as indicated by the instances shown on the heatmap. Most of these instances, except for Zone 1 (the most remote zone), happen during the winter months when maritime traffic is significantly reduced or nonexistent. In these cases, the current iteration is stopped, and the model moves on to the next one.

The heatmap indicates zones with higher occurrence of incomplete rescue operations such as Zonez 9 and 13. Although the occurrence of such instances is significantly lower for the summer months, they are also present. One example is September which had 274 and 278 occurrences respectively for zones 9 and 13. Based on this heatmap, 3 zones were selected to interpret occurrences of incomplete rescue operations and investigate whether these correspond to unfavorable conditions. Probability density graphs are presented below for zones 1, 15 and 16.

Zone 1 was chosen because in the heatmap, all months had occurrences of no rescue operations. Figure 44 shows the distribution of the weather factors in the helicopter SAR operations simulation model for zone 1, in January.

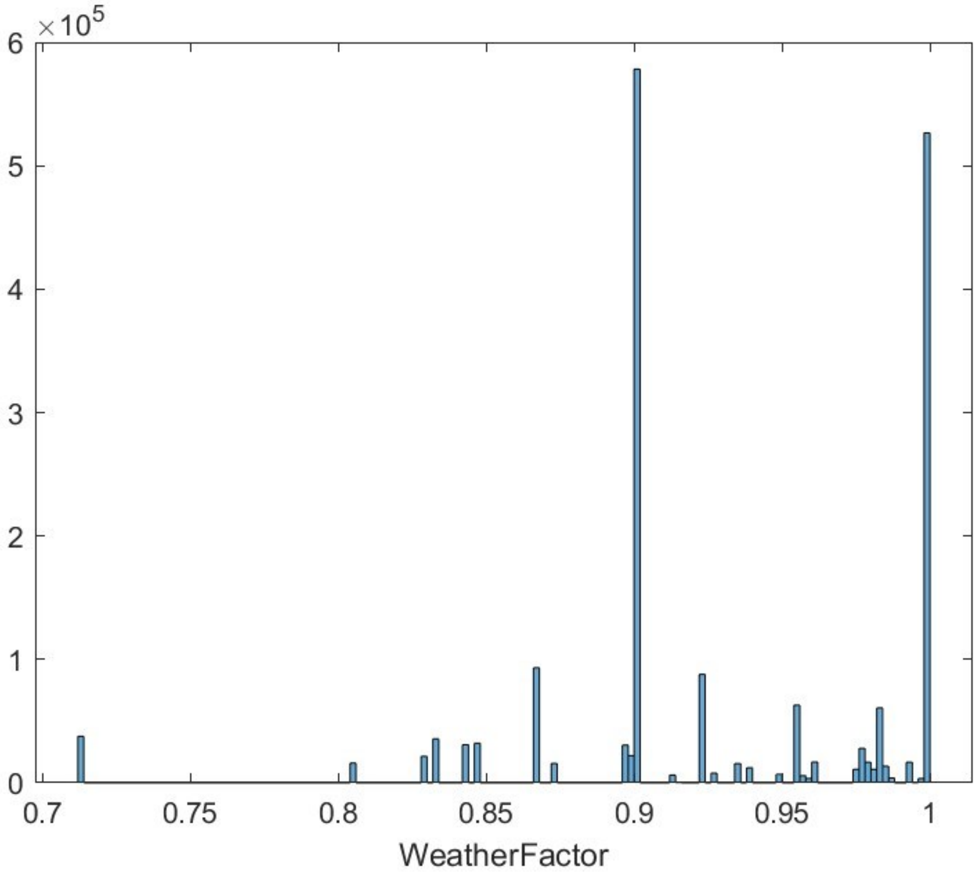

Figure 44: Probability distribution of the 'weather factor' variable of the SAR helicopter operations model for Zone 1 in January

Figure 44 shows that there is a high incidence of weather delay factor of 0.9, which is higher than incidences of weather delay factor 1, which represents favorable conditions. The weather factor in this context reflects the impact of weather on the helicopter's speed. For example, a value of 1 indicates Favorable conditions, so there is no impact in the helicopter speed. On the other hand, factor 0.9 indicates that the helicopter's speed is reduced by 10% due to unfavorable weather conditions. This reduced speed leads to delays, increasing the total SAR operation time.

Figure 45 shows the distribution of weather factors in the helicopter SAR operations simulation model for Zone 1 in September.

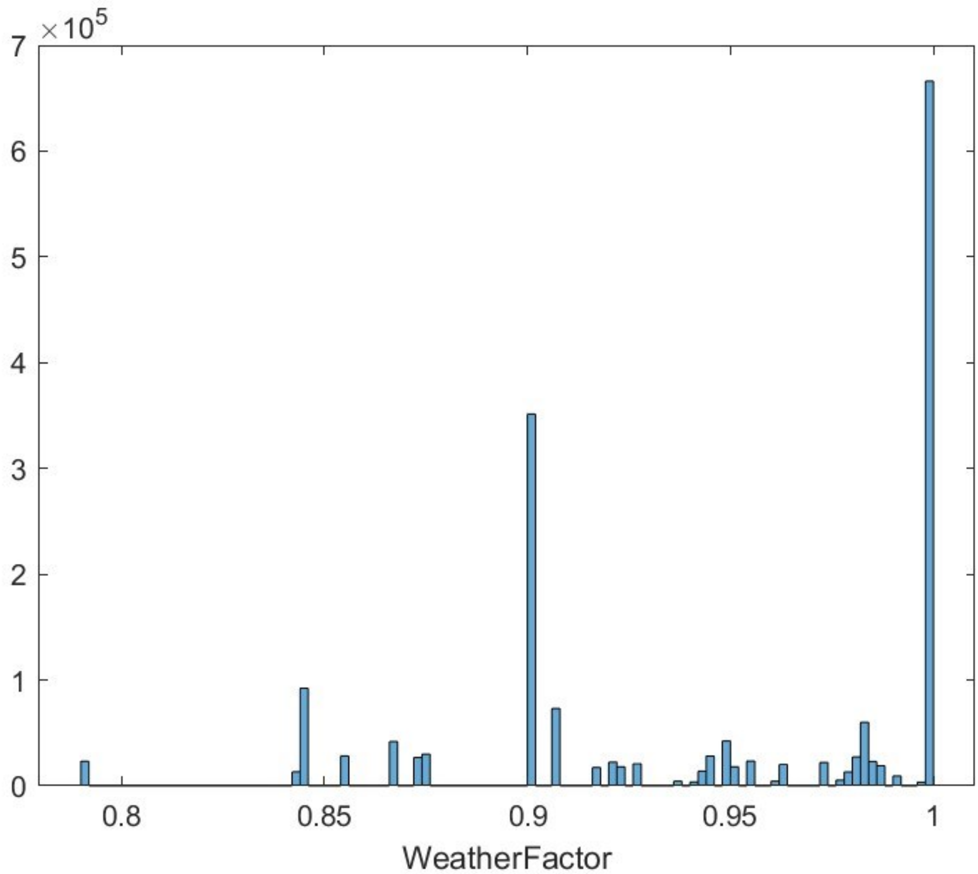

Figure 45: Probability distribution of the 'weather factor' variable for the SAR helicopter operations model for Zone 1 in September

While a weather factor of 0.9 is lower than Favorable conditions (where the weather factor would be 1, indicating no speed reduction), it still significantly contributes to higher METR-HT and increases the likelihood of incomplete rescue operations in the model.

Zone 15 was chosen in contrast to Zone 1, where for all months and all iterations the helicopter was able to complete rescue operation. Figure 46 shows that for January in Zone 15, there is a high probability of weather factor 0.9 (caused by high probability of Unfavorable conditions), significantly higher when compared to weather factor 1.

The heatmap in Figure 43 shows how weather factors impact incomplete rescue operations by directly influencing the helicopter's range. In previous zones, the weather factor - reflecting how much weather slows the helicopter - was emphasized to show its role in reducing the helicopter's speed and range. This reduction, combined with long distances between refueling stops, can lead to incomplete rescues. However, in Zone 15, no incomplete rescues occur despite the presence of unfavorable weather. This suggests that, while weather factors are crucial, they only lead to incomplete rescues when the distance between refueling stops is greater than the helicopter's range under reduced conditions. Therefore, highlighting weather factors is essential to understanding how these elements contribute to incomplete rescues, particularly in zones where distances between stops exacerbate the effects of unfavorable conditions. Figure 46 below shows the distribution for Zone 15.

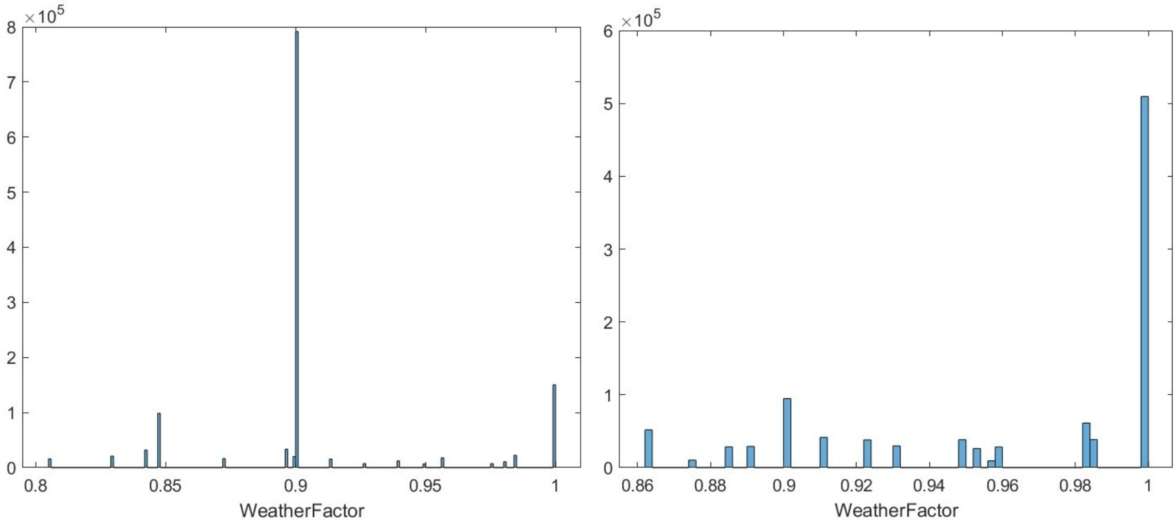

Figure 46: Probability distribution of the ‘weather factor’ variable for the SAR helicopter operations model for Zone 15 in January (left) and August (right)

Finally, Zone 16 was chosen for analysis because, in some months, the SAR helicopter could not complete the rescue, whereas in others, all operations were successful in the simulation. February, for example, had 909 instances of incomplete rescues, while August had none (Figure 43). This difference is directly linked to weather conditions. February’s higher probability of unfavorable conditions is evident in the weather factor distribution in

Figure 47, which shows significantly more weather-related delays compared to August. These unfavorable conditions reduce the helicopter’s speed, impacting both the likelihood of completing the operation and the total operation time. For instance, in Figure 39, February’s total SAR time is 24.6 hours, compared to August’s 20.1 hours. Therefore, the weather factors not only explain the incomplete rescues but also lead to an increase in the overall SAR operation time.

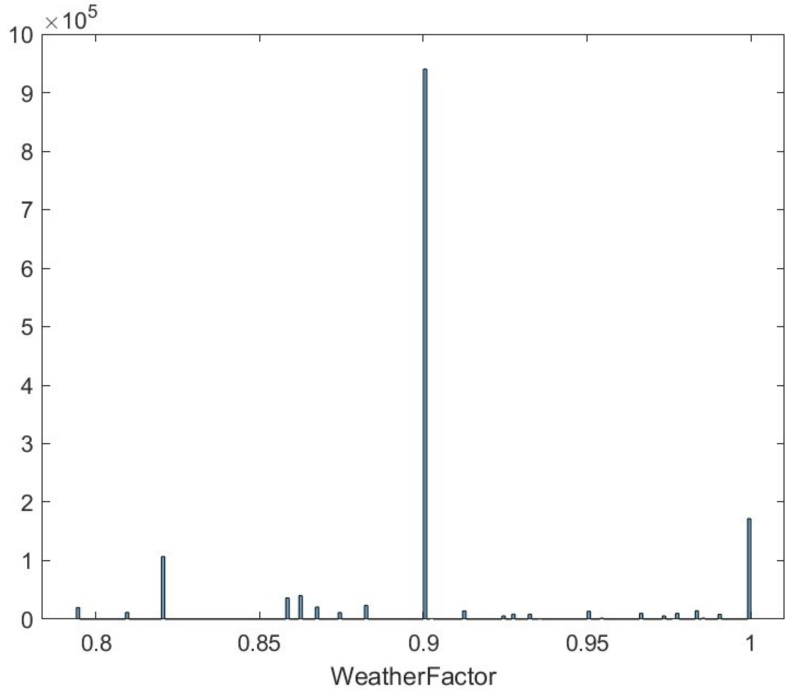

Figure 47: Probability distribution of the 'weather factor' variable of the SAR helicopter operations model for Zone 16 in February

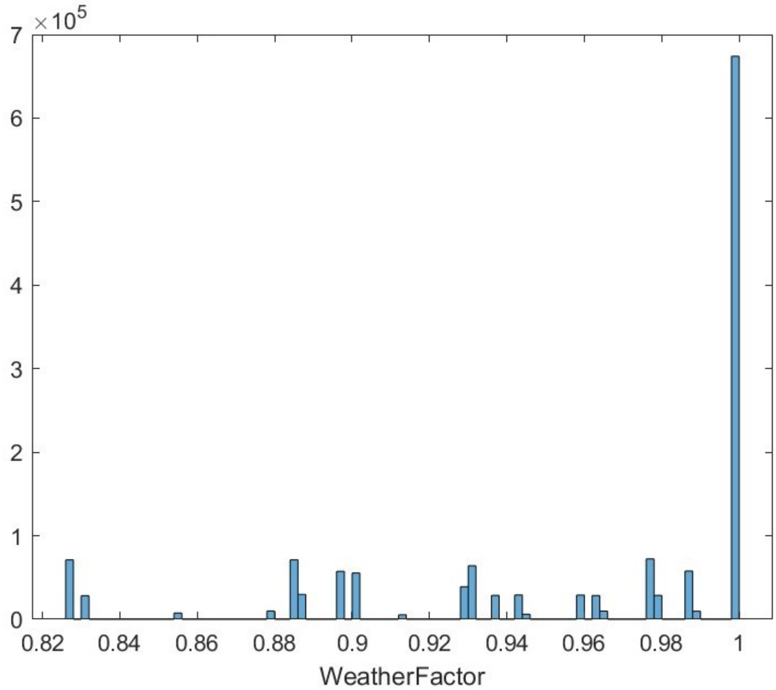

Figure 48: Probability distribution of the 'weather factor' variable of the SAR helicopter operations model for Zone 16 in August

4.3.2 Additional tests for different number of Persons in Distress

The analyses executed in Section 4.1 for the different zones in the Canadian Arctic, over the course of a year across various months, assume 12 PID. This number reflects the capacity of the RCAF SAR helicopter, as described in Table 4, Section 3.2.2. This selection also represents a plausible upper limit for rescue needs in a significant number of incident cases occurring in Canadian Arctic marine areas, as demonstrated by Stoddard & Pelot (2020). This is due to the high rate of incidents involving fishing and recreational vessels in the region. According to PAME (2020), fishing vessels are common in these waters, typically manned by crews lower than 15 people, reflecting their smaller size compared to large cargo ships or tankers.

Nevertheless, it is important to consider other types of vessels navigating in the Canadian Arctic, as their rescue needs may vary significantly based on the type of vessel. As noted by Copland et al. (2021), besides fishing vessels, there has been a notable increase in pleasure craft, bulk carriers, and passenger ships in the region, particularly since 2005. Additionally, Stewart et al. (2010) and Johnston et al. (2012) have documented a rise in cruise ship activity in the Arctic, with itineraries more than doubling between 2005 and 2013 (Dawson et al., 2014). This highlights the growing presence of expedition cruise ships, which often carry between 100 to 200 passengers.

Given the diversity of vessels operating in the Canadian Arctic, it is essential to consider varying rescue needs based on vessel type and capacity. A PID scenario of 50 was selected for commercial vessels, as these ships generally carry fewer passengers compared to larger vessels like cruise ships. However, commercial vessels can still reach capacities of around 50 individuals, as observed in instances where large pleasure crafts or cargo vessels operate in the region. Johnston et al. (2017) highlighted that in three out of the four most recent years studied, pleasure crafts with over 50 people on board were recorded. Furthermore, the growing presence of expedition cruise vessels, which can carry significantly more passengers, supports the use of a 200 PID scenario. This choice aligns with experts' opinions from the first phase of interviews (Section 3.1.1) and findings in Mostaghimi (2024), where vessel capacity plays a crucial role in determining rescue needs. Therefore, both the 50 and 200 PID scenarios account for a range of rescue needs across different vessel types, making them crucial for modeling SAR operations effectively.

In addition to the choice of PID, the month of September was selected for testing the scenarios in this section. Stoddard & Pelot (2020) indicate that months within the navigational season - June, July, August, and September - see the highest number of maritime incidents, with September still being part of this season. This period presents relatively favorable weather conditions, which allow for continued vessel activity. As shown in Figure 39, September also features higher total response times compared to July and August, which makes it particularly important for studying METR-HT. The combination of incident frequency and response time patterns justifies September as a sensible month for testing these scenarios.

Results for PID 50 in zone 13 in September

A scenario for 50 PID requiring rescue in Zone 13 during the month of September was tested, for which various results are described below. The aim is to understand the impact of the number of PID on the METR-HT. For the route, the same graph types as in Figures 16 and Figure 23 are used for the case of 12 PID, enabling a comparison. For this scenario, the results of the total distance traveled by the SAR helicopter over time are shown in Figure 35.

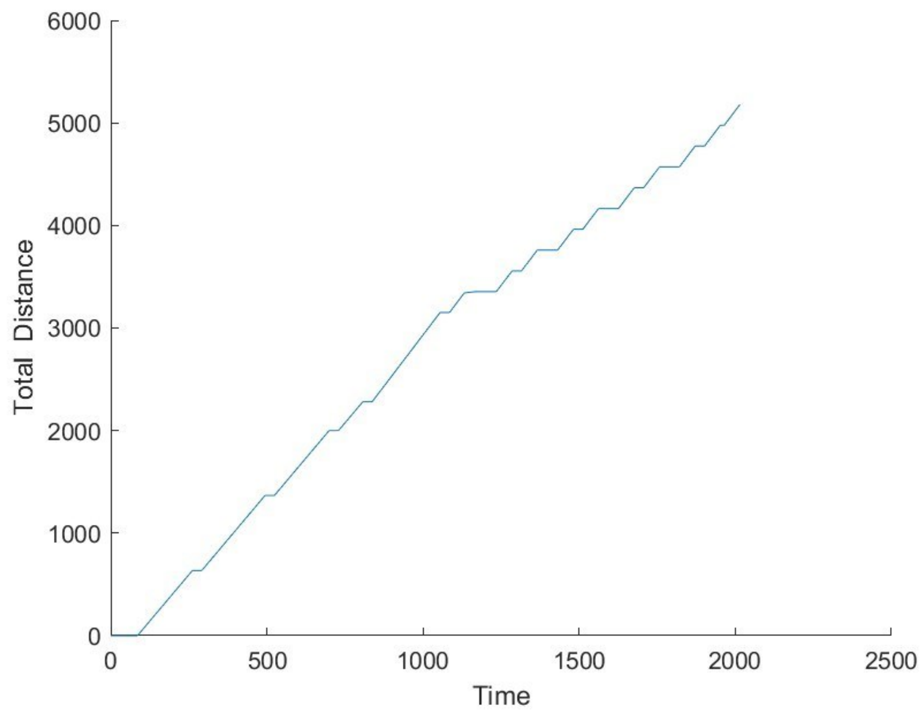

Figure 49: Total distance (in km) in function of the total time (in minutes) in zone 13 with 50 PID in September

Since the capacity of the SAR helicopter is limited to 12, when arriving at the scene, the helicopter will hoist 12 people, go back to the temporary base (Pond Inlet in this case), disembark the rescued people, and then go back to the PID location to rescue another batch of people. This process is repeated until all 50 PID are rescued. This explains why Figure 49 has more steps with shorter time intervals from ca. 1,200 min onwards, since the distances between the PID location and the temporary base are shorter than other legs of the trip.

The timeline chart complements Figure 49 by illustrating the various stages of the rescue operation, highlighting key differences when compared to the case of 12 PID scenario (Figure 29 in Section 4.2.1). The detailed results are in Figure 50.

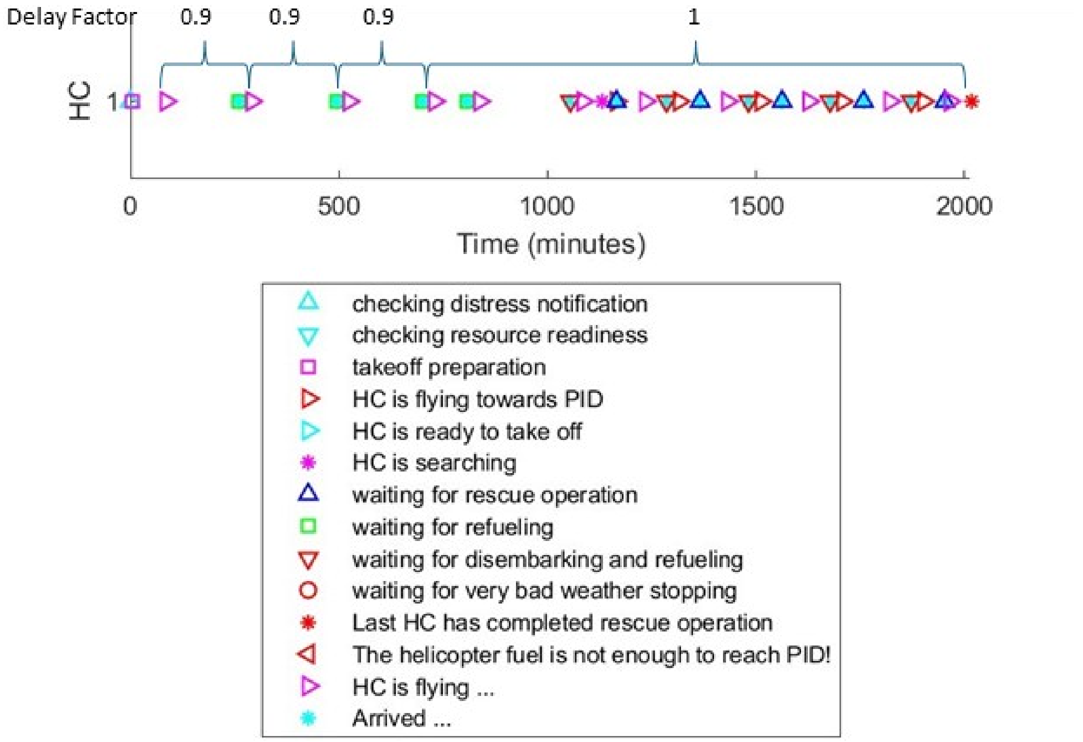

Figure 50: Timeline showing the sequence of the operational status of the responding helicopter over time, example case for a rescue in zone 13 with 50 PID in September

In this figure, the helicopter arrives for the first time at the PID location around minute 1,200, after which the rescue operation starts. Subsequently, the helicopter must go back four times to rescue the remaining people. Thus, the rescue operation is completed only after around 2,000 minutes (i.e, ca, 1.5 days).

For this scenario, the total SAR operation time is shown in Figure 51, with the highest peak appearing around 32 hours.

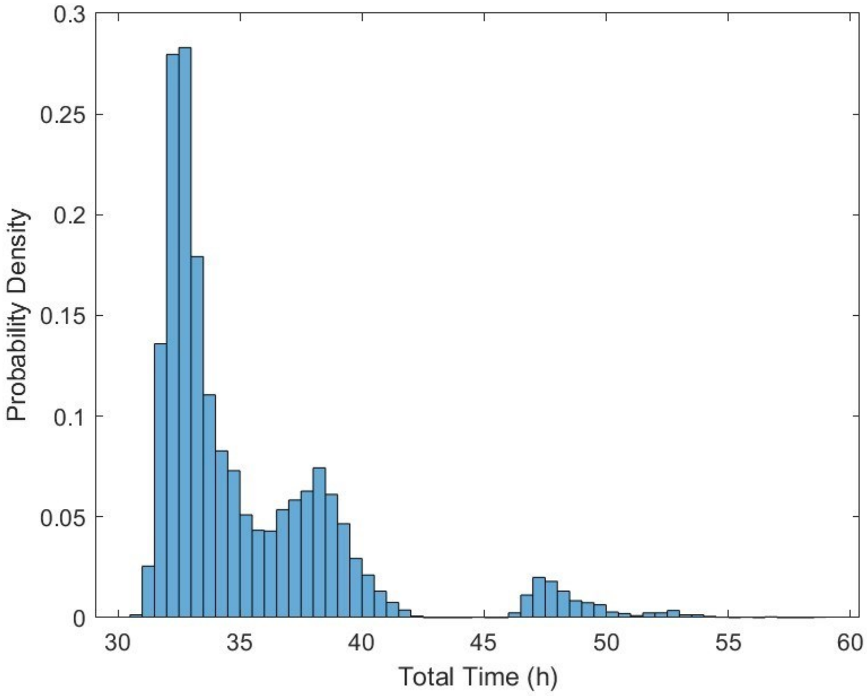

Figure 51: Total time distribution for zone 13 in September PID 50

This histogram represents the probability density distribution of the total SAR helicopter operation time (in hours) for zone 13 in September for a scenario with PID 50. The histogram now shows three distinct peaks. The first and highest peak occurs around 32 hours, indicating that the most common total time for the operation is around this number. The second, smaller peak is around 38 hours. The third and smallest peak appears around 47 hours.

The presence of multiple peaks in the histogram likely results from the interaction between the increased mission complexity and the impact of unfavorable and No-go weather conditions. In the PID 12 scenario, the second peak was primarily influenced by wait times due to No-go conditions. However, with a PID of 50, additional legs are required for refueling, and longer distances must be covered. As a result, the helicopter is more susceptible to delays caused by its speed and delay weather factors. This contributes to a wider distribution of total SAR operation times, reflected in the additional peaks. Each peak represents a cluster of operations with varying delays due to differences in weather and refueling requirements, which makes sense given the increased complexity of the higher PID scenario.

Table 15 shows information related to how many legs it took for the RCAF SAR helicopter to complete the rescue operation for the scenario of 50 PID in zone 13 in September.

Table 15: Time and route distribution September in zone 13 PID 50 based on 10,000 iterations of the HESARO model

Month	Cannot rescue	16 Legs	17 Legs	3rd Quartile	Time (hours)
9	763	6295	2942	17	36.9
Note: Cannot Rescue: number of iterations (out of 10,000) where the helicopter was unable to complete the rescue. 16 and 17 Legs: The number of iterations that required either 16 or 17 legs (refueling stops and flight segments) to complete the SAR operation, with varying legs based on operational conditions and flight paths.					

Table 15 shows that in most cases, the helicopter could complete the SAR operation with 16 legs. Each time the helicopter travels to the PID location and returns to the temporary base to disembark people, 2 legs are added. Compared to PID 12, 4 extra hoist operations are needed, which results in 8 extra legs.

The histogram shown in Figure 52 below shows the distribution of weather factors impacting the helicopter speed for all 10,000 iterations in the Monte Carlo simulation.

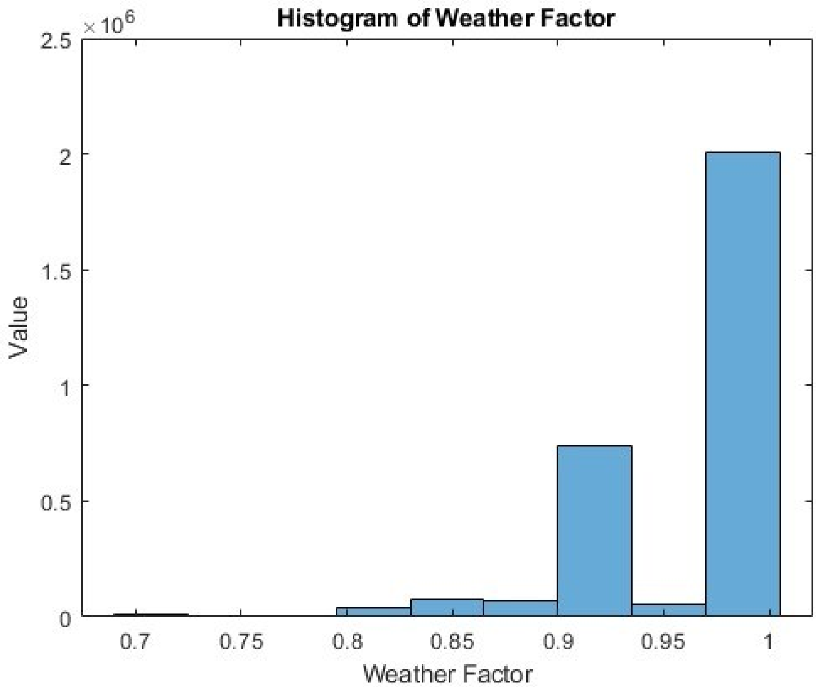

Figure 52: Histogram of the 'weather factor' variable of the SAR helicopter operations model for Zone 13 in September 50 PID

The histogram shows that in most cases, the helicopter speed is not significantly impacted by weather conditions, as the most frequently occurring weather factor is 1. This factor indicates favorable conditions for each leg of the operation. However, since weather conditions are sampled for each refueling stop, the weather factor can vary by leg, potentially leading to delays or adjustments in speed. The overall distribution reflects these varying conditions, as some legs may experience unfavorable conditions, influencing the total operation time. The second most common value is a weather factor of 0.9, which is fixed as described in section 3.2.2, indicating unfavorable temperature. To visualize the No-go conditions, a box plot of the distribution of the wait time due to No-go conditions is presented in Figure 53.

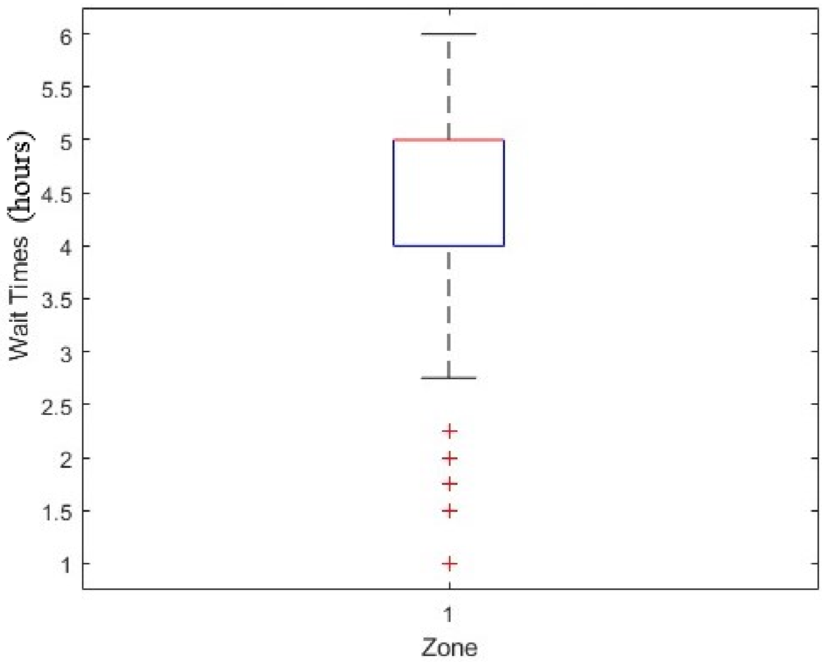

Figure 53: Box plot showing statistical metrics of the distribution of wait times due to No-go conditions, case of PID 50 in Zone 13 in September

The box plot shows that the third quartile lies around 5 hours with a median of 4.5 hours and a maximum value of 6 hours, and a minimum around 3 hours. The distribution also contains some outliers between 1 and 2.5 hours.

Results for PID 200 in zone 13 in September

The case for 200 people in distress for September was also tested for Zone 13, and the results are described below. The goal is to understand the impacts for a higher number of PID and check patterns as the one described after Table 15. The graph of total distance over time is presented below.

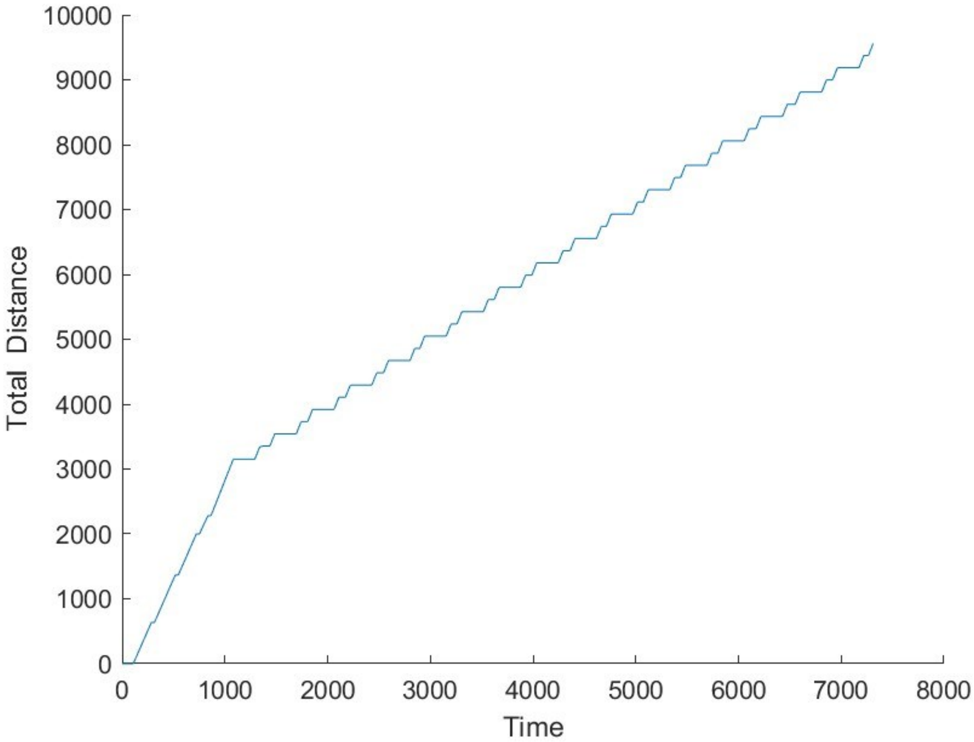

Figure 54: Total distance (in km) in function of the total time (in minutes) in zone 12 for PID 200 in September

In this case, when getting into the scene, the helicopter will hoist 12 people, and as for PID 50, go back to the temporary base, disembark and go back to the PID location to rescue another load of people. The process is repeated until 200 people are rescued. This explains why in figure 33 the process is repeated multiple times.

The chart showing the timeline complements Figure 55 showing multiple steps of the rescue operation, which differs when compared to PID 12.

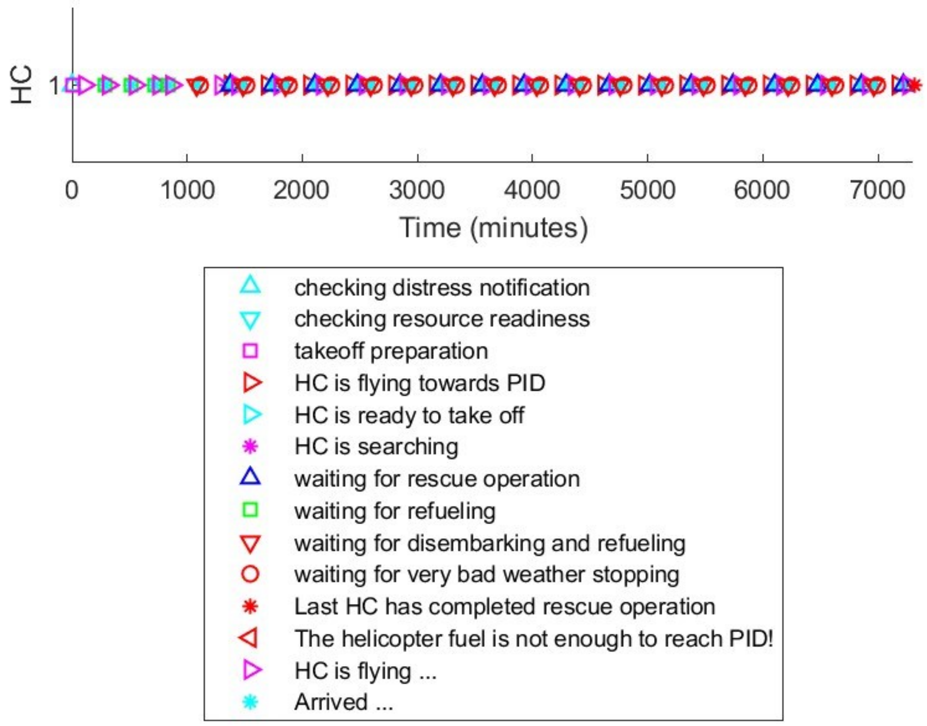

Figure 55: Timeline showing the sequence of the operational status of the responding helicopter over time, example case for a rescue in zone 13 with 200 PID in September

In this chart, the process of going back to the base, disembarking and refueling is repeated 17 times.

The total time graph now shows the highest peak around 71 hours.

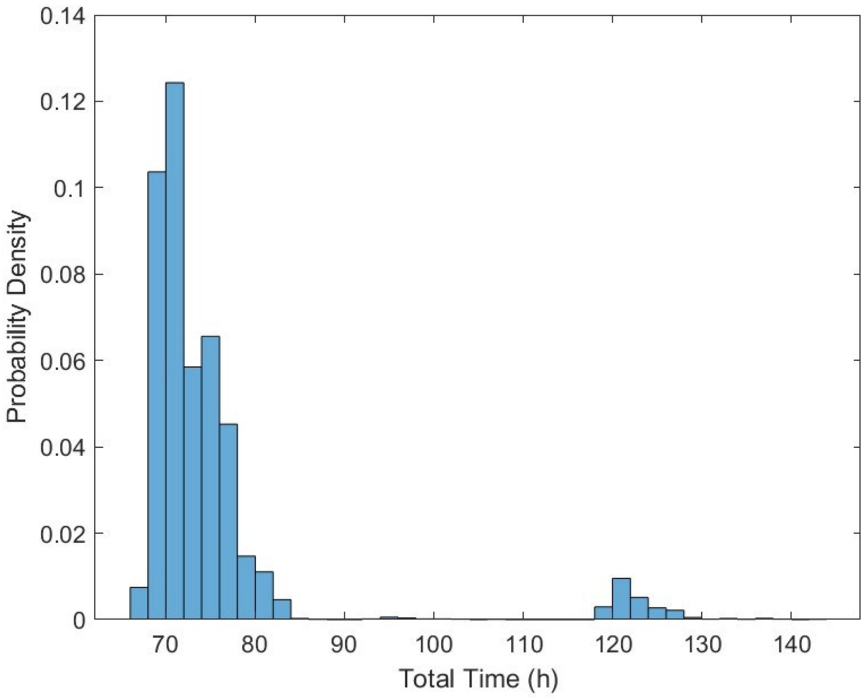

Figure 56: Total time distribution for zone 13 in September for PID 200

This histogram represents the probability density distribution of the total time (in hours) for zone 13 in September related to SAR helicopter operations for PID 200. The histogram shows now two distinct peaks. The majority of the data is concentrated around the 70 to 80-hour range, with the highest probability density (around 0.12) occurring near 70 hours. This indicates that most occurrences in the dataset have a total time in this range. There is a smaller cluster of data points around 120 hours (exactly 5 days), indicating that there are some cases where the total time is significantly longer than the primary group.

Lastly, compared to PID 50, that mostly completed the rescue with 16 legs, PID 200 results had 40 legs, totaling 75 hours (around 3 days) to complete the rescue operation. In terms of total SAR helicopter times, PID 12 results were 21.7 hours, PID 50 were 36.9 hours and PID 200 were 75 hours.

Comparing results for PID 12, 50 and 200 in zone 13 in September

Comparing the results of the different PID scenarios in Zone 13 (12, 50, and 200) reveals how the number of people in distress (PID) directly impacts the SAR operation's complexity and overall duration. Table 16 below shows how these differences in PID impact total SAR operation time.

Table 16: Comparison of 3rd Quartile for total SAR operation time for PID 12, 50 and 200

PID	12	50	200
Hours	21.7	36.9	75
Days	0.9	1.5	3.1
Legs	8	16	40

In the base case of PID 12, the RCAF helicopter can complete the operation within one cycle, leading to shorter rescue times, fewer refueling stops, and less exposure to adverse weather conditions. This results in a relatively predictable and condensed operation time, with the majority of operations being completed within 22 hours.

However, the introduction of PID 50 and PID 200 demonstrates the increasing challenges faced during larger-scale rescues. As the number of people to be rescued increases, so does the number of legs required, leading to significantly longer operation times. The SAR helicopter must undertake multiple trips between the incident site and the temporary base, so it is possible to hoist people and place them safely in the temporary base. This is reflected in the multiple peaks in the total time distribution for both scenarios, where mission delays and operational difficulties introduce greater variability.

In particular, the PID 200 scenario exemplifies the strain on SAR resources, with operation times stretching up to 75 hours. This suggests that as the PID rises, the helicopter's capacity limitations and the extended mission duration contribute to a growing risk of mission failure, as seen in the instances where the helicopter could not complete the rescue (278 for PID 12 compared 763 for PID 50).

4.4 MODEL VALIDATION: COMPARISON WITH ZARRIN MEHR’S MODEL

As a partial validation of the HESARO model developed in this thesis, the original model by Zarrin Mehr et al. (2023) was applied for the same locations (all 17 zones), refueling stops and bases as presented for the test matrix in Section 3.5. The tests were made for PID 12. In addition, as his model only allows making a distinction between summer and winter conditions in a relatively high-level manner, the summer scenario was selected, as these are assumed to be comparable with the weather conditions of the month of September as used in the HESARO model. The results are presented in Table 17.

Table 17: Comparison of results from Zarrin Mehr et al. (2023) for the summer and PID 12 and the HESARO model (September) and PID 12

Summer		Current model (Sep)	Comparison
Zone	Time (hours)	Time (hours)	
Zone 1.1	21.7	23.0	Higher
Zone 2	20.1	20.1	Higher
Zone 3	25.2	29.1	Higher
Zone 4	16.1	17.6	Higher
Zone 5	19.6	21.6	Higher
Zone 6	20.3	22.0	Higher
Zone 7	17.9	19.5	Higher
Zone 8	17.1	20.1	Higher
Zone 9	18.7	19.7	Higher
Zone 10	16.9	17.7	Higher
Zone 11	15.8	15.5	Lower
Zone 12	14.6	15.9	Higher
Zone 13	20.7	21.7	Higher
Zone 14	17.3	22.8	Higher
Zone 15	14.1	15.4	Higher
Zone 16	18.8	21.7	Higher
Zone 17	12.3	12.6	Higher

Table 17 presents a comparison of model outputs for the summer season with a PID of 12, highlighting differences between the current model and Zarrin Mehr's original model, which serves as the baseline. In Zone 11, the current model yields a lower METR-HT value, with a reduction of 0.3 hours (18 minutes) compared to Zarrin Mehr’s model. While, in general, the HESARO model tends to produce higher METR-HT values as expected based on the RHEO model, it can also show lower values due to other variables within the model that influence the total METR-HT.

5. DISCUSSION

5.1 DISCUSSION ON SENSITIVITY ANALYSIS

This chapter aims to interpret and discuss the results shown in Chapter 4 and how they answer the research questions presented in Chapter 1. Section 5.1 presents a discussion using sensitivity analysis, showing how changing key variables can affect the results presented in Chapter 4. Section 5.2 shows a summary of the assumptions used in the model, to provide transparency on the evidential basis, possible optimistic or conservative biases, and to provide transparency about the choices made in the model. Additionally, Chapter 5 will discuss the study's limitations and offer suggestions for using and extending the results for practical applications in section 5.4, and directions for future research in section 5.5.

The findings suggest that weather factors have significant impacts on helicopter SAR operations and consequently, play a big role in whether the 5-day requirement for METR can be achieved. The SAR helicopter operation time especially depends on the time of year and on the location in Canada where the incident occurs, which influences the number of refueling stops available and the routes taken. The following discussion provides an interpretation of the sensitivity analysis and how each parameter impacts the results.

5.1.1 Incident locations

The locations of the incidents selected in this thesis comprehensively cover the entire Canadian Arctic waters, making use of the segmentation into the SSCZs shown in Figure 11 and selecting a representative location within each. Nevertheless, each SSCZ zone covers a very extensive area, especially zones 1, 6 and 9 for example that cover vast amounts of sea. Incident locations in other locations even within these SSCZ might change the results of the total SAR operation times presented in Figure 39. When comparing Zones 1 and 3 (neighbor zones), it is clear how these values can vary significantly, not only due to the larger distances involved but also because different routes may require additional or alternative refueling stops. Figure 39 in section 4.3 shows how zone 1.1 presents lower values of the total SAR operation time, with an average of 23 hours compared to 27 hours in zone 1.3 for summer months. In this case, this was due to smaller distances between incident location and the RCAF base when comparing 1.1 and 1.3. However, the results also indicate that the RCAF SAR helicopter cannot rescue people in zone 1.1 from October to May. In addition, for zone 1.2 operations are not possible for any time of the year.

To complete this analysis, Table 18 shows how a change in incident locations can impact the total rescue time even within the same zone.

Table 18: Total SAR operation time differences (hours) within the same zone for PID 12

Location in zone 9	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
South	20.5	20.7	21.1	20.2	19.7	17.8	16.6	16.6	17.0	18.4	20.3	20.5
North	23.9	23.8	24.0	22.6	22.1	21.3	19.8	19.3	19.7	21.5	22.5	22.7
Originally tested and presented in Figure 39	23.0	22.7	23.3	21.9	21.3	20.4	19.7	19.3	19.7	20.5	22.2	21.8

Note: South location refers to latitude 67.9 and longitude -62.4 while North is latitude 72 and longitude -72.7

The table shows the impact of the location of incident locations even within the same zone due to longer distances from helicopter bases or even the need of extra refueling stops or different ones.

5.1.2 Helicopter bases

The location of helicopter bases is another factor influencing the SAR helicopter operation total time. In case these were located closer to the incident location, helicopters would need to fly shorter distances, and fewer refueling stops would be needed. Bouchard (2020) addresses the need for air bases in Northern locations, and the test results by Zarrin Mehr et al. (2023) provide insights into the difference of using a base up north versus using bases which are already currently operational (e.g. in Gander). The author investigates a case using Gander as the main base compared to a scenario in which there were a base in Iqaluit, with results showing a total SAR operation time of around 10 hours for the summer months with 15 PID, compared to 19 hours when a helicopter is deployed from Gander for the same conditions. A difference of 9 hours plays a significant role in the survivability of people in distress, due to the often harsh and extreme weather conditions in the Canadian Arctic.

In this study, the total SAR operation times for different base locations were also tested. This test mirrors the work by Zarrin Mehr et al. (2023), which compared response times when the helicopter took off from a base in Gander versus one in Iqaluit. For Zone 13 in September with a PID of 12, the results showed a total SAR operation time of 14.2 hours when hypothesizing the base in Iqaluit. This contrasts with the 21-hour total time shown in the heatmap (Figure 39) for the same month and zone when the base is in Gander. Additionally, the test with Iqaluit as the base indicated that only one refueling stop was required.

5.1.3 Refueling stops and refueling times

Throughout the testing phases described in Section 3.1.1and 3.1.2, improvements in the selection of the refueling stops used in the model were made based on validations in the interviews and testing the model. One example of the improvement in the usage of refueling stops is presented below for zone 8, for which a series of tests was performed.

Table 19: First round of tests for zone 8, PID 12 and 3 refueling stops

Month	Cannot rescue	6 legs	7 legs	8 legs	9 legs	10 legs	3rd quartile	Time (hours)
1	7721	1605	250	422	2		3	14.7
2	6629	2511	324	534	2		6	16.7
3	7506	1790	255	447	2		3	16.1
4	5629	3001	431	935	4		6	18.5
5	4908	3380	522	1181	9		6	18.8
6	2749	5732	521	991	7		6	18.7
7	1360	7257	390	992	1		6	18.6
8	1378	7364	471	787	0		6	18.6
9	2633	4976	786	1576	22	7	6	19.3
10	6712	2073	377	828	9	1	6	16.3
11	7301	1585	320	778	13	3	6	16.3
12	8262	1070	186	475	7		3	12.3

The first test reveals a high number of iterations where the helicopter was not able to complete the mission, which is represented by the second column in Table 20. This is because, in the first test, the distance in leg 3 was too long for the helicopter to reach the next refueling stop.

Table 20: Second round of tests for zone 8, PID 12 and 4 refueling stops

Month	Cannot rescue	7 legs	8 legs	9 legs	10 legs	11 legs	3rd quartile	Time (hours)
1	7721	7381	850	1759	10		8	21.6
2	6629	7931	702	1360	7		7	21.3
3	7506	7667	820	1503	10		7	22.5
4	5629	7127	840	2012	21		8	21.2
5	4908	7109	734	2128	27	2	8	21.3
6	2749	7986	667	1338	9		7	20.1
7	1360	8451	403	1138	8		7	19.5
8	1378	8544	533	922	1		7	19.4
9	2633	7114	913	1946	26	1	8	20.5
10	6712	6928	881	2152	37	2	8	20.4
11	7301	6823	790	2342	44	1	8	22.1
12	8262	6983	729	2266	22		8	21.2

When comparing both results, the second test shows that all iterations were able to complete the rescue operation, unlike the previous test where most iterations presented failures, preventing the rescue. By adding an extra stop at Kangiqsijuaq Airport, as shown in Figure 57, the helicopter was able to complete all iterations.

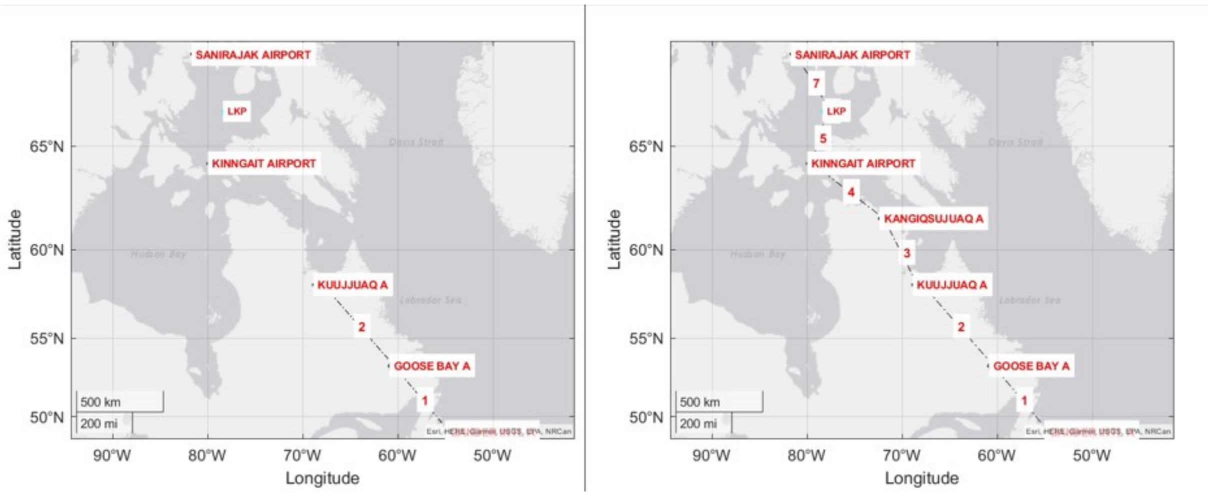

Figure 57: Helicopter route for incident location in zone 18

Figure 57 shows not only the importance of a strategic choice of refueling stops in order to complete the mission, but also the impact of one extra stop on the total rescue time. Although, it is important to account that in the first table, the results of time were reduced because most values when calculating from the 10,000 iterations were zero or close to zero because operations could not be completed.

Furthermore, when considering refueling times, the value used in the model was 30 minutes. But as discussed in section 3.2.2 this time can take up to 3 hours. If considering this time, the total time would increase considerably. For zone 13, for example, the results in section 4.2.1 show that the helicopter had to stop 5 times for refueling, which could increase the total rescue time by 15 hours.

5.1.4 Weather assumptions

The two main categories related to the weather which impact the total SAR operation time are the unfavorable conditions and the No-go conditions, as explained in chapter 3. The unfavorable conditions impact the speed, range and fuel consumption of the responding helicopter, while No-go conditions will affect the wait time, which extends until weather conditions improve so that the helicopter can resume its operations. Based on the descriptive statistics of those conditions (presented in Section 4.1.1), in this model the third quartile for both unfavorable and No-go conditions was selected to use in the model simulation. Based on that, variations on that choice could impact the total SAR operation time when varying between more and less conservative approaches.

The average duration of No-go conditions due to visibility across all airports (i.e. bases and refueling stations) and all months is 3.9 hours for the third quartile of wait times due to No-go conditions. On the other hand, the first quartile amounts to 1.1 hours. At the other extreme, the maximum duration of No-go conditions due to visibility averages 23 hours across all zones and months. For No-go conditions due to precipitation, this average of maximum values is 6.2 hours, and 7.6 hours for wind-related No-go conditions. This analysis demonstrates that using more conservative assumptions in the model can lead to an increase in total SAR operation time of up to one day (PID 200 compared to PID 12). This increase could be even greater when considering higher PIDs. For instance, in the case of cruise ships with 2000 passengers, the total operation time could exceed the 5-day guidance for METR, underscoring the importance of PID as a critical factor influencing SAR total times.

5.1.5 Helicopter speed and takeoff preparation

Other important variables influencing helicopter times include aircraft speed and takeoff preparation time. This section explores the impact of varying assumptions related to these factors, drawing insights from initial findings.

One exploration focused on helicopter speed. For instance, it was observed that when reducing the speed from 240 to 180 knots in zone 13, helicopter operations could not complete rescues in January and February. Although this observation stems from adjusting a key operational parameter, it serves as an initial insight rather than a conclusive test.

Regarding takeoff preparation, as discussed in Chapter 3, a triangular distribution was assumed, with a minimum of 45 minutes, a mode of 75 minutes, and a maximum of 120 minutes. Subject Matter Experts (SMEs) during the second phase of interviews noted that the standard 2-hour response posture could occasionally be exceeded, for instance, due to helicopter maintenance. If an additional 120 minutes were factored into preparation times, this would entail a significant increase when considering exposure times, especially given the harsh conditions of the Arctic.

5.2 DISCUSSION OF STUDY RESULTS

The analysis of the model results offers key insights into the helicopter operability and its impact on METR-HT across the Canadian Arctic. The results reveal significant spatial and temporal variations, reflecting the influence of both geographical and seasonal factors on SAR operations in the harsh and remote Canadian marine areas.

The heatmap shown in Figure 39 provides a clear representation of how the total time varies throughout the year. An important observation is that there are higher SAR operation times during the winter months, particularly from November to March, across most zones. For instance, zones 1, 3, and 6 exhibit notably high times in the early winter months, with values of third quartile reaching up to 31 hours (for PID of 12). This suggests that these areas experience challenging weather conditions during the harsh winter months, which results in more significant effects of weather conditions for both unfavorable and No-go conditions. In contrast, the summer months, especially from June to September, generally show lower total SAR operational times, indicating better conditions for helicopter missions. The results indicate a reduction in the total time to complete operations during these months. Zones such as 17, 10, and 9 illustrate these improved conditions, with operation times dropping below 15 hours.

For the winter months, an important consideration is the number of incomplete rescue operations, as shown in Figure 43 (Section 4.3.1). If these incomplete operations were successfully completed and included in the METR-HT calculations, the overall numbers would likely increase. This is because incomplete rescue operations are primarily caused by unfavorable conditions, which are often the main contributors to delays in total SAR operation times.

Figure 40 in Section 4.3 maps out the zones and their corresponding operation times, offering a spatial perspective on the results. It highlights significant geographic variability across the Canadian Arctic. More northerly zones like zones 1 and 3 (as also observed from the heatmap), consistently report the longest operation times, especially during the early winter months, with values exceeding 26 hours. This reinforces the understanding that northern regions face more severe weather conditions which delay rescue operations.

In contrast, southerly zones like zones 10, 9, and 17 demonstrate shorter operation times, reflecting better weather conditions in these regions. The proximity of these zones to the bases in the south also contribute to these lower times, suggesting that rescue operations can be conducted more expeditiously.

5.3 IMPLICATIONS OF THE RESULTS

The insights gained from the analysis of helicopter SAR response operations could guide adjustments to IMO policies, leading to updates in the guidance documentation associated with the Polar Code. In particular, the updated knowledge about helicopter response times, the operational difficulties in the Canadian Arctic, and the estimates for METR-HT could be used to define more realistic METR values for use on the Polar Ship certificate. In this context, it is important to link the relationship between METR and METR-HT. While METR is focused on the Maximum Expected Time of Rescue of any asset (the main focus is to guarantee survivability), METR-HT is focused on Maximum Expected Time of Rescue of the Helicopter Cormorant operations which can often be the same depending on contexts of the incident (e.g. locations, PID, weather).

An example of a scenario where METR-HT could differ from METR is during a large-scale maritime disaster that involves both helicopters and ships in the rescue effort. In such cases, while helicopters might arrive faster and start evacuating people, ships may take significantly longer to reach the incident due to factors like distance, sea conditions, or ice barriers. In this scenario, METR-HT would reflect the shorter helicopter rescue time, while the overall METR would be extended to account for the longer ship arrival time. Consequently, METR would be defined by the ship's slower response, leading to a longer time compared to METR-HT, as the full rescue operation includes both assets. On the other hand, if an incident occurs in a location with difficult ship access, such as areas with harsh ice conditions where icebreakers may be delayed or unable to operate, the helicopter becomes the primary response asset. In this situation, METR would align with METR-HT, as the helicopter would be responsible for the rescue operations.

The findings underscore the critical need for tailored SAR strategies across different zones and seasons. For instance, in Zones 1 and 3, where the total SAR operation duration is consistently high, assuming an increase in shipping and marine activity as introduced in Chapter 1, there is a pressing need for enhanced preparedness, including possibly of resources availability up north and specialized equipment to cope with the harsh weather conditions. Additionally, the lower variability in operation times during the summer months suggests that this period allows for more reliable planning of complex SAR operations, such as major cruise ship incidents. This predictability ensures that helicopters can be strategically deployed, even in the face of large-scale emergencies requiring extensive coordination and resources.

The findings suggest that the number of Persons in Distress (PID) significantly impacts helicopter SAR operations, which in turn influences the feasibility of meeting the Polar Code's 5-day METR requirement. As demonstrated in the analysis of PID 12, 50, and 200 scenarios, increasing the number of PID places additional strain on SAR operations. This not only increases operation times but also pushes the METR-HT closer to or beyond the 5-day threshold, particularly in scenarios involving larger groups of people. In addition, these challenges suggest that marine support, especially in more remote northern zones, becomes essential for larger-scale rescues, where relying solely on aerial assets may not be sufficient.

Understanding spatial and temporal variations is crucial for optimizing the efficiency and effectiveness of SAR missions across the Canadian Arctic. These results provide critical support for decision-makers, particularly in determining when reduced response times are justified based on specific factors such as location, season, and the nature of the emergency. Mastaghimi (2024) highlights the importance of assessing METR to ensure devising a realistic and consistent approach for recommendations to flag states on safety exemptions and operational guidelines. Additionally, gaining insights into METR will assist in the review and approval of polar operation manuals, offering an evidence-based evaluation of proposed response times and enhancing the reliability of helicopter SAR operations. In this way, this analysis can contribute to establishing practical and efficient regulatory standards, thereby improving the safety measures for ships navigating polar areas, as the METR value is related to the need for safety equipment and supplies onboard.

The findings from the METR-HT analysis offer an important analytical foundation to guide ship operators with more accurate response time expectations based on simulated real-world scenarios. These results can help in advising on necessary operational preparations, such as the adequacy of onboard survival equipment and the strategic positioning of rescue assets, ultimately improving compliance and safety in Arctic operations.

Moreover, the insights gained from this study can inform the Canadian Coast Guard and Canadian Armed Forces for strategic and tactical planning, especially with respect to the deployment of helicopters in response to changing environmental conditions and operational challenges in the Arctic. The findings could set a basis for re-evaluating current strategies, such as greater preparedness of ships traveling to locations with higher METR-HT values, to improve survivability in case adversity strikes. Finally, the results can be used in discussions about investments in better infrastructure up north to prepare for the increased traffic of ships in this region.

5.3.1 Impact of final assumptions

Building upon the approach outlined by Mostaghimi (2024), various factors in the development of this model also directly impact the METR-HT output. To evaluate the conservativeness of the model and its outcomes, a conservativeness rating was calculated for the final assumptions influencing these outputs. Table 21 presents the ranked assumptions by their conservativeness within each category (with higher ranks indicating more conservative assumptions). The final assumptions used in the model are highlighted in yellow.

Table 21: Different assumptions for each factor with their relative ranking

Factors influencing METR-HT	Assumption count	Possible values	Rank	Unit	Final assumption rank
Helicopter passenger capacity	2	15 seated	1	People	2
		Can carry up to 12 stretchers	2		
Temporal division of weather data	2	Hourly	1	Day/hour	1
		Daily	2		
Wait time distribution	4	25th	1	Hours	3
		50th	2		
		75th	3		
		Highest Value	4		
Final cut-off for homogenizing helicopter SAR time	4	25th	1	Hours	3
		50th	2		
		75th	3		
		Highest Value	4		
Aggregating results over 7 years	3	Minimum	1	-	2
		Average	2		
		Maximum	3		

To quantify the conservativeness of the assumptions, the same method employed by Mostaghimi (2024) was adapted. The following formula was used to determine the scale portion for each assumption:

$$Scale\ portion\ per\ assumption = \frac{4}{Assumption\ count} \quad (3)$$

The scale is set to 4, representing the highest conservativeness level, and the assumption count is the number of possible values for a given factor. After determining the scale portion, the final assumption rank is multiplied by this portion to compute the final assumption score, using the formula:

$$Final\ assumption\ score = final\ assumption\ rank\ x\ Scale\ portion\ per\ assumption \quad (4)$$

The final conservativeness rating is then obtained by rounding the final score to the nearest whole number. For example, for the factor "Helicopter passenger capacity," which has two possible values, the scale portion is calculated as 4/2 = 2. Multiplying this by the final assumption rank of 2 (representing the assumption of carrying up to 12 stretchers), it is obtained 2 x 2 = 4. Thus, the final assumption score is 4. The conservativeness rating was obtained by conventional rounding the calculated score to the nearest whole number and in this way, in this case, the conservativeness rating was also 4.

The conservativeness ratings for the model's final assumptions are summarized in Table 22, which follows the same methodology to rank the assumptions. The final scores indicate how conservative each assumption is within its respective category.

Table 22: Final assumptions conservativeness ratings

Factors influencing METR-HT	Assumption count	Final Assumption Rank	Scale portion per assumption	Final Assumption Score	Conservativeness rating
Helicopter passenger capacity	2	2	2	4	4
Temporal division of weather data	2	1	2	2	2
Wait time distribution	4	3	1	3	3
Final cut-off for homogenizing helicopter SAR time	4	3	1	3	3
Aggregating results over 7 years	3	2	1.333333333	2.66666667	3

This approach provides a standardized and quantitative evaluation of the model's assumptions, allowing for clear communication of conservativeness levels, similar to Mostaghimi's method, offering transparency and aiding in the interpretation of the results.

5.4 LIMITATIONS AND RECOMMENDATIONS

While the current model provides valuable insights into helicopter SAR operations in the Arctic, several elements could be improved. If a priority were to be selected, Section 5.4.8

would take precedence. The model offers significant insights, but to be fully utilized by experts, authorities, or companies, some level of training would be necessary. Additionally, creating an intuitive interface could facilitate broader interaction and application.

The model can also be adapted to other geographical locations beyond the Canadian Arctic, but this would require validation updates, such as recalibrating base locations, incident points, and refueling stops. Differences in operational phases and times, depending on the organizational structure in each country, would also need to be explored. Further limitations and recommendations for future work are discussed in the subsections below.

5.4.1 Extended dataset

While the model is based on historical weather data and provides a robust analysis of patterns of weather impacts on helicopter operations, it is important to consider that ongoing climate change may alter these patterns in the future. This could result in more frequent or more severe unfavorable and No-go conditions, e.g. longer periods of No-go conditions, potentially affecting the accuracy of the model's predictions over time. Future studies should account for these changes to ensure the continued accuracy and relevance of the model.

5.4.2 Route and optimization models

The selection of refueling stops was a critical factor in determining the final route for helicopter operations. This selection was based on expert judgments and verified using SkyVector (n.d.) to ensure that the refueling points were along the route or conveniently located between the base and the incident site. However, the current approach, while effective, could be further enhanced by integrating optimization models into the route selection process. This could better account for the possibility that helicopters re-route their flight paths in case of unfavorable or No-go conditions in certain areas of the Canadian Arctic, instead of continuing the originally determined flight path and waiting at a station when that station has No-go conditions.

Incorporating optimization models for the helicopter route selection could refine the selection of refueling stops by considering various factors such as airport size, which affects the types of fuel available and the refueling methods (e.g., drum refueling or fuel pumps), fuel availability, and the strategic location of these airports to ensure optimal travel distances. This approach could potentially lead to more efficient and reliable route planning by improving how the model accounts for the total distance the helicopter must travel during the SAR operation and the reliability of fuel availability at each airport.

5.4.3 Further validation of model

One of the key aspects of model plausibility, as highlighted by Zarrin Mehr et al. (2023), is the validation process through real-world case studies. Zarrin Mehr's research successfully replicated the timeline of the Viking Sky incident, with the model results closely aligning with actual rescue operations, thereby indicating the model's plausibility. In contrast, in the current study such a validation process is not performed, which represents a limitation. While this research provides important insights into the helicopter times and operability in the Arctic through testing different conditions as discussed in section 5.1, the lack of a direct validation against historical SAR incidents leaves uncertainty regarding the model's accuracy under real-world conditions, indirect validation through comparisons with Zarrin Mehr's model notwithstanding.

5.4.4 Use of historical incident data and shipping traffic

While the incident locations were selected based on geographical centers and adjusted for proximity and relevance, future work could explore a more nuanced selection process that incorporates the volume of shipping traffic and the associated risk factors for each zone. High-traffic areas may represent greater probabilities for ship accidents, making them more vulnerable and critical for SAR operations. In particular, zones with frequent shipping routes and harsher weather patterns may present heightened risks, which could influence the selection of incident locations.

Future iterations of the model could prioritize these factors by using real-world data on shipping traffic densities, accident histories, and maritime risks. By integrating this information, the model could provide a more comprehensive analysis of SAR resource allocation and response times, particularly in areas where the risk of incidents is higher.

5.4.5 Weather at incident location

In the current model, weather conditions were primarily considered at SAR bases and refueling stops, as these locations are crucial for helicopter operations due to the critical nature of landing and takeoff. The model also accounted for weather at the temporary base nearest to the incident location, which provided valuable insights into the operational feasibility of SAR missions. However, one limitation of the model is that it did not directly include weather conditions at the incident location itself.

While the weather at incident locations can significantly impact No-go conditions, and thus potentially significantly affect exposure time, there were no public data available to incorporate these conditions into the current model. Recognizing this gap, future research could aim to include weather data at incident locations by using improved datasets. This would provide a more comprehensive assessment of METR-HT.

5.4.6 Search Model

As highlighted by Zarrin Mehr (2023), in actual SAR operations, the choice of search patterns depends on factors such as the location of the incident, elapsed time since the initial alert, weather conditions, and other critical variables. Enhancing the model with these different search algorithms would allow for a more comprehensive and realistic simulation of SAR missions, as the current approach accounts for search time is very simplistic.

5.4.7 Factors impacting METR

While the model developed in this study provides crucial insights into the effects of weather conditions and other essential variables that impact helicopter operability in Arctic SAR operations, it is important to recognize that the model does not fully account for all the influencing factors identified in the literature. As discussed by Kennedy et al. (2013), factors such as the physical state of response resources and crews, type of response resource (e.g. marine response versus air response), state of evacuees and the training of crew members can all significantly impact the total response time during marine incidents in the Arctic. Given these complexities, there are factors that could complement the total METR. Future work could aim to integrate these factors comprehensively, enhancing the accuracy of the estimates for METR-HT under varying conditions.

5.4.8 Incomplete Rescue Operations

The numbers shown in Figure 43 (Section 4.3.1) reflect a limitation of the RHEO model that could be addressed in future work. If the helicopter is unable to reach the next refueling stop, the operation is marked as incomplete, and the simulation proceeds to the next iteration. A possible improvement would be to incorporate wait times for unfavorable conditions, similar to how No-go conditions were handled (Section 3.3.1). After these wait times, the weather delay factor would return to 1 (representing Favorable conditions where range and speed are unaffected). This adjustment would allow these delays to be factored into the METR-HT calculations, resulting in times that more closely reflect realistic total SAR operation durations.

6. CONCLUSION

This research aimed to address two critical questions related to helicopter-based SAR operations in the Canadian Arctic. The first focused on understanding how weather conditions impact the operability of SAR helicopters, specifically the Cormorant, which plays a pivotal role in SAR missions in this region. The second question aimed to determine the Maximum Expected Time of Rescue based on helicopter operations (METR-HT) and the factors influencing it. To achieve this, the research had three main objectives:

Evaluating the influence of weather conditions on helicopter operability.

Estimating the METR for helicopter-based rescues.

Simulating strategic scenarios to understand how METR-HT varies for different weather conditions and operational challenges.

Through addressing these research questions and objectives, this study provides valuable insights into the operational constraints and challenges faced by SAR missions in the Arctic.

This study has demonstrated that weather conditions in extreme Arctic climates are a dominant factor affecting helicopter SAR operation times and operability for SAR missions. The findings reveal that helicopters often face No-go or unfavorable conditions due to weather constraints including visibility, wind speeds and directions, precipitation and temperature, significantly affecting the METR-HT. Notably, the analysis showed that METR-HT is heavily influenced by location and seasonality, with more favorable conditions and shorter response times generally occurring more frequently during the summer months. Conversely, winter conditions contribute to a longer METR-HT and an increased probability that a helicopter SAR operation cannot be completed.

The strategic simulations provided a detailed understanding of how various factors – weather, location, base proximity, and refueling stop options – interact to determine helicopter rescue times. The results also highlighted the need for adaptable SAR strategies across different zones, as operability varied significantly based on regional weather patterns and remoteness.

The insights from this study offer a significant contribution to both the academic understanding and practical application of SAR missions in the Canadian Arctic. These findings can have direct implications for updating and refining IMO policies, specifically the Polar Code, and associated national technical guidance documents, by offering evidence-based recommendations for response times and operational limitations. In particular, the contribution of METR-HT serves as a key metric for policymakers and industry stakeholders on which to base operational decisions, especially regarding preparedness in remote Arctic zones.

Further, this study underscores the importance of enhancing SAR preparedness in regions with consistently high total time values. Improved infrastructure, availability of refueling stops, and the strategic deployment of specialized rescue equipment are crucial for ensuring safe maritime operations in the Arctic. These findings also support the Canadian Coast Guard and Armed Forces in optimizing their SAR strategies to account for changing environmental conditions and operational challenges, especially in northern regions experiencing increasing traffic intensity.

While this research provides a comprehensive analysis of METR and weather impacts on helicopter operability, several limitations and directions for future work are also highlighted. Moreover, while the current model effectively identifies strategic refueling stops and routes, it could be further improved by integrating advanced optimization models to determine the flight path given evolving weather patterns. These models could consider additional factors such as airport size, fuel availability, and proximity to both bases and incident sites, to construct realistic routes. Future research could also focus on validating the model against historical SAR incidents, ensuring its accuracy in real-world scenarios.

In conclusion, this research provides essential insights into the operational challenges faced by helicopter SAR missions in the Canadian Arctic. By developing a comprehensive model to evaluate METR-HT accounting for weather conditions, it offers a critical analytical foundation for improving SAR strategies in this harsh and dynamic environment. As the Arctic becomes increasingly accessible due to climate change, the findings of this study provide critical insights for improving the safety of maritime operations. By addressing the unique operational challenges faced in the Arctic, this research contributes to a safer and more resilient SAR framework for supporting decisions on future shipping operations.

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