SEARCH AND RESCUE (SAR) MODELING FOR THE COASTAL REGIONS OF EASTERN CANADA AND THE ARCTIC GATEWAY

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Abstract

The Search and Rescue (SAR) system plays a critical role in ensuring the safety of maritime activities in Eastern Canada and the Arctic Gateway. This thesis presents a comprehensive method for assessing SAR time in the region, specifically focusing on scenarios where helicopters are utilized as the primary rescue resource. The developed macro-scale SAR model incorporates a Discrete Event simulation approach with stochastic elements to account for uncertainties and variability inherent in SAR operations.

By utilizing the SAR model, a wide range of scenarios can be analyzed, allowing users to define various factors such as helicopter deployment time variability, helicopter parameters, and more. The model employs a time-stepping approach, enabling real-time decision-making and operational adjustments at each time step. It considers multiple factors, including incident and helicopter location, weather conditions, and the number of individuals in distress, to assess SAR effectiveness.

The model underwent rigorous verification tests, demonstrating close alignment with hand calculation methods. Furthermore, a validation test was conducted using data from a real-life incident involving the Viking Sky, where the model's predictions closely matched the actual incident timeline within a certain percentage of accuracy.

The model was further utilized to examine the influence of incident location, the number of survivors, and refueling requirements systematically. Additionally, Arctic-based scenarios were explored to account for specific conditions in the Arctic region. The research findings indicate that incident location, the number of individuals in distress, and weather conditions significantly impact SAR time. Specifically, the total rescue time shows a greater increase with distance from the helicopter base compared to the number of survivors, particularly for smaller survivor groups. When the helicopter base was relocated to an Arctic location, the total rescue time for smaller survivor groups was halved.

The importance of optimizing the location of SAR assets and facilities is emphasized throughout the research. The study also examines the effects of operating two or more helicopters simultaneously on SAR time, providing insights into its impact.

Overall, this thesis underscores the importance of continuous improvement and collaboration to enhance SAR capabilities and ensure maritime safety in the coastal regions of Eastern Canada and the Arctic Gateway. The findings contribute valuable insights for policymakers, SAR organizations, and stakeholders involved in the maritime domain, aiming to reduce response times, increase operational efficiency, and ultimately save lives at sea.

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Table of Contents

List of Figures

List of Tables

Abbreviations

CANSARP	Canadian Search and Rescue Planning Program
CASP	Computer Assisted Search Planning
CCG	Canadian Coast Guard
CCGA	Canadian Coast Guard Auxiliary
DFO	Department of Fisheries and Oceans
DND	Department of National Defense
DSB	Norwegian Directorate for Civil Protection and Emergency Planning
ELT	Emergency Locator Transmitter
EPIRB	Emergency Position Indicating Radio Beacon
ESDA	Exploratory Spatial Data Analysis
GIS	Geographical Information System
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
JRCCs	Joint Rescue Coordination Centers

JRCC-SN	Joint Rescue Coordination Center for Southern Norway
LKP	Last Known Position
LOI	Location of Incident
LSA	Life Saving Appliances
MCTS	Canadian Maritime Communications and Traffic Services
MMR	Mixed Methods Research
MORA	Maritime Operations Risk Assessment
MRSCs	Maritime Rescue Sub-Centers
nm	Nautical Miles
OTC	Offshore Technology Conference
PID	People in Distress
PLB	Personal Locator Beacon
QUAL	Qualitative
QUAN	Quantitative
RCCs	Rescue Coordination Centers
SAR	Search and Rescue

SARMIS	Search and Rescue Management Information System
SRRs	Search and Rescue Regions
SRUs	Search and Rescue Units
TSB	Transportation Safety Board of Canada
UNSARs	Unnecessary Search and Rescue Alerts
USCG	United State Coast Guard
VOO	Vessels of Opportunity

1 INTRODUCTION

1.1 Background

The annual observation of maritime traffic within the coastal areas of Eastern Canada and the Arctic is anticipated to increase without any foreseeable alteration. According to a study by Humpert (2018), shipping activity has significantly increased in Canada's Arctic region. The study found that between 1990 and 2015, traffic nearly tripled, with the total distance traveled by all vessels rising from approximately 350,000 kilometers to over 900,000 kilometers annually. The notable increase in traffic predominantly happened in the last decade.

This region hosts a diverse array of maritime activities, encompassing commercial fishing, transporting items such as ore from mines and offshore oil, and providing bulk goods to remote communities. The region also encounters a noteworthy surge of visitors aboard cruise vessels, a trend that has exhibited substantial growth recently. The rise in adventure tourism-associated maritime transportation operations poses a distinct obstacle to maritime safety, particularly in the Canadian Arctic. The region's inclement weather conditions and variable environments render it arduous to guarantee the safety of individuals and vessels.

The coastal regions of Eastern Canada exhibit some of the most severe and unpredictable climate conditions. A combination of low temperatures, strong winds, high waves, and substantial ice coverage can present significant hazards to the safety and navigation of vessels traversing the region. According to the Canadian Coast Guard (CCG, 2019), it is not uncommon for gusts of up to 160 kilometers per hour to occur during winter storms, and waves can reach heights of up to 30 meters. The prevailing conditions pose a significant challenge to the navigation of ships, and even seasoned mariners may encounter distressing situations.

Furthermore, extensive regions of fog in the spring and summer seasons significantly diminish visibility, further adding to the challenges.

The risks of operating in the Arctic region are compounded by variable ice conditions that can also pose serious safety hazards. As such, all maritime activities in these areas are cause for concern, and safety precautions are of paramount importance.

Fishing vessels usually carry a small number of people, ranging from 1 to 7 individuals. Cargo ships carry more people, with a range of 25 to 30 people. However, the increase in cruise ship traffic has become a particular cause for concern with maritime safety, as the number of passengers and crew on these vessels can be significantly higher than other types of vessels ranging from hundreds to thousands of people. Additionally, pleasure crafts and other smaller vessels are also increasing in number, further adding to the challenge. As such, it is critical to have efficient and effective SAR systems in place to respond to any maritime distress situations that may arise.

According to the Transportation Safety Board of Canada (TSB) Annual Report to Parliament 2019-2020 (TSB, 2020 a), the reported number of marine incidents increased to 947 in 2019, up 65% above the 5-year average, but only 2% more than in 2018. Similar to prior years, technical or mechanical failures were the leading cause of most reported incidents (84%). Figure 1 illustrates Canada's marine incidents, accidents, and fatality rates between 2015 and 2019.

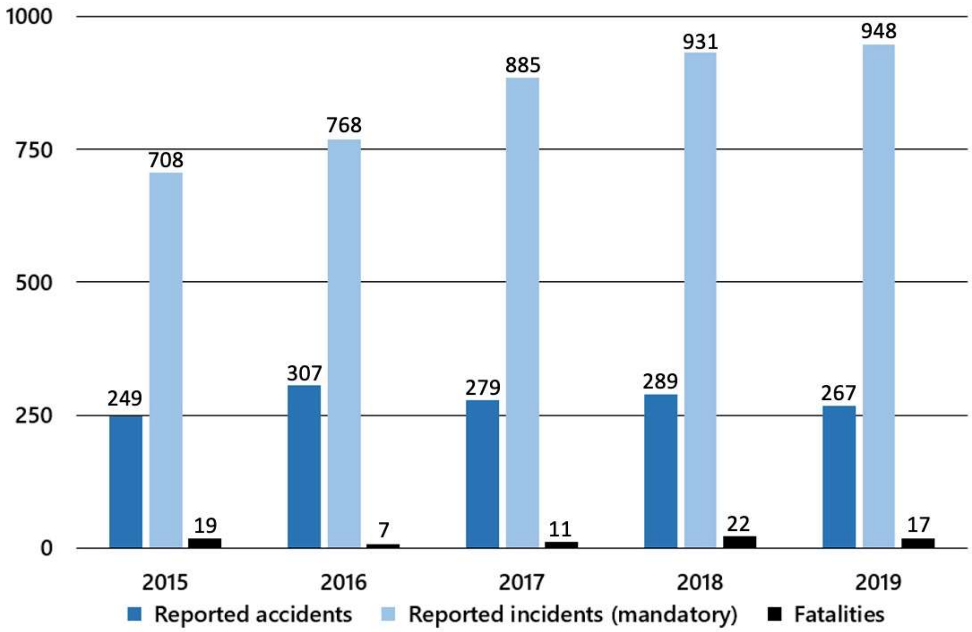

Figure 1:Marine incidents, accidents, and fatalities, 2015 to 2019 (TSB, 2020 a).

In this report, a total of 267 marine accidents were reported in 2019, which is below the 2018 and the 10-year average. In 2019, 78% of marine accidents were related to shipping accidents, while the remaining 22% were related to accidents aboard ships. Also, 17 marine fatalities were reported in 2019, which is below 2018 but slightly above the 10-year average. Thirteen of the 17 fatalities occurred aboard ships. As in previous years, most marine fatalities (10 of the 17) were related to fishing vessels (TSB, 2020 a).

The subsequent explanations pertain to maritime incidents that necessitate reporting as mandated by the Canadian Transportation Accident Investigation and Safety Board Act and the TSB Regulations (TSB, 2020 b):

1. **Marine Occurrence** (TSB,2020 b)**:**

- Any accident or incident linked to ship operation.

- Any situation or condition that the Board reasonably believes could lead to an accident or incident if not addressed.

2. **Marine Accident** (TSB,2020 b)**:**

- An accident directly stemming from ship operation (excluding pleasure crafts).
- Accidents aboard ship leading to death or serious injury due to boarding, being on board, falling overboard, or direct contact with ship parts or contents.

3. **Shipping Accident** (TSB,2020 b)**:**

- Instances where the ship: sinks, founders, or capsizes, collides with another object, experiences a fire or explosion, runs aground, sustains damage impacting its seaworthiness or renders it unfit for its intended use, goes missing or is abandoned.

4. **Marine Incident** (TSB,2020 b)**:**

- Person falling overboard.
- The ship: makes unintentional bottom contact without grounding, gets entangled with utility cables, pipes, or underwater pipelines, faces collision risk, suffers total failure in navigation equipment, main/auxiliary machinery, propulsion, steering, or deck machinery, posing threats to safety, loses cargo overboard, is anchored, grounded, or beached to prevent an incident, crew member crucial for ship safety is incapacitated, posing a safety threat, accidental release or emission of dangerous goods or radiation surpassing regulated levels.

1.2 SAR System Overview in Canada

The aim of SAR is to rescue people and prevent injuries by alerting and operating local, national, and international resources. For Canada, SAR falls within its federal jurisdiction, as outlined in agreements with the International Civil Aviation Organization (ICAO) for aeronautical SAR and with the International Maritime Organization (IMO) for maritime SAR. The Canadian Great Lakes and St. Lawrence River systems are included in this federal SAR area of responsibility (DND, National SAR Manual (B-GA-209-001/FP-001, DFO 5449), 2014).

The National SAR Manual for Canada states that the Department of National Defence (DND) and the Canadian Coast Guard (CCG) shall provide primary Search and Rescue Units (SRUs). DND and CCG support the National Search and Rescue Program through SAR operation. This operation focuses on detection, response, and rescue. Additionally, they work on SAR prevention, which aims to reduce the number and severity of SAR incidents by enforcing relevant regulations and educating the public.

Based on agreements with the IMO and ICAO, Canada has divided the country and the surrounding ocean areas into three Search and Rescue Regions (SRRs) for coordination of maritime and aeronautical SAR (see Figure 2, (DND, 2018 b)).

Through the Joint Rescue Coordination Centers (JRCCs), DND and the CCG manage the response to aeronautical and maritime SAR incidents as part of the national SAR program. The JRCCs are located in Victoria (British Colombia), Trenton (Ontario), and Halifax (Nova Scotia). In addition to the three JRCCs, Canada has two Maritime Rescue Sub-Centres (MRSCs) which are located in Québec City (Québec), and St. John’s (Newfoundland and Labrador). In these regions, which have a great deal of marine activity, the purpose of MRSCs is to reduce the JRCC's workloads.

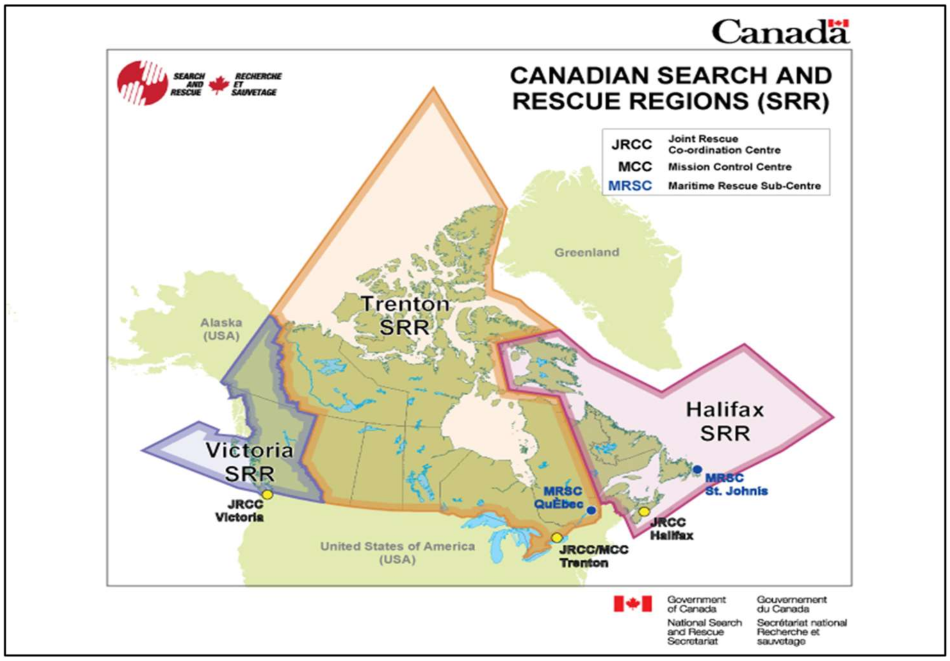

Figure 2:Canadian Search and Rescue Regions (DND, 2018 b).

The JRCCs/MRSCs are tasked with planning, coordinating, conducting, and controlling SAR operations. These centers are staffed with well-trained personnel, equipped with detailed operational plans, and a reliable communication system. The SAR coordinators at these centers have the expertise to assess different scenarios and dispatch the most suitable resources to handle a particular incident. In more complicated events, several resources may be deployed or assigned to provide assistance.

Saving lives and preventing injuries during SAR operations involves several crucial factors, including receiving timely and reliable notifications, compiling and verifying the information quickly, making accurate and prompt decisions, deploying efficient assets and facilities, and planning the SAR effort.

Typically, the following categories of vessels are used in maritime SAR incidents (CCG, 2019):

1. **Primary SAR vessels** are ships that have SAR as their main responsibility and are equipped with specialized equipment. They are stationed in areas that are considered high risk for SAR incidents and are ready to respond to an emergency.
2. **Multi-Tasked SAR vessels** are ships that have been assigned to perform SAR duties in addition to other operational programs. They must remain within a specific SAR area and comply with all SAR operational standards. They are used to increase efficiency and reduce costs and can act as backup vessels for primary SAR ships.
3. **Secondary SAR vessels** include all other government vessels that are not primary or multi-tasked SAR vessels.
4. **The Canadian Coast Guard Auxiliary (CCGA)** is a volunteer organization that supports the Coast Guard in SAR response and prevention activities. CCGA members receive specialized SAR training from the Coast Guard, and the Coast Guard can rely on the CCGA's members and vessels to augment its SAR capabilities.
5. **Vessels of Opportunity (VOO)** are any other vessels that are close enough to provide assistance in a SAR incident and are required by law to do so under the Canada Shipping Act (TC, 2001) and international law.

Fixed-wing airplanes and helicopters are both used in maritime SAR operations in the JRCC Halifax SAR region. The Halifax SRR is a vast area with more than 29,000 kilometers of coastline and approximately 4.7 million square kilometers, which is about 80 percent water. It includes all four Atlantic provinces, the eastern half of Quebec, the southern half of Baffin

Island in Nunavut, and the north-western quadrant of the Atlantic Ocean. The Halifax SRR receives about 2,500 calls for assistance each year, with 75% related to maritime incidents, 10% air incidents, and 15% requests for humanitarian aid (DND, 2018 a):

The Halifax SRR has the following primary CAF SAR squadrons:

- The 103 Search and Rescue Squadron from 9 Wing Gander, Newfoundland.
  The squadron flies CH-149 Cormorant helicopters.
- The 413 Transport and Rescue Squadron from 14 Wing Greenwood, Nova Scotia.
  The squadron flies:
    - CC-130 Hercules tactical transport aircraft, and
    - CH-149 Cormorant helicopters

1.3 SAR Response

In SAR operations, once the JRCC/MRSC receives a distress notification indicating that a person(s) is in danger, the SAR coordinator begins to organize the rescue. All available information about the person(s) in danger is gathered and recorded, and the positions of potential assisting resources in the area of the incident are determined.

Distress notifications can be received through various means, such as emergency beacons (ELT, EPIRB, PLB, etc.) that typically provide a specific location. Mayday calls, received via radio or phone, can also serve as distress notifications, but they may not include a specific location. Additionally, reports of overdue persons are common, although they often lack a specific location. It is important to note that while mayday calls and overdue reports can be distress notifications, their effectiveness is limited due to the lack of real-time updates on the accident's location. This can potentially lead to longer SAR operations.

There are three types of beacons that are usually used for sending a distress notification: 1) an Emergency Locator Transmitter (ELT), designed for aircraft; 2) an Emergency Position Indicating Radio Beacon (EPIRB), designed for vessels; and 3) a Personal Locator Beacon (PLB) for use on land.

EPIRBs and PLBs are distinct from ELTs because they send a coded message that identifies the specific beacon being used. It is mandatory for EPIRB owners to register their beacons with the National Search and Rescue Secretariat. During registration, crucial details such as the owner's name and the vessel's description are documented in a computer database. This database helps the JRCC/MRSC coordinator access essential information in the EPIRB registry to facilitate any rescue efforts.

Saving lives and preventing injuries during SAR operations involves several crucial factors, including receiving timely and reliable notifications, compiling and verifying the information quickly, making accurate and prompt decisions, deploying efficient assets and facilities, and planning the SAR effort.

1.4 Software Tools to Support SAR

To facilitate search planning and resource allocation, every JRCC/MRSC is equipped with the Canadian Search and Rescue Planning Program (CANSARP), which calculates drift plots and conducts search planning. CANSARP is the primary means for search planning in all maritime searches (DND, National SAR Manual (B-GA-209-001/FP-001, DFO 5449), 2014) . Additionally, a computerized search planning program called Computer Assisted Search Planning (CASP) is available through United States Coast Guard (USCG) Rescue Coordination Centers (RCCs) in Norfolk and Seattle. CASP uses simulation methods and is particularly useful in cases where incident position information is vague. Canadian users can access CASP by having RCC contact a USCG RCC.

To increase the probability of detecting objects at sea, several computer software programs have been developed for search planning. These programs include SARPlan, SARIS, SAROPS, SARMAP, and TRANSAS, each with its own strengths and weaknesses for use in different conditions (Vidan et al., 2015). Additionally, some SAR planning and operation models have been created to assist decision-makers in SAR operations. However, these models have had some limitations in assessing the impact of factors that affect response to an incident. Some of those models and methods are reviewed in Section 2.

To improve maritime SAR operability, an objective way for assessing system performance is needed to enhance decision-making abilities at the strategic level.

This research discusses the development of a macro-scale SAR model to represent helicopter operations performing rescue in a maritime environment in the eastern coastal region of Canada and the Arctic gateway. The model developed in this research uses a Discrete Event simulation approach and incorporates stochastic elements to represent the inherent uncertainties and variability in SAR operations. This approach may help improve strategic decision-making and resource allocation in SAR operations.

1.5 Research Objectives and Hypothesis

The primary objective of this research is to develop a numerical model that utilizes Discrete Events and Monte Carlo simulation methods. The purpose of this model is to investigate and analyze the factors that have the most significant impact on total SAR time in maritime operations. By utilizing this model, the aim is to identify key variables and parameters that influence the efficiency and effectiveness of helicopter SAR operations.

Furthermore, the research aims to conduct thorough verification and validation tests to assess the reliability and accuracy of the developed model. Verification tests involve comparing the model's results with established analytical or hand calculation methods to ensure consistency and correctness. On the other hand, validation tests focus on comparing the model's predictions with real-world data or documented incidents to assess its ability to accurately represent and simulate helicopter SAR scenarios.

The expert interviews revealed that the following key factors have an influence on the overall time of SAR operations:

- Incident location (distance from the shoreline and/or helicopter base)
- Number of individuals in distress,
- Number of helicopters involved in SAR operation,
- Weather conditions.

1.6 Research Questions

The research aims to address the following questions:

- When a helicopter responds to maritime distress, what are the primary factors that influence the SAR operation?
- Among the variables considered, which one has the most significant impact on helicopter SAR operations? Is it the number of helicopters deployed, the number of

people in distress, the distance to the helicopter base, or the prevailing weather conditions?

- In the context of Arctic maritime incidents, how does the distance from the helicopter base affect the total SAR time? Can a closer proximity to the base lead to reduced response times?
- What is the impact of simultaneously operating two or more helicopters on the overall SAR time?
- How well does the developed model perform in terms of verification and validation? Are the model's predictions consistent and accurate when compared to the actual outcomes of SAR operations?

1.7 Research Approach

This research involved a mixed methods research (MMR) design. The MMR design is a type of research that combines elements of quantitative and qualitative research approaches to gain more understanding and corroboration. In this research, expert knowledge and information are utilized to enhance the quantitative modeling approach. This acknowledges the significance of incorporating qualitative insights within the quantitative methodology, reinforcing the importance of expert knowledge in informing the modeling process.

This integrated methodological approach is commonly referred to as "QUAN+qual research," reflecting the synergy between quantitative and qualitative methodologies in informing the modeling work, and it is defined by Johnson et al. (2007, pages 123&124) as:

> "Quantitative dominant mixed methods research is the type of mixed research in which one relies on a quantitative, postpositivist view of the research process, while concurrently

> recognizing that the addition of qualitative data and approaches are likely to benefit most research projects."

Based on the methodology outlined, this research program followed the following steps:

- The SAR decision-making process and action plan were analyzed. In this step, discussions were held with JRCC experts to better understand their action plans in a real case. The output of this step was a detailed algorithm(s) that explained the SAR operation step by step. This algorithm(s) was used to guide the code development of the SAR model in the following steps.
- The data gathering, sourcing, and assembly took place in the second step. The datasets in this research include but are not limited to 1) the time to process emergency notifications and mobilize resources for response, 2) the operability of assets in given environmental conditions, and 3) the proximity and capability of resources and assets. Where appropriate, expert knowledge was used for cases where datasets were limited or unavailable.
- During the third step, probabilistic mathematical models (mainly using the Monte Carlo method) for helicopter operations were developed, which used Discrete Event simulation to represent SAR operations for given scenarios, utilizing performance data for the helicopter. The output of this step is a macro-scale generalized SAR model which represents the high-level organization of the system. This model was developed to allow continual implementation of new methods, techniques, and datasets as they become available.
- The model was tested and validated in the fourth step. Various scenarios have been modeled based on typical or common SAR occurrences, and the outcomes have been assessed by comparing them to real-world data and distress reports.

2 LITERATURE REVIEW

SAR modeling has become an important area of maritime studies and research in recent years, and a wide range of modeling approaches have been used to develop SAR models. This literature review highlights the importance of understanding the nature of SAR incidents and risk analysis in SAR modeling. Additionally, the review examines several numerical SAR models and modeling methods such as Discrete Events and Monte Carlo simulation. This literature review provides a comprehensive overview of the existing literature on SAR modeling and provides a basis for future research in this area.

2.1 Nature of SAR Incidents, Risk Analysis, and Incident Location Assessment

Incidents requiring SAR response occur in diverse environments, including coastal areas, where they can be impacted by complex environmental variables such as weather conditions, maritime activity, and the nature of the coastline. Consequently, comprehending the characteristics of such incidents is essential in enhancing the effectiveness of SAR operations. Performing risk analysis is considered a crucial component of SAR operations, as it facilitates the identification of possible hazards and susceptibilities that require corrective action. A comprehensive risk evaluation should consider multiple variables, including but not limited to the nature of the SAR incident, the environment in which it happens, and the current response resources. Evaluating incident location is a crucial aspect of SAR operations. It entails determining the most suitable site for SAR resources and facilities to be positioned while considering variables such as response time, accessibility, and the frequency and severity of SAR incidents in a given region. This section of the literature review aims to comprehensively understand SAR incidents, risk analysis, and incident location assessment by examining various aspects of these topics.

The review begins with Pelot et al. (2008) paper which focused on the spatial analysis of traffic and risks in the coastal zone. The authors posited that the coastal zone represents a region of a higher risk owing to its tendency for both recreational and commercial activities and its vulnerability to extreme weather events such as storms and floods. The objective of the research was to establish a systematic approach for evaluating the spatial distribution of hazards in the coastal region, with emphasis on marine transportation. The researchers employed spatial analysis techniques based on Geographic Information System (GIS) to detect regions with higher vessel traffic and associated hazards in the coastal zone. The authors analyzed vessel traffic data obtained from the Canadian Coast Guard and integrated it with environmental data, including wind speed and wave height, to evaluate the potential risks of accidents. The spatial distribution of critical infrastructure, including ports and navigational aids, was taken into consideration by the authors. Additionally, the authors examined the vulnerability of coastal communities to hazards. The study found that the spatial distribution of vessel traffic and risk in the coastal zone is highly concentrated, with certain areas experiencing a disproportionately high amount of traffic and risk (Pelot et al., 2008). The authors emphasized the importance of using GIS-based spatial analysis tools in coastal zone management and decision-making processes to identify and mitigate areas of high risk.

Shahrabi (2003) dissertation investigates the spatial and temporal patterns of maritime incidents associated with fishing and shipping traffic. This study is founded on data obtained from the Canadian Marine Communications and Traffic Services (MCTS) and examines incidents occurring within the Canadian waters of the Atlantic Ocean between 1988 and 1997. The research by Shahrabi utilizes a GIS to perform a spatial analysis of the collected data. The findings indicate that most of the incidents occurred in the coastal regions, with a specific focus on Cape Breton Island and Newfoundland. The investigation also detected temporal trends in the incidents, exhibiting a surge in the frequency of incidents throughout the summer and a decline during the winter. Shahrabi's study exhibits a notable advantage in utilizing GIS to scrutinize maritime incidents' spatial arrangements. GIS facilitates the identification of concentrated areas of incidents and hotspots, thereby enabling effective SAR planning and allocation of resources. Furthermore, the study's emphasis on fishing and shipping traffic incidents underscores the significance of incorporating human factors into maritime safety (Shahrabi, 2003).

Nevertheless, the research also exhibits certain limitations. The scope of the analysis is constrained to a particular temporal and spatial domain, potentially reducing its relevance to other temporal and spatial contexts. Furthermore, the study does not explore the causes of the incidents, which would be important information for developing effective risk-reduction strategies.

Stoddard et al. (2020) provide an overview of the data analysis techniques employed in evaluating maritime SAR incidents in the book chapter "Maritime Search and Rescue". The authors provide a comprehensive analysis of the datasets used in this field, including a review of their quality and limitations, and several statistical methods that can be used to analyze and model SAR incident data. The authors begin by emphasizing the critical role of historical SAR incident data for understanding the nature of these incidents and recognizing trends over time. The authors then discuss the various sources of SAR incident data, including databases maintained by various organizations, as well as the various categories of data typically collected, such as the location, nature, and severity of incidents. The authors also describe the challenges of analyzing historical SAR data, such as data quality issues, completeness, and accuracy.

To overcome these challenges, the authors present a range of statistical techniques for analyzing SAR incident data, including exploratory data analysis, time series analysis, and regression. These methods can aid in identifying trends and patterns in SAR incidents and provide insight into the factors contributing to these incidents (Stoddard et al., 2020). In addition, the authors emphasize the significance of employing visualizations to facilitate the comprehension and communication of SAR incident data.

Marven et al. (2007) applied Exploratory Spatial Data Analysis (ESDA) techniques to aid in maritime SAR planning. The authors underscore the significance of spatial data analysis in SAR operations, as precise and current information about the search area is essential for efficient planning and decision-making. This paper offers a case study of a simulated SAR operation conducted in the Strait of Gibraltar, which serves as a crucial link between the Atlantic Ocean and the Mediterranean Sea. The study employs ESDA techniques to examine the spatial distribution of search objects and to pinpoint regions with a high likelihood of detection.

The authors highlight the usefulness of ESDA techniques, such as kernel density estimation and hot spot analysis, in identifying areas of high probability of occurrence and detection. They also discuss the limitations of traditional search planning techniques, which often rely on subjective assumptions and do not fully consider the spatial variability of search objects. The paper suggests that ESDA techniques can help SAR planners to better understand the spatial patterns of search objects and optimize the deployment of search resources (Marven, et al., 2007).

Breivik et al. (2008) paper presents an operational SAR model for the Norwegian Sea and the North Sea. This model provides a practical approach to SAR planning, highlighting the importance of considering various factors, such as weather conditions, vessel characteristics, and SAR resources. Their research used a grid system to divide the area of interest and considered factors such as wind speed, wave height, and visibility to predict the location of drifting vessels. The authors used a Monte Carlo simulation to model vessel behavior and rescue outcomes, and their results showed that the model improved rescue efficiency compared to previous methods that relied solely on random search patterns.

The paper highlights the importance of considering environmental factors when developing SAR models and demonstrates the value of a data-driven approach to improve rescue efforts (Breivik et al., 2008). By using a grid system and considering weather conditions, the authors were able to better predict the location of drifting vessels and allocate resources accordingly. The research could be applied to other regions to improve SAR operations in areas with similar environmental conditions.

Malik et al. (2012) introduced a visual analytic process for maritime response, resource allocation, and risk assessment. The paper addresses the challenge of managing and allocating resources during maritime incidents, where time and accuracy are critical factors. The authors present a visual analytics tool called the Maritime Operations Risk Assessment (MORA) that aims to provide situational awareness and support decision-making in maritime emergencies.

MORA is designed to integrate multiple data sources, including real-time sensor data, historical records, and expert knowledge. The tool provides a range of visualizations to support different stages of the response process, from situation awareness and risk assessment to resource allocation and decision-making (Malik et al., 2012). The authors also highlight the importance of user-centered design in creating effective visual analytics tools for emergency management.

The study evaluates MORA through a series of case studies, including a simulated oil spill response in the Gulf of Mexico. The authors found that the tool improved the efficiency and accuracy of decision-making during emergency response operations. MORA's ability to integrate multiple data sources and provide real-time situational awareness was particularly effective in addressing the complex and dynamic nature of maritime incidents.

Akbari et al. (2017) and (2018a) present a maritime SAR location analysis considering multiple criteria with simulated demand. These papers propose a model for selecting optimal locations for SAR resources, taking into account various factors, such as response time, resource capacity, and demand.

Their first paper in 2017, aimed to analyze the optimal location of maritime SAR facilities considering multiple criteria and simulating demand. The authors conducted their research by utilizing integer programming and simulated demand to optimize the locations of SAR facilities along the coastline of Nova Scotia, Canada. They considered multiple criteria, including the probability of incidents, the distances from high-risk areas, and the number of vessels passing through the region. The study found that optimizing the locations of SAR facilities can significantly improve response times and reduce risks. The authors emphasized that their proposed model could be adapted to other regions, and it would be beneficial for governments to use this analysis in their decision-making process (Akbari et al., 2017).

Moreover, the authors compared their proposed model with the existing model, and the results showed that the new model could identify more effective locations for SAR facilities. The study also highlighted the importance of considering the varying demand for SAR services during different times of the day and time of year.

Their paper in 2018 (a), conducted a maritime SAR location analysis that builds upon their previous work in 2017. The authors proposed a multi-objective optimization model that aims to minimize both the expected response time and the expected number of fatalities while maximizing the expected number of rescues.

To illustrate the model's effectiveness, the authors conducted a case study in the Strait of Georgia, Canada. The results showed that the proposed model could significantly improve response times and reduce the number of fatalities compared to the current configuration of SAR facilities in the region (Akbari et al., 2018 a). Furthermore, the authors introduced a modular approach to the model that allows policymakers to make decisions based on different scenarios or objectives. The modular approach allows policymakers to change the decision variables and the objective function, making the model more flexible and adaptable to different regions and decision-making contexts.

Furthermore, Akbari et al. (2018 b) present a modular capacitated multi-objective model for locating maritime SAR vessels. This model proposes a practical approach to locate SAR vessels based on different criteria, such as vessel availability, demand, and operational cost. The authors note that SAR operations are critical for saving lives in maritime accidents and disasters and that the effectiveness of these operations can be improved through optimal location of SAR facilities and vessels. The paper builds on their previous work that focused on the location of SAR facilities.

The authors use a multi-objective optimization approach that considers both the distance of a vessel from its assigned coverage area and the response time of the vessel to reach the incident location. The model also takes into account the capacity of each vessel and the demand for SAR services. The authors use a case study in the Gulf of Saint Lawrence to demonstrate the effectiveness of their model in identifying the optimal location of SAR vessels.

The paper contributes to the existing literature on SAR facility location analysis by incorporating the location of SAR vessels into the optimization model. The use of a multi-objective optimization approach is also a novel contribution to the field (Akbari et al., 2018 b). The authors note that the model can be adapted to different regions and that decision-makers can use it to inform their decision-making process in terms of SAR vessel location.

Solberg et al. (2017) propose the practical implementation of the functional-based International Code for Ships Operating in Polar Waters (IMO Polar Code (IMO, 2009)) in the Arctic cruise sector. The authors emphasize the significance of adopting a functional-based methodology for safety management and risk mitigation. The present research holds significance as it illuminates the execution of the IMO Polar Code in the Arctic cruise sector, which is crucial in ensuring the security of vessels and personnel functioning in polar regions. The findings presented by the authors provide strong support for their assertion that the implementation of the Polar Code represents a significant measure toward mitigating the potential hazards and ecological harm in the Arctic region.

The case study approach used by Solberg et al. (2017) allowed for a thorough analysis of the impact of the Polar Code on the Arctic cruise industry. The study found that the implementation of the Polar Code led to a significant reduction in the risk of accidents and environmental damage. This was achieved through the implementation of a functional-based approach to safety management, which emphasizes the identification and management of risks associated with specific ship functions. This approach is highly effective as it allows for a targeted risk management strategy, making it easier to mitigate risks associated with specific ship functions (Solberg et al., 2017).

The authors' discovery regarding the favorable influence of implementing the Polar Code on the industry's reputation holds great significance. The significance of safety and environmental protection is gaining traction among customers and stakeholders, and adopting the Polar Code enhances the industry's reputation. The significance of this matter is amplified by the growing popularity of the Arctic region as a preferred destination for cruise ships.

The Solberg et al. (2017) study's suggestion that the implementation of the Polar Code could be extended to other maritime sectors operating in polar waters to achieve similar risk reduction benefits is also important. Solberg et al. (2017) further notes that the Polar Code has already proved highly effective in the Arctic cruise industry, and its implementation in other maritime sectors could help to reduce the risk of accidents and environmental damage across the board.

Despite its significant contributions, the study by Solberg et al. (2017) has a few limitations. For example, the study focused only on the Arctic cruise industry, and its findings may not be generalizable to other maritime sectors. Additionally, the study did not provide a detailed analysis of the costs associated with the implementation of the Polar Code, which could be a barrier to its adoption in other sectors.

2.2 Previous Numerical SAR Models

Several numerical SAR models have been developed to help optimize rescue operations. In this section, some of the recent models are reviewed.

Solberg et al. (2020) investigated the time it takes for people to be rescued following a marine incident, depending on different resources used to for rescue. The authors emphasized that the time to rescue is critical in saving lives, and a delay in response can lead to fatalities.

The study used a modeling approach, analyzing data from the Norwegian maritime incident database covering the period between 2004 and 2017. The authors considered six different paths of survival, including lifeboats, rafts, immersion suits, personal flotation devices, swimming, and clinging to floating objects. They investigated the time it took to rescue survivors who followed each path of survival, including the time it took to locate and rescue them.

The research discovered significant disparities in the time required to rescue survivors based on the route they took to survive. The authors observed that the median rescue time for survivors in lifeboats was 1.7 hours. In contrast, those who swam had the longest median rescue time, at 7.7 hours. The authors also reported that the time required to locate survivors depended on their method of survival, with those in immersion suits and those adhering to floating objects being located the quickest.

In addition, the study examined the effects of weather, time of day, and distance from the coast on time required to rescue survivors (Solberg et al., 2020). The authors observed that weather conditions and distance from the coast substantially impacted the time to rescue, with lengthier rescue times in adverse weather conditions and for incidents further from the coast. The time to rescue was not significantly affected by the time of day.

The study findings provide maritime authorities and rescue personnel with crucial information for developing effective response strategies to maritime incidents. According to the authors, understanding the various survival routes and their respective rescue periods could optimize rescue resource positioning and increase rescue operations' efficacy. To increase survivability in the event of a maritime incident, the study emphasizes the significance of proper safety apparatus and training.

Kennedy et al. (2013) used expert knowledge to assign SAR times for different locations in the Canadian Arctic. The authors used a structured communication technique (a survey), to collect information from experts about the most likely SAR times for different scenarios. The survey involved a series of questions administered to a group of Arctic transportation and SAR experts. The authors used the results of the survey to develop a model that can be used to inform SAR planning and decision-making in the Arctic.

The study surveyed experts with experience in Arctic SAR operations. The experts were asked to estimate the time required to respond to an incident, the time required to travel to the incident location, and the time required to transport the survivors to a medical facility. The experts were also asked to estimate the probability of various scenarios, such as the likelihood of an incident occurring in a particular location or during a particular time of year (Kennedy et al., 2013).

Results were used to develop a model that assigns SAR times based on the probability of different scenarios. The model considers the probability of an incident occurring in a particular location, the time required to respond to the incident, and the time required to transport survivors to a medical facility. The model also considers the time of year and the weather conditions, which can have a significant impact on SAR times in the Arctic. The model can be used to assess the effectiveness of current SAR resources and to identify areas where additional resources may be needed (Kennedy et al., 2013).

Piercey et al. (2019) built on the work of Kennedy et al. (2013) to develop a new methodology for estimating exposure time in Polar Regions. The authors developed a deterministic formula that takes into account several variables, such as rescue craft speed, capacity, and range, proximity of bases and ports to the route of interest, the number of individuals awaiting rescue, and the number of survival crafts deployed. They also consider factors related to SAR response, such as the time to deploy a task force, the time to receive communications, and SAR time.

The allows for exposure time to be estimated at any location in the Polar Regions. The authors compare the estimated exposure time with the maximum expected time of rescue stipulated by the Polar Code, which requires that Life Saving Appliances (LSA) support human survival for no less than five days. The study results indicate that estimated exposure time may exceed the 5 days expected time of rescue, particularly as new and more remote routes open in the Polar Regions

(Piercey et al., 2019). This highlights the need for improved SAR response times and capabilities in these regions.

Compared to the earlier study by Kennedy et al. (2013), this paper provides a more specific and detailed methodology for estimating exposure time in Polar Regions. Although both studies consider similar variables and factors, the Piercey et al. (2019) study uses a more refined formula and implementation in Python, allowing for more accurate and comprehensive estimates of exposure time. Additionally, the 2019 study focuses specifically on the unique challenges of Polar Regions, such as extreme weather, limited infrastructure, and difficult access (Piercey et al., 2019). Moreover, the method used by Kennedy et al. (2013) is deterministic, meaning it always produces the same result when the variables remain unchanged. This simplicity makes it easy to understand and run, but it may be seen as a drawback since it doesn't capture the variable nature of SAR operations.

2.3 Modelling Methods

Discrete Events and Monte Carlo simulation are two important techniques which can be used in SAR modeling to evaluate system performance and to represent the probability of different outcomes.

Discrete Events simulation entails the simulation of distinct occurrences within a system, such as the arrival of rescue teams, the positioning of survivors, and the development of rescue events. The Discrete Event approach can assess a system's efficacy across various scenarios and identify areas of inefficiency or opportunities for enhancement. Discrete Event simulation can also help optimize resource allocation, such as determining the optimal number and location of rescue teams or the most effective search pattern.

On the other hand, Monte Carlo simulation is a technique that employs stochastic sampling to approximate the efficacy of a given system. This approach proves to be especially advantageous in situations where the system is ambiguous, such as instances where the locations of survivors are unknown or when weather conditions are unpredictable. The Monte Carlo simulation methodology involves the generation of a considerable quantity of randomized scenarios, which are subsequently consolidated to furnish a probability assessment of various outcomes. This can aid decision-makers in assessing the prospective risks and advantages of diverse rescue strategies and distributing resources correspondingly.

Both Discrete Events simulation and Monte Carlo simulation have been used in SAR modeling in various research studies. For instance, in Kennedy et al.'s (2013) study, Discrete Event simulation was used to model the exposure time until recovery by location in cold regions, while Razi et al. (2016) used Monte Carlo simulation to evaluate the performance of SAR boats. In Solberg et al.'s (2020) study, both Discrete Event simulation and Monte Carlo simulation were used to model the time to rescue for different paths to survival following a marine incident.

Overall, the choice of simulation method depends on the specific goals of the study and the characteristics of the system being modeled. While Discrete Event simulation is more appropriate for modeling complex systems with many interacting components, Monte Carlo simulation is more suitable for modeling systems with uncertain parameters.

In this thesis, both methods have been used to model the helicopter operation in SAR incidents in eastern coastal Canada. These concepts and methodologies are presented in the next section to outline the model developed. Section 6 and 7 will showcase the model's functionalities by evaluating its performance under various scenarios.

3 SAR MODEL: CONCEPT AND METHODOLOGY

3.1 Methodology Overview

The current research employs a combination of mathematical modeling and simulation methods, specifically the Monte Carlo method and Discrete Event simulation. The model is designed to represent the behavior of the SAR system by encoding a sequence of well-defined events that take place over time. The Discrete Event simulation encompasses various stages of the process, such as receiving distress notifications, preparing for take-off, flying to a Last Known Position (LKP), refueling, and searching for survivors. It also considers the anticipated events, such as rescuing (picking up the survivors) and disembarking ashore, while tracking the elapsed time since the process began.

To accommodate the uncertainties, complexities, and changes that may occur during the process, a time-stepping approach is used in the model. This approach allows for modifications or decision-making based on the current state of knowledge at each time step, considering the scenario, asset status, and system configuration. The model is coded in MATLAB and employs data sourced from multiple SAR databases in Canada. Key parameters are inputted into the model as statistical distributions, which allows for random choices to be made at each time step.

It is worth noting that the Monte Carlo simulation method is particularly useful when there is uncertainty in the system being modeled. The approach enables the estimation of probabilities for different outcomes, which can provide valuable insights into the performance of the SAR system under different scenarios. Furthermore, the Discrete Event simulation method is well-suited for modeling complex systems with multiple interacting components, making it a suitable approach for modeling SAR operations. The combination of these methods can provide a robust framework for evaluating the effectiveness of the SAR system and identifying areas for improvement.

3.2 Developing an Algorithmic Framework for the SAR Process

An overall algorithm for helicopter SAR operations in Canada has been created, based on the National SAR Manual and consultations with SAR operators to gain insight into their experiences and perspectives. The purpose of this algorithm is to identify the key stages of the SAR process, such as decision-making, selecting the appropriate assets, and mobilizing them for the response. A detailed comprehensive algorithm is reported in Appendix A. However, this algorithm has been simplified to focus specifically on SAR operations involving helicopters. Figure 3 provides a visual representation of this simplified flow chart and a clear and concise overview of the key steps involved in a SAR operation by helicopters.

Using the algorithm and methodology outlined above, a paper titled "A Macro-scale Generalized Search and Rescue (SAR) Model for the Coastal Regions of Eastern Canada and the Arctic" was recently published and presented at the Offshore Technology Conference (OTC) 2023. The paper is included in Appendix C of this document.

Based on Figure 3, the SAR operation can be divided into several distinct phases, each of which represents a critical step in the SAR process. In this section, each of these phases is explored in-depth and a comprehensive explanation of the model's components and variables is provided, along with limitations involved in each phase.

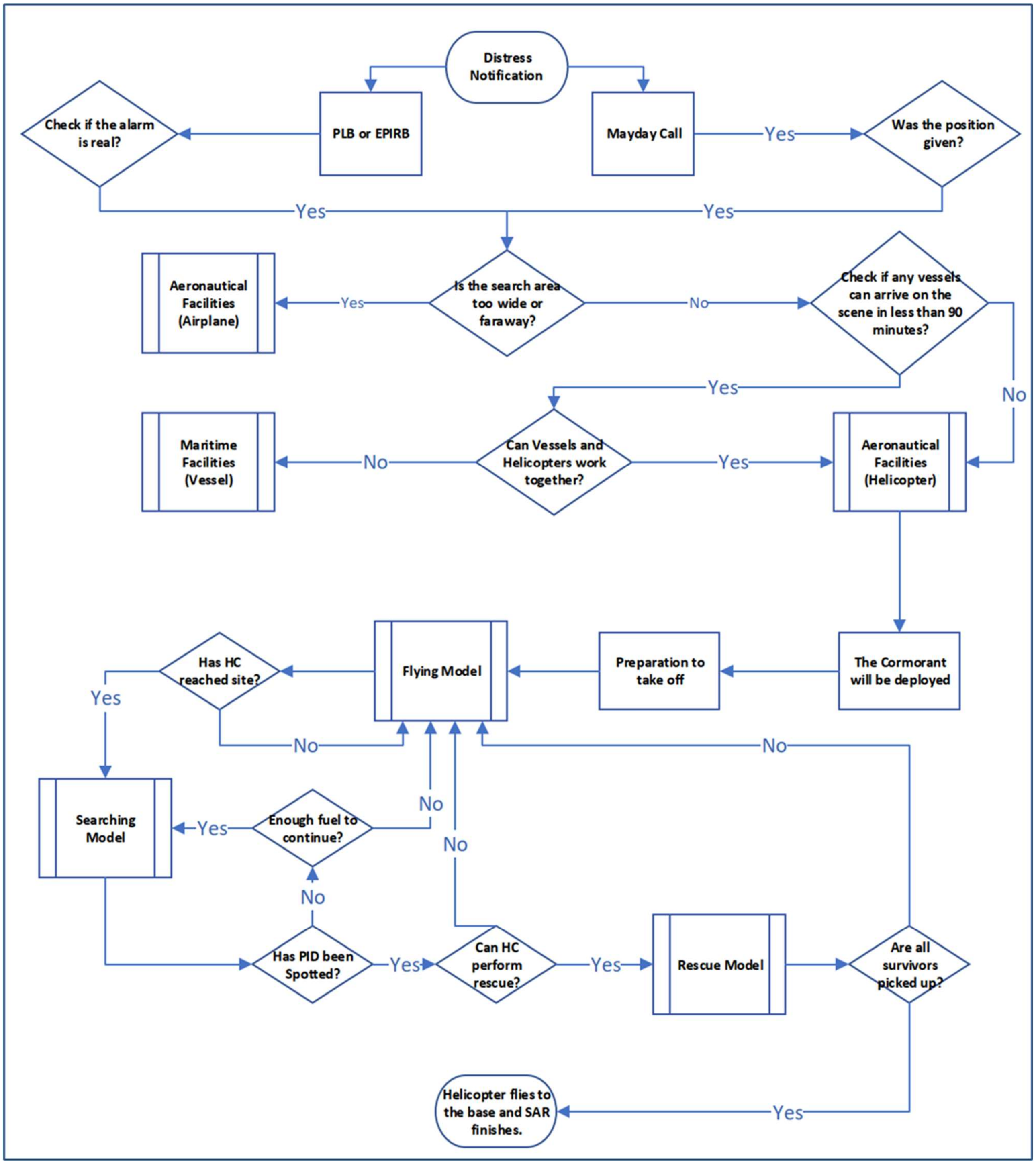

Figure 3:Simplified SAR Operation Flow Chart for Helicopters (Zarrinmehr et al., 2023).

3.2.1 Phase One: Confirmation of Distress Notification

While there are several different ways in which a distress notification can be received, for the present stage of development it is assumed that distress notifications are received either through a PLB or EPIRB signal, or a mayday call. In the case of PLBs or EPIRBs, it is assumed that the distress position is known and updated regularly. However, in the case of a mayday call, it is assumed that the distress position is initially known but not updated regularly. PLBs and EPIRBs send a coded message identifying the specific beacon used, providing coordinators with crucial information about their owners. Coordinators use this information to confirm the distress and initiate the SAR operation. To prevent hoaxes and Unnecessary Search and Rescue Alerts (UNSARs), it is essential to report them to local authorities (DND, National SAR Manual (B-GA-209-001/FP-001, DFO 5449), 2014). The importance of reporting hoaxes cannot be overstated, as they can divert valuable resources from genuine distress situations.

After receiving the notification, coordinators initiate the SAR operation and gather all the essential information. The coordinators will need to establish contact with the device's owner or company to confirm the distress and gather further information.

The first phase of the SAR process must be executed within a reasonable time frame. For the current stage of development, a fixed time of 15 minutes is assumed for this phase.

3.2.2 Phase Two: Decision-Making

After the SAR incident is confirmed, the coordinators initiate a quick review of the location, weather conditions, and available resources to ensure a timely response. This stage is crucial as any delay or error in this phase can significantly affect the outcome of the SAR operation. The availability and readiness of resources and assets, including public, civilian, volunteer, and opportunistic, are thoroughly evaluated to ensure that the most suitable options are selected.

The SAR model developed in this study was designed to simulate the high-level organization of the system with the capability of sub-model development for aeronautical and maritime activities. However, only the helicopter deployment and operation sub-model has been developed and presented.

To introduce some uncertainty to this phase, the decision-making time has been randomly selected from a uniform distribution between 0 and 15 minutes. A uniform distribution is a type of probability distribution in which every value between an interval from "a" to "b" is equally likely to occur. This approach ensures that the model reflects the reality of the SAR system, where decision-making times can vary depending on the situation's complexity and available resources.

3.2.3 Phase Three: Helicopter Preparation

The helicopter preparation time affects the response time of the SAR system. It is the time required by the flight crew to become airborne after receiving the distress notification. This time varies based on the time of day and day of week that the notification is received. According to the Department of National Defense information, aeronautical SRUs hold a 30-minute response posture during normal working hours, which are 8AM to 4 p.m.. However, during the remaining period, the response posture increases to 2 hours (DND, Search and rescue posture review 2013, 2019).

In the SAR model, all types of helicopters can be selected based on the Location of the Incident (LOI) and the number of People in Distress (PID). However, in this thesis and in all test scenarios, the CH-149 (Cormorant) helicopters will be deployed. These helicopters have a maximum speed of 277 km/h and a maximum range of 1185 km with one full fuel tank. Additionally, the maximum capacity of these helicopters is assumed to be 15 passengers. Capacity refers to the number of survivors that can be taken on board for one trip from the incident to the base station.

The speed of the helicopter can vary based on weather conditions such as wind direction and strength, and this variability is considered in the weather influence factor part of the model.

To introduce uncertainty in the preparation time phase, the code incorporates a randomization process. Initially, a random value between 0 and 1 is selected. If this value is less than 0.238 (40/168), it signifies that the incident occurred during weekdays and within normal working hours. The proportion of 0.238 is determined by considering that there are 168 hours in a week, of which normal working hours constitute 40 hours (8 hours per day for 5 days).

If the random value is less than 0.238, indicating a weekday and normal working hours, the helicopter preparation time is randomly chosen from a normal distribution. The mean of the distribution is set to 20 minutes, with a standard deviation of 10 minutes. It is important to note that no values greater than 30 minutes are considered in this case.

On the other hand, if the random value exceeds 0.238, it implies that the incident occurred outside of weekdays and normal working hours. In this scenario, the helicopter preparation time is randomly selected from a normal distribution with a mean of 90 minutes and a standard deviation of 30 minutes. The maximum value considered in this case is 120 minutes.

By incorporating this randomization process, the model introduces uncertainty and allows for the simulation of more realistic scenarios, where the preparation time can vary based on the time and day of the incident.

3.2.4 Phase Four: Flying Model

A sub-model was created to simulate the helicopter's flight and determine the optimal route between various locations, including the bases, potential re-fueling stations, the LKP, and the PID. The base is usually the starting point of the helicopter's flight and sometimes the location to which the rescued survivors are returned. It also provides facilities for refueling the helicopter. The model takes into account potential fuel stations that may be required for long-distance operations, such as local airports and offshore platforms.

The final location of the people in distress is considered as the final destination and is determined by the search model, which will be explained in the following phase five. The LKP is obtained through information provided during the distress notification phase described above. The sooner the distress notification is received and the greater the accuracy of the LKP, typically the shorter the search phase is.

For the current stage of model development, it is assumed that the helicopter follows a direct path (the shortest distance) between bases, fuel stations, and the last known position without taking into account any geographical features, such as high mountains or hills, or weather systems. When there are several fuel stations available, the model can decide which one to use by considering various factors such as the distance, amount of fuel available, and refueling rate. At each time step, the model checks the remaining fuel, the distance remaining to the next destination, and the location of the destination. The helicopter model can be adjusted to incorporate uncertainties, such as modifying the last known position based on updated information and weather conditions, which can affect the helicopter's speed and fuel consumption.

The model has the ability to simulate rescuing one or more individuals, even if it exceeds the helicopter's capacity, by using fuel caches to overcome range limitations. It is important to mention that the model prioritizes the safety of the aircraft and crew and will not make any decisions that put them at risk.

The model assumes a 30-minute refueling time for the helicopter if refueling stops are needed. However, in reality, longer-duration missions will require crew changes and maintenance stops, which are not taken into account in the model at this time.

3.2.5 Phase Five: Searching Model

To aid in search planning, computer programs have been developed to increase the probability of object detection at sea. Vidan et al. (2015) reviewed some of these programs, noting that each has its own strengths and weaknesses, which can impact their suitability for use in different conditions. While computer programs can be helpful, search planning can also be done manually. The focus of this phase of the model is to represent the time spent searching when the helicopter has reached the LKP. This could be done by representing the different search patterns typically used in helicopter searches, however, weather and ocean conditions can significantly affect the total search time and the likelihood of detecting a vessel or people in distress. Reduced visibility due to fog or storm conditions, for example, can make it challenging to spot objects or individuals from the air. Similarly, rough sea states can make it difficult to detect smaller objects such as life rafts or people in the water. Time of day is also a crucial factor to consider, as it can affect visibility and search effectiveness. The altitude of the helicopter, as well as the shape of the object or vessel being searched for, can also impact search time and success.

Given the significant number of unknowns associated with representing the physics of searching for and detecting targets, it was decided that this phase of the model would not simulate different search patterns or specific real-world search operations. Instead, the model randomly chooses a search time for each run from a distribution of search times, which is assumed to be normally distributed with a mean of 30 minutes and a standard deviation of 10 minutes. When sufficient historical data becomes available, the representative distribution will be incorporated. Also, in the scenarios presented in this research, it is assumed that the PID has used a PLB or EPIRB for distress notification for which their location is accurately known. The effects of weather conditions are discussed in phase seven.

To represent the search process, a random location for the PID is selected within a search area with a 6 nautical miles (nm) radius around the LKP. The chosen search area with a 6 nm radius was determined based on the guidelines outlined in the National SAR Manual, Chapter 7, and was selected to be a starting point to simulate the real-world searching operation.

For each run of the model, the helicopter flies from the LKP to the randomly selected location to begin the rescue operation. This new location is considered the model's final destination in the case of multiple travel scenarios.

3.2.6 Phase Six: Rescue Model

The rescue time for the helicopter operation encompasses the required time for airlifting survivors from the water, lifeboat, or sinking or damaged vessel to the helicopter. The weather conditions, ocean conditions, and survivors’ conditions (e.g., the severity of their injuries), in reality, affect the rescue time.

The rescue time may be influenced by various factors such as the prevailing weather and ocean conditions, as well as the medical state of the survivors, which could determine the severity of their injuries. Unfavorable weather conditions such as strong winds, high sea states, and poor visibility may hinder rescue operations by making it difficult for the helicopter to reach the location or to operate effectively. Similarly, rough ocean conditions could lead to difficulties in reaching and retrieving survivors. Survivors with severe injuries or disabilities may require additional time and resources to be lifted to the helicopter, which could impact the overall rescue time.

Kennedy et al. (2013) provided an estimation of rescue time per person for air facilities, which ranged from 10 to 30 minutes. However, in this model, the rescue time per person is not assumed to be fixed but rather varies with different weather and incident scenarios and is randomly chosen for each lift. To obtain more realistic estimates, the model uses historical data to extract the rescue time distribution for each scenario. By randomly selecting a rescue time per person from the distribution, the model simulates the variability and uncertainty associated with actual rescue operations. The total rescue time is calculated by summing the rescue times per person rescued.

The model randomly selects the rescue time per person from a normal distribution with a mean of 5 minutes and a standard deviation of 2 minutes. The distribution is expected to be refined as available representative data is available. As emphasized before, the safety of the helicopter and crew is the top priority in this model. Therefore, the weather conditions and remaining fuel are monitored in every time step to determine the range of the helicopter. Sometimes, the rescue operation is halted to allow for refueling, and if there are still PIDs in the area, the helicopter returns to the location to continue the rescue operation. This approach ensures the safety of the aircraft and its crew while minimizing the risk of not completing the rescue operation.

3.2.7 Phase Seven: Weather Effect

The impact of weather conditions on SAR operations is a critical factor to consider for successful outcomes. However, this study highlights that weather effects are not just limited to a dedicated phase but are implemented throughout the entire model, including the decision-making phase.

Previous SAR papers have also emphasized the importance of considering weather effects on SAR operations. For example, Vidan et al. (2015) discussed the impact of weather on the effectiveness of various computer programs designed to increase the probability of object detection at sea.

Implementing weather effects in the SAR model is a complex task as it requires accurate and up-to-date information on changing weather conditions in each geographical location and their realistic effects on each phase of the SAR operation. The weather conditions can significantly affect the helicopter's ability to fly, speed, fuel consumption, and rescue time for each person. For instance, cold and freezing weather conditions may prevent helicopters from flying, while high-speed winds and storms can reduce the helicopter's speed and increase fuel consumption. The wind direction is also a critical factor that can affect the helicopter's speed. Additionally, fog can reduce visibility, leading to longer search times and longer rescue times for each person. Thus, it is crucial to incorporate accurate weather data and their real impact on SAR operations in the model to improve its effectiveness. The present study involves an initial implementation of a weather factor, with the aim of a more detailed representation of weather effects in future research.

To implement the weather factor, the model has considered two seasons: summer and winter. In addition, four weather conditions have been defined, each with a corresponding weather coefficient factor: very good (factor = 1), good (factor = 0.99), bad (factor = 0.97), and very bad (factor = 0.96). While the Arctic might require dividing the seasons into six sub-seasons, for this study, two seasons were selected as a starting point. The weather coefficient factors are not fixed and can be updated as more real-world data becomes available. The model creates a normal distribution for each season such that during summer, very good and good weather conditions are more likely, whereas during winter, bad and very bad conditions are more common. As the operation progresses, the model generates a weather forecast by selecting a weather condition for each time step from the corresponding distribution, thereby creating a new distribution specific to that time step. The helicopter actively considers the prevailing weather condition and its associated factor at each time step, adjusting its action and decision-making accordingly.

Before each helicopter movement, the weather coefficient factor is selected from the weather forecast distribution. If the factor is 0.96 or lower (indicating very bad weather), the helicopter remains at the base or fuel station and checks the weather again after 30 minutes by selecting another factor from the distribution. Notably, due to the higher probability of random selection bad or very bad weather conditions during winter, the likelihood of obtaining good or very good weather conditions is very low. Consequently, bad weather conditions are more frequently selected. However, if the selected weather is bad or good, the helicopter flies, and the chosen coefficient factor is multiplied by the helicopter's speed. Conversely, if very bad weather is chosen again, the helicopter maintains its position at the base or station and rechecks the weather status after a 30-minute period.

Furthermore, before starting the search at the LKP, the helicopter checks the weather conditions again. If the weather is very bad, the helicopter returns to the base and remains there for 2 hours. After 2 hours, the weather is checked again, and if it is suitable for flight, the helicopter returns to the LKP to begin the SAR operation. The weather coefficient factor will affect the rescue time, and in the case of bad weather conditions, the rescue operation will take more time.

These effects have been thoroughly examined and described in the testing scenarios in Section 5.

3.2.8 Phase Eight: Multiple Helicopter Operations

While this phase is not specifically dedicated in the model, it does have the capability to select and coordinate two or three helicopters to collaborate on a mission.

In practical SAR missions, it would be necessary to deploy two or more helicopters simultaneously to cover a larger search area or to perform multiple rescue operations at the same time. Quan et al. (2018) recognized this need and proposed a novel model for planning the SAR routes for multiple helicopters at a single location. The model considers a variety of factors such as the number of helicopters available, their flight range, the size of the search area, and the need for refueling. The goal of the model is to find the optimal route plan that minimizes time and energy consumption while maximizing the probability of finding the object.

To achieve this objective, Quan et al. (2018) developed a strategy optimization algorithm that can quickly generate a set of candidate solutions. These solutions are then evaluated based on their performance criteria, such as the time required to complete the mission and the fuel consumption of each helicopter. The algorithm iteratively improves upon the initial solutions until it finds the optimal route plan that meets all the constraints.

Although the proposed method and model are highly effective, this research utilizes a simplified model and algorithm for SAR missions involving two or three helicopters. If the incident happened near the shoreline and/or near the helicopter base, the first helicopter will be responsible for flying to the LKP and initiating the search operation. Once the PID is located, the first helicopter reports it and begins the rescue operation. If two helicopters are selected, the second helicopter is deployed once the first helicopter completes the rescue operation and returns to the base. The second helicopter then flies from the base to the PID to continue the rescue operation.

If three helicopters are selected, one helicopter remains at the base, and the other two helicopters are deployed to the field. In the case of three helicopters, one helicopter is designated as the rescuer, while the second helicopter waits at a holding point near the first helicopter. Meanwhile, the third helicopter remains at the base until called upon. Once the first helicopter completes its mission and returns to the base, the second helicopter moves to the PID and begins the rescue operation, while the third helicopter moves to the holding point.

Alternatively, in cases where the incident occurs at a considerable distance from the shoreline or the helicopter base, such as in Arctic regions, the helicopters would collectively fly to the nearest base before commencing the rescue operation. This relocation allows for a more strategic approach, ensuring that the rescue efforts are effectively coordinated from the new base.

This process will be repeated until all the remaining survivors have been picked up.

In Section 5 of this document, a real case will be presented and analyzed to illustrate and further clarify the operational procedures described above.

3.2.9 Phase Nine: Disembarking the Survivors

Sometimes, the helicopter may need to discontinue its rescue operation due to various reasons, such as adverse weather conditions, low fuel levels, or when the number of individuals in distress exceeds its capacity. When such a situation arises, the helicopter would return to the base for refueling and to allow the rescued survivors to disembark.

The time required for disembarking the survivors can be affected by their physical condition, such as if they are injured or not. For the purposes of this research, it is assumed that the survivors are capable of disembarking on their own, and the time required for disembarking is selected randomly from a normal distribution. The mean value of the distribution is 0.5 minutes, and the standard deviation is 0.2 minutes. As new data becomes available, this assumption may be modified in future model updates.

3.2.10 Total Search and Rescue Time

The total SAR time is given as the time when the last survivor is rescued by the helicopter. However, this time is not found by deterministic means but rather depends on various factors such as weather conditions, fuel availability, number of survivors, and their conditions. These factors are influenced by random variables which are randomly chosen each time the simulation is run. Since the model uses a Monte Carlo approach, it generates a distribution of SAR times rather than a single value, which is based on the accumulation of these random factors in the model.

4 INPUT DATA

4.1 Sources

The initial plan for developing the model involved conducting thorough testing and modifications using data from reputable sources such as the Search and Rescue Management Information System (SARMIS) and the Transportation Safety Board (TSB) of Canada. However, it is worth noting that the availability of these crucial datasets was not provided during the timeframe of this thesis. As a result, the model had to be tested and validated using alternative approaches. Considering the limited available information, various scenarios representing typical or common SAR occurrences were carefully modeled. To assess the model's performance, the outcomes were rigorously compared against real-world data and distress reports (described in in Section 5), enabling an evaluation of its effectiveness and accuracy in simulating SAR operations.

Moreover, to enrich the model with industry expertise and insights, the modelling plan was discussed with experts from the SAR community in Canada. These discussions enabled the collection of information about the JRCC's action plans in real-life cases, serving as a foundation for creating realistic distributions and operation details within the model, aligning with their established working procedures and industry best practices. By incorporating expert knowledge and leveraging existing data sources, the model strives to provide a comprehensive and reliable representation of SAR operations.

4.2 Main Parameters

The model requires several key parameters to be identified as input, which significantly shape the SAR operation. These parameters are as follows:

1- **Location of the Incident (LOI):** The LOI serves as the initial input data for the model, which in the early stages of the operation is the Last Known Position (LKP) discussed previously. This crucial information determines the deployment of facilities and aids in establishing the appropriate response strategy. The model can accurately plan the SAR mission by identifying the LOI.

2- **Number of People in Distress (PID):** At the outset of the simulation, it is essential to determine the number of individuals in distress. This parameter influences the overall duration of the SAR operation and plays a crucial role in decision-making processes. Knowing the number of people in distress helps determine the required resources and facilitates effective deployment strategies to address the situation promptly.

3- **Helicopter Base(s) and Fuel Stations' Locations:** As previously mentioned, the helicopter base serves as both the departure point for helicopter flights and (typically) the destination for returning rescued survivors. Additionally, it plays a crucial role in providing refueling facilities for helicopters. To ensure the effectiveness of the model, it considers the inclusion of potential fuel stations that may be required for longer distance operations, such as local airports and offshore platforms.

   The flying sub-model within the simulation requires the accurate identification and specification of the locations of these bases and fuel stations. By incorporating this information, the model can accurately simulate the flight paths and fuel requirements of the helicopters during SAR missions, considering the availability and proximity of the designated bases and fuel stations. For the present stage of development, the model assumes that fuel stations have an unlimited supply for helicopter operations.

4- **Helicopter Specifications:** The model considers various helicopter specifications, such as fuel tank capacity, maximum speed, maximum range, passenger capacity, and other relevant factors. These specifications are essential in accurately representing the capabilities and limitations of the deployed helicopters. Considering these parameters, the model can optimize resource allocation, fuel consumption, and transportation capacity during the SAR mission.

5- **Quantity of Deployed Helicopters:** Another critical input parameter is the number of helicopters deployed to the LOI. This factor directly impacts the effectiveness and efficiency of the SAR operation. Determining the appropriate number of helicopters ensures adequate coverage, enhances search capabilities, and enables simultaneous rescue efforts, especially in situations involving many people in distress or extensive search areas. For the current state of development, the model does not represent the actual number of helicopters at a given base, rather, the number deployed is an input parameter.

6- **Season:** The season selection at the simulation's beginning is a pivotal decision that influences the entire SAR operation. The season determines the prevailing weather conditions, including temperature, wind speed, direction, precipitation, and visibility. By specifying the season, the model represents weather conditions, which affect various aspects of the SAR mission, including search time, rescue operations, and overall operational efficiency.

5 VERIFICATION USING TEST SCENARIOS

In this section, a series of simple verification test cases were developed to examine the effectiveness of the model at a basic level. Initially, manual calculations were performed by hand to establish a baseline for comparison. Subsequently, the model was implemented in MATLAB code, and the results obtained were tabulated to facilitate a comprehensive analysis.

To provide a clearer understanding of the formulas employed in these calculations, Appendix B has been included. Throughout the subsequent verification tests outlined below, it's important to note that fixed values were employed in the manual calculation for the times that the model randomly selects, such as rescue time and search time.

5.1 Test 1: Simple Rescue Operation, No Searching, No Refueling.

In this case study, the investigation revolves around a scenario where a single individual is in distress, and the precise location of the incident is already known. The obtained results from the analysis are summarized and presented in Table 1.

Input Data:

Base Location: 52.5146, -56.3489

PID Location: 53.0956, -54.3508

PID No.: 1

Rescue Time for 1 person: 5 minutes (in manual calculation)

Table 1: Verification Test No. 1

Test 1	Calculated Distance (km)*	Distance from Code (km)	Calculated Total Time (min)**	Total Time from Code (min)	Rescue time for 1 person (min) from code
	149.04	149.04	69.5	68.14	3.6

*: Calculated Distance with google map measure distance tools.

**: For calculation the total time, helicopter speed has been considered 277 km/h.

As evident from the comparison between the results obtained from manual calculations and the code implementation in Table 1, the disparity between the two is minimal. The slight variation can be attributed to the fact that in the manual calculations, a fixed value of 5 minutes was assumed as the rescue time for a single individual, whereas the code incorporates a random number generation mechanism, which in this specific instance resulted in a value of 3.6 minutes.

5.2 Test 2: Simple Rescue Operation, No Searching, But Refueling is Needed

In this case study, the helicopter needs to be refueled, but there is no need to search, it means that the location of incident can be updated. The obtained results from the analysis are summarized and presented in Table 2.

<u>Input Data:</u>

Base Location: 52.5146, -56.3489.

Fuel Station Location: 54.575547, -57.536165.

PID Location: 56.464938, -61.024402.

PID No.: 1

Rescue Time for 1 person: 5 minutes (in manual calculation)

Refueling Time: 30 minutes

Table 2:Verification Test No.2

Parameters	Verification Test 2 Values	
	Calculated	Code
Distance (km) between the base and fuel station	242.21	242.21
Distance (km) between the fuel station and PID	303.83	306.64
Distance (km) between the PID and base	532.78	532.94
Total Time	268.67	269.94
Rescue time for 1 person	5	5.6

5.3 Test 3: Simple Rescue Operation, No Refueling, But Searching is Needed

In this case study, helicopter flies to the last known position and start the searching to find the PID location, but there is no need to refueling. The obtained results from the analysis are summarized and presented in Table 3.

Input Data:

Base Location: 52.5146, -56.3489

LKP Location: 53.0956, -54.3508

PID Location: 53.0755646513421, -54.1790622940594 (this location is identified randomly by code)

PID No.: 1

Rescue Time for 1 person: 5 minutes (in manual calculation)

Search Time: 30 minutes (in manual calculation)

Table 3: Verification Test No.3

Parameters	Verification Test 3 Values	
	Calculated	Code
Distance (km) between the base and LKP	149.04	149.04
Distance (km) between the LKP and PID	11.82	11.79
Distance (km) between the PID and base	158.75	158.66
Total Time	104.22	105.56
Rescue time for 1 person	5	7.1
Search time (min)	30	31.8

5.4 Test 4: Simple Rescue Operation, Both Searching and Refueling are Needed

In this case study, both searching and refueling are needed. The results from the analysis are summarized and presented in Table 4.

Input Data:

Base Location: 52.5146, -56.3489

Fuel Station Location: 54.575547, -57.536165

LKP Location: 56.464938, -61.024402

PID Location: 56.4638429646223 , -61.1467849117915 (this location is identified randomly by code)

PID No.: 1

Rescue Time for 1 person: 5 minutes (in manual calculation)

Search Time: 30 minutes (in manual calculation)

Refueling Time: 30 minutes

Table 4:Verification Test No.4

Parameters	Verification Test 3 Values	
	Calculated	Code
Distance (km) between the base and fuel station	242.21	242.21
Distance (km) between the fuel station and LKP	303.83	306.64
Distance (km) between the LKP and PID	7.52	7.9
Distance (km) between the PID and base	537.19	537.36
Total Time	301.26	292.53
Rescue time for 1 person	5	5.9
Search time (min)	30	21.34

5.5 Summary of Verification Tests

The fact that all the results obtained from the code closely match those derived from manual calculations is an indication of the model's reliability and the code's ability to generate accurate estimations. This close alignment demonstrates that the implemented approach successfully captures the essential aspects of emergency response dynamics. While acknowledging the presence of uncertainties resulting from random data selection, the overall agreement between the code's results and the manual calculations suggests that the model and code perform acceptable estimates of total helicopter SAR time.

6 VALIDATION USING TEST SCENARIOS

Validation involves comparing the model components as a whole with real or realistic measured results, providing a more comprehensive assessment. However, validating complex systems like SAR can be challenging due to limited granularity and data availability. Fortunately, the 2019 incident involving the Viking Sky cruise ship offers a unique opportunity for validation testing. In this incident, helicopters were exclusively used for rescuing a substantial number of people, and detailed information about the incident is well-documented and publicly available.

To ensure accuracy for this validation test, two primary sources were utilized: "Assessment of Viking Sky Incident" by The Norwegian Directorate for Civil Protection and Emergency Planning (DSB) 2020, and "Interim Report 12 NOVEMBER 2019 on the Investigation into the Loss of Propulsion and Near Grounding of Viking Sky, 23 MARCH 2019" by the Accident Investigation Board Norway. These reports served as essential references for accurately simulating the accident scenario and validating the model's performance. By aligning the simulated outcomes with the actual incident data, it was possible to assess the model's reliability and effectiveness in representing real-world situations.

6.1 Viking Sky Validation Case Study (Information from Accident Report)

In March 2019, the Viking Sky cruise ship encountered a critical incident near the Norwegian shoreline. The ship, carrying a large number of passengers and crew members, experienced engine failure in rough seas and stormy weather conditions. As a result, the vessel lost propulsion and started drifting dangerously close to the rocky coast. The incident prompted a large-scale SAR operation involving multiple entities, including the Norwegian Joint Rescue Coordination Centre, local authorities, and nearby vessels. Helicopters were dispatched as the primary means to airlift passengers from the ship's deck (DSB, 2020.).

Despite the formidable challenges posed by turbulent waves and adverse weather conditions, the helicopter rescue operation proved to be a remarkable success. Over the course of 18 grueling hours, a total of 475 individuals were evacuated from the stricken cruise ship. This included 466 passengers from the Viking Sky and nine crew members from the nearby vessel Hagland Captain. The rescue teams exhibited exceptional coordination, professionalism, and unwavering determination throughout the operation, ensuring the safety and well-being of every individual involved (DSB, 2020.).

The successful outcome of the Viking Sky incident exemplified the exceptional SAR capabilities of Norway. The collaborative efforts of multiple organizations, including the JRCC, local authorities, and dedicated individuals, showcased the country's preparedness and effectiveness in handling such a challenging maritime emergency.

6.1.1 Viking Sky Case Study - Input Data

As described in Section 4, the model relies on various input data to facilitate incident simulation. The following essential data parameters are utilized within the simulation framework:

1- **Last Known Position of People in Distress:** In the sequence of events, the initial incident took place at coordinates 63.005° N and 6.99333° E (AIBN, 2019.). As the Viking Sky cruise ship attempted to hold position using two anchors, it encountered difficulties and started drifting towards land, specifically near Male near Hustadvika. The deployment of the anchors effectively slowed down the drift towards nearby shoals, preventing the ship from running aground. To mitigate the situation, one of the ship's engines was successfully restarted, providing additional power along with the weight of the anchor chains to halt the drift. Although the ship managed to hold its position, the circumstances remained uncertain and critical. With the vessel now only 100 meters away from the land and near the nearest shoal, the ship experienced significant movement due to the large swells (DSB, 2020.). Given the severity of the situation, both the captain of the Viking Sky and the Joint Rescue Coordination Centre for Southern Norway (JRCC-SN) agreed that the evacuation of passengers should commence. While the precise location of the ship at that moment was not explicitly reported, a location approximately 100 meters away from the land was considered as the designated People in Distress location. For the purposes of the simulation, this PID location was established at coordinates 62.97387° N and 7.07092° E.

The geographical positioning of the Viking Sky and the Brynhallen that was designated as helicopter base are shown in Figure 4.

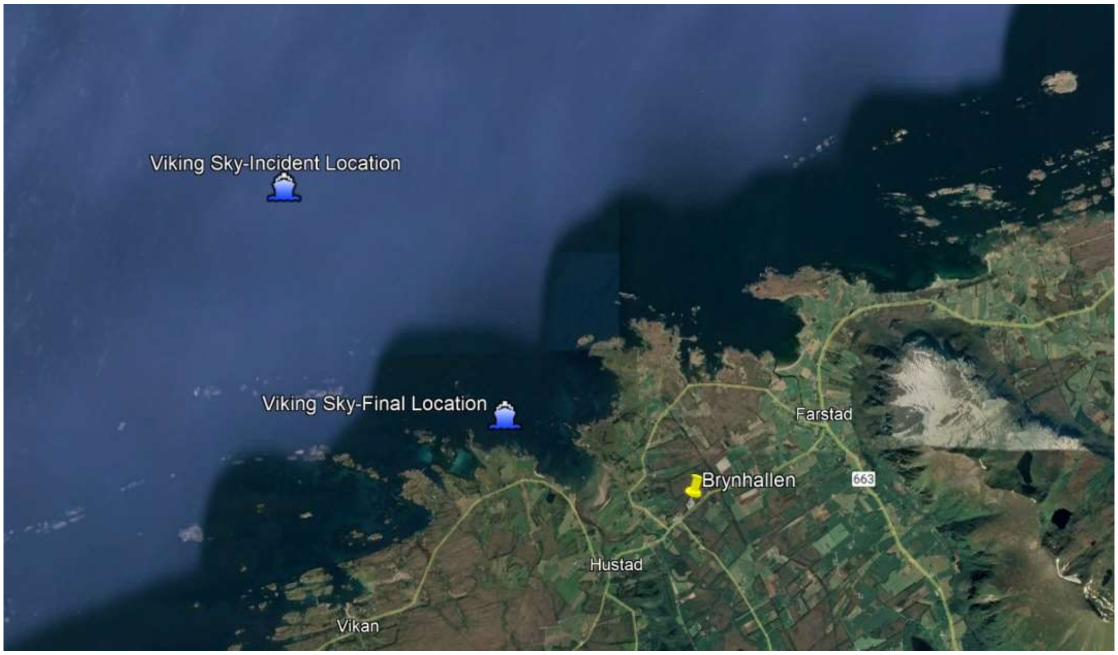

Figure 4: Viking Sky Incident Location and Helicopter Base (Brynhallen) Location (Google Earth Pro. Image)

2- **Number of People in Distress:** As mentioned before, a total of 475 individuals were evacuated from the stricken cruise ship.

3- **Season:** In the simulation, the accident is assumed to have occurred during the winter season. As a result, the model incorporates corresponding distributions and weather forecasts specifically tailored for winter conditions. These winter-specific parameters are utilized to represent the environmental factors and challenges associated with SAR operations during this season.

4- **Searching Time:** The searching time in the model is a crucial aspect of the SAR operation. However, in this case where the LKP and PID are accurately reported and updated, and the final location of the ship is near the shore and visible, the need for an extensive searching phase in the modelled case may be eliminated. By skipping the searching phase and considering a searching time of zero in the simulation, the model reflects the specific circumstances where immediate visual identification of the distressed vessel is possible. This eliminates the need for extensive search efforts and expedites the rescue operation as happened in reality.

5- **Helicopter Base and Refueling Station:** The decision has been made to designate Brynhallen as the primary reception center for individuals airlifted by helicopter from the cruise ship. To facilitate efficient operations, the Police incident commander took measures to ensure that helicopters had access to refueling facilities near Brynhallen (DSB, 2020.). Instead of having to fly to the nearest airport, Molde Airport, for refueling, helicopters were able to conveniently refuel at Hustad Elementary and Junior High School (Hustad School), which is situated alongside Brynhallen. This strategic arrangement significantly reduced the time required for refueling. To facilitate the refueling process, a tanker that is typically utilized at Molde Airport has been transported to Hustad School. This ensured a seamless refueling operation and minimized any potential delays (DSB, 2020.).

In the simulation, the location of Brynhallen, situated at coordinates 62.96283° N, 7.11963° E, has been selected as both the base for helicopters and the designated fuel station.

6- **Type and Quantity of Deployed Helicopters;** JRCC-SN initiated an alert to public rescue helicopters on Ørlandet and in Florø, as well as to CHC Helicopter Service, which operates an SAR rescue helicopter at Kristiansund airport. The CHC helicopter headed towards Hustadvika (DSB, 2020.). By 15:00 h, the first vessels, namely MS Holmfoss, Bergen Viking, and Fiskenes, along with SAR helicopters from Florø's rescue helicopter base, arrived in the vicinity of Hustadvika. Subsequently, additional helicopters from both 330 Squadron (from Ørland, Norway) and CHC Helicopter Service joined the operation, preparing to evacuate passengers from the ship. Three rescue helicopters were actively engaged in the evacuation process, transporting passengers to the designated reception center at Brynhallen. Initially, attempts were made to employ two hoisting points simultaneously (bow and stern of the ship); however, due to safety concerns and turbulent wind conditions affecting the helicopters, hoisting passengers from more than one position on the cruise ship was deemed impractical. This limitation impacted the speed of the evacuation process. To ensure maximum safety and efficiency, a rotation pattern was established, incorporating Viking Sky, Brynhallen, and a designated holding area (DSB, 2020.).

In the simulation, three Cormorant helicopters, which share the same specifications as the CHC helicopters, were utilized to model the SAR operation. These helicopters followed a consistent rotation pattern, happened in the real operation, ensuring an organized and efficient approach to the rescue mission.

7- **Rescue Time Distribution:** The rescue operation presented significant challenges due to adverse weather conditions, rough seas, and a large number of older passengers with limited physical abilities. Evacuating individuals using lifting slings and stretchers became particularly demanding, especially during the initial lifts that involved multiple passengers with physical injuries. These factors contributed to the time-consuming nature of the rescue process. On average, it took approximately 2 minutes and 20 seconds to evacuate each passenger (DSB, 2020.).

   To simulate the rescue time in the model, a normal distribution was employed. The mean rescue time is set at 2 minutes, with a standard deviation of 20 seconds. By summing the rescue times per person, the model calculated the total rescue time for the operation.

8- **Confirmation of Distress Notification, Decision Making and helicopter Preparation Time:** In the simulation, it is assumed that the helicopters and their crews are prepared and ready for flight at the start of the simulation, which is set at time zero (15:30 h). Therefore, the confirmation, decision making, and preparation times are not taken into consideration in the simulation.

9- **Total Rescue Time:** The initial accident occurred on March 23, 2019, at 13:50h, and Viking Sky transmitted a Mayday call at 14:00h. Subsequently, the arrival of helicopters was delayed. By approximately 15:30h, the reception center was prepared to receive the first evacuees from Viking Sky. The evacuation operation continued into the following day, March 24, 2019, and by 09:30h, all 475 individuals had been successfully evacuated, marking the completion of the rescue mission (DSB, 2020.). The total rescue time conducted by helicopters amounted to approximately 18 hours.

6.1.2 Viking Sky Case Study - Outputs and Results

Using the input data described above, the simulation was conducted for 10,000 iterations, and the results of the total SAR time are presented in Table 5. Figure 5 illustrates the distribution of the total SAR time, providing an overview of the variability in the results. Additionally, Figure 6 displays the distribution of the weather forecast, which plays a crucial role in the SAR operation. It showcases the likelihood of different weather conditions occurring during the simulation. Furthermore, Figure 7 presents a sample operation timeline, depicting the status of the helicopters at each time step, including their locations and actions. These figures provide valuable insights into the performance and outcomes of the SAR model.

Table 5:Results for Viking Sky Scenario

Total SAR Time (h)		
50th Percentile	90th Percentile	99th Percentile
16.4	16.8	17.5

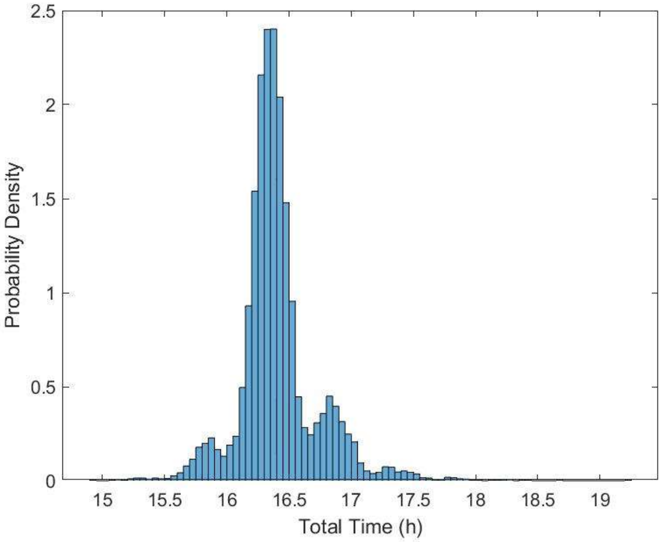

Figure 5: Viking Sky, Total Search and Rescue Time Distribution

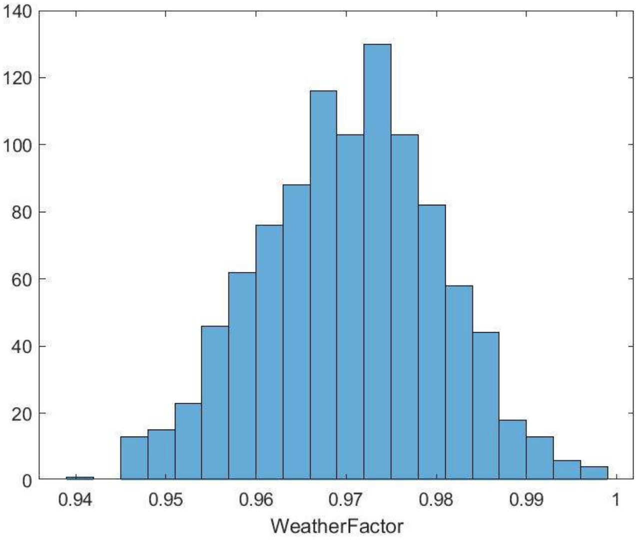

Figure 6: Viking Sky, Weather Forecast Distribution

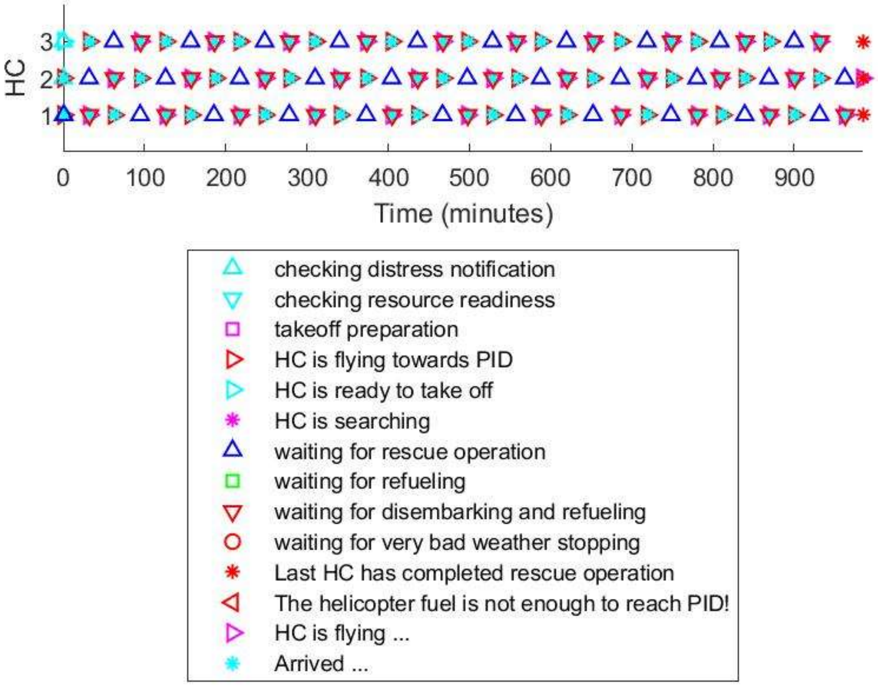

Figure 7: Viking Sky, Timeline of Sample Case

Based on the findings presented in Table 5, the SAR model successfully estimated the total SAR time with a relatively small deviation from the actual total SAR time observed in real-world scenarios. This indicates the model's capability to approximate the rescue time effectively. It is worth noting that if the precise weather forecast distribution for the given period had been available, the model's accuracy would be expected to have further improved, resulting in more precise calculations.

Furthermore, the operation timeline of the helicopters demonstrates their adherence to a consistent rotation pattern, reflecting the real-life operation. This consistency in the rotation pattern ensures that the rescue efforts are carried out efficiently, with each helicopter fulfilling its designated role within the SAR mission. The simulation accurately captured this aspect of the operational procedure, enhancing the realism and reliability of the model's outputs.

7 HELICOPTER MODEL TEST SCENARIOS

This section presents a series of test scenarios to demonstrate the functionality of the model. These scenarios build upon the research paper by Zarrin Mehr et al. (2023) and include additional tests conducted after the publication date.

To begin, the model is tested with four incident scenarios occurring in the coastal regions of Eastern Canada. These scenarios, denoted as A, B, C, and F, are thoroughly examined, and analyzed in Section 7.1.

Subsequently, the model was used to test to three incident scenarios in the Canadian Arctic region, labeled as D1, D2, and D3, as outlined in Section 7.2. These scenarios specifically focus on the unique challenges and characteristics of the Arctic environment. By testing the model in this context, we can assess its adaptability and effectiveness in extreme conditions.

Furthermore, an additional test was conducted to explore the impact of SAR base location on Arctic accident scenarios. This test examines how varying the location of the SAR base affects response times and overall efficiency in rescue operations.

7.1 Eastern Canada's Coastal Regions

Four scenarios, namely A, B, C, and F, have been created to simulate SAR incidents occurring in the Atlantic Ocean and the coastal areas of Newfoundland. In these scenarios, specific locations have been designated for survivor drop-off and fuel station purposes. The St. John's airport serves as the survivor drop-off base and fuel station, while the Hibernia offshore platform, situated on the Grand Banks, is identified as a potential fuel station. The geographical positioning of the Gander and St. John's airport bases, the Hibernia Platform, and the various scenario locations are shown in Figure 8. These arrangements facilitate a realistic simulation and enable an assessment of the model's performance in response to incidents in the specified regions.

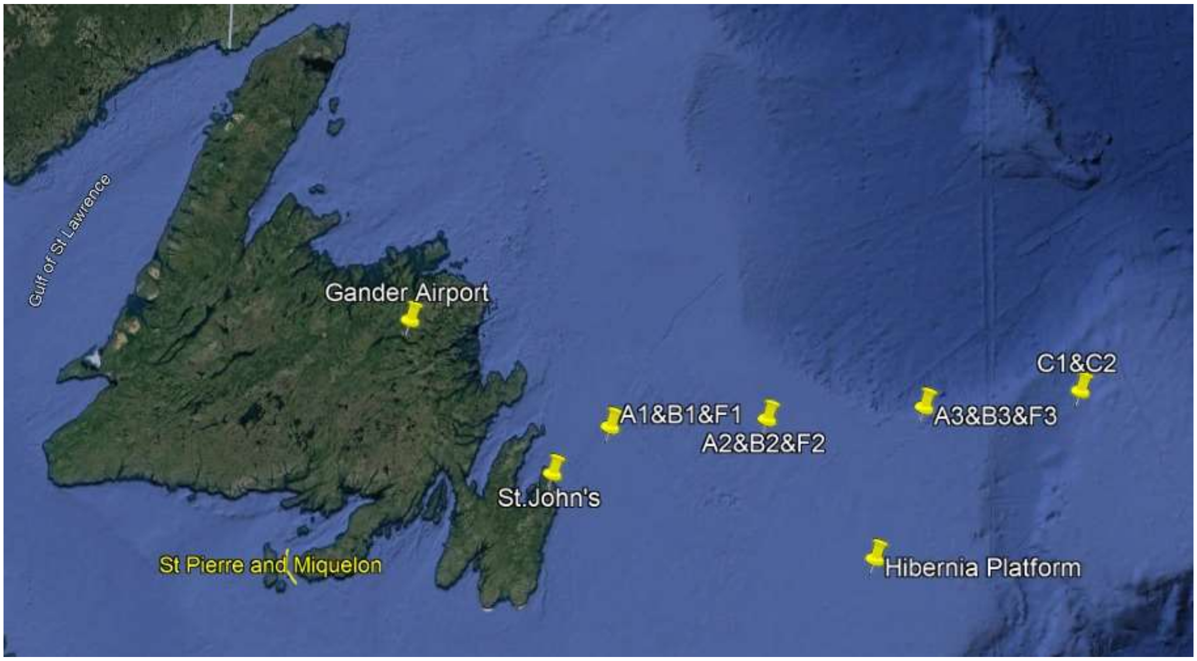

Figure 8: Scenario Locations, SAR bases, and Possible Fueling Stations in East Coast Canada (Google Earth Pro. Image)

7.1.1 Scenario A – Simulating a Single Individual in Distress

Scenario A focuses on a distress situation involving a single individual but show the effect of distance on SAR time for three designated locations: A-1, A-2, and A-3, which are detailed in Table 6. In this scenario, the deployment of a single helicopter is assumed. Additionally, the total times for various weather conditions are presented. To provide further insights, Figures 9 to 17 showcase the distribution of the total SAR time, flight map and the operation timeline of the helicopter specifically for the summer season, respectively. It is evident that there are minimal differences in the required SAR time between summer and winter scenarios, as the accidents occur near the base and shoreline. However, significant differences are observed in cases where the accident location is distant. It is important to note that the inclusion of a real weather forecast distribution would be necessary to accurately assess the model's capability in accounting for the weather factor. Nevertheless, the model demonstrates its ability to incorporate weather forecasts and integrate the weather factor into all calculations and simulations throughout the SAR operation.

Table 6:Input Data and Results for Scenario A

Case			**A-1**	**A-2**	**A-3**
Distance to Gander Airport (km)			**218**	**354**	**497**
Total SAR Time (h) for 1 HC	**Summer**	**50th Percentile**	3.2	4.2	6
		90th Percentile	3.9	4.9	6.6
		99th Percentile	4.2	5.2	7
	Winter	**50th Percentile**	3.2	4.3	6.1
		90th Percentile	3.9	4.9	6.7
		99th Percentile	4.2	5.2	7

In scenario A-1, depicted in Figures 9 and 10, the helicopter departs from Gander and flies to the LKP. After the searching phase, the location of the PID is determined, and the survivor is successfully retrieved. The helicopter then returns to St. John's without the need for refueling. As observed, the distribution of total time displays two peaks. The first peak corresponds to SAR incidents occurring during weekdays and normal working hours, while the second peak represents accidents happening on weekends and outside of normal working hours.

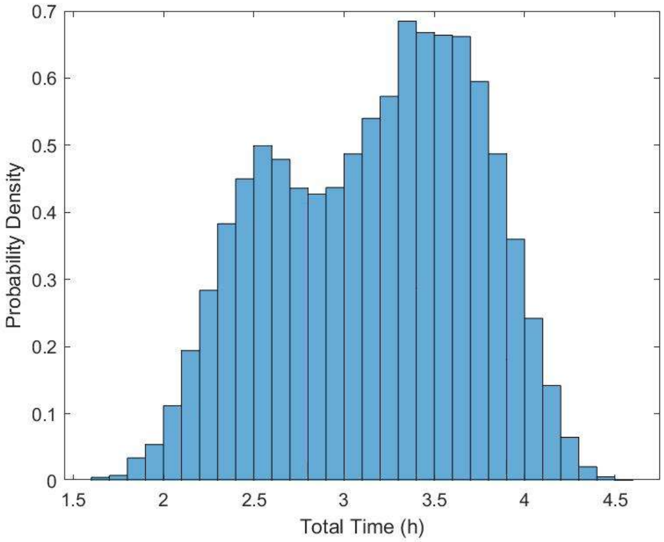

Figure 9: Case A-1, Total Search and Rescue Time Distribution

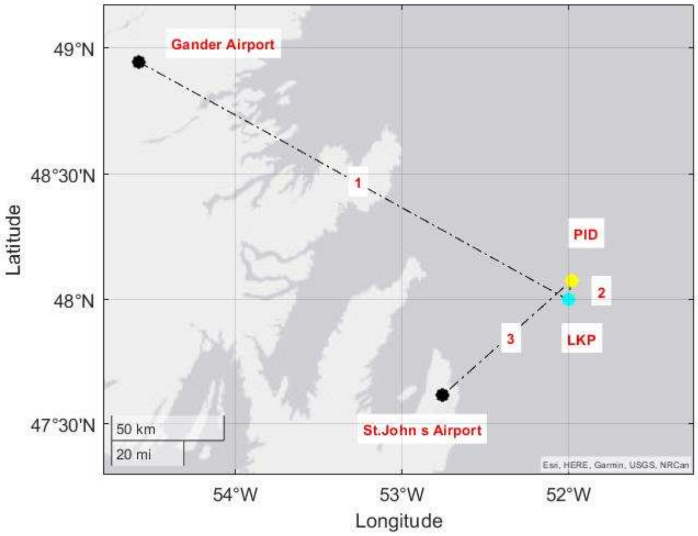

Figure 10: Case A-1, Flight Map of Sample Case

As depicted in Figure 11, for the sample case, the process of distress notification and resource readiness assessment requires approximately 25 minutes. Subsequently, helicopter preparation takes around 106 minutes before the flight commences at the 131st minute. The helicopter reaches the LKP at the 179th minute and initiates the search operation. At the 202nd minute, it arrives at the PID location and begins the rescue operation, which is completed within 7 minutes. Afterward, the helicopter departs for the base at the 209th minute and arrives at St. John's airport by the 226th minute.

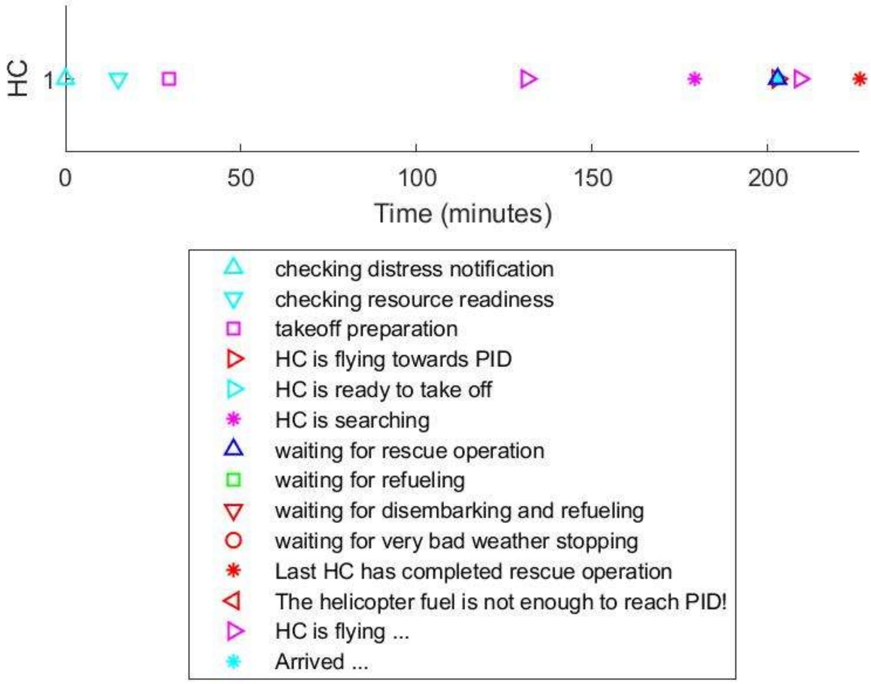

Figure 11: Case A-1, Timeline of Sample Case

In case A-2, illustrated in Figures 12 to 14, the flight map is similar to scenario A-1, however, the distance and the total SAR time are different.

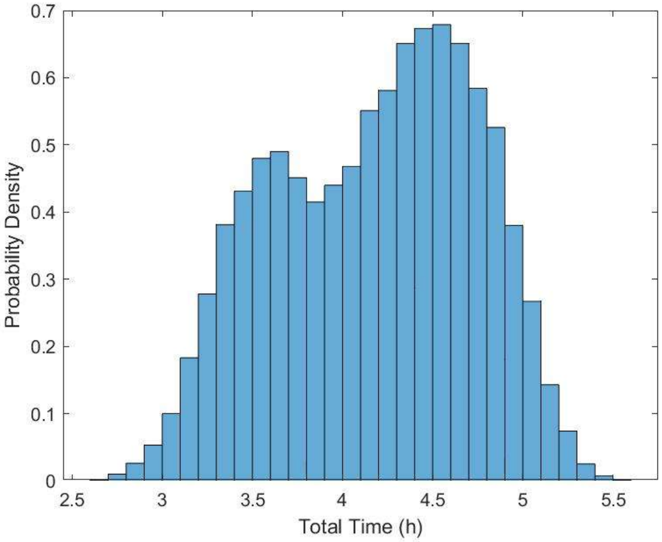

Figure 12: Case A-2, Total Search and Rescue Time Distribution

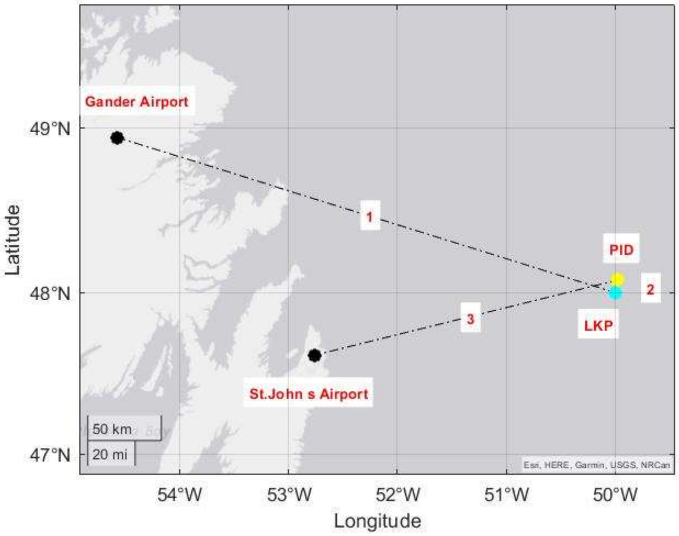

Figure 13: Case A-2, Flight Map of Sample Case

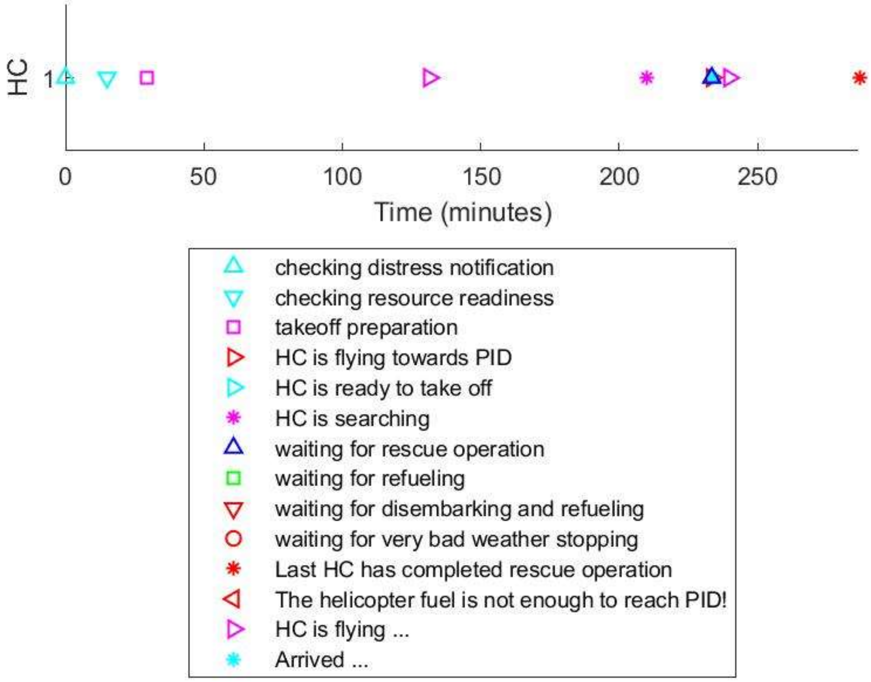

Figure 14: Case A-2, Timeline of Sample Case

In case A-3, illustrated in Figures 15 to 17, for the sample case, the helicopter files to St. John's for refueling and then flies to the LKP.

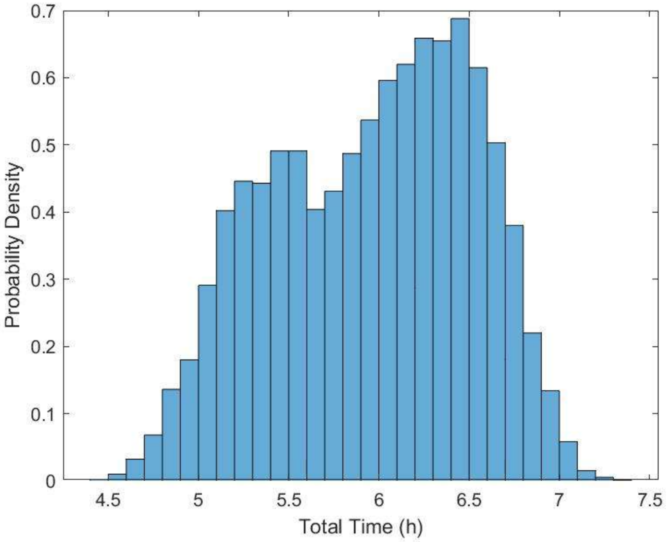

Figure 15: Case A-3, Total Search and Rescue Time Distribution

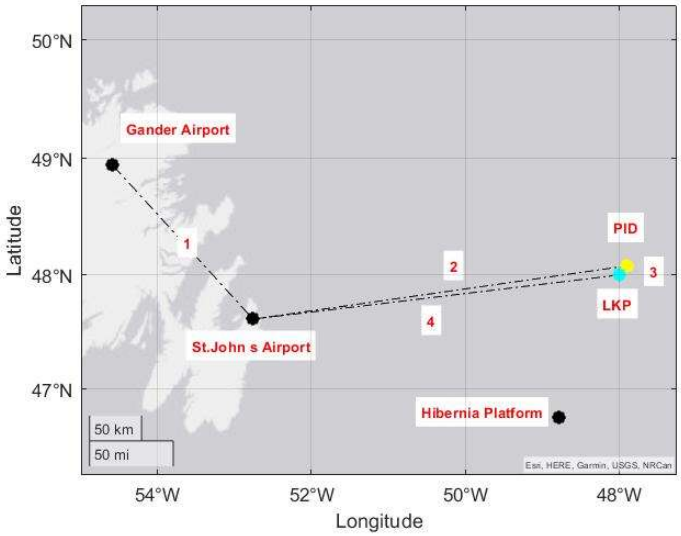

Figure 16: Case A-3, Flight Map of Sample Case

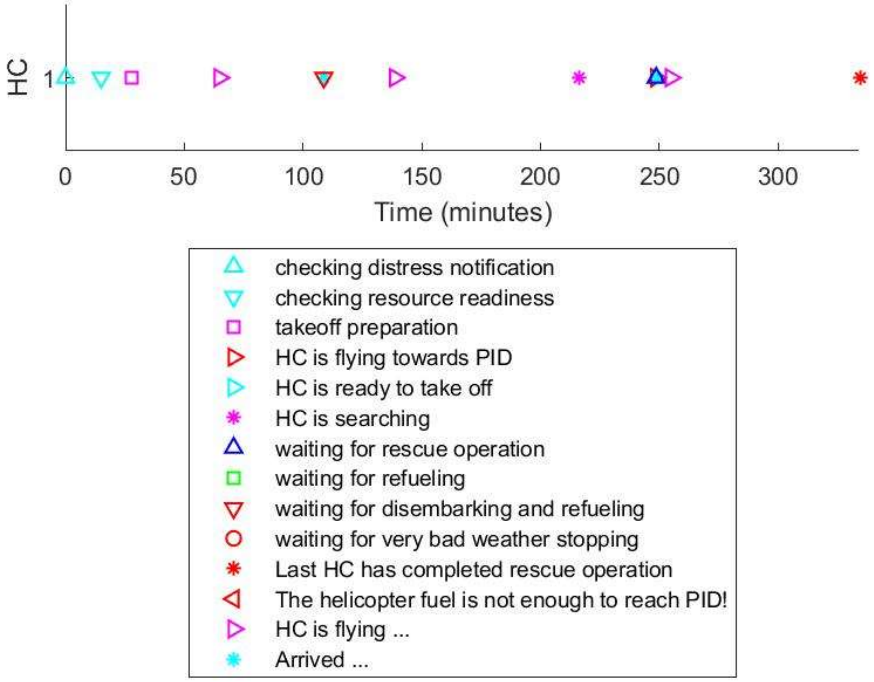

Figure 17: Case A-3, Timeline of Sample Case

7.1.2 Scenario B – Simulating 15 Individuals in Distress

In scenario B, the model simulates an incident involving 15 individuals in distress, utilizing the same locations as scenario A. The SAR operation is designed for both single helicopter and two helicopter deployments. The total times for different weather conditions are also provided.

In contrast, Scenario B involves a larger number of individuals in distress, and the impact of weather conditions on the total rescue time is significant. Similar to Scenario A, when the incident locations are far from the base and shoreline, the weather factor plays a crucial role and leads to substantial differences in the outcome.

Table 7 displays the incident location and model results for each case: B-1, B-2, and B-3. The distribution of total SAR time as well as the flight map and timeline of the helicopter specially for two helicopters and for summer season (Except case B-3) are shown in Figures 18 to 29 respectively.

Table 7:Input Data and Results for Scenario B

Case			B-1	B-2	B-3
Distance to Gander Airport (km)			218	354	497
Total SAR Time (h) for 1 HC	Summer	50th Percentile	4.4	5.4	7.6
		90th Percentile	5.1	6.1	8.7
		99th Percentile	5.4	6.6	9.1
	Winter	50th Percentile	4.5	5.5	7.8
		90th Percentile	5.1	6.2	8.8
		99th Percentile	5.5	7.4	9.2

Total SAR Time (h) for 2 HC	**Summer**	**50th Percentile**	4.4	5.4	7.6
		90th Percentile	5.1	6.1	8.7
		99th Percentile	5.4	6.6	9.1
	Winter	**50th Percentile**	4.4	5.5	7.8
		90th Percentile	5.1	6.2	8.8
		99th Percentile	5.5	7.4	9.2

In scenario B-1, where two helicopters are deployed, both helicopters take off simultaneously. The first helicopter flies directly from Gander to the LKP, while the second helicopter flies to the nearest base, which is St. John's airport, and waits there. Once the first helicopter reaches the LKP, it initiates the search operation to locate the PID location. In most cases, all 15 survivors are picked up by the first helicopter. Afterwards, the first helicopter returns to St. John's. Since the PID location is often close to the base and the number of survivors is within the capacity of one helicopter, the second helicopter is not typically involved in the operation. Additionally, there is no need for refueling at any point during the operation. The flight map (Figures 19 and 20) and timeline of the helicopters reflects this result.

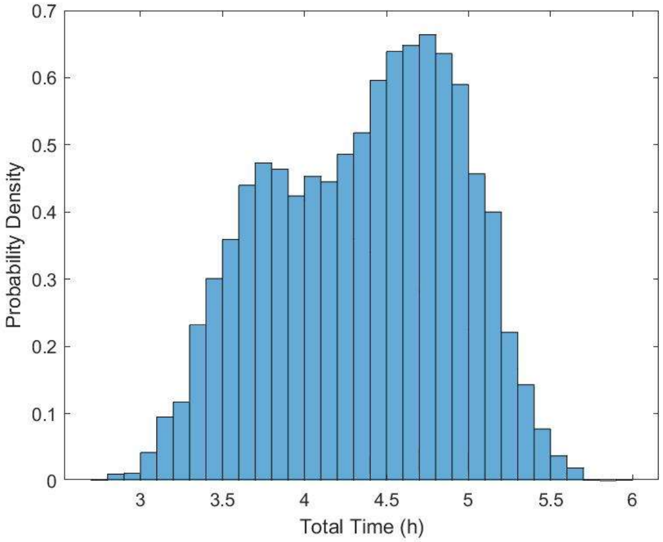

Figure 18: Case B-1, Total Search and Rescue Time Distribution

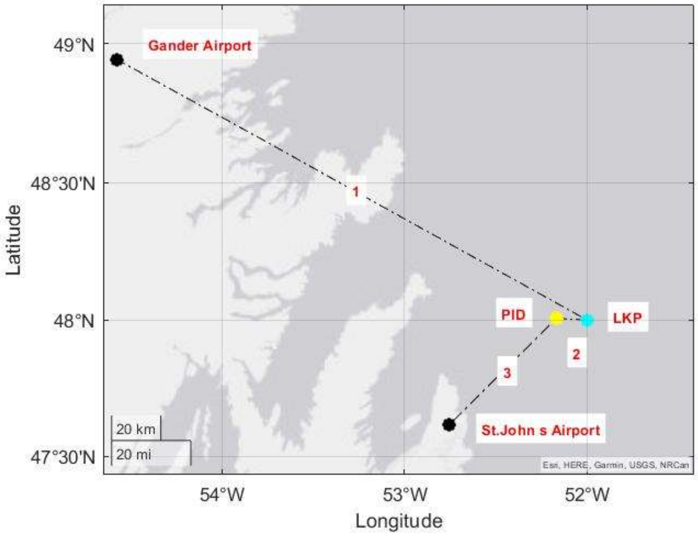

Figure 19: Case B-1, Flight Map of First Helicopter

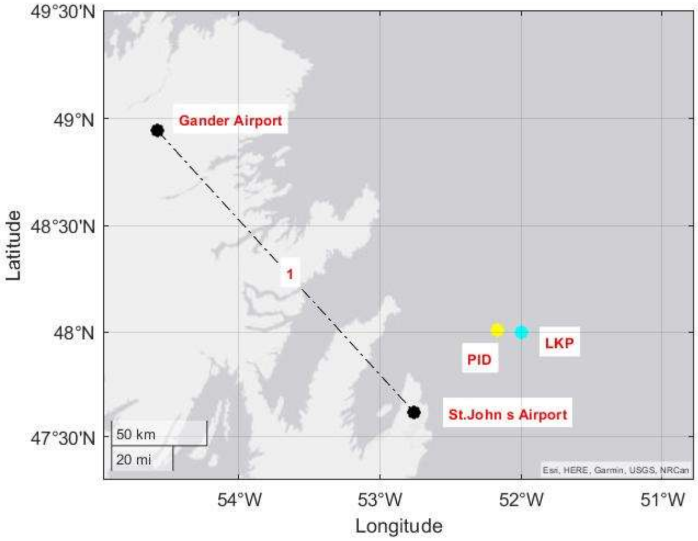

Figure 20: Case B-1, Flight Map of Second Helicopter

As depicted in Figure 21, the process of distress notification and resource readiness assessment requires approximately 25 minutes. Subsequently, helicopters preparation takes around 41 minutes before the flight commences at the 66th minute. Both helicopters start to fly, and second helicopter arrives in St. John's airport at 111th minutes and will wait there. The first helicopter reaches the LKP at the 115th minute and initiates the search operation. At the 149th minute, it arrives at the PID location and begins the rescue operation, which is completed within 84 minutes. Afterward, the helicopter departs for the base at the 233rd minute and arrives at St. John's airport by the 247th minute.

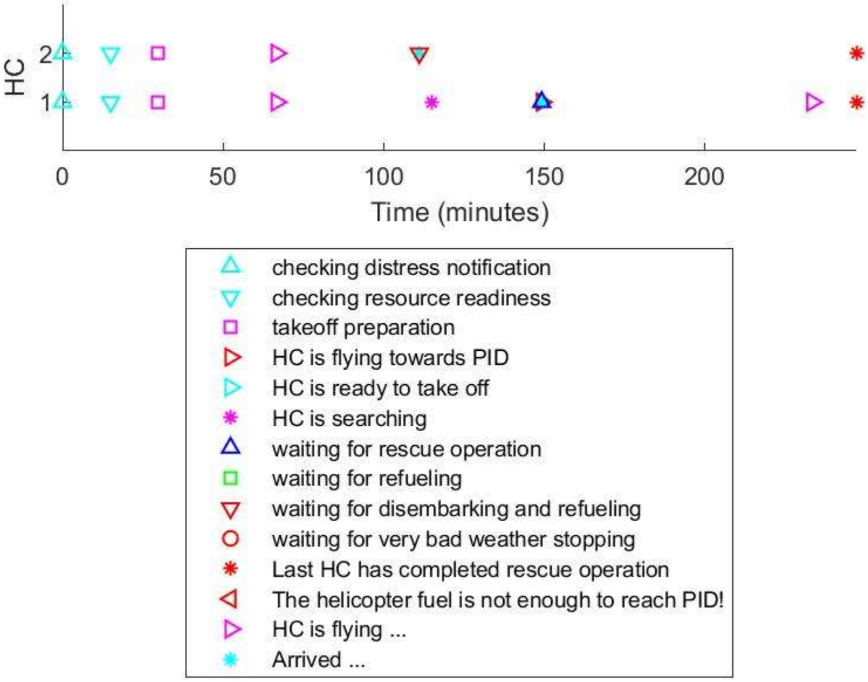

Figure 21: Case B-1, Timeline of Sample Case

In case B-2, the flight map and details of operation are like scenario B-1.

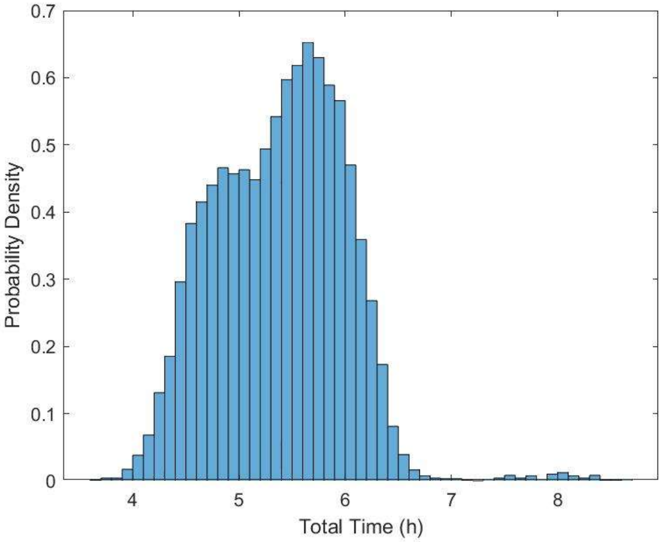

Figure 22: Case B-2, Total Search and Rescue Time Distribution

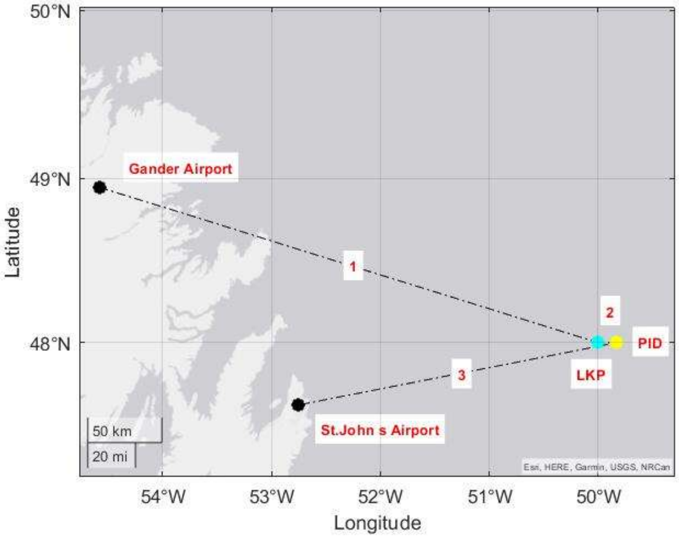

Figure 23: Case B-2, Flight Map of First Helicopter

Figure 24: Case B-2, Flight Map of Second Helicopter

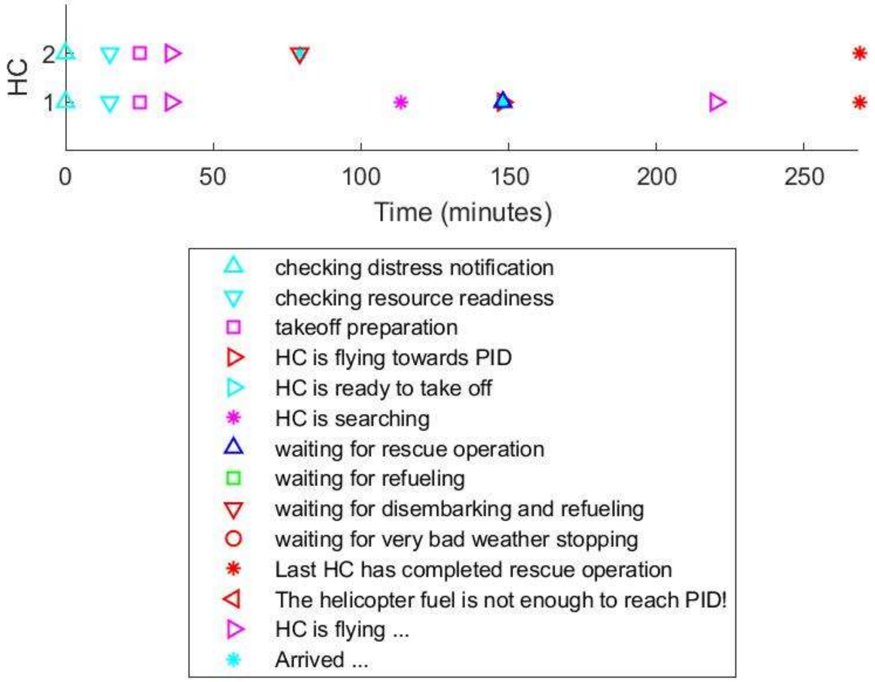

Figure 25: Case B-2, Timeline of Sample Case

In the case of B-3, the flight map (Figure 27 & Figure 28) follows a similar pattern to scenarios B-1 and B-2. However, in certain instances where the random search time is prolonged and the PID location is distant, coupled with unfavorable weather conditions, particularly in winter, the first helicopter may require refueling. the helicopter may initially pick up some survivors, then proceed to the Hibernia Platform for refueling, return to the PID location to rescue the remaining survivors, and finally return to St. John's. In some cases, the helicopter will first pick up all survivors and then proceed to the Hibernia Platform for refueling, before finally returning to St. John’s. The last specific scenario is illustrated in the accompanying figures for reference.

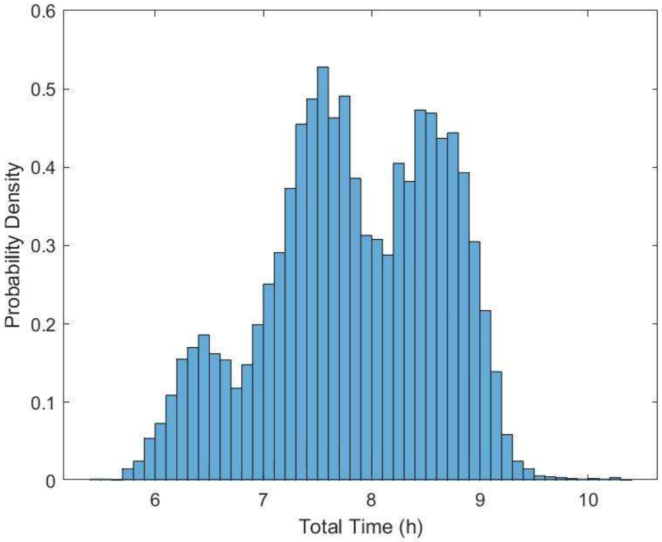

Figure 26: Case B-3, Total Search and Rescue Time Distribution

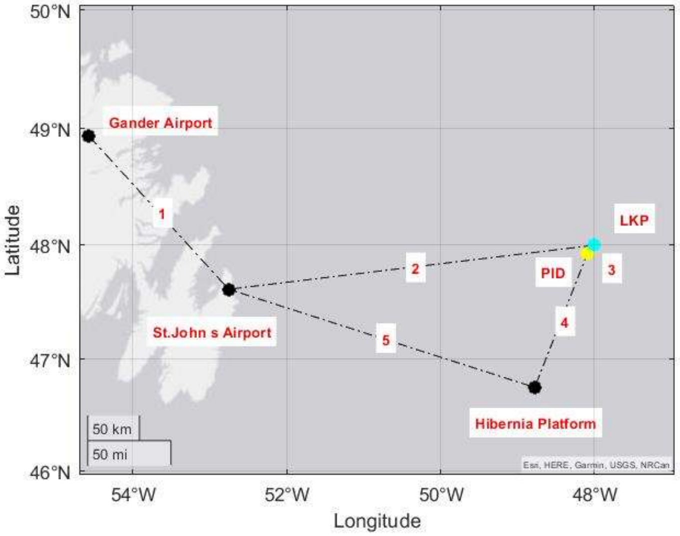

Figure 27: Case B-3, Flight Map of First Helicopter

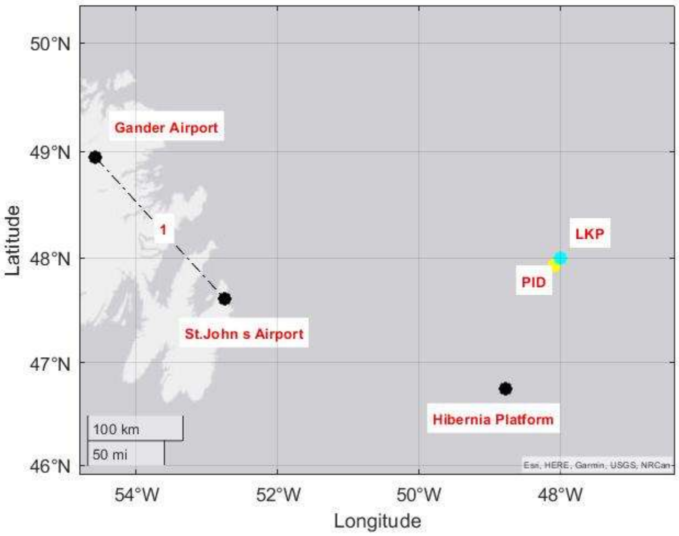

Figure 28: Case B-3, Flight Map of Second Helicopter

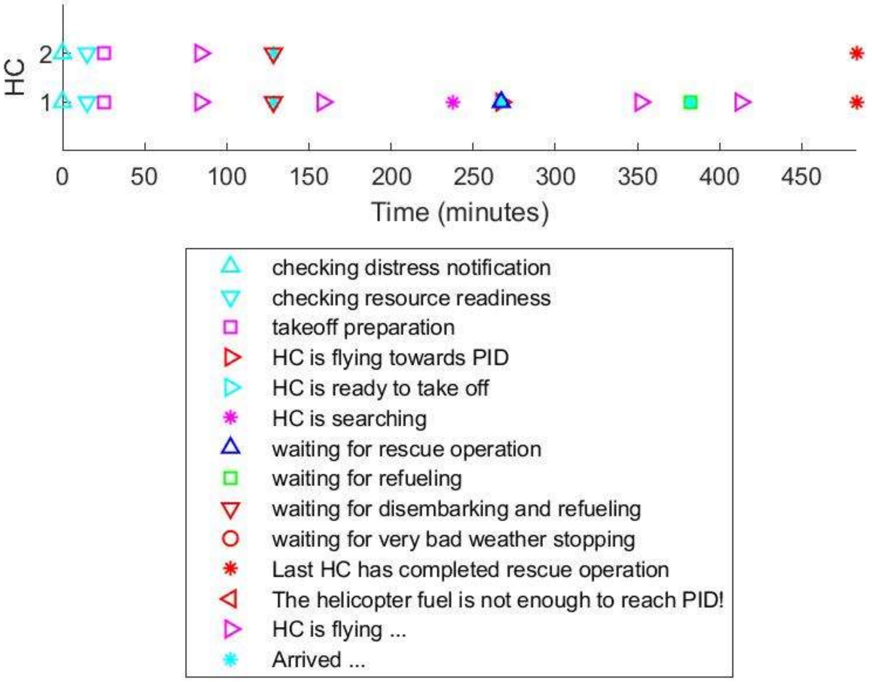

Figure 29: Case B-3, Timeline of Sample Case

7.1.3 Scenario C – Simulating Individual in Distress in Remote Locations

In Scenario C, the model considers an incident that occurred in a remote location away from the Eastern Coastal regions. Specifically, Cases C-1 and C-2 are simulated for the same incident location but with different numbers of individuals in distress. The incident location and corresponding model results are provided in Table 8. Additionally, Figures 30 to 36 illustrate the distribution of total SAR time and the flight map for a sample case in Scenario C.

In case C-1, where only one person is in distress, the number of survivors is manageable for a single helicopter. Consequently, the second helicopter usually isn't engaged in the operation. Therefore, in the testing scenario and in Table 8, the involvement of two helicopters has not been reported.

Table 8:Input Data and Results for Scenario C

Case			C-1	C-2
Distance to Gander Airport (km)			642	642
PID No.			1	15
Total SAR Time (h) for 1 HC	Summer	50th Percentile	7.8	10.5
		90th Percentile	8.4	11.2
		99th Percentile	8.8	11.6
	Winter	50th Percentile	7.6	10.7
		90th Percentile	8.5	11.3
		99th Percentile	8.8	11.8

Total SAR Time (h) for 2 HC	**Summer**	**50th Percentile**	-	10.5
		90th Percentile	-	11.2
		99th Percentile	-	11.6
	Winter	**50th Percentile**	-	10.7
		90th Percentile	-	11.3
		99th Percentile	-	11.8

In Case C-1, where there is one person in distress, the helicopter departs from Gander to St. John's. After refueling, it proceeds to the LKP and then to the PID location to pick up the survivor, before returning to St. John's. However, in certain situations where the search time is longer, the PID location is far, or the weather is unfavorable (even in summer), the helicopter may require additional refueling. In such cases, the helicopter retrieves the survivor, flies to the Hibernia Platform for refueling, and then returns to St. John's. The accompanying figures illustrate these scenarios during the summer season.

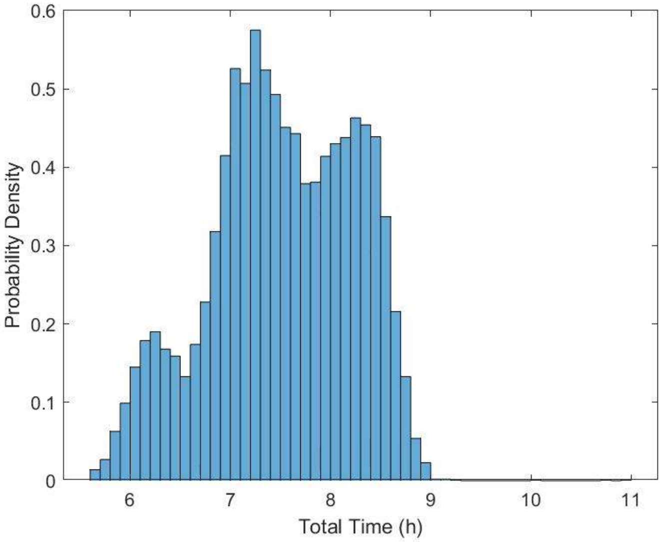

Figure 30: Case C-1, Total Search and Rescue Time Distribution

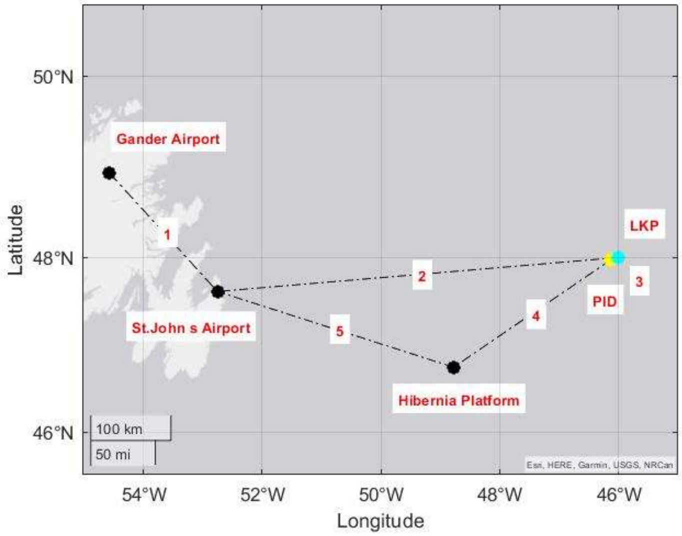

Figure 31: Case C-1, Flight Map of Helicopter

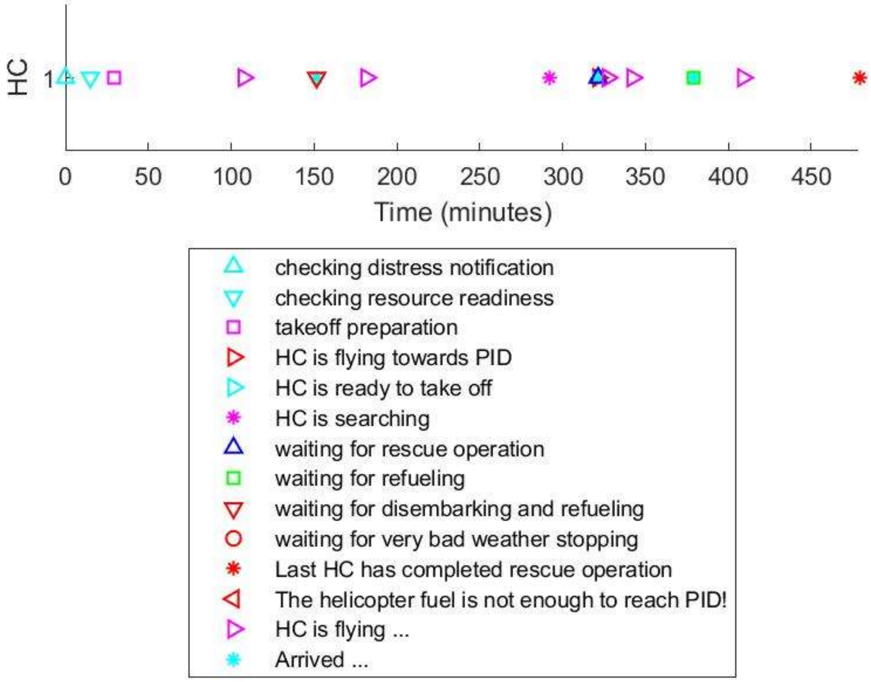

Figure 32: Case C-1, Timeline of Sample Case

In Case C-2, where there are 15 persons in distress, some flight maps resemble those in Scenario C-1. However, in most instances, the helicopter picks up some survivors and then flies to the Hibernia Platform for refueling. Afterward, it returns to the PID location to retrieve the remaining survivors before returning to St. John's. Similar to Scenario B, if two helicopters are deployed and the number of people in distress is less than the capacity of one helicopter, the second helicopter typically remains at St. John's airport and is not directly involved in the operation. The following figures illustrate this case during the summer season, when two helicopters are deployed.

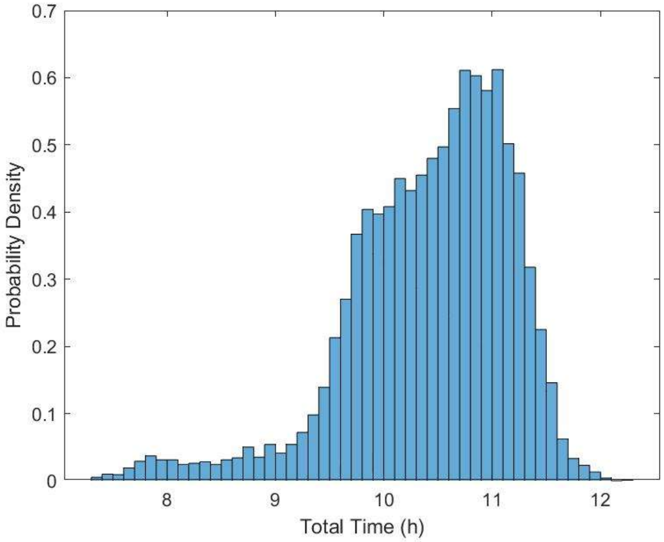

Figure 33: Case C-2, Total Search and Rescue Time Distribution

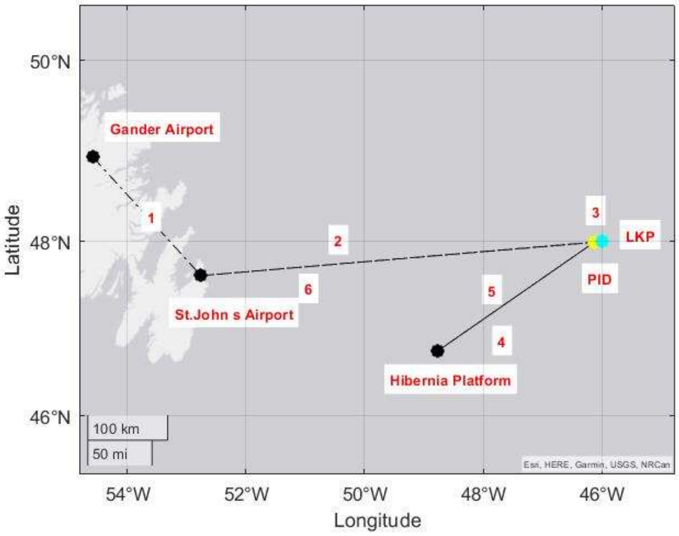

Figure 34: Case C-2, Flight Map of First Helicopter

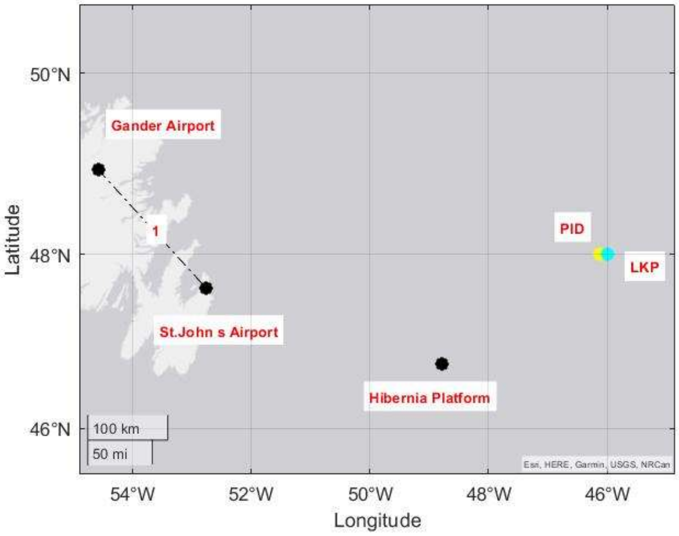

Figure 35: Case C-2, Flight Map of Second Helicopter

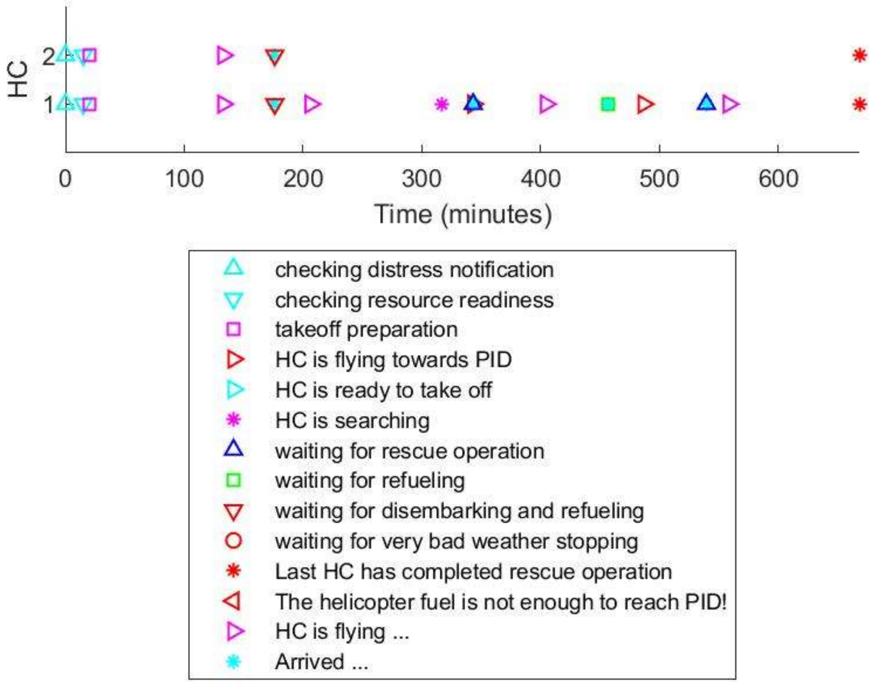

Figure 36: Case C-2, Timeline of Sample Case

7.1.4 Scenario F - Simulates 35 Individuals in Distress with Different Helicopter Deployments

In Scenario F, the model simulates an incident involving 35 individuals in distress, utilizing the same locations as Scenario A and B. The SAR operation is designed for single helicopter deployment, as well as two and three helicopter deployments. Total rescue times for various weather conditions are also provided. In this scenario, the larger number of individuals in distress amplifies the impact of weather conditions on the total rescue time. Similar to previous scenarios, when the incident locations are far from the base and shoreline, the weather becomes a critical factor that significantly affects the outcome. Furthermore, in incidents occurring far from the shoreline, particularly during winter, the deployment of three helicopters has significantly reduced the total SAR time.

Table 9 presents the incident location and model results for each case: F-1, F-2, and F-3. The distribution of the total SAR time, along with the flight map and timeline of the helicopter, specifically for the three-helicopter deployment and during the summer season are illustrated in Figures 37 to 51, respectively.

Table 9:Input Data and Results for Scenario F

Case			**F-1**	**F-2**	**F-3**
Distance to Gander Airport (km)			**218**	**354**	**497**
Total SAR Time (h) for 1 HC	**Summer**	**50th Percentile**	8.1	11.2	15.6
		90th Percentile	8.9	11.9	16.7
		99th Percentile	9.3	12.6	17.2
	Winter	**50th Percentile**	8.2	11.3	15.9
		90th Percentile	8.9	12.1	16.9
		99th Percentile	9.4	13.5	17.5
Total SAR Time (h) for 2 HC	**Summer**	**50th Percentile**	6.6	8.6	11.6
		90th Percentile	7.3	9.4	12.3
		99th Percentile	7.7	9.9	12.8
	Winter	**50th Percentile**	6.7	8.7	11.7
		90th Percentile	7.4	9.5	12.4
		99th Percentile	7.8	10.5	12.9

Total SAR Time (h) for 3 HC	**Summer**	**50th Percentile**	6.1	7.7	9.6
		90th Percentile	6.8	8.4	10.4
		99th Percentile	7.2	9	11
	Winter	**50th Percentile**	6.2	7.7	9.8
		90th Percentile	6.8	8.4	10.6
		99th Percentile	7.2	9	11.3

In Scenario F-1, where three helicopters are deployed, all of them take off simultaneously. The first and second helicopters fly directly from Gander to the LKP, while the third helicopter flies to the nearest base, which is St. John's airport, and remains there in a holding position. Once the first and second helicopters reach the LKP, they begin the search operation to locate the PID location.

The first helicopter starts picking up survivors, continuing until it has picked up 15 individuals or its fuel capacity limits further operations. Meanwhile, the second helicopter, which was in a holding position near the first helicopter, begins its own pick-up operation. The third helicopter flies directly to a holding point near the PID location. This process is repeated until all survivors have been rescued, and the helicopters return to the base. In most cases, refueling is not required during the operation. The flight map and timeline of the helicopters reflect this sequence of events.

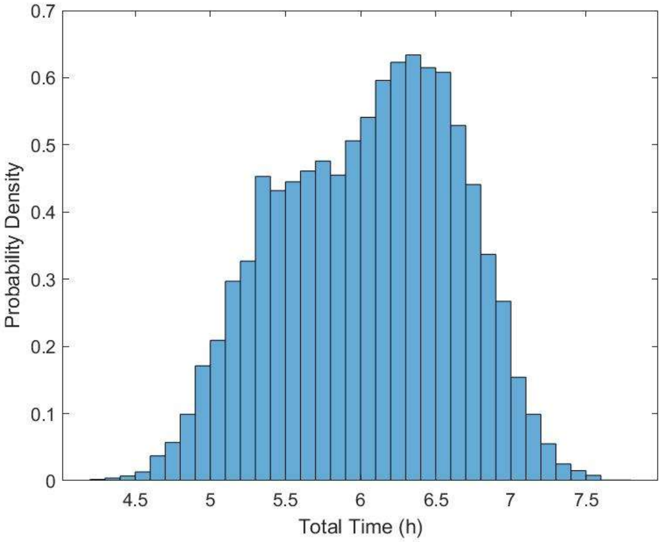

Figure 37: Case F-1, Total Search and Rescue Time Distribution

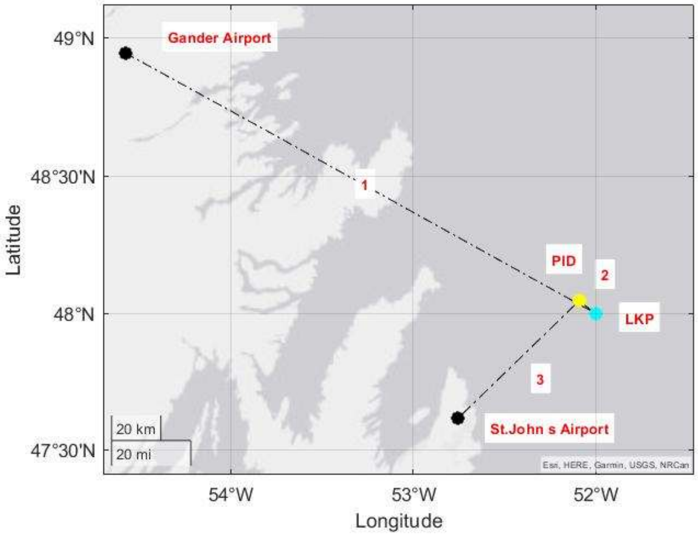

Figure 38: Case F-1, Flight Map of First Helicopter

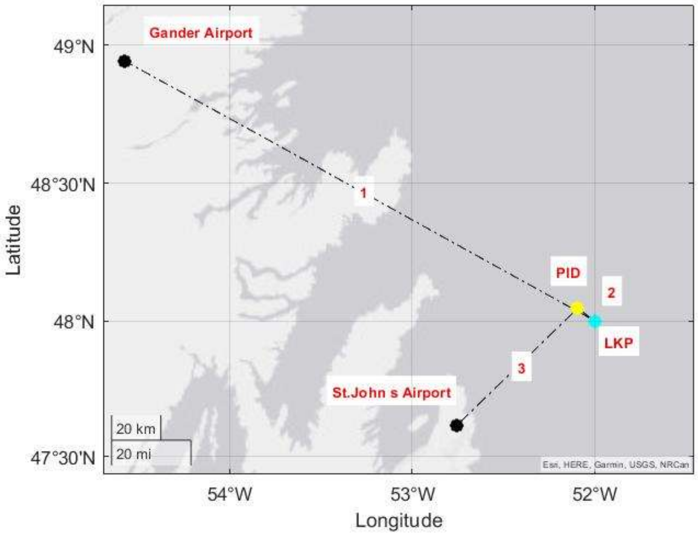

Figure 39: Case F-1, Flight Map of Second Helicopter

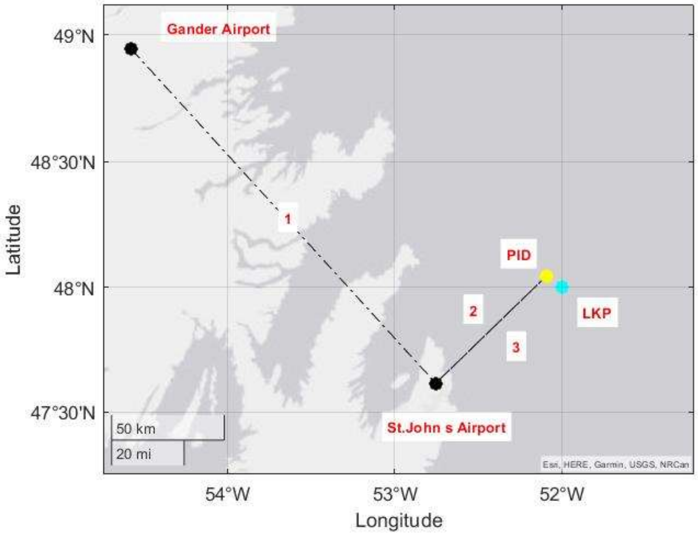

Figure 40: Case F-1, Flight Map of Third Helicopter

As shown in Figure 41, all helicopters were engaged in the operation, with the first helicopter initiating the operation and the third helicopter concluding it.

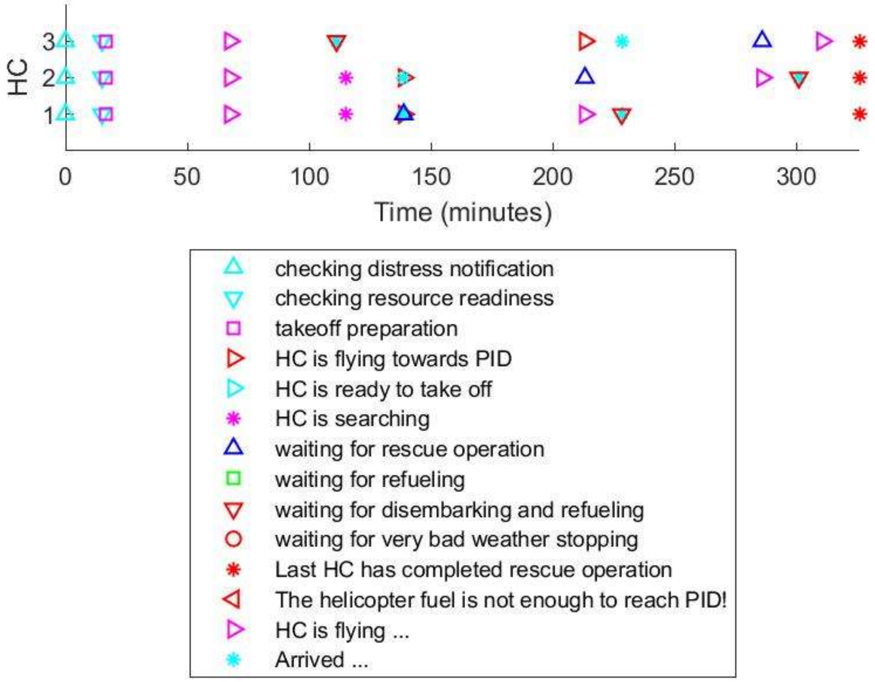

Figure 41: Case F-1, Timeline of Sample Case

In case F-2, the flight map and operational details are similar to scenario F-1. However, in certain situations, like the one described in this section and illustrated in Figure 44, the second helicopter needs to refuel before completing the pickup of 15 individuals. This occurs because the second helicopter flies alongside the first helicopter and experiences a significant waiting time, depleting its fuel reserves and preventing it from reaching the base or completing the operation entirely. In this scenario, while the third helicopter is engaged in the pickup process, the second helicopter will fly to Hibernia for refueling. Once refueled, it will return to the PID location to complete the remaining pickups. Further details are provided below.

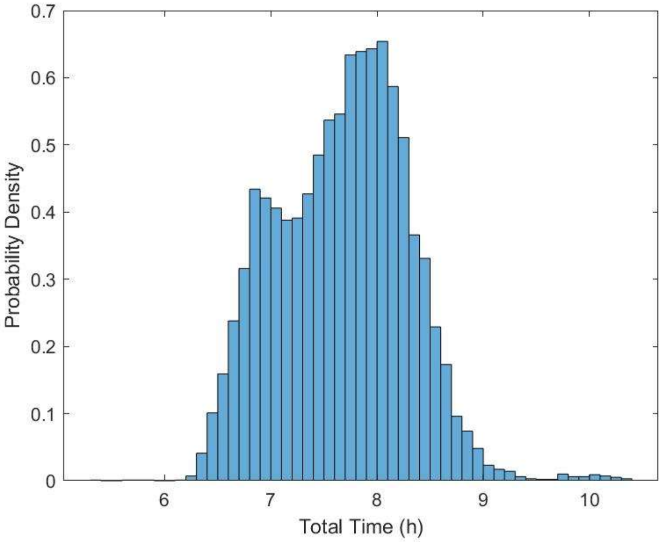

Figure 42: Case F-2, Total Search and Rescue Time Distribution

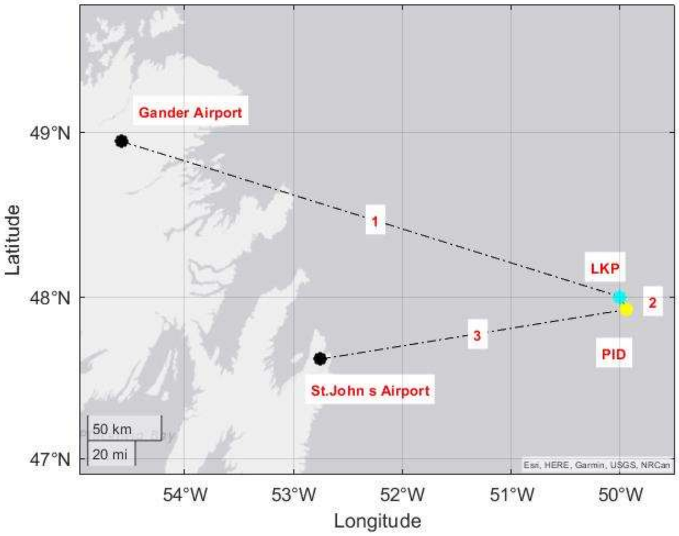

Figure 43: Case F-2, Flight Map of First Helicopter

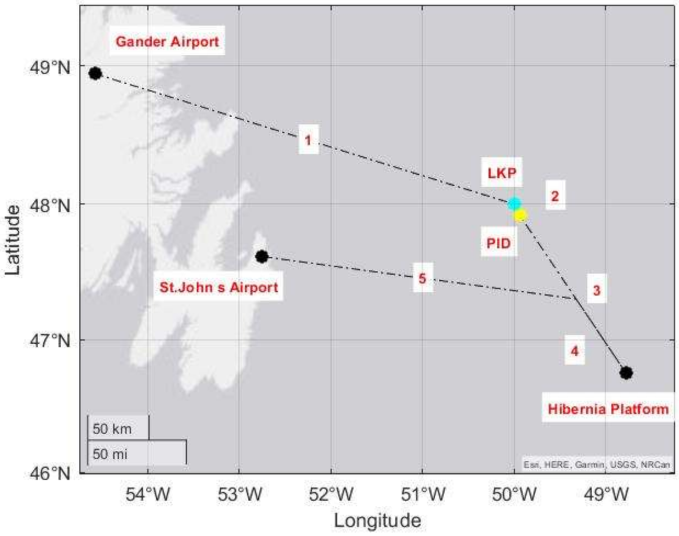

Figure 44: Case F-2, Flight Map of Second Helicopter

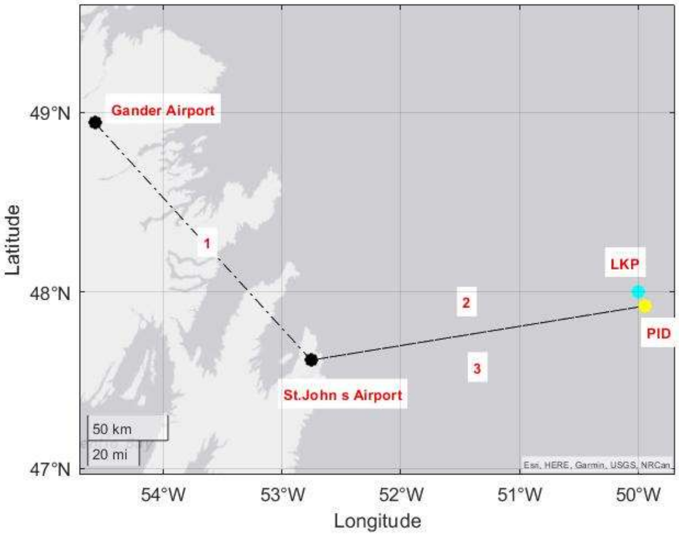

Figure 45: Case F-2, Flight Map of Third Helicopter

As illustrated in Figure 46, all helicopters initiate their flights simultaneously. The first and second helicopters fly to the LKP, reaching the location at the 178th minute and commencing the search operation. Meanwhile, the third helicopter flies to St. John's airport and arrives there at the 143rd minute. At the 205th minute, the PID location is identified, and the first helicopter begins the rescue operation while the second helicopter hovers at the holding point. The first helicopter successfully picks up all 15 survivors and returns to St. John's airport at the 289th minute. As the first helicopter starts its return, the second helicopter begins picking up individuals, while the third helicopter flies to the holding point. The second helicopter manages to rescue 7 persons and suspends the operation at the 318th minute to refuel at Hibernia. At the 337th minute, the third helicopter arrives at the PID location and commences the rescue operation. After refueling, the second helicopter realizes that the third helicopter has not completed the rescue yet. Consequently, it flies back to the PID location at the 383rd minute. While the second helicopter is flying to the PID, the third helicopter successfully rescues all the remaining survivors and concludes the operation at the 399th minute and returns to St. John’s. at the same time, the second helicopter change the destination and flies back to St. John's airport.

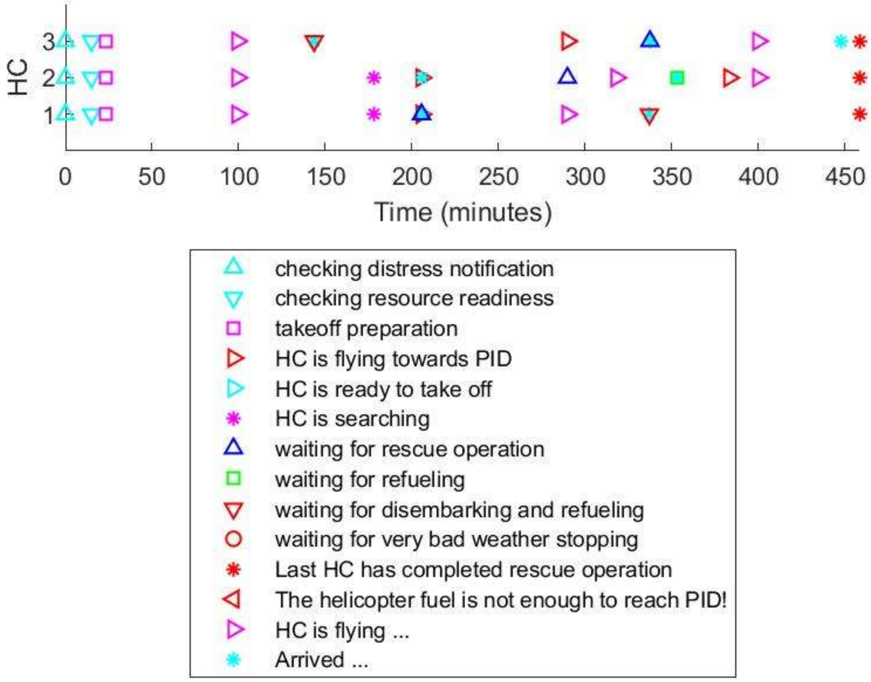

Figure 46: Case F-2, Timeline of Sample Case

In case F-3, the flight map and operational details are similar to scenario F-2. However, in most cases, the first and second helicopters are required to fly to Hibernia for refueling. First helicopter after finishing the rescue operation needs to go to the Hibernia, but the second helicopter is required to suspend the rescue operation and then fly to Hibernia. This is due to the extended duration of the operation and the need for additional fuel to complete the mission successfully.

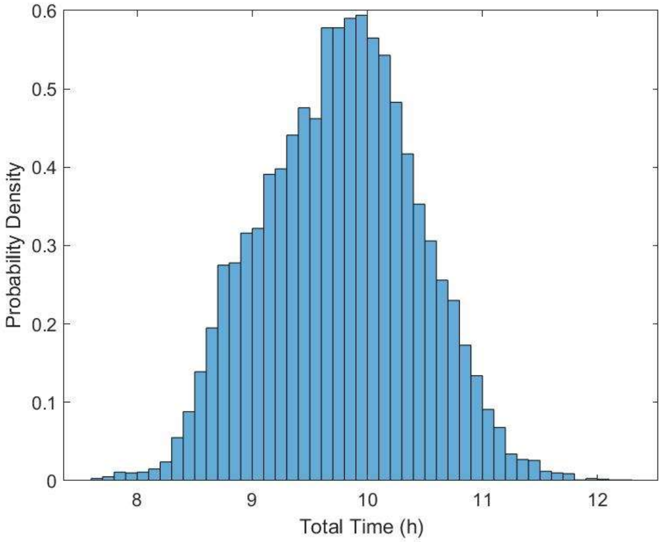

Figure 47: Case F-3, Total Search and Rescue Time Distribution

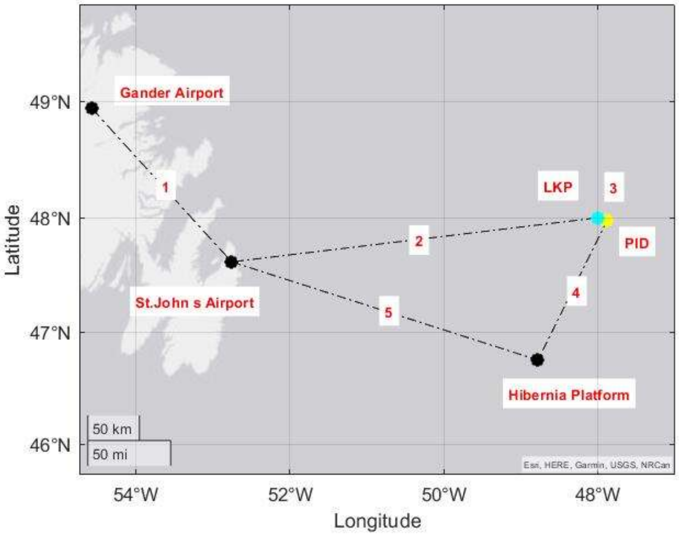

Figure 48: Case F-3, Flight Map of First Helicopter

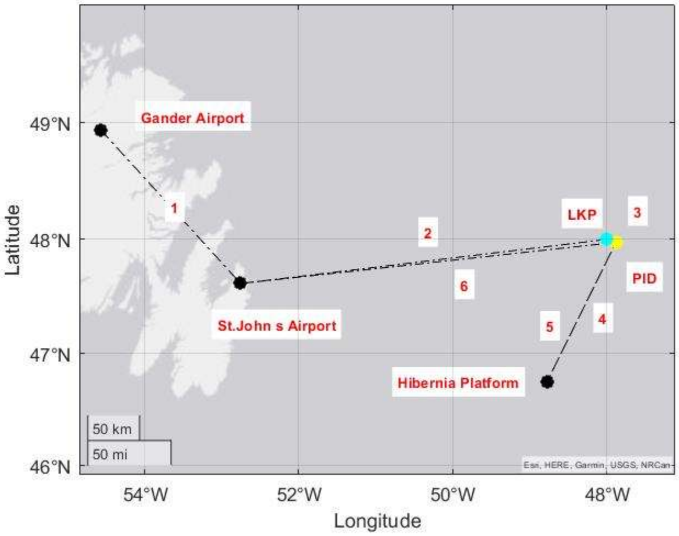

Figure 49: Case F-3, Flight Map of Second Helicopter

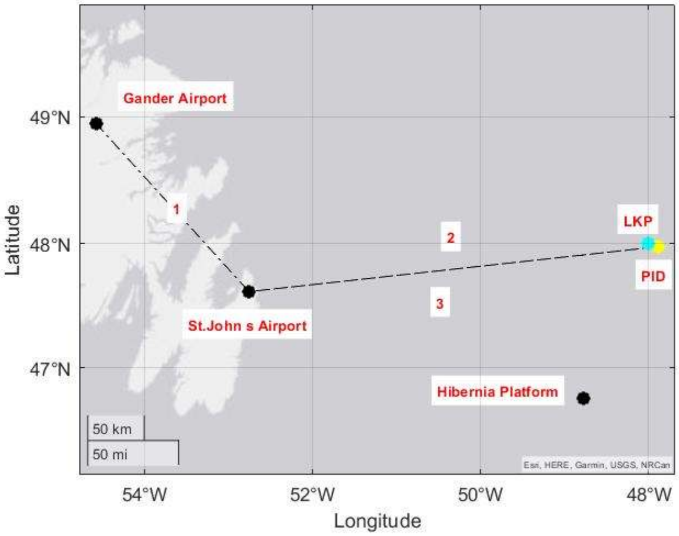

Figure 50: Case F-3, Flight Map of Third Helicopter

As depicted in Figure 51, similar to case F-2, when the second helicopter completes refueling at Hibernia, the third helicopter is still in the process of conducting the rescue operation. Therefore, the second helicopter flies to the PID location and waits for the third helicopter to finish its operations. Since the third helicopter can pick up the remaining survivors, both helicopters return to St. John's airport after completing the rescue mission.

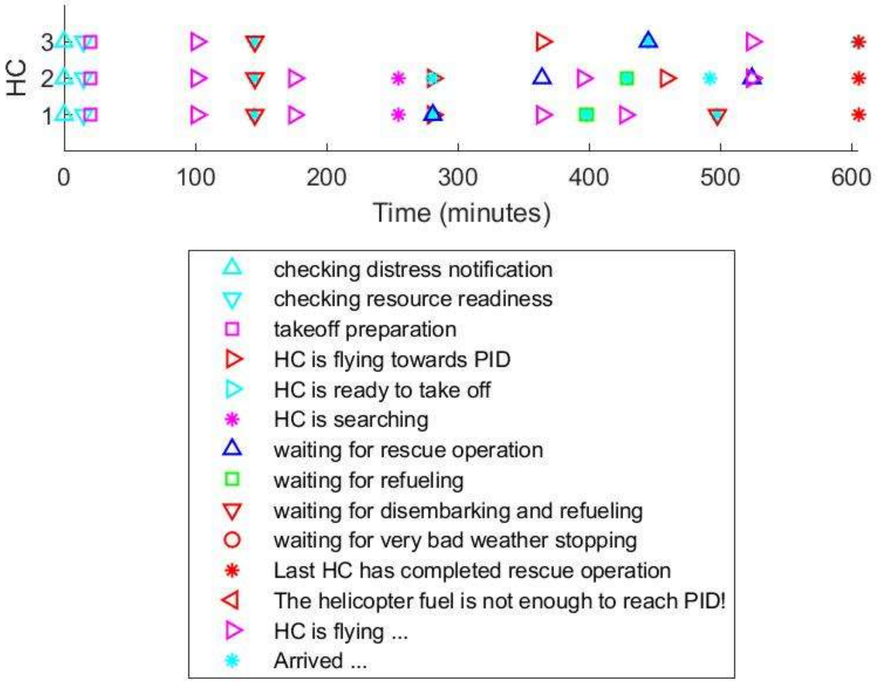

Figure 51: Case F-3, Timeline of Sample Case

7.2 Arctic Regions

Scenario cases D-1, D-2, and D-3 were specifically designed to simulate incidents that required SAR response in the Arctic region. In scenario D-1, D-2 and D-3, the helicopters will once again be deployed from Gander airport, with the Arctic Bay airport serving as a temporary base in the Arctic. The Longstaff Blf airport, Iqaluit airport, Cape Dorset airport, Hopedale airport, and Goose Bay airport will be utilized as potential fuel stations during these scenarios. Furthermore, in scenarios D-Iqaluit, the helicopters will be deployed from Iqaluit airport to examine the impact of SAR base location in Arctic incidents. Figure 52 provides a visual representation of the bases, fuel stations, and incident locations involved in these scenarios.

Figure 52: Locations of incidents, SAR bases, and possible fueling stations in the Arctic Region (Google Earth Pro. Image)

7.2.1 Scenario D- Gander Considered as the Main Base

In Scenario D, the simulation assumes that an incident has occurred in a remote location within the Arctic. Cases D-1, D-2, and D-3 are set in the same location, but the scenarios show the effect of different numbers of individuals in distress on total SAR time. Furthermore, the scenarios incorporate variations in seasons and the deployment of multiple helicopters.

Table 10 presents the incident location and model results, while Figures 53 to 63 showcase the distribution of total SAR time and provide the flight maps for a sample case. In all scenarios within this section, the helicopter departs from Gander and proceeds to refuel at Hopedale airport, Iqaluit airport, Longstaff Blf airport, and finally Arctic Bay airport. From there, the helicopter flies to the LKP, locates and retrieves the survivor at the PID location, and subsequently returns to Arctic Bay airport.

In cases D-1 and D-2, the number of survivors is manageable for a single helicopter. Consequently, the second helicopter usually isn't engaged in the operation. Therefore, in the testing scenario and in Table 10, the involvement of two helicopters has not been reported.

Table 10:Input Data and Results for Scenario D-Gander as a Main Base

Case			**D-1**	**D-2**	**D-3**
PID No.			**1**	**15**	**35**
Total SAR Time (h) for 1 HC	**Summer**	**50th Percentile**	17.2	18.4	24.3
		90th Percentile	17.9	19.1	25
		99th Percentile	18.2	19.4	25.5
	Winter	**50th Percentile**	17.4	18.6	24.6
		90th Percentile	18	19.3	25.3

		99th Percentile	18.4	19.6	25.8
Total SAR Time (h) for 2 HC	**Summer**	**50th Percentile**	-	-	21.7
		90th Percentile	-	-	22.4
		99th Percentile	-	-	22.8
	Winter	**50th Percentile**	-	-	22
		90th Percentile	-	-	22.7
		99th Percentile	-	-	23.1
Total SAR Time (h) for 3 HC	**Summer**	**50th Percentile**	-	-	20.1
		90th Percentile	-	-	20.9
		99th Percentile	-	-	21.5
	Winter	**50th Percentile**	-	-	20.4
		90th Percentile	-	-	21.2
		99th Percentile	-	-	21.8

As mentioned earlier, the utilization of multiple helicopters in SAR operations becomes particularly significant when the number of individuals in distress exceeds the capacity of a single helicopter. In the case of three helicopter deployments, its impact becomes evident when there are 35 people in need of rescue. Additionally, adverse weather conditions play a significant role when the accident location is distant from the main base (Gander) and there is a high number of individuals requiring assistance.

In scenario D-1, the incident involves one person in distress, and a single helicopter is deployed for the SAR operation. The distribution of the total SAR time, along with the flight map, can be observed in Figures 53 to 56, for the summer case.

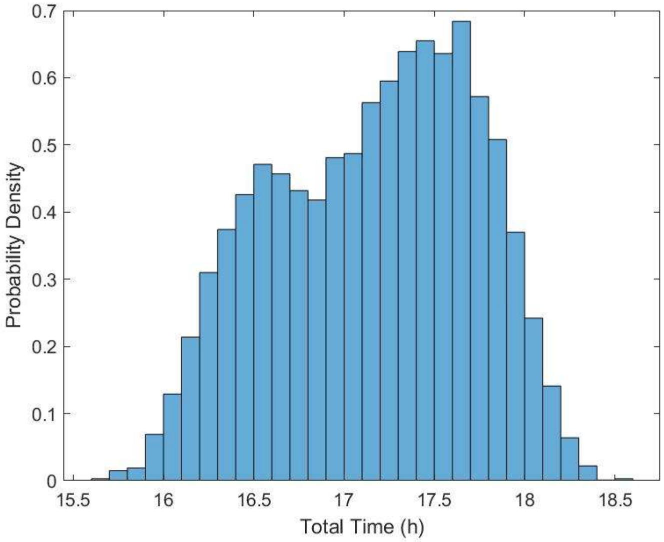

Figure 53: Case D-1, Total Search and Rescue Time Distribution

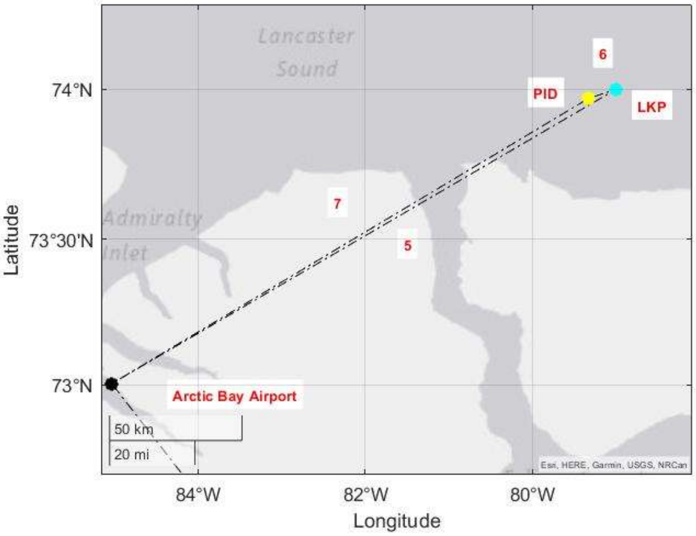

Figure 54: Case D-1, Flight Map of Sample Case

Figure 55: Case D-1, Flight Map of Sample Case from Gander to Arctic Bay

The timeline of the sample case, as depicted in Figure 56, clearly illustrates the quantity and timing of refueling required throughout the operation.

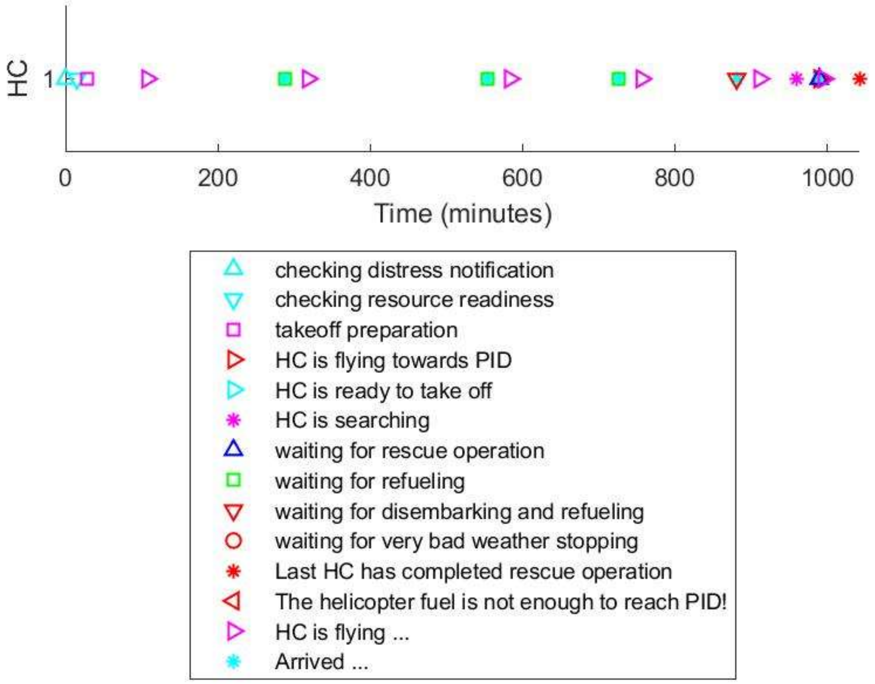

Figure 56: Case D-1, Timeline of Sample Case

For case D-2, the scenario assumes that 15 individuals are in distress at the same location as in case D-1. The figures depicting the distribution of total SAR time, the flight map, and the timeline of the sample case can be found in Figures 57 to 59.

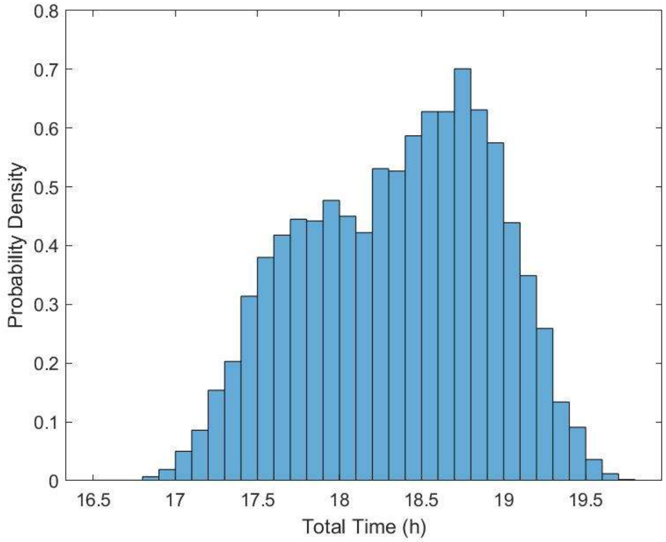

Figure 57: Case D-2, Total Search and Rescue Time Distribution

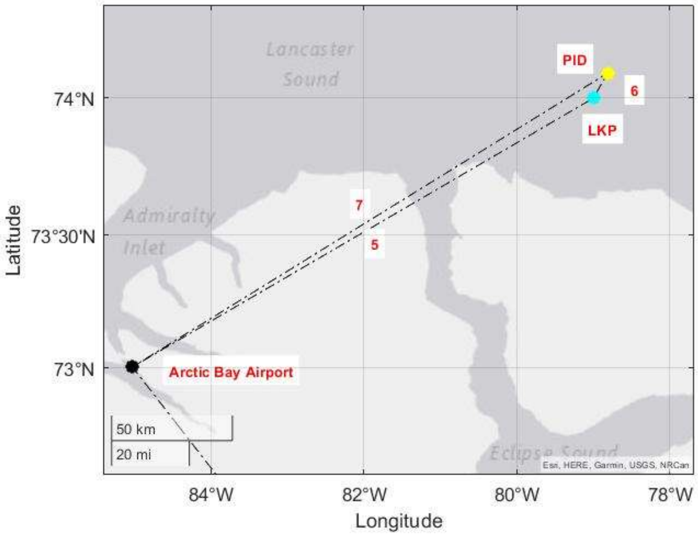

Figure 58: Case D-2, Flight Map of Sample Case

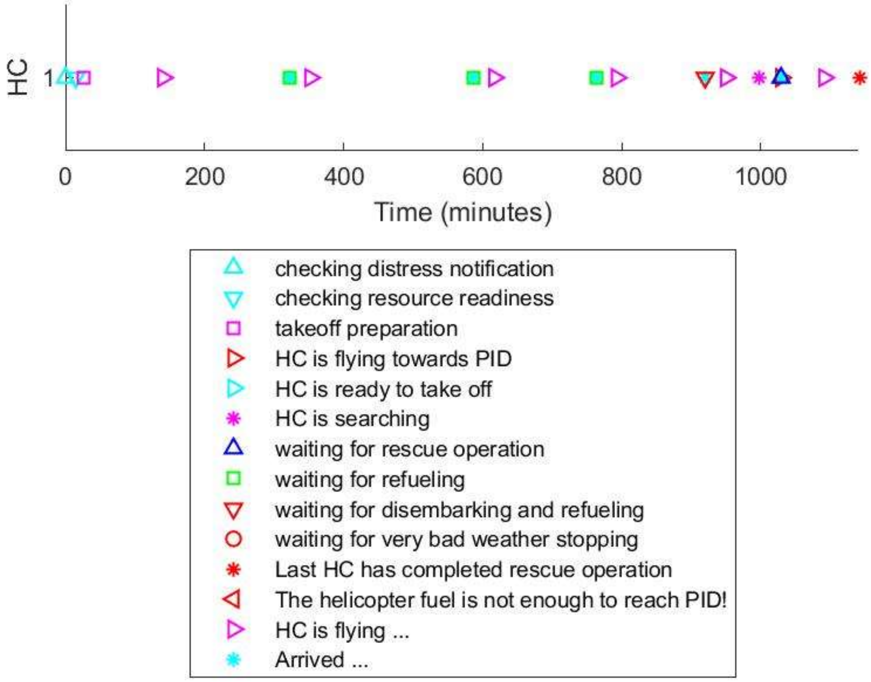

Figure 59: Case D-2, Timeline of Sample Case

In case D-3, the scenario assumes that 35 individuals are in distress at the same location as in case D-1. The figures illustrating the distribution of total SAR time, the flight map, and the timeline of the sample case for three helicopter deployment can be found in Figures 60 to 63.

In this case, all three helicopters initiate their flight simultaneously and reach the Arctic Bay Airport at the same time. Similar to previous cases, two helicopters proceed towards the LKP while the third helicopter remains stationed at the base until the first helicopter completes the pickup of 15 individuals and returns to the base.

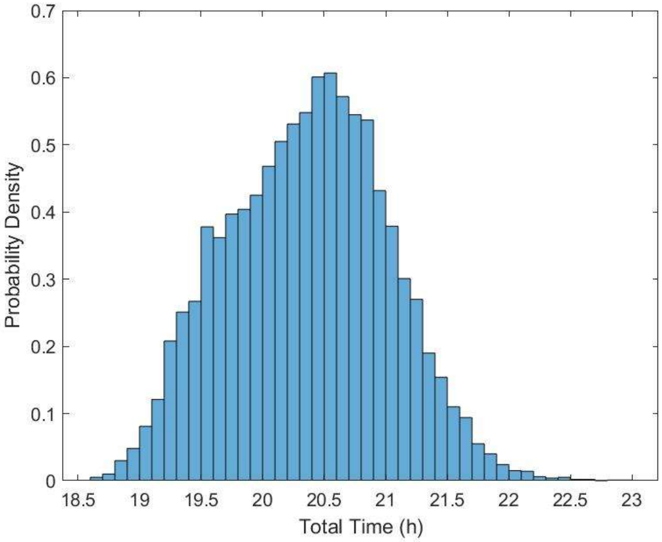

Figure 60: Case D-3, Total Search and Rescue Time Distribution

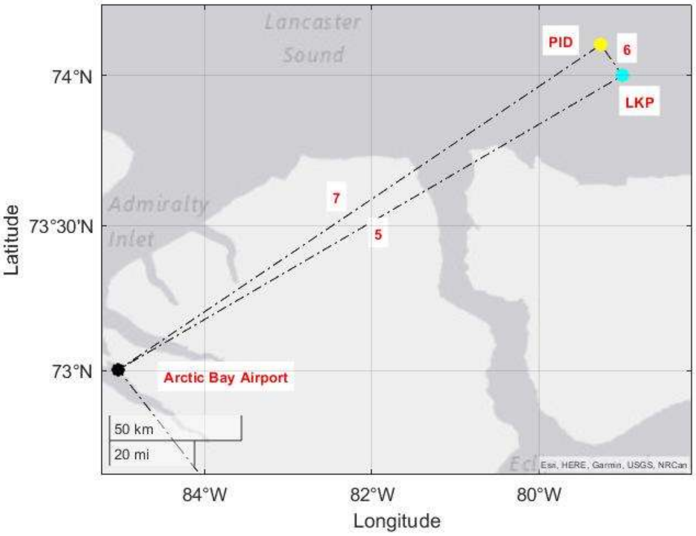

Figure 61: Case D-3, Flight Map of First and Second Helicopter

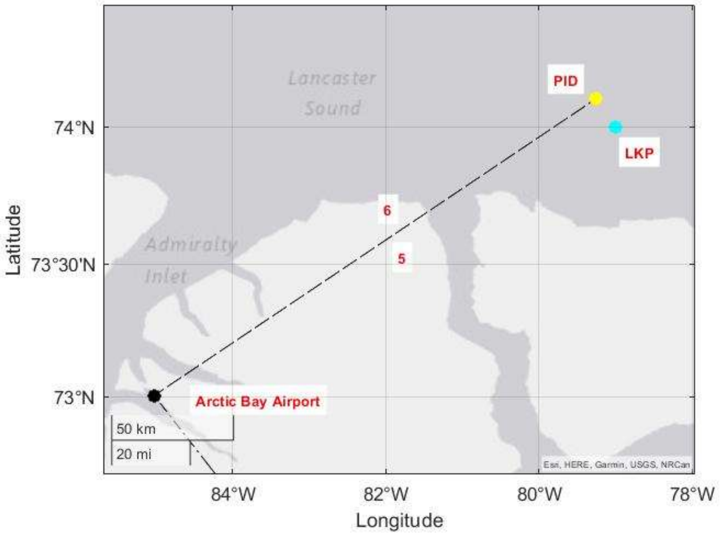

Figure 62: Case D-3, Flight Map of Third Helicopters

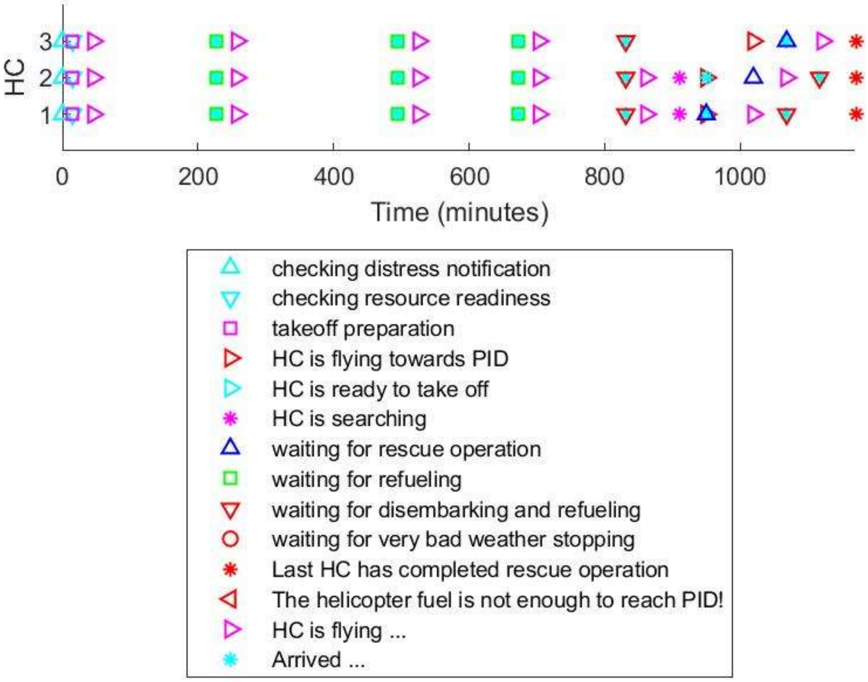

Figure 63: Case D-3, Timeline of Sample Case

7.2.2 Scenario D- Iqaluit Considered as the Main Base

In this scenario, the Iqaluit Airport is designated as the main base, with the helicopter(s) deployed from this location. The updated scenarios in this section involve the helicopter departing from the Iqaluit Airport and making refueling stops at the Longstaff Blf Airport and Arctic Bay Airport. From Arctic Bay Airport, the helicopter proceeds to the LKP, where it locates and retrieves the survivor at the PID location, and then returns to Arctic Bay Airport.

Table 11 provides information on the incident location and model results for these scenarios.

Table 11:Input Data and Results for Scenario D-Iqaluit as a Main Base

Case			D-1	D-2	D-3
PID No.			1	15	35
Total SAR Time (h) for 1 HC	Summer	50th Percentile	9.3	9.4	16.4
		90th Percentile	9.9	10	17.1
		99th Percentile	10.3	10.4	17.6
	Winter	50th Percentile	9.4	10.6	16.6
		90th Percentile	10	11.2	17.3
		99th Percentile	10.4	11.6	17.8
Total SAR Time (h) for 2 HC	Summer	50th Percentile	-	-	13.8
		90th Percentile	-	-	14.5
		99th Percentile	-	-	14.9
	Winter	50th Percentile	-	-	13.9

		90th Percentile	-	-	14.6
		99th Percentile	-	-	15.1
Total SAR Time (h) for 3 HC	**Summer**	**50th Percentile**	-	-	12.2
		90th Percentile	-	-	12.9
		99th Percentile	-	-	13.6
	Winter	**50th Percentile**	-	-	12.3
		90th Percentile	-	-	13.2
		99th Percentile	-	-	13.8

In the Arctic region, reaching the incident location poses a significant challenge due to the vast expanse and harsh conditions of the area. As demonstrated in this section, the choice of the main base location plays a crucial role in minimizing the flying time and expediting the arrival at the scene. When the main base is strategically positioned in the northern region of the Arctic, the helicopter's journey to the incident location becomes more efficient. The reduced flying time enables a quicker response to distress calls, increasing the chances of successful SAR operations. By optimizing the base location in proximity to the Arctic region, SAR teams can effectively mitigate the challenges posed by long distances and extreme weather conditions, ultimately enhancing the overall efficiency and effectiveness of their operations.

8 RESULTS AND DISCUSSION

8.1 Effect of Distance on Rescue Time

The analysis of various scenarios in Eastern Canada's coastal regions reveals the critical role of distance in SAR operations. The findings demonstrate a direct correlation between distance and rescue time, emphasizing the significance of accounting for this factor in SAR planning and execution.

In Scenario A, where a single individual is in distress, proximity to the base and shoreline results in minimal variations in SAR time between summer and winter scenarios. However, as the distance from the base increases, such as in Scenario A-3, the rescue time significantly lengthens, highlighting the challenges and prolonged response times associated with longer distances.

Scenario B, involving 15 individuals in distress, further emphasizes the impact of distance on rescue time. Weather conditions play a crucial role, particularly when the incident location is far from the base and shoreline. The involvement of multiple helicopters and the need for refueling during the operation also contribute to variations in the total rescue time.

Similarly, in Scenario C, which focuses on remote locations away from the Eastern Coastal regions, the distance to the SAR base significantly affects the rescue time. Factors such as refueling needs, search time, and weather conditions contribute to variations in the total rescue time.

The results also suggest that in the Arctic region, reaching the incident location poses the primary challenge in SAR operations. The remote and harsh conditions of the Arctic make travel to these areas particularly demanding. While the analysis conducted thus far focuses on simplified cases, the findings resemble those observed in the Atlantic region, where increased distance also leads to longer rescue times when compared with the effect of increased numbers of people in distress.

Overall, the analysis highlights that as the distance from the SAR base increases, the rescue time also increases due to travel time, search efforts, and return to the base. These findings underscore the importance of considering distance and contextual factors when planning and executing SAR operations, especially in challenging and remote environments. By accounting for distance and its implications, SAR teams can optimize their strategies, allocate resources effectively, and enhance the efficiency of rescue missions, ultimately ensuring the safety and well-being of those in distress.

8.2 Effect of Weather on Rescue Time

The test scenarios conducted in the Atlantic and Arctic regions provide insights into the impact of weather conditions on SAR time.

In Scenario A, involving a single individual in distress, minimal differences in SAR time are observed between summer and winter scenarios when accidents occur near the base and shoreline. However, significant variations occur in winter conditions when the accident location is distant. Unfavorable weather conditions can considerably affect SAR time in such cases, as the model incorporates weather forecasts and integrates the weather factor into all calculations and simulations throughout the SAR operation.

In Scenario B, which involves 15 individuals in distress, the influence of weather conditions on SAR time becomes more pronounced. When incident locations are far from the base and shoreline, weather factors play a crucial role, resulting in substantial differences in the total rescue time.

Similarly, in Scenario C, where incidents occur in remote locations away from the Eastern Coastal regions, SAR time for one or more individuals in distress is influenced by factors such as the distance to Gander Airport, weather conditions, and the need for refueling. Instances where search time is longer, the incident location is far, or the weather is unfavorable may require additional refueling, contributing to the total rescue time.

In Arctic scenarios, the vast distances involved contribute to significant weather changes, resulting in prolonged SAR operations. The extreme Arctic weather poses substantial challenges for SAR operators and decision-makers alike.

Based on these test scenarios, it is evident that weather conditions, particularly when incidents occur in distant or remote locations, can have a significant impact on SAR time. Unfavorable weather conditions can prolong the overall rescue operation and increase the time required to reach and retrieve individuals in distress. Therefore, SAR teams must consider weather forecasts and adapt their operations accordingly to ensure effective and timely responses in challenging weather conditions.

8.3 Effect of Number of People in Distress

The analysis of the test scenarios presented in this study provides insights into the effect of the number of people in distress on SAR operations in different regions. The scenarios examined include incidents occurring in the coastal regions of Eastern Canada, specifically in Newfoundland and the Atlantic Ocean, as well as in the Canadian Arctic region. Additionally, the impact of SAR base location on Arctic accident scenarios is explored.

In the Eastern Canada coastal regions, Scenario A focuses on a distress situation involving a single individual. The SAR operation for this scenario demonstrates that the total SAR time is relatively short, particularly when the accident occurs near the base and shoreline.

Scenario B involves incidents with 15 individuals in distress in the same locations as Scenario A. The analysis considers both single helicopter and two helicopter deployments. The results show that when the incident locations are far from the base and shoreline, weather conditions have a significant impact on the total rescue time. In instances where the survivors' locations are close to the base and within the capacity of one helicopter, the second helicopter is typically not involved in the operation.

In Scenario C, a remote location away from the Eastern Coastal regions is considered. The analysis includes cases with one (C-1) and 15 individuals (C-2) in distress. The SAR operation for Scenario C-1 demonstrates that the total SAR time can be prolonged when the search time is longer, the survivor's location is far, or the weather is unfavorable. The model accurately captures the dynamics of SAR operations in remote regions, including the need for refueling and the impact of unfavorable weather conditions.

Based on the test scenarios and results, it is evident that the number of people in distress has a significant effect on SAR operations. Larger numbers of individuals in distress require more resources and coordination, potentially leading to longer total rescue times.

8.4 Effect of Helicopter Base Location

A test scenario was conducted in the Arctic region to assess the impact of changing the main SAR base location on SAR operations. Reaching incident locations in this vast and harsh environment poses significant challenges. The scenario examined the effectiveness of different base locations in minimizing flying time and expediting response times to distress calls. Two scenarios were considered: one with Gander Airport as the main base and the other with Iqaluit Airport as the main SAR base.

The results demonstrate that strategically positioning the main base in the northern region of the Arctic improves SAR operations' efficiency. The optimized base location reduces flying time, enabling quicker responses to distress calls, and enhancing the chances of successful SAR missions. By shortening the distance between the base and incident locations, the challenges posed by long distances and extreme weather conditions are effectively mitigated.

Conversely, relocating the main base to more central or southern areas of the Arctic results in longer flying times and slower response rates. The increased distances that helicopters must cover to reach incident locations lead to delayed responses to distress calls, potentially hindering the effectiveness of SAR operations in the Arctic region.

The findings underscore the critical role played by the SAR base location in optimizing SAR operations. By strategically positioning the SAR base, SAR teams can enhance their efficiency, expedite response times, and improve outcomes in challenging environments.

8.5 Effect of Simultaneous Use of Multiple Helicopters in the Same Location

The study also investigates the effect of the simultaneous use of multiple helicopters in the same location on SAR operations. By deploying multiple helicopters, SAR teams aim to enhance their capabilities and potentially reduce the total rescue time. The analysis examines scenarios where multiple helicopters are involved in rescuing individuals in distress in Eastern Canada's coastal regions.

In Scenario B, which involves incidents with 15 individuals in distress, the study considers both single helicopter and two helicopter deployments. The results reveal that the involvement of multiple helicopters can significantly impact the total rescue time, particularly when incident locations are far from the SAR base and shoreline. In instances where survivors' locations are close to the base and within the capacity of one helicopter, the second helicopter is typically not involved in the operation. However, when the incident location is distant, the additional helicopter becomes crucial in reducing the time required for search, transportation, and rescue.

In Scenario F, which involves incidents with 35 individuals in distress, the study considers single, two and three helicopters' deployments. The results reveal that the involvement of multiple helicopters significantly impacts the total rescue time, particularly when incident locations are far from the SAR base and shoreline. However, when the incident location is distant, the additional helicopter becomes crucial in reducing the time required for search, transportation, and rescue.

The simultaneous use of multiple helicopters can offer several advantages in SAR operations. Firstly, it allows for the distribution of rescue resources and personnel, enabling simultaneous SAR efforts in different areas. This can lead to more efficient coverage and potentially faster identification and retrieval of individuals in distress. Secondly, by reducing the search time through parallel search operations, the total rescue time can be shortened. This is particularly beneficial when incidents occur in vast or challenging environments where a single helicopter may have limited capacity or face obstacles in reaching all survivors in a timely manner.

However, it is important to note that the simultaneous use of multiple helicopters also introduces coordination challenges. Effective communication and coordination between the helicopters and the SAR command center are essential to ensure efficient allocation of resources and avoid duplication of efforts. Moreover, factors such as weather conditions, fuel availability, and the availability of landing sites must be carefully considered to optimize the utilization of multiple helicopters.

9 CONCLUSIONS

In conclusion, the developed macro-scale SAR model and MATLAB code have demonstrated their capability to simulate SAR operations in the East Coast region of Canada and the Arctic Gateway. The model successfully underwent verification, validation tests, and testing scenarios, confirming its accuracy and reliability. Specifically, the helicopter model showcased the ability to simulate single, two, three, or multiple helicopters operating simultaneously in the same area and during the same SAR mission.

The model incorporates weather forecast data, enabling the calculation of total time and operational details under similar circumstances. The results highlight that the number of individuals in distress, incident location, and weather conditions are the three primary factors influencing the duration of the SAR operation. By utilizing time steps in the modeling process, the model allows for adjustments of variables during the operation, especially when dealing with incidents located far from the base or rapidly changing weather conditions.

The findings of this study confirm that the developed SAR model accurately reflects the real-time requirements for SAR operations. However, further improvements are necessary to enhance the model's functionality. Future developments should focus on incorporating different facilities such as airplanes, and vessels working collaboratively and simultaneously at the same time which can provide improved situational awareness, possibly reduce search time, and perform rescue in different conditions.

In summary, the SAR model and MATLAB code have proven their effectiveness in simulating SAR operations in the East Coast region of Canada and the Arctic Gateway. The model's ability to capture real-time variables and provide accurate estimates for the required SAR time underscores its value. By continually improving and expanding the model's capabilities, it can serve as a valuable tool for decision-making and resource allocation in complex SAR missions involving multiple assets and challenging environments.

10 RECOMMENDATIONS FOR FUTURE WORK

10.1 Weather Effect on Helicopter Function and SAR Efficiency

The developed model successfully incorporates a preliminary method to account for the influence of weather factors in SAR simulations. Although the results demonstrate the model's capability to consider weather conditions, there are slight differences observed between summer and winter scenarios. This highlights the need for further improvements to ensure that the weather forecast distribution closely aligns with real-world conditions. By refining the model's integration of weather factors, SAR operations can better adapt to the variability and unpredictability of weather patterns.

Moreover, the model could not highlight the impact of fog on SAR operations. Fog presents substantial challenges by reducing visibility and complicating navigation, making it crucial for future research to specifically address its effects. By comprehensively understanding and incorporating the impact of fog, decision-makers can gain valuable insights to optimize search strategies in foggy conditions.

10.2 Incorporate Multiple Assets Working Together in SAR Operation

The integration of multiple assets in the model will enable a comprehensive examination of the interplay between different SAR elements. It will facilitate the evaluation of response times, search coverage, and the utilization of resources in scenarios where helicopters, airplanes, and vessels are deployed together. By simulating these complex interactions, the model can provide decision-makers with a clearer understanding of the challenges and opportunities associated with coordinating diverse assets during SAR operations.

Moreover, incorporating multiple assets working together will require the consideration of factors such as interoperability, communication protocols, and logistical support. The model should account for the specific capabilities and limitations of each asset, including their range, speed, and capacity. Additionally, the model should address the challenges associated with information sharing, resource sharing, and decision-making processes among different assets and their respective crews.

10.3 Advancing Search Algorithms for Improved SAR Operations

The current model, as previously mentioned, does not simulate different searching algorithms and patterns utilized in real-world SAR operations. In actual SAR missions, helicopters and airplanes employ various search patterns based on factors such as the accident location, elapsed time since the first notification message, weather conditions, and other relevant variables. Enhancing the model to simulate these different searching patterns will enable the evaluation of their effectiveness and efficiency in locating individuals or vessels in distress. Further development of the model would focus on incorporating different search algorithms that are commonly employed in SAR operations. The development of search algorithms within the model will involve considering factors such as search area coverage, search speed, and the ability to adapt to changing conditions. Different search patterns, including grid searches, expanding square searches, sector searches, and parallel track searches, should be integrated into the model. Each algorithm can be evaluated based on its ability to efficiently cover the search area, minimize search time, and increase the likelihood of locating distressed individuals or vessels.

10.4 Integrating Vessel Drift and Movement into the Model

In the current model, the representation of the search area assumes that the distressed vessel can drift within a radius of 6 nautical miles (11.11 km) around the LKP. However, this is a simplified assumption that may not capture the full extent of vessel drift. Factors such as weather conditions, sea conditions, vessel dimensions, and shapes can significantly impact the actual drift range of a distressed vessel. Consequently, the search area could be wider, and the search time would be prolonged. To enhance the accuracy of the model, it is crucial to incorporate the drift and movement of the distressed vessel into the simulation.

In future iterations of the model, it is recommended to integrate a more realistic representation of vessel drift. This would involve considering various factors that influence drift, such as wind speed and direction, ocean currents, and vessel characteristics. Incorporating these variables, the model can simulate the potential drift range of the distressed vessel more accurately, leading to a more precise determination of the search area.

10.5 Operational Consideration

The current model overlooks crucial aspects such as mechanical failures, inspection requirements, and maintenance considerations. To address this, it is important to incorporate inspection and maintenance checks during longer SAR missions. Continuous operation of SAR assets, such as helicopters or vessels, without proper maintenance, can lead to performance issues or even failures. In real-world scenarios, routine inspection and maintenance schedules are followed, and it is essential to factor these into the total SAR time. Therefore, it is recommended to include these considerations in the future model development.

In addition, the well-being and rest periods of SAR crew members must be given due consideration. Prolonged missions can place significant physical and mental strain on the crew, potentially impairing their decision-making abilities and overall performance. To mitigate these challenges, the implementation of crew rotation strategies becomes imperative. By allowing for necessary rest periods and ensuring the availability of fresh and focused personnel throughout the operation, the overall effectiveness of SAR missions can be enhanced. However, it should be noted that incorporating crew rotation strategies may increase the total SAR time, as it accounts for the required rest periods and crew transitions.

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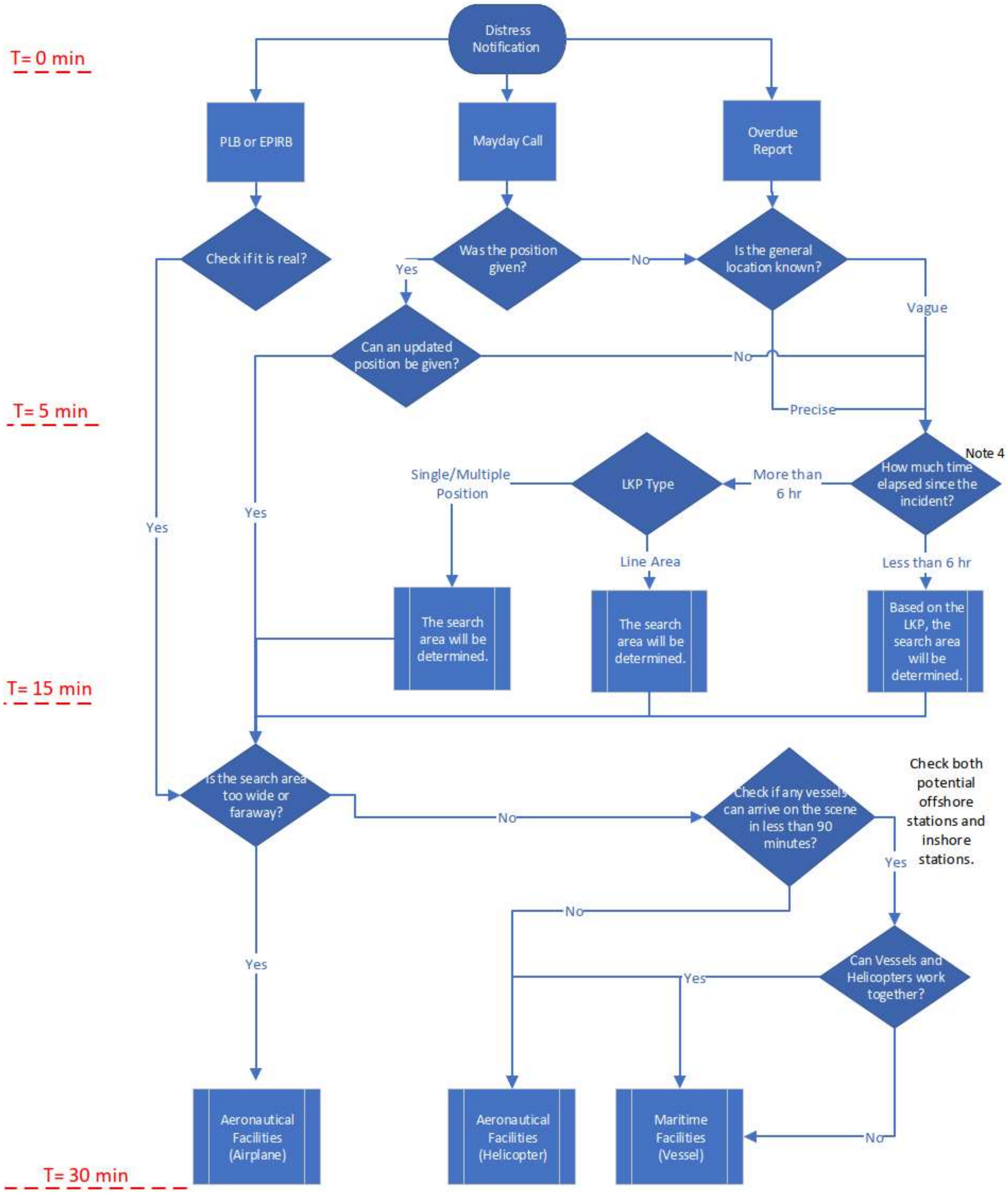
12 APPENDICES

APPENDIX A: OVERALL ALGORITHM FOR SEARCH AND RESCUE (SAR) OPERATIONS



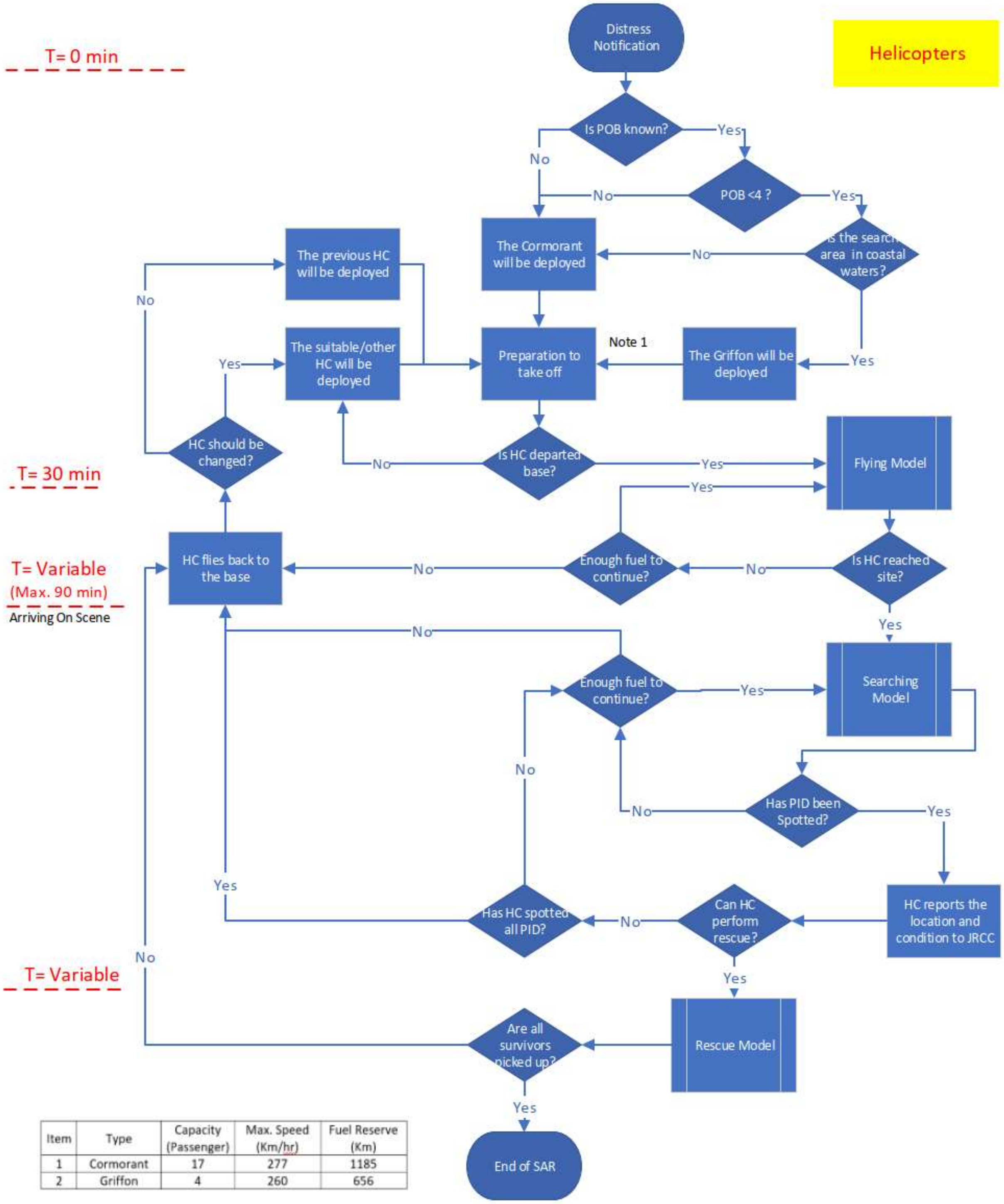
Notes:

1- Initial action should begin within five minutes of initial notification of a distressing incident.

2- The review resource readiness shall not take more than 30 minutes after the announcement.

3- SAR units should arrive on the scene within 90 minutes after deployment

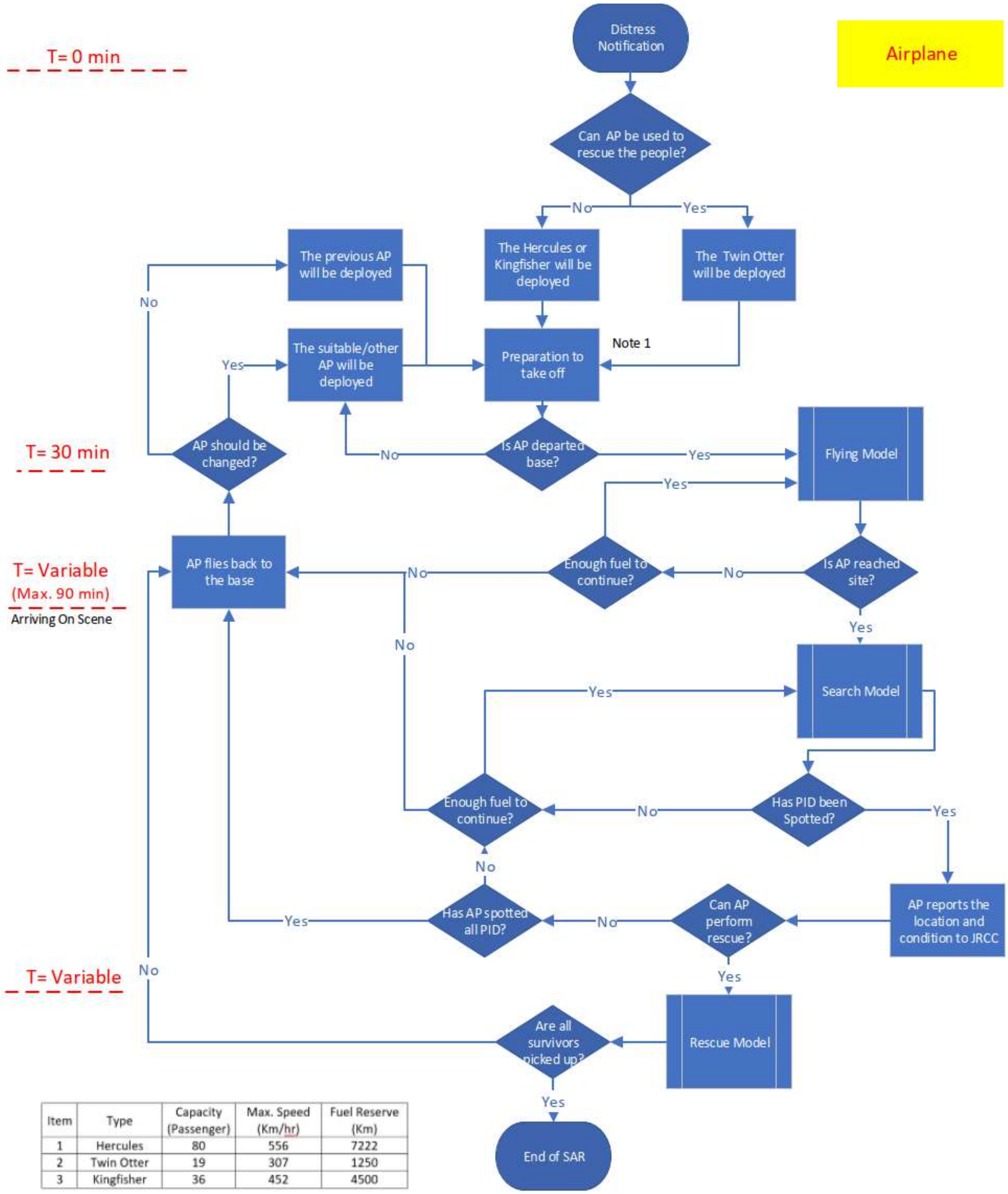
4- The drift time should be considered 6 hr for an incident in coastal waters and 4 hr for an incident in the oceanic environment.



Item	Type	Capacity (Passenger)	Max. Speed (Km/hr)	Fuel Reserve (Km)
1	Cormorant	17	277	1185
2	Griffon	4	260	656

Notes:

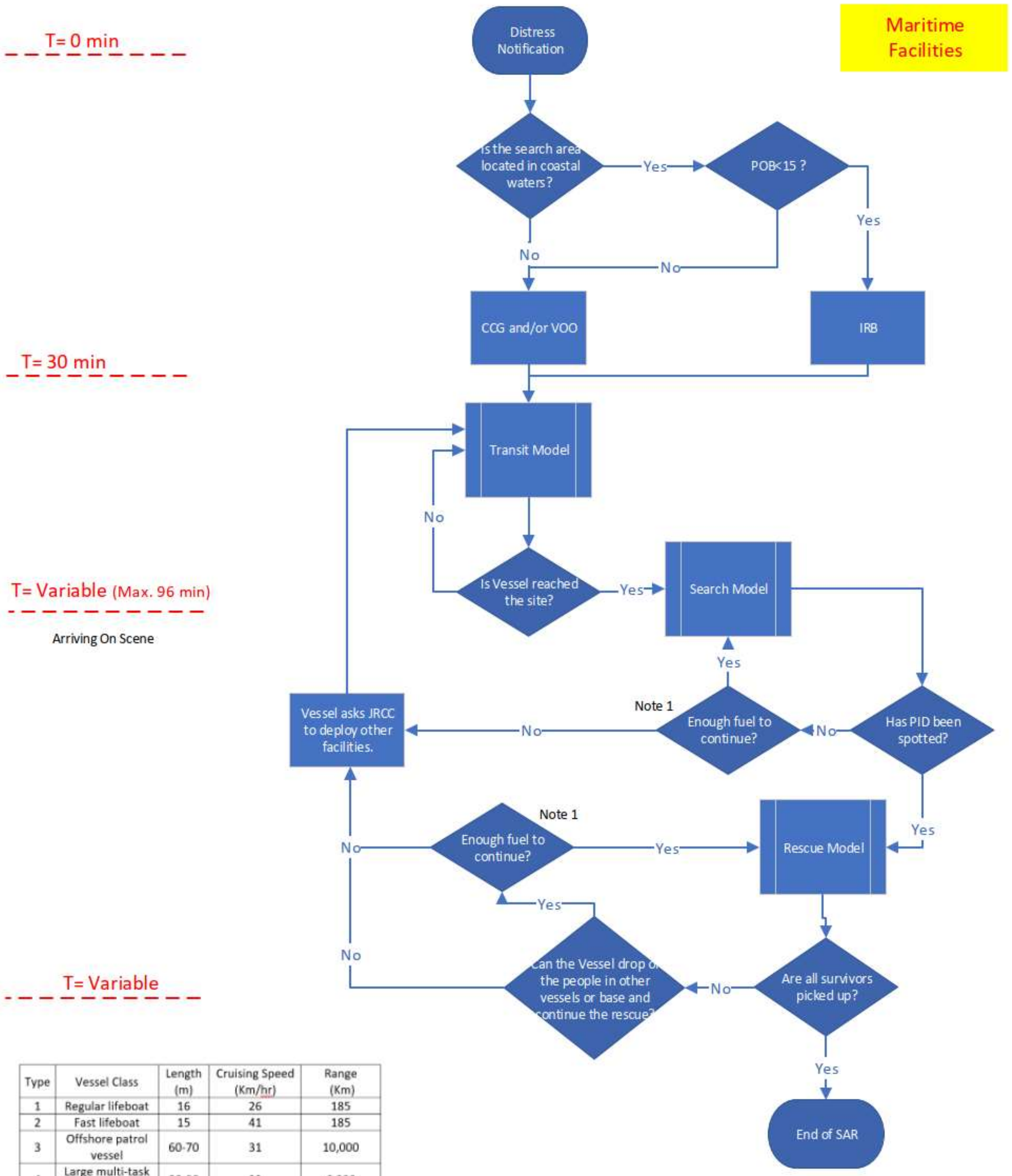
1- The helicopter needs 30 minutes to drop off the injuries and people, then it would require 30 minutes for refueling, 2 hours for inspection, or 2 hours for crew switching.



Item	Type	Capacity (Passenger)	Max. Speed (Km/hr)	Fuel Reserve (Km)
1	Hercules	80	556	7222
2	Twin Otter	19	307	1250
3	Kingfisher	36	452	4500

Notes:

1- The Airplane needs 30 minutes to drop off the injuries and people, then it would require 30 minutes for refueling, 2 hours for inspection, or 2 hours for crew switching.



Type	Vessel Class	Length (m)	Cruising Speed (Km/hr)	Range (Km)
1	Regular lifeboat	16	26	185
2	Fast lifeboat	15	41	185
3	Offshore patrol vessel	60-70	31	10,000
4	Large multi-task vessel	80-90	22	6,000

Notes:
1- At each step, small vessels (e.g. IRB) would check the fuel to continue.

APPENDIX B: EQUATIONS AND FORMULAS

Throughout this thesis, a numerical model employing Discrete Events and Monte Carlo simulation methods has been developed to enable calculation of total rescue time using helicopters for given scenarios. The process of verifying model outputs involved comparing manual calculations for simple scenarios with the model's output, revealing a close alignment between the two. This correspondence underscores the model's dependability and the code's capacity to produce accurate estimations. For clarity regarding the general formulas used in these calculations, this Appendix has been included to provide details of the formulae used in the model code.

Furthermore, Section 3.2 provides a comprehensive breakdown of the SAR operation's various phases and emphasizes the necessity of accounting for the time required at each stage. Utilizing a Monte Carlo approach, the model generates a distribution of total search and rescue times instead of a singular value. This distribution is the outcome of the cumulative impact of diverse random factors within the model, making it unfeasible to pinpoint a fixed duration. The total SAR time is not computed directly the people model but rather is produced as the total simulation time (through a time stepping process), which ends when all people in distress have been rescued by the helicopter. Details are provided below:

1. **Confirmation of Distress Notification Time ($t_{Not.}$)**

The timeframe for this phase, discussed in section 3.2.1, is set at a constant 15 minutes.

2. **Decision-Making Time ($t_{Dec.}$)**

As outlined in section 3.2.2, this phase does not adhere to a fixed duration. The model selects a time from a distribution.

3. **Helicopter Preparation Time ($t_{Pre.}$)**

As detailed in section 3.2.3, this phase also lacks a fixed timeframe. Instead, the model draws times from varied distributions, depending on whether the incident was during regular working hours on workdays or outside this time.

4. Flight Duration (t_{Fly})

This time frame, discussed in section 3.2.4, can depend on the distance flown in a time step and whether refueling is required, which may divert the helicopter to a different location.

To calculate the distance traveled in each time step (D_i), the helicopter's speed (V_{hc}) is multiplied by the weather factor ($F_{weather}$) and the time step (T_i), and the simple equation is $D_i = V_{hc} * F_{weather} * T_i$.

It is important to note that the helicopter's speed is treated as a vector quantity, encompassing both speed and direction. The selection of the flight direction is contingent on the simulation's context. For instance, if the helicopter is not yet at the incident location, it continues along its current trajectory. On the other hand, if it is at the scene and needs to search for survivors, the flight direction changes accordingly. Similarly, the simulation's programmed logic determines decisions like heading to a refueling station due to low fuel or returning to base. The model assesses whether the helicopter has reached the incident location at every time step. If the helicopter has not reached the scene, the simulation proceeds to the next time step while maintaining the current flight direction. This iterative approach ensures a continuous simulation of the helicopter's movement until it arrives at the designated location. Then

5. Time of Searching (t_{Search}):

This phase's duration is detailed in section 3.2.5 and is determined through random sampling from a distribution rather than using a fixed value in the model.

6. **Time of Rescue ($t_{Res.}$):**

Section 3.2.6 outlines this phase, and it's subject to variation through a distribution rather than being fixed in the model.

7. **Time of Disembarking ($t_{Dis.}$):**

As explained in section 3.2.9, the duration of this phase is not fixed but is rather drawn from a distribution in the model.

8. **Total SAR Time Calculation:**

The total Search and Rescue Time (t_{SAR}) can be estimated by summing the durations of the different SAR phases that have been explained above.

It is crucial to highlight that during the hand calculation used to validate the model, the focus was primarily on the helicopter's speed and the distances between the helicopter base, fuel station, and the incident site. The calculations considered the direct speed vector between these points and the corresponding vector directions.

Moreover, in this calculation, the assumption of ideal weather conditions was made, effectively rendering the weather factor's impact irrelevant in the SAR operation context.

APPENDIX C: RESEARCH PAPER

OTC-32486-MS

A Macro-Scale Generalized Search and Rescue (SAR) Model for the Coastal Regions of Eastern Canada and the Arctic

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Abstract

Given the complexity of Search and Rescue (SAR) activities in the coastal regions of Eastern Canada and the Arctic, there is a need to objectively assess system capabilities at a high level to determine the expected rescue time for multiple scenarios and system configurations. This paper outlines a new macro-scale generalized SAR model to simulate the main activities within the SAR system in Eastern Canada and the Arctic. The model uses discrete event simulation to represent the SAR operations and a probabilistic Monte Carlo approach to incorporate uncertainties in performance data for the different components of the system. Algorithms are first developed to identify the major decision-relevant components of SAR response, including the time to interpret emergency notifications and mobilize helicopter resources, the operability of assets in given environmental conditions, and the proximity and capability of resources. Following this, the model is coded in MATLAB, using a time-stepping approach, enabling changes in the scenario, asset status, and system configuration at any time step. Case scenarios are used as initial verification, beginning with a simplistic approach, and building complexity in the model parameters.

For this paper, we will discuss simple and complex scenarios which are based on common incident occurrences and SAR system operational details in eastern Canada's coastal regions and the Arctic. We assess the sensitivity of the overall SAR system to various input parameters to better understand how factors such as the Location of Incident (LOI) and number of People in Distress (PID) influence SAR response time in remote coastal areas, as well as the impact of refueling station locations for more distant and longer duration scenarios.

Introduction

Every year, ship traffic increases in Eastern Canada's coastal regions and in the Arctic, a trend that is not expected to change soon. According to a new study (Humpert, 2018) on shipping in Canada's Arctic, traffic nearly tripled between 1990 and 2015. The researchers found that the annual distance traveled by all vessels increased from around 350,000 kilometers to over 900,000 kilometers in that area, with most of the increase occurring over the last decade (Humpert, 2018).

In this region, there is a wide range of maritime activities including commercial fishing, shipping of bulk materials (ore from mines, offshore oil, and supply of bulk goods to remote communities), as well as tourism from passengers on cruise ships. Recently, the rapid growth in adventure tourism-related shipping activity presents a unique challenge to maritime safety, especially in the Canadian Arctic.

This region is also known for its harsh and unpredictable conditions, which increase the risk to vessels operating there. Similarly, these harsh and remote conditions pose severe challenges for Search and Rescue (SAR) operations tasked with aiding in maritime distress situations.

Canada's coastal areas provide some of the most challenging environmental conditions for maritime SAR activity in the world. There are severe sea states, gale-force winds on the East Coast, freezing spray, ice cover, and fog. Waves can reach up to 30 meters in height during winter storms, and gusts of up to 160 kilometers per hour are not uncommon. Large areas of fog reduce visibility to near zero during the spring and summer months (Canadian Coast Guard, 2019). The noted weather conditions impose significant risks, and this, combined with variable ice conditions, can pose serious safety and navigation hazards to vessels operating in the Arctic. While all maritime activities in harsh and remote areas are cause for concern, the increase in cruise vessel activity is particularly worrisome from a SAR perspective. The growing number of pleasure crafts also presents SAR challenges. Naturally, all maritime incidents, including those involving fishing vessels or involving offshore oil and gas activities, require appropriate levels of SAR support.

Deciding where to position public SAR resources (e.g., helicopters, fixed-wing aircraft, ships, and small response boats) should allow for the most effective provision of assistance when needed. Such decisions are difficult to make objectively, due to the complex interrelations between the impact of weather, faults or deficiencies in the SAR system, and variations in system configuration or assets (such as introducing new technologies and procedures). The maritime SAR system can be understood as a server-to-customer service system for the purpose of an asset location problem, similar to ambulance location problems on shore. In this type of problem, the most crucial concern is to meet all service demands, or at least as many as possible. As with any other emergency service, response time is critical because getting to the incident in the shortest time possible is a must (Akbari et al., 2018 a). SAR incident data is a multivariate, spatiotemporal dataset that can be used for a wide range of research. When spatial attribute data are available, spatial statistics and geo-referenced data processing techniques can be employed (Shahrabi, 2003), whereas temporal attribute data enable time series analysis and the investigation of temporal phenomena and trends (Malik et al., 2012). The Department of National Defence (DND), Canadian Coast Guard (CCG), and academic researchers have extensively used this type of data to investigate marine SAR resource planning and evaluation issues, such as manning levels assessment (Marven et al., 2007; Department of National Defence, 2019) and permanent SAR resources' critical areas identification (Akbari et al., 2017; Akbari et al., 2018 b; Pelot & Plummer, 2008).

Even though several strategic SAR preparedness planning models have been proposed, they have been limited because of the use of simple key metrics, and a simplistic incident analysis method. In this research, we present the early-stage development of a macro-scale SAR model to represent helicopter operations performing a rescue in a maritime environment. This is accomplished by developing a discrete event simulation model with stochastic elements to represent helicopter SAR operations for given scenarios. For cases where datasets are limited, unavailable, or unreliable, the performance of the assets is measured in situations that were as realistic as possible, as well as basing it on local, traditional, and expert knowledge, where appropriate. The significance of this model lies in its potential ability to aid SAR personnel in tactically determining how several factors would affect the overall SAR response time, conditional to factors such as the number of people in distress (PID), the location of the incident (LOI), and variations in weather and system response conditions.

The following section 2 will present the approach to developing the model, and section 3 will demonstrate the model functions by testing the different scenarios.

SAR model: Concept and methodological approach

Methodology Overview

This research applies a mathematical modeling approach, involving a Monte Carlo method with discrete event simulation. This type of simulation codifies the SAR system's behavior as an ordered sequence of well-defined events in time. The model represents the discrete events that occur after the process begins (i.e., receiving distress notification, preparing for take-off, flying to a last known position, refueling as needed, searching), events that are anticipated during the process (e.g., rescuing, disembarking ashore), and tracks the time that has elapsed since the process began.

A time-stepping approach is used in the model which enables changes at each time step resulting from uncertainties, complexities, and changes in the scenario, asset status, and system configuration. The model is coded in MATLAB, using data available from the different Search and Rescue databases in Canada. Statistical distributions of key parameters are used as inputs to the model, from which random choices are made at each time step.

Algorithmic Conceptualization of the SAR Process

A SAR operation flow chart has been developed based on the National SAR Manual for Canada (B–GA–209–001/FP–001, DFO 5449) and interviews with SAR operators, aimed at determining the steps of the SAR process. This flow chart includes decision-making elements, asset selection, and movement for the response. For this paper, a simplified flow chart, especially for the helicopter (HC), has been determined based on the detailed flow chart, see Figure 1.

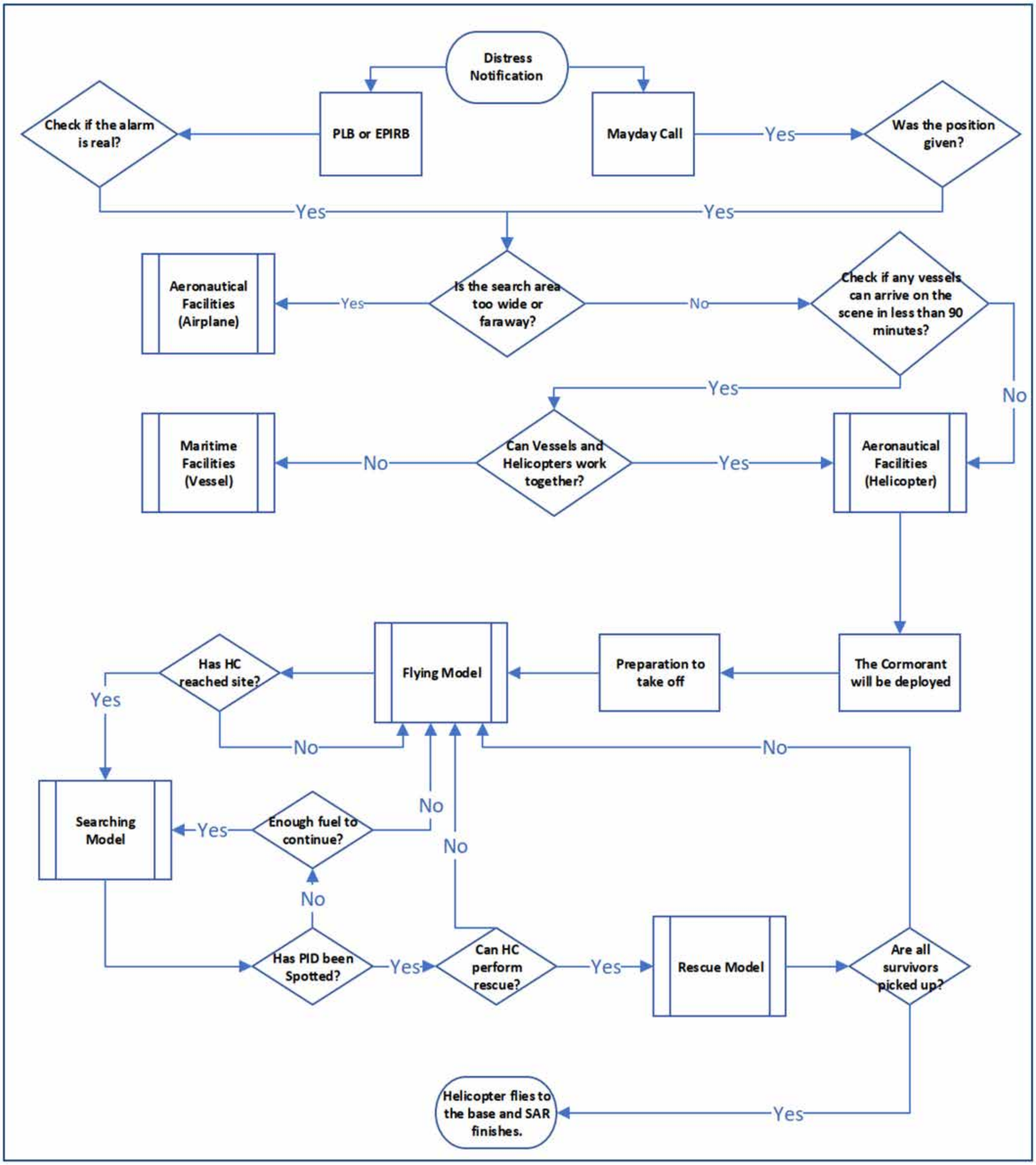

Figure 1—Simplified SAR Operation Flow Chart

Based on Figure 1, the SAR Operation is divided into the following phases:

Phase One: Distress Notification, Confirmation, and Decision-Making. It is assumed that distress notifications are received via one of two sources: case 1) signals from Personal Locator Beacons (PLB) and Emergency Position Indicating Radio Beacons (EPIRB); or case 2) a Mayday Call. In case 1, when a PLB or

EPIRB is triggered, it is assumed that the distress position is known and updated regularly. In case 2, when a mayday call is broadcast it is assumed that the distress position is known initially but not regularly updated.

After incident confirmation, SAR operators check the location and weather conditions and review the resource availability and state of readiness. The model was designed to represent the system's high-level organization with sub-model development capability to simulate aeronautical (helicopters and fixed-wing aircraft) and maritime activities (alone or together) within the SAR system. However, only the helicopter deployment and operation will be presented in this paper.

The total time of phase one (t_{Dec}) shall not take more than 30 minutes after receiving the initial distress notification. For the present stage of development, we assume this takes 30 minutes.

Phase Two: Helicopter Preparation. Helicopter preparation time (t_{Pre}) accounts for the time required by the flight crew to become airborne and varies based on the time of the day that the distress notification is received (i.e. 20 to 30 minutes on working days before 4 p.m. and 2 hours on the weekend and on working days after 4 p.m.). In this study, the Cormorant helicopter will be deployed for all scenarios in a time of 30 minutes, without considering the Location of the Incident (LOI) and the number of People in Distress (PID). However, in the model, based on the LOI and PID, other helicopter types with different specifications (e.g., Griffon) may be selected. In addition, in all scenarios presented in this paper, only one helicopter will be deployed; however, it is possible that multiple helicopters would be deployed at the same time.

The Cormorant specifications considered in the model include: 1) a Maximum Speed of 277 km/hr; 2) a Maximum Range with one full fuel tank of 1185 km; and 3) a Maximum Capacity of 15 passengers. Capacity refers to the number of survivors that can be taken on board for one trip from the incident to the base station.

The helicopter's speed varies based on the weather conditions (e.g., wind direction and strength), and in principle can be changed in each time step of the model. For the current model version, only a fixed speed (maximum) is used.

Phase Three: Flying Model. A flying sub-model has been developed to find the best routes between the helicopter's base, potential fuel stations, last known position (LKP), and final destination (location of PID). Generally, the base is where the helicopter starts flying and where survivors are returned to when rescued. In the base, refueling facilities are available. The model can also include potential fuel stations available for helicopters, when refueling is required in long-distance operations (e.g., local airports and offshore platforms). The last known position is given by information from a PLB, EPIRB, or Mayday call. The location of the PID is taken as the final destination, and will be found as a result of the search model (detailed in the following phase four).

In the helicopter model, a straight route (shortest distance) between bases, fuel stations, and last known position will be followed by the helicopter, and geographical features (e.g., high mountains or hills) are not considered. If multiple fuel stations are available, the model can decide which is the best to use, based on a number of parameters (e.g. distance, amount of fuel available, refueling rate). Due to the time-stepping approach, the model checks the residual fuel, the remaining distance to the next destination, and the location of a destination at each time step. It is possible to add uncertainties to the helicopter model, such as changing the last known position based on updated information and weather conditions, which may change the helicopter speed and fuel consumption. The model can simulate rescuing single or multiple persons, even beyond the capacity of the helicopter, with range limitations alleviated by strategically placing fuel caches in the region. In addition, it should be noted that while the helicopter's mission is to locate and rescue PID, as in the real world, the model will not make decisions that put the safety of the aircraft or crew at risk.

If refueling stops are required, in this paper it is assumed that the helicopter refueling time (t_{Fuel}) is 30 minutes. In the real world, crew changes and maintenance stops will be required, particularly for longer-duration missions. However, these are not considered in this paper.

Phase Four: Searching Model. The total search time and ability to detect the vessel or people in distress is affected by the weather conditions (e.g., reduced visibility from fog or storm conditions), ocean conditions (e.g., sea states), time of the day, the helicopter altitude and the shape of the object (e.g., boat or life raft). Search planning can be done by computer programs or manually. Some computer software has been developed to increase the probability of object detection at sea. For example, SARPlan, SARIS, SAROPS, SARMAP, and TRANSAS are used by maritime authorities worldwide. Each has its own strengths and weaknesses that impact its suitability for use in different conditions (Vidan et al., 2015).

In this study, the model focuses on the search time. It does not simulate the different search patterns or specific real-world search operations. Instead, a search time for each model run is randomly chosen from a distribution of search times. In this paper, this is assumed to be normally distributed with a mean of 30 minutes and a standard deviation of 10 minutes. Historical data will be used for this parameter when this becomes available.

For the scenarios presented in this paper, it is assumed that the incident happened in the daytime, with no effects of weather conditions. To represent the search process, a random location for the PID is selected in a search area with 6nm (11.11 km) radius around the LKP. For each run of the model, the helicopter will fly from the LKP to this location to start the rescue operation. This new location will be considered to be the model's final destination in the case of multiple travel scenarios.

Phase Five: Rescue Model. The rescue time for the helicopter operation encompasses the required time for airlifting the survivors from the water, lifeboat, or sinking or damaged vessel to the helicopter. The weather conditions, ocean conditions, and survivors' conditions (e.g., the severity of their injuries) affect the rescue time.

Kennedy et al. (2013) estimated a range of 10 to 30 minutes of rescue time per person for the air facilities. However, in this model, the rescue time distribution for each weather condition and incident scenario (e.g., rescuing survivors from a lifeboat, water, or vessel) would be extracted from historical data. The model uses this distribution to randomly select a rescue time per person. The total rescue time (t_{Res}) will be calculated as the sum of rescue times per person rescued.

For this paper, the rescue time per person is randomly selected from a normal distribution with a mean value of 5 minutes and a standard deviation of 2 minutes. This will be updated as improved datasets become available. As noted above, the overarching principle of this model is to protect the helicopter and crew at all costs. Therefore, at each time step, the weather conditions and residual fuel are checked (both of which affect the range), and in some cases, the rescue operation is cut short to enable refueling. After refueling, if there are still PIDs in the field, the helicopter would fly back to the location to complete the rescue.

Phase Six: Disembarking the Survivors. In some cases, the helicopter stops the rescue operation early due to the harsh weather, insufficient fuel to continue, or when the number of people in distress is beyond its capacity. In these situations, the helicopter flies back to the base for refueling and disembarking the survivors.

The survivors' conditions (e.g., injured) affect the disembarking time. In this paper, it is assumed that survivors can disembark on their own and the time is randomly chosen from a normal distribution with a mean value of 0.5 minutes and a standard deviation of 0.2 minutes. This will be updated in future model refinements as new information becomes available.

Total Search and Rescue Time. The total Search and Rescue time (t_{SAR}) is determined as the time step when the final survivor has been rescued to the helicopter. Rather than being a value found through deterministic means, it depends on the factors described above which are influenced by stochastic variables as the model progresses. Because the model uses a Monte Carlo approach, it does not produce a single rescue time, but rather a distribution of rescue times which depends on the accumulation of random factors interacting in the model.

Test Scenarios

The following sections demonstrate how the model functions using a series of test scenarios. First, the model is tested with three incident scenarios in the coastal regions of Eastern Canada (denoted as scenarios A, B, and C as explained in Section 3.2). Then, the model is tested with three incident scenario cases in the Canadian Arctic region (denoted as scenario cases D1, D2, and D3 as explained in Section 3.3).

Scenario Parameters and Assumptions

The variables of each scenario and normal distributions of search time, rescue time, and disembarking time are used as inputs to the model, and the distribution of total search and rescue time and maps indicating the chosen routes and stations are shown in the following subsections.

All cases were performed in benign conditions and during peak times of the year for SAR operation. As such, the cases assume that the incident happened in the summer and on weekdays before 4 p.m, that the distress notification is rapid and location accurate, the weather conditions and visibility are good and there is no fog nor high seas on scene. Further, for all cases, one Cormorant helicopter is deployed from Gander Airport, Newfoundland, Canada.

It should be noted that a fixed 60 minutes has been considered for all scenarios as the required time for decision-making and helicopter preparation ($t_{Dec}+t_{Pre}$).

Eastern Canada's Coastal Regions

Scenarios A, B, and C were developed to simulate incidents requiring SAR response, which happened in the Atlantic Ocean and near the Newfoundland coastal regions. For these scenarios, the St. John's airport will be considered a survivor drop-off base and fuel station, and the Hibernia offshore platform, located in the Grand Banks, will be used as a potential fuel station. Figure 2 shows the location of the Gander and St. John's airport bases, the Hibernia Platform, and different scenarios locations.

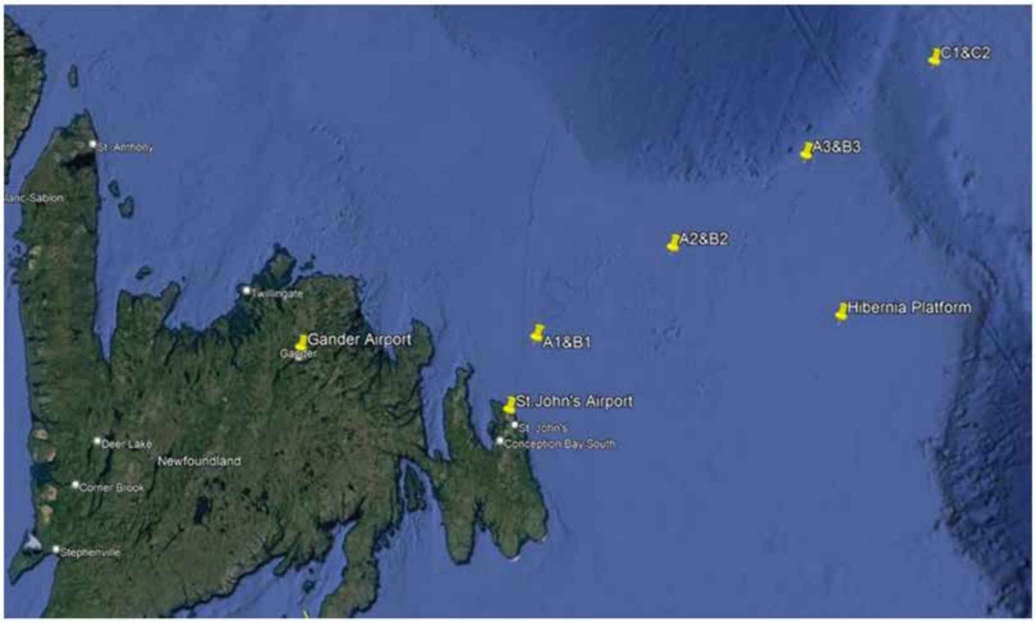

Figure 2—Scenario Locations, SAR bases, and Possible Fueling Stations in East Coast Canada

Scenario A. In scenario A, it is assumed that only one person is in distress, and the SAR operation was modeled for three locations (A-1, A-2, and A-3), listed in Table 1. The distribution of total Search and Rescue time as well as the flight map of the sample cases are shown in Figures 3 to Figures 8 respectively.

Table 1—Input Data and Results for Scenario A

Case	Lat.	Lon.	PID No.	Distance to Gander Airport (km)	Total SAR Time (h)		
					50th Percentile	90th Percentile	99th percentile
A-1	48	−52	1	218	2.6	2.8	3.0
A-2	48	−50	1	354	3.6	3.8	4.0
A-3	48	−48	1	497	4.6	4.9	5.0

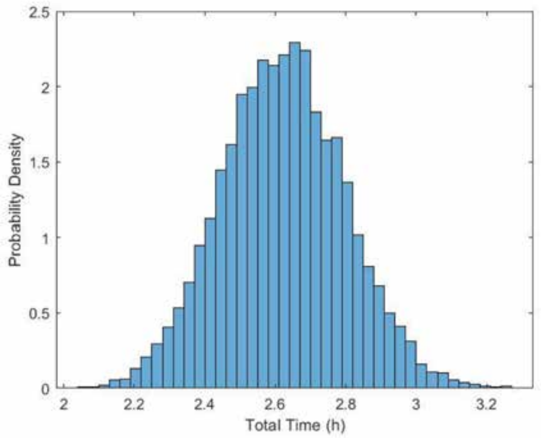

Figure 3—Case A-1, Total Search and Rescue Time Distribution

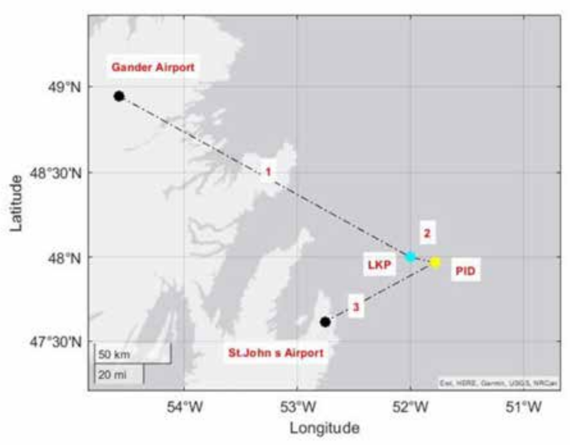

Figure 4—Case A-1, Flight Map of Sample Case

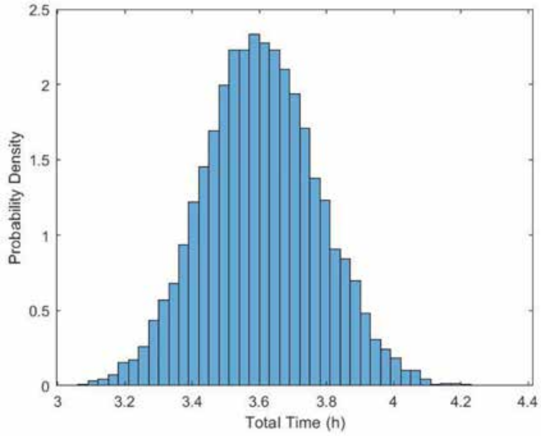

Figure 5—Case A-2, Total Search and Rescue Time Distribution

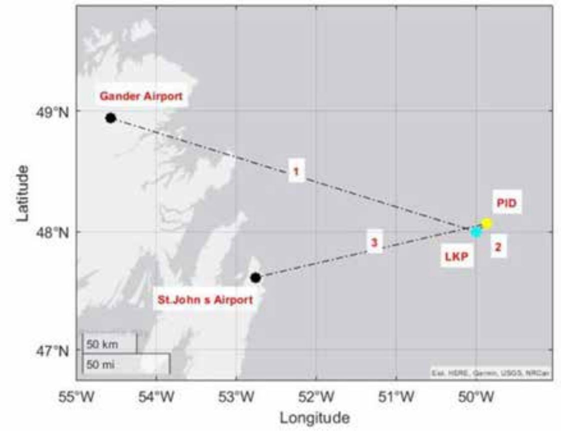

Figure 6—Case A-2, Flight Map of Sample Case

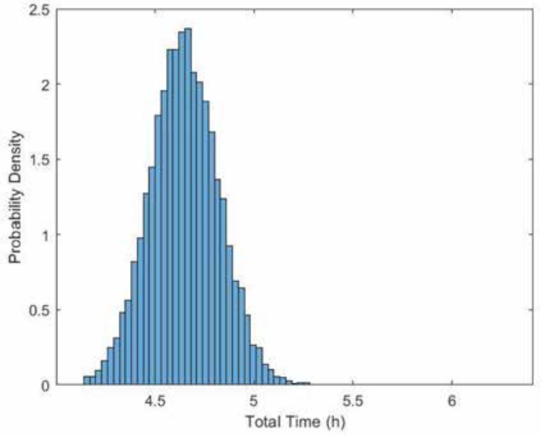

Figure 7—Case A-3,Total Search and Rescue Time Distribution

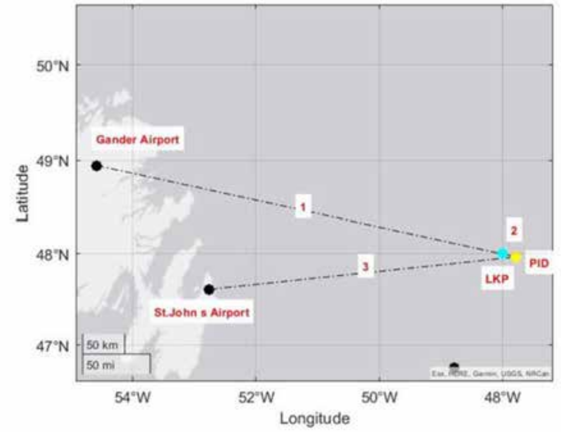

Figure 8—Case A-3, Flight Map of Sample Case

In case A-1, illustrated in Figures 3 and 4, the helicopter flies from Gander to the LKP, the PID location is found after searching time, the survivor is picked up, and then the helicopter returns to St. John's without needing to refuel.

In case A-2, illustrated in Figures 5 and 6, the flight map is similar to scenario A-1, however, the distance and the total Search and Rescue time are different.

In case A-3, illustrated in Figures 7 and 8, the flight map is similar to scenarios A-1 and A-2, however, the distance and the total Search and Rescue time are different.

Scenario B. In this scenario, it is assumed that 15 persons are in distress, and the SAR operation was modeled for the same locations as scenario A. The incident location and model results for all three cases (B-1, B-2, and B-3) are listed in Table 2. The distribution of total search and rescue time as well as the flight map of the sample cases are shown in Figures 9 to Figures 14 respectively.

Table 2—Input Data and Results for Scenario B

Case	Lat.	Lon.	PID No.	Distance to Gander Airport (km)	Total SAR Time (h)		
					50th Percentile	90th Percentile	99th Percentile
B-1	48	−52	15	218	3.8	4.1	4.3
B-2	48	−50	15	354	4.8	5.1	5.3
B-3	48	−48	15	497	6.7	7.7	7.9

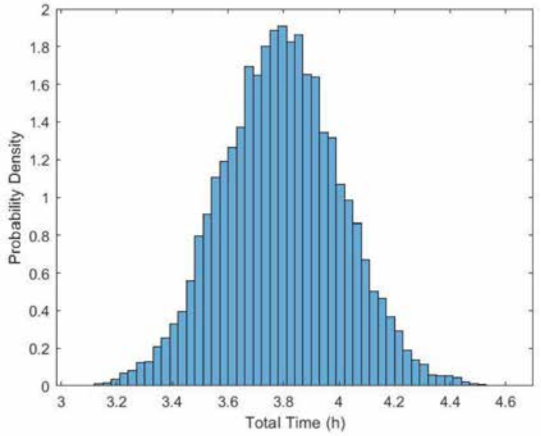

Figure 9—Case B-1, Total Search and Rescue Time Distribution

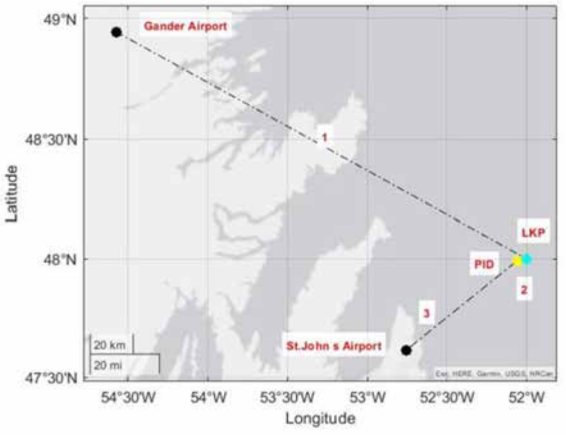

Figure 10—Case B-1, Flight Map of Sample Case

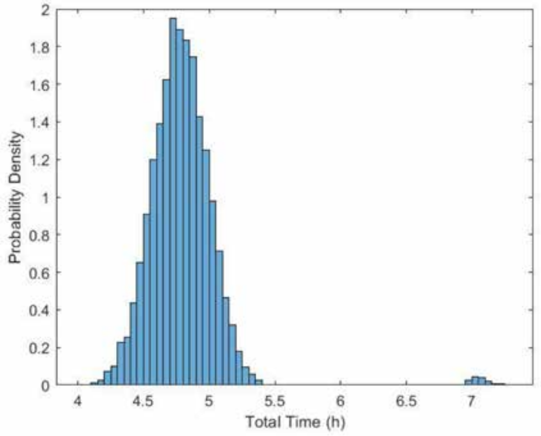

Figure 11—Case B-2, Total Search and Rescue Time Distribution

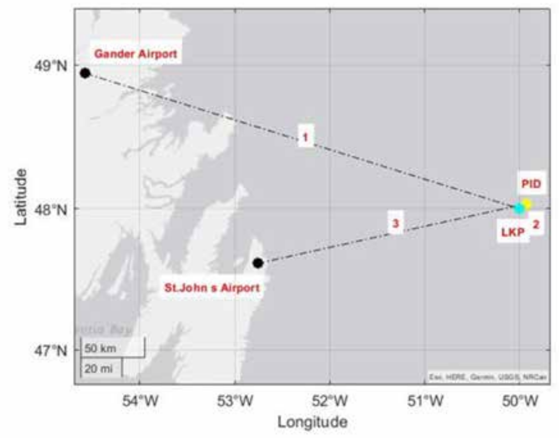

Figure 12—Case B-2, Flight Map of Sample Case

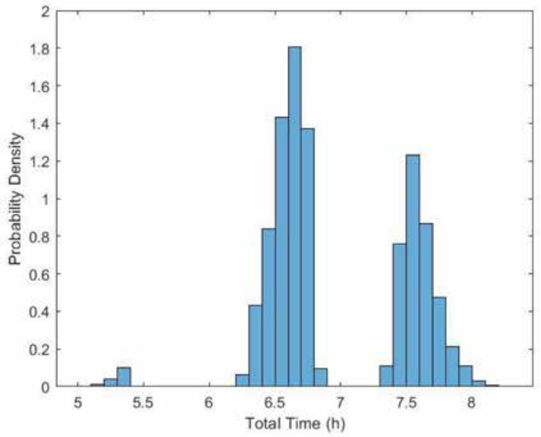

Figure 13—Case B-3, Total Search and Rescue Time Distribution

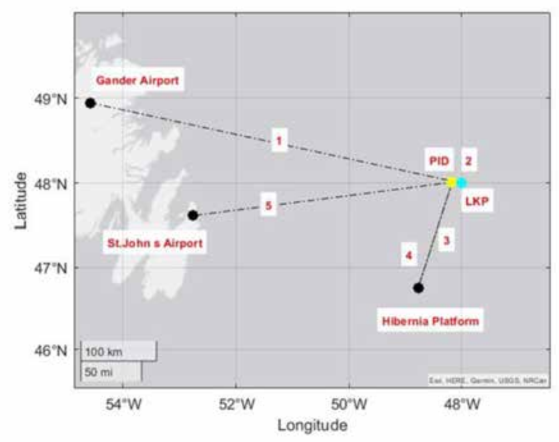

Figure 14—Case B-3, Flight Map of Sample Case

In case B-1, the helicopter flies from Gander to the LKP, the PID location is found after searching time, all 15 survivors are picked up, and then the helicopter returns to St. John's. There is no need to refuel anywhere.

In case B-2, the flight map is similar to scenario B-1. But in some cases, if the random search time is high and the PID location is far, then the helicopter would need to refuel. In this case, the helicopter picks up some survivors, then flies to Hibernia Platform for refueling, returns to the PID location to pick up the remaining survivors, and then flies back to St. John's. These cases are visible in the total SAR time distribution in Figure 11.

In case B-3, some flight maps are similar to scenario B-2. However, in more cases, the helicopter flies to the Hibernia platform for refueling, returns to the PID location to pick up all survivors, and then flies back to St. John's. These cases are visible in the total SAR time distribution in Figure 13, and also in the flight map of the sample case in Figure 14.

Scenario C. In Scenario C, it is assumed that the incident happened in a remote location from the Eastern Coastal regions. Cases C-1 and C-2 happen in the same location, but the SAR operations are modeled for two different numbers of people in distress. The incident location and model results are listed in Table 3, and the distribution of total Search and Rescue time and the flight map of the sample case are shown in Figures 15 to 18.

Table 3—Input Data and Results for Scenario C

Case	Lat.	Lon.	PID No.	Distance to Gander Airport (km)	Total SAR Time (h)		
					50th Percentile	90th Percentile	99th Percentile
C-1	48	−46	1	642	6.4	7.3	7.5
C-2	48	−46	15	642	9.8	10.1	10.4

In case C-1, it is assumed that one person is in distress. The helicopter flies to St. John's and, after refueling, flies to the LKP and then to the PID, picks up the survivor, and returns to St. John's. However, in some cases, if the random search time is high and the PID location is far, then the helicopter needs to refuel again. In this case, the helicopter picks up the survivor, flies to the Hibernia Platform for refueling, and then flies back to St. John's. These two cases are visible in the total SAR time distribution in Figure 15.

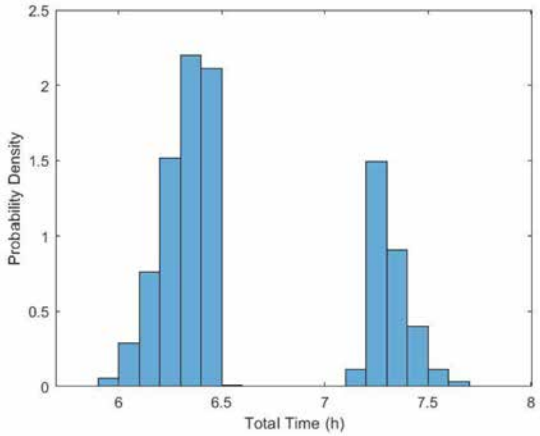

Figure 15—Case C1, Total Search and Rescue Time Distribution

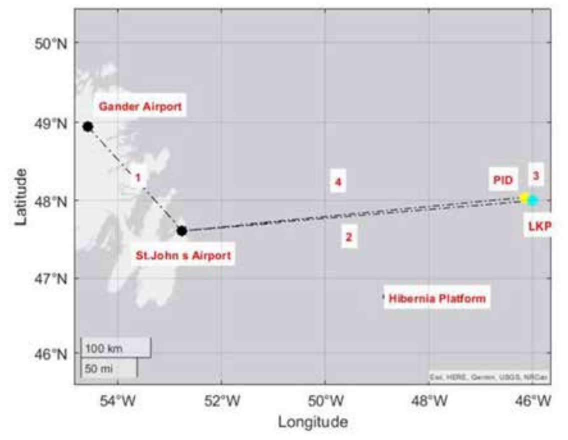

Figure 16—Case C-1, Flight Map of Sample Case

In case C-2, it is assumed that 15 persons are in distress. Some flight maps are similar to scenario C-1. However, in more cases, the helicopter can pick up some survivors, then flies to the Hibernia Platform for refueling, returns to the PID location to pick up all remaining survivors, and then flies back to St. John's. These cases are visible in the total SAR time distribution in Figure 17 and also in the flight map of the sample case in Figure 18.

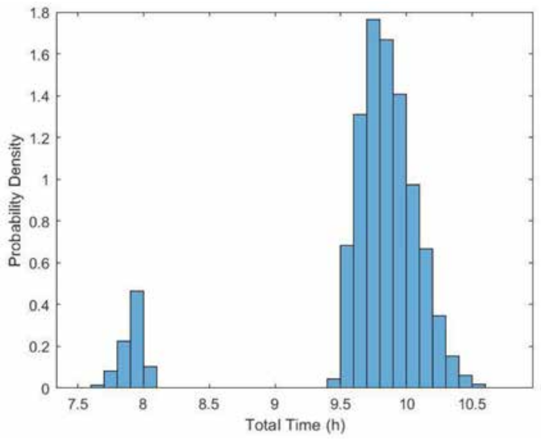

Figure 17—Case C-2, Total Search and Rescue Time Distribution

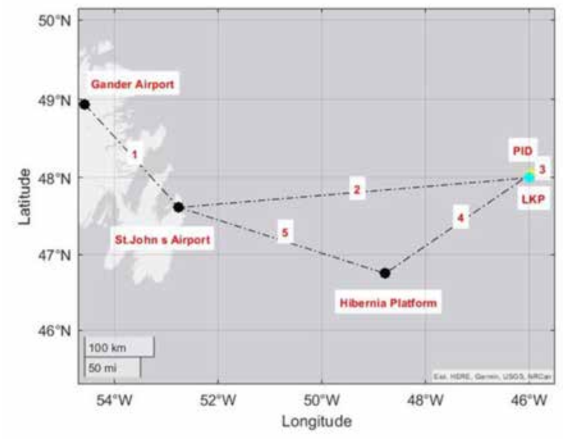

Figure 18—Case C-2, Flight Map of Sample Case

Arctic Regions

Scenario cases D-1, D-2, and D-3 were developed to simulate incidents requiring SAR response that happened in the Arctic region. For these scenario cases, the Arctic Bay airport is considered as base, and the Longstaff Blf airport, Iqaluit airport, Cape Dorset airport, Hopedale airport, and Goose Bay airport will be used as potential fuel stations. Figure 19 shows the location of bases, fuel stations, and incident locations.

Figure 19—Locations of incidents, SAR bases, and possible fueling stations in the Arctic Region

Scenario D. In Scenario D, it is assumed that the incident happened in a remote location in the Arctic. Cases D-1, D-2, and D-3 happen in the same location, but the SAR operations are modeled for three different numbers of people in distress. The incident location and model results are listed in Table 4, and the distribution of total Search and Rescue time and the flight map of the sample case are shown in Figures 20 to 26 respectively. For all scenarios in the Arctic region, the helicopter flies from Gander to the Hopedale airport, Iqaluit airport, Longstaff Blf airport, and finally, Arctic Bay airport for refueling. Then flies to the LKP, and PID picks up the survivor, and returns to the Arctic Bay airport.

Table 4—Input Data and Results for Scenario D

Case	Lat.	Lon.	PID No.	Distance to Arctic Bay Airport (km)	Total SAR Time (h)		
					50th Percentile	90th Percentile	99th Percentile
D-1	74	−79	1	221	16.5	16.7	16.9
D-2	74	−79	15	221	17.6	17.9	18.1
D-3	74	−79	35	221	23.5	23.9	24.2

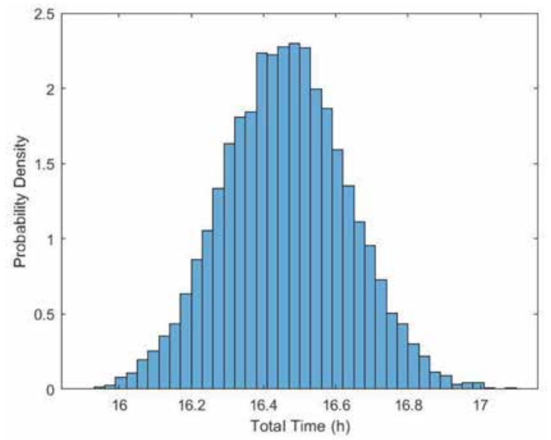

Figure 20—Case D-1, Total Search and Rescue Time Distribution

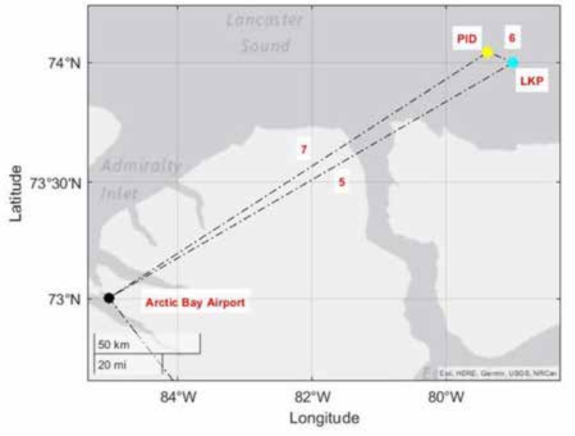

Figure 21—Case D-1, Flight Map of Sample Case

Figure 22—Case D-1, Flight Map of Sample Case from Gander to Arctic Bay

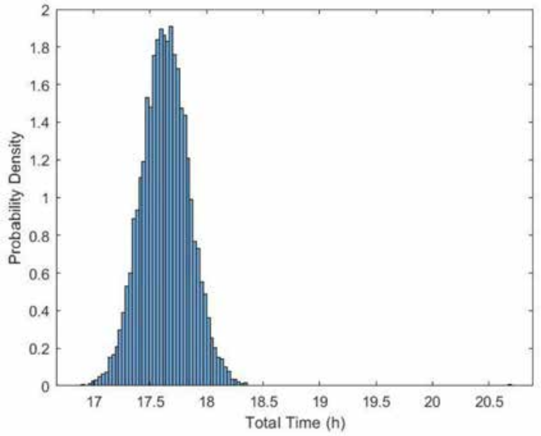

Figure 23—Case D-2, Total Search and Rescue Time Distribution

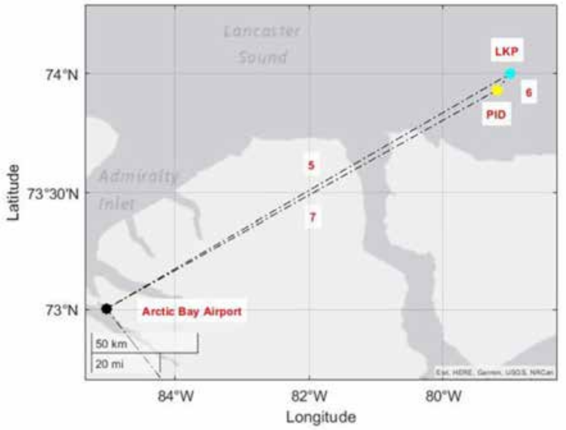

Figure 24—Case D-2, Flight Map of Sample Case

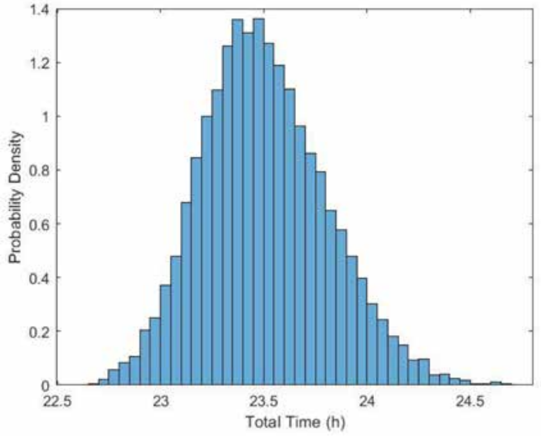

Figure 25—Case D-3, Total Search and Rescue Time Distribution

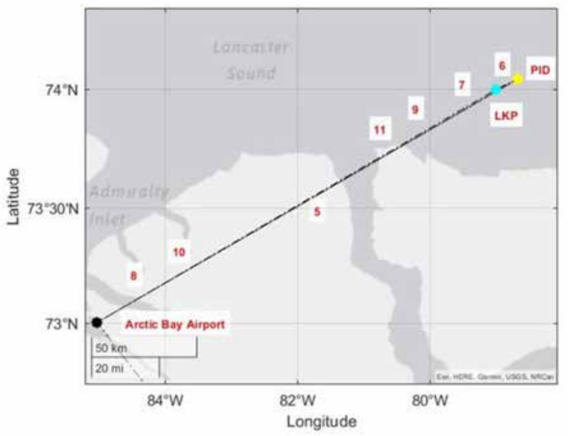

Figure 26—Case D-3, Flight Map of Sample Case

In case D-1, it is assumed that one person is in distress. The distribution of total search and rescue time and the flight map of the sample case are shown in Figures 20 to 22.

In case D-2, it is assumed that 15 persons are in distress in the same location as in case D-1. The distribution of total Search and Rescue time and the flight map of the sample case are shown in Figures 23 and 24.

1- In case D-3, it is assumed that 35 persons are in distress in the same location as in case D-1. The distribution of total search and rescue time and the flight map of the sample case are shown in Figures 25 and 26. In this case, multiple travels to the PID location are required to pick up all survivors.

Discussion

Model Results for Eastern Canada's Coastal Scenarios

For the Eastern Canada coastal region scenarios shown, all A and B cases were co-located, with each A involving 1 people in distress and each B involving 15 people in distress. Comparing these cases allows us to demonstrate the effect of distance as well as the number of people in distress involved for cases where the distance from the helicopter base is within the helicopter range and the number of people in distress is less than the helicopter capacity. For C cases, we can show the effect of distances greater than the helicopter range for 1 and 15 people in distress.

Results show that if the incident is close to the shore or bases, the number of people in distress has little effect on the total SAR time, and only the time spent picking up survivors is added to the time spent traveling back and forth to that location. As the distance to the incident increases, we see that the effect of the number of people in distress becomes more significant for total SAR time because the helicopter must refuel in most cases. Thus, after picking up some survivors, it flies to the nearest fuel station and returns to the position to pick up the remaining survivors. The results of scenarios in the Atlantic region are summarized in Table 5.

Table 5—Summary of Scenarios in the Atlantic Region

	Case	Lat.	Lon.	PID No.	Distance to Gander Airport (km)	Total SAR Time (h)		
						50th Percentile	90th Percentile	99th Percentile
Atlantic	A-1	48	−52	1	218	2.6	2.8	3.0
	A-2	48	−50	1	354	3.6	3.8	4.0
	A-3	48	−48	1	497	4.6	4.9	5.0
	B-1	48	−52	15	218	3.8	4.1	4.3

	Case	Lat.	Lon.	PID No.	Distance to Gander Airport (km)	Total SAR Time (h)		
						50th Percentile	90th Percentile	99th Percentile
	B-2	48	−50	15	354	4.8	5.1	5.3
	B-3	48	−48	15	497	6.7	7.7	7.9
	C-1	48	−46	1	642	6.4	7.3	7.5
	C-2	48	−46	15	642	9.8	10.1	10.4

Model Results for the Arctic Scenarios

In the Arctic region, the main challenge is flying to the incident location (for cases D-1, D-2 and D-3, this accounts for 83%, 78%, and 59% respectively of the total SAR time). As the model develops and we use input distributions that allow us to simulate the effect of weather, this effect can be shown. The model shows that for the simplistic cases shown, the results will be similar to those in the Atlantic region where distance and the number of people in distress result in an increased rescue time.

The results of scenarios in the Arctic region are summarized in Table 6. Given that the helicopter is able to refuel at Arctic Bay, as well as drop survivors at this location, we can compare the effect of the number of people in distress (1 vs 15) to cases A-1 and B-1 where the flight distance is similar. Doing so, we also see a similar time difference between cases A-1/B-1 and D-1/D-2. For the case where the number of people in distress is greater than two times the helicopter capacity, we see a much larger rescue time, due to the fact that more than two trips are required by the helicopter. In the future model development, we will include factors such as the total quantity of fuel available at a given location (e.g. Arctic Bay), as well as the availability of resources to sustain survivors in a given location, which may result in the need to fly to more distant locations for drop-off of survivors and refueling the helicopter, thus further extending the total rescue time.

Table 6—Summary of Scenarios in the Arctic Region

	Scenario	Lat.	Lon.	PID No.	Distance to Arctic Bay Airport (km)	Total SAR Time (h)		
						50th Percentile	90th Percentile	99th Percentile
Arctic	D-1	74	−79	1	221	16.5	16.7	16.9
	D-2	74	−79	15	221	17.6	17.9	18.1
	D-3	74	−79	35	221	23.5	23.9	24.2

Conclusions and Future Work

A relatively simplistic model representing helicopter SAR operations has been developed which includes the stochastic effects of these operations. We have used the model with assumed but realistic input distributions to systematically test scenarios to show how the Location of Incident (LOI) and the number of People in Distress (PID) influence SAR rescue time. We have shown that as the distance from the helicopter base increases, the number of persons to be rescued has a greater effect on total rescue time.

Results show that the model can determine the best route to the PID and the best location for refueling and disembarking survivors. As the model is further developed and experimental and historical SAR performance data are included to represent the stochastic nature of the overall SAR process, we will be able to improve model reliability and perform model validation using known SAR cases.

In future developments of the model, we will include operations in which more than one helicopter is involved, or helicopters and ships working together to perform the rescue, as well as the impact of weather conditions on operations.

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