A Network-based Simulation Model for Helicopter Rescue Time Estimation in the Canadian Arctic

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ABSTRACT

Search-and-rescue (SAR) helicopter operations in Arctic areas with limited infrastructure are crucial for saving lives under harsh weather conditions. This study develops a SAR helicopter response model that first identifies all possible paths for a rescue mission using path network optimization, then quantifies the effects of weather on travel time for each route and finally employs discrete-event and Monte Carlo simulation to evaluate the performance of SAR missions. The approach leverages meteorological data to classify favorable, unfavorable, or no-go conditions for SAR helicopter operability, offering insights into travel and rescue times from SAR bases to people in distress across the Canadian Arctic. Preliminary findings highlight how route selection, weather severity, and refueling constraints influence mission durations. While further work is needed to develop, test, and validate the model, these results indicate the model's promise to enhance SAR planning, reinforcing community resilience under harsh, changing Arctic environments.

KEY WORDS

Search and Rescue, Rescue time estimation, Helicopter operations, Canadian Arctic, Emergency Management

INTRODUCTION

Helicopter-based Search and Rescue (SAR) operations in the Arctic face unique challenges, including extreme temperatures and harsh environmental conditions, rapidly shifting weather systems, and sparse infrastructure (Funston, 2014). Much of the existing literature has concentrated on maritime SAR, overlooking the complexities of aerial response missions in these northern regions (Kennedy et al., 2013; Kikkert, 2019; Akbari, Pelot, & Eiselt, 2017; Stoddard, Pelot, Goerlandt, & Etienne, 2024). However, emerging operational challenges indicates the need for more accurate modeling of helicopter operability, given that factors such as unpredictable weather, limited fuel capacity, and mechanical unreliability can significantly influence rescue timelines (Karatas et al., 2017; Zarrin Mehr et al., 2023; Ash, 2023).

In response to these challenges, researchers have increasingly adopted simulation-based approaches, particularly discrete event simulation (DES) and Monte Carlo methods, that capture the stochastic nature of SAR tasks (Simonsen et al., 2015). By integrating elements to account for system and environmental uncertainties (e.g., adverse weather episodes and equipment malfunctions) into structured models, these techniques can provide valuable insights into where operational bottlenecks may arise, along with the likelihood of encountering adverse scenarios (Cucinelli et al., 2023). Such findings can support strategic decision-making and interventions to address potential mission delays, whether caused by unfavorable conditions, limited resource availability, or logistical constraints.

Building on these methodological foundations, the present work focuses on helicopter SAR operations in the Canadian Arctic, particularly on how environmental factors (weather volatility) and logistical constraints (refueling requirements), affect mission performance. By integrating helicopter operability parameters with historical data, this study aims to improve the predictive accuracy of earlier presented models. Specifically, the research seeks to answer the following question: How do weather variability and refueling constraints influence helicopter SAR response times and overall mission effectiveness in the Canadian Arctic, focusing on the time needed to complete a SAR mission?

The goal is to offer actionable guidance for policymakers, SAR coordinators, and frontline responders, thereby enhancing rescue efforts in one of the most challenging and remote environments on the planet, contributing to Arctic community resilience.

BACKGROUND

Environmental and Climatic Changes in the Arctic

Since at least the 1970s the Arctic has undergone significant climatic shifts with rising temperatures intensifying the hydrological cycle, leading further to increased humidity, precipitation, river discharges, glacier retreat, and land ice loss. Concurrently, diminishing sea ice and warming permafrost underscore the need for ongoing weather monitoring (Box et al., 2019). These changes complicate emergency responses in a region characterized by vast, sparsely navigated waters, extreme weather, and limited infrastructure, especially in winter when rapid SAR response is especially crucial (Mathisen, 2017).
Remote communities, such as those in Nunavut, face even greater challenges in emergency response. Kikkert et al. (2023) emphasize that the region's harsh environment, combined with insufficient local resources and the considerable distance from southern SAR assets, underscores the necessity for effective SAR systems, both maritime, aerial, and local ground rescue. This is relevant to SAR operations across the Canadian Arctic (Kikkert & Lackenbauer, 2021), (Kikkert et al., 2023)

Search and Rescue Operations in the Arctic

Given the expansive and harsh conditions of the Arctic, effective SAR operations are vital. The International Maritime Organization (IMO) defines SAR as activities intended to assist persons in distress at sea, governed by global agreements such as the International Convention on Maritime Search and Rescue (SAR) and the Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic. However, despite these agreements, SAR missions in the Arctic remain exceptionally challenging due to unpredictable weather, remote locations, and limited response assets (International Maritime Organization, 1979; Arctic Council, 2011).

In Canada, over 1,000 SAR cases occur annually above 55° N latitude, with nearly one-fifth involving medical emergencies. The SAR incidence rate in these regions is markedly higher than the national average (Ford & Clark, 2019). Coordination of these operations relies on a network of agencies including the Canadian Coast Guard (CCG) and the Royal Canadian Air Force (RCAF) which operate from three Joint Rescue Coordination Centres (JRCCs) located in Victoria, Trenton, and Halifax (Department of National Defence, 2018). Nevertheless, SAR in remote Arctic regions is hampered by fragmented governance, limited infrastructure, and coordination challenges among multiple stakeholders (Cucinelli et al., 2023; Kikkert, Pedersen, & Lackenbauer, 2023; Fernandes, 2024).

Figure 1 represents the three Canadian JRCCs, the division of responsibilities between Joint Rescue Coordination Centre (JRCC) which manage missions in different locations. JRCCs respond to approximately 2,500 annual calls and conducting about 1,000 SAR missions (Christensen et al., 2021).

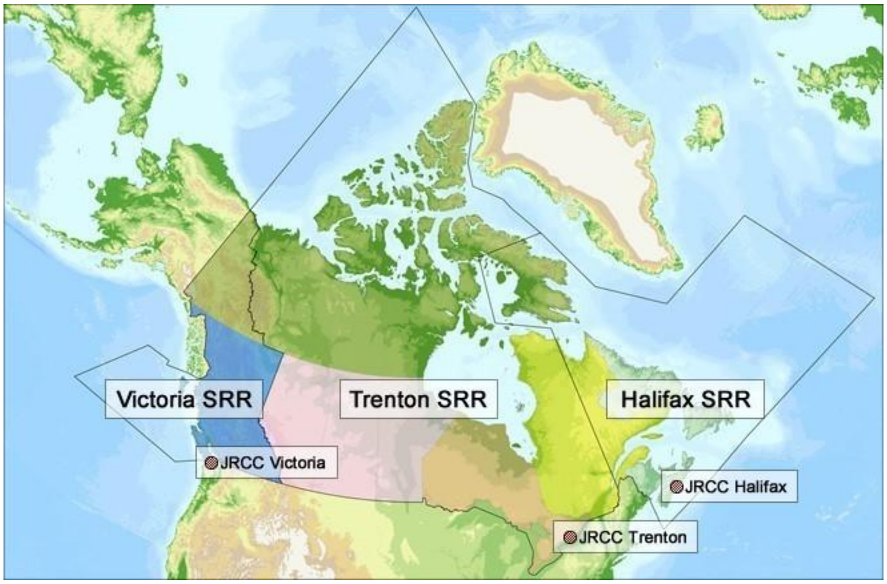

Figure 1. Map of Canada showing 3 Search and Rescue regions (SAR Course 49, n.d.)

Helicopter Operations in SAR Missions

Helicopters are a critical component of SAR operations, particularly in the Canadian Arctic, where terrain and weather often preclude ground access. The CH-149 Cormorant, a long-range helicopter designed for SAR missions, exemplifies the specialized equipment used in these operations. Capable of transporting up to 12 passengers, the Cormorant is engineered to operate under extreme conditions. Since its introduction in 2001, this fleet comprising 3 aircraft stationed at bases such as Gander, Greenwood, and Comox have played a vital role in rescue efforts (Government of Canada, n.d.; The Standing Senate Committee on Fisheries and Oceans, 2018). Modernization plans are underway to update and expand the fleet, ensuring continued effectiveness in meeting the region's SAR needs. Helicopter specifications are provided in Table 1.

Table 1. CH-19 Cormorant Search and Rescue Helicopter Specifications

Specification	Details
Helicopter model	CH-149 Cormorant
Role	Canada's Search and Rescue Helicopter
Number in service (RCAF)	3
Range	1000+ km
Capacity	Up to 12 stretchers, or 5,000 kg of cargo
Average SAR Sorties per Year	260
Canadian SAR Land Area	18 million km²
Canadian Coastline Covered	243,800 km

Rescue Capabilities	- High altitudes in the Canadian Rockies - Extreme weather conditions - Inhospitable oceans - Arctic environments
Bases	Gander, NL; Greenwood, NS; Comox, BC

The Cormorant is a robust, three-engine helicopter engineered for extended search missions. It lowers SAR technicians to remote areas or vessels and can carry up to 12 passengers. Its performance in challenging conditions such as like cold weather and strong winds makes it indispensable for maritime SAR operations (The Standing Senate Committee on Fisheries and Oceans, 2018; Fernandes, 2024).

Figure 2. CH-19 Cormorant (Government of Canada, n.d.)

While fixed-wing aircraft play a key role in Canada's aerial SAR network—especially for wide-area searches and long-range surveillance—our study focuses exclusively on helicopters due to their unique operational advantages in Arctic missions. These include the ability to hover, perform vertical take-offs and landings, and access terrain that lacks runway infrastructure. Additionally, helicopter missions are subject to specific logistical and meteorological constraints, such as limited fuel capacity, sensitivity to adverse weather, and frequent refueling needs, which differ significantly from fixed-wing aircraft operations. Addressing these distinct characteristics enables a focused and realistic modeling framework for time-sensitive Arctic rescue scenarios (Fernandes, 2024; Karatas et al., 2017).

Advances in SAR Modeling and Simulation

Recent SAR research has increasingly employed simulation modeling to estimate response times and optimize resource allocation. For example, SARPlan, a decision support system for the Canadian Forces, integrates search theory, optimization techniques, and constraint programming to enhance mission planning, improving search success rates while reducing costs (Abizaid & Frost, 2005).

Other studies have modeled SAR behaviors using an agent-based framework with modified Truncated Lévy walks and an auction-based task allocation mechanism (Jian et al., 2018), and applied Bayesian network-based probabilistic risk analysis to assess Arctic grounding incidents (Kandel & Baroud, 2023).

Helicopter response times have been simulated with models such as HESARO and RHEO, which incorporate Monte Carlo methods to account for weather uncertainties, refueling constraints, and operational delays (Fernandes, 2024). Other models suggest that relocating SAR helicopter bases to Arctic regions could notably improve response times (Zarrin Mehr, 2023).

While analytical or probabilistic models offer useful insights into SAR trends or average conditions, they often rely on assumptions such as independence of events or steady-state parameters. These approaches may struggle to capture the dynamic sequencing of real SAR operations. Simulation-based approaches, particularly discrete-event and Monte Carlo methods, allow for explicit modeling of time-dependent decisions, stochastic weather changes, equipment readiness, and cascading delays. This enables more granular scenario analysis and operational insights, especially valuable in the highly variable and harsh Arctic context (Zarrin Mehr et al., 2023; Cucinelli et al., 2023).

Building on these advancements, the current study focuses on helicopter SAR operations in the Canadian Arctic. By integrating updated planning parameters with localized weather data, this research aims to enhance the predictive accuracy of strategic planning and provide actionable insights for policymakers, SAR coordinators, and frontline responders in one of the world's most challenging environments.

METHODOLOGY

This study employs a four-phase methodology to estimate SAR helicopter rescue times for incidents occurring in the northern regions of Canada, whether on land or over water. These phases are depicted in Fig. 3 below and briefly introduced. The phases are further elaborated in phase one to phase four.

Phase one

In this phase, weather data from Spire is collected and processed (Spire Global, n.d.). This involves extracting and converting GRIB (Gridded Binary) files into a format suitable for subsequent analyses.

Phase Two

The second phase focuses on determining all feasible routes from each base to any potential incident location, subject to fuel constraints and helicopter range. From the set of possible routes, three candidates are selected for each base.

Phase Three

In the third phase, a weather model designed to assess SAR helicopter operability under specific meteorological conditions is introduced and integrated with Spire data. Each candidate route is divided into multiple segments, allowing for detailed evaluation of weather conditions along both terrestrial and aquatic segments. This dynamic assessment enables the identification of the fastest rescue path.

Phase Four

The final phase presents the Helicopter Search and Rescue (SAR) Operations Model. This model evaluates the rescue time for each of the three possible routes, considering all mission steps, including take-off, flight, landing, refueling, on-scene hovering for hoist operations, and adjustments for changing weather conditions. The route with the fastest estimated total rescue time is then selected for the operation.

As mentioned earlier throughout the study, the Cormorant CH-19 helicopter model is considered, incorporating its operational parameters, such as fuel consumption and hover time during rescues, as outlined in the Fig. 3 a flow chart summarizing the four phases of the model is also presented.

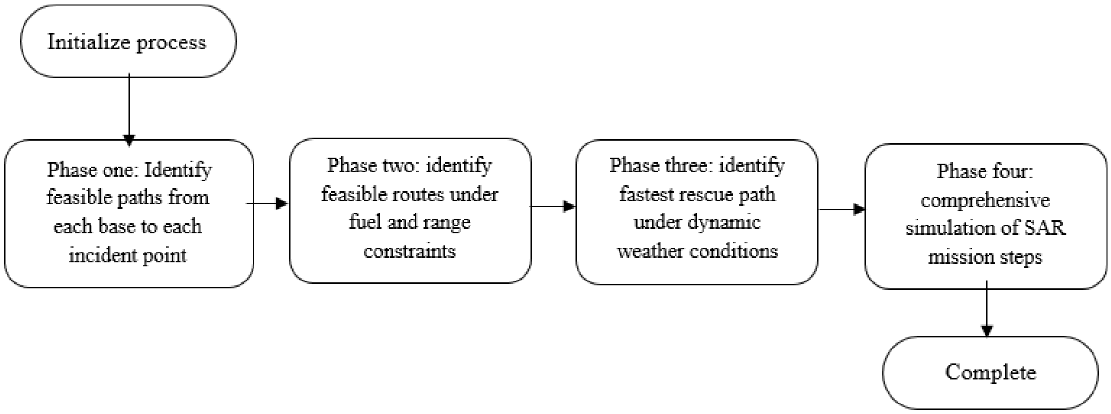

Figure 3. Flow Chart of Overview of the four-Phase Methodology

Figure 4 summarizes the key factors incorporated in our SAR helicopter model—ranging from helicopter specifications (such as fuel consumption, speed, and operational limits) to the number of helicopters, their stationing bases, the number of people in distress, incident locations, fuel constraints, and weather conditions. These factors shape the data requirements, route selection logic, and operational constraints in our helicopter SAR simulations.

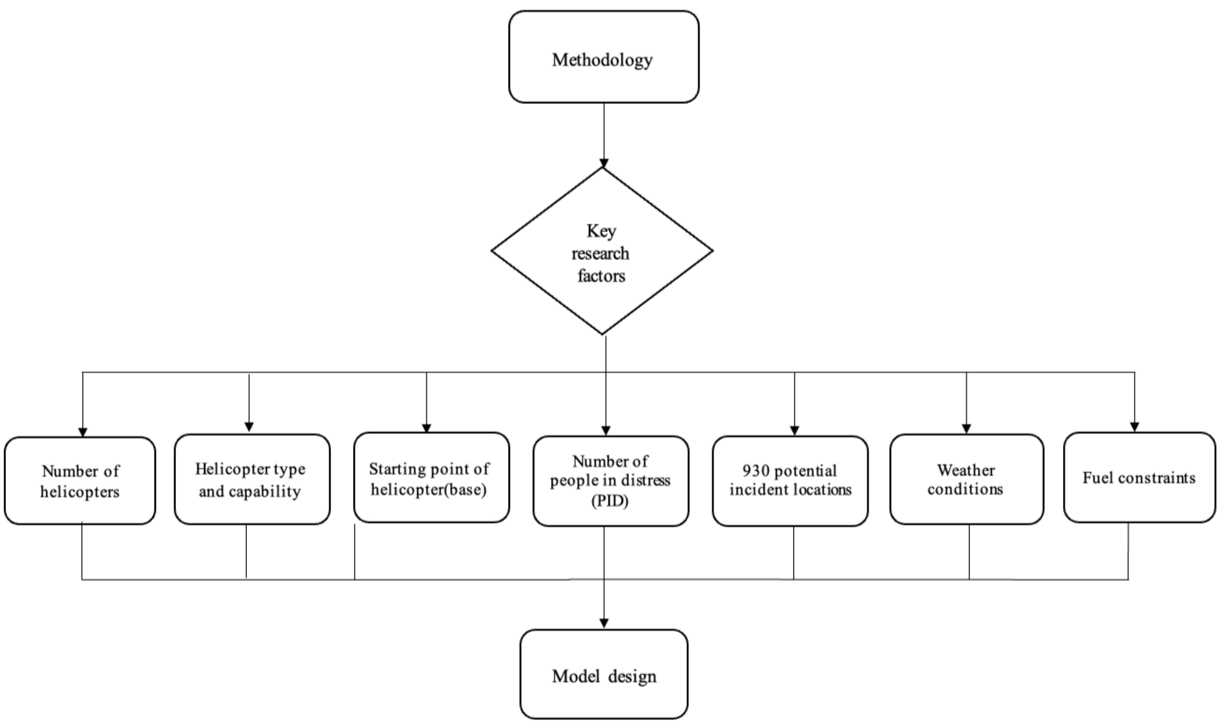

Figure 4. Flow chart Indicating Key Input Variables and Operational Constraints for Helicopter SAR Planning

Phase one

In the first phase, weather data is collected and analyzed using Spire's high-resolution forecasting datasets (Spire Global, n.d.). These datasets are extracted as GRIB (Gridded Binary) files for further processing, including the conversion into a structured format suitable for analysis. Spire generates forecasts by assimilating diverse satellite-derived inputs such as radio occultation measurements, ocean wind data, and soil moisture readings, and employs advanced data assimilation techniques to produce hourly predictions up to six days in advance. These forecasts, which can be accessed through either an API or Spire's Deep Insights platform, offer a spatial resolution of approximately 3 km for the continental United States and parts of Europe (Spire Global, n.d.). Table 2 presents the variables contained in each GRIB file from the Spire weather dataset. Based on expert opinions and previous research, the key weather factors affecting helicopter operations have been identified. Table 2 below highlights the variables used in this study.

Table 2. Weather Data Set Variables and Descriptions

Data set	Variable name	Weather factor	Variables used in this research
0	tcc	Total Cloud Cover (%)	-
1	t2m	2 metre temperature (K)	✓
2	si10	10 metre wind speed (m/s)	✓
2	wdir10	10 metre wind direction (Degree true)	✓
3	gust	Wind speed (gust) (m/s)	✓
4	swell	Significant height of swell waves (m)	-
4	swper	Mean period of swell waves (s)	-
4	swh	Significant height of combined wind waves and swell (m)	-
5	sst	Sea surface temperature (K)	-
6	ptype	Precipitation type (code table (4.201))	✓
7	tp	Total Precipitation (kg m**-2)	✓
7	asnow	Total snowfall (m)	-

Spire weather data was selected for this study due to its high spatial resolution, global coverage, and availability in a standardized GRIB file format, which is compatible with our automated processing workflow. Its integration of satellite-based inputs enables consistent forecasting in remote Arctic areas where ground-based stations may be sparse. However, a key limitation of the Spire dataset is its reliance on model forecasts, which may underrepresent localized microclimatic phenomena. We acknowledge this as a constraint in the current model and propose that future iterations incorporate blended data sources—such as Environment Canada archives—for greater precision in regional weather modeling(Spire Global, n.d.; Environment Canada, 2024).

Phase two

In this phase, all feasible helicopter routes connecting three operational bases (Gander, Greenwood, and Comox—home to Cormorant CH-149 helicopters) to potential incident sites across Northern Canada are determined. The region is divided into 100 km × 100 km grid squares, with each square's center representing a possible incident location (see Figure 5). These centers are generated using ArcGIS Pro (Esri, 2024), and their coordinates are exported for further processing.

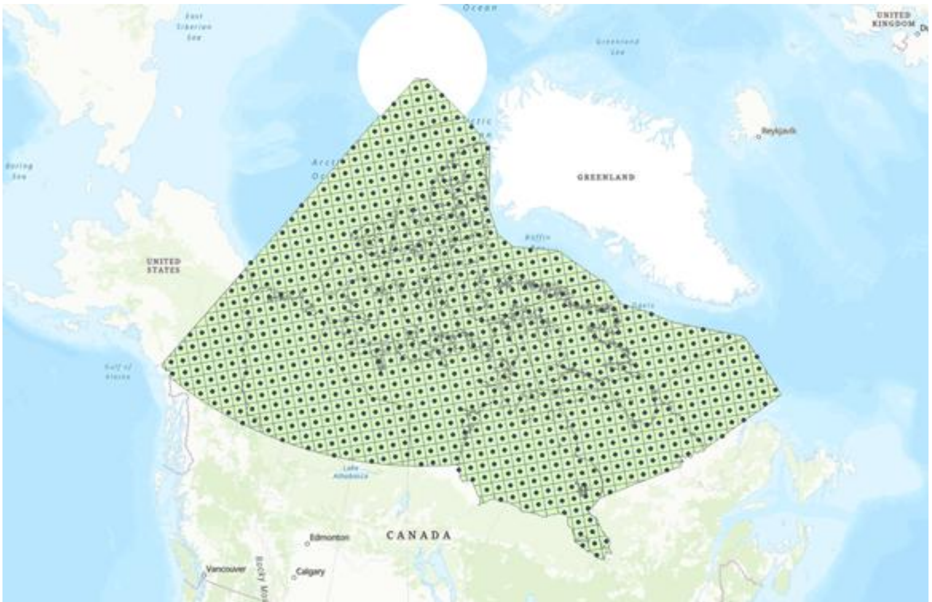

Figure 5. Gridded map with center points

The grid cell size of 100 km × 100 km was selected to strike a balance between computational feasibility and operational detail. Given the vast spatial scale of the Canadian Arctic and the intensive processing required for pathfinding and weather evaluation, smaller grids would significantly increase computational load. Moreover, this resolution aligns with previous SAR modeling studies, allowing for meaningful comparisons with past work in maritime and air rescue planning contexts (Mostaghimi, 2024).

A structured methodology is employed to generate and assess rescue paths. Since any base may be called upon to respond, every route combination from each base to each grid center is considered. Initially, all forward-moving paths are generated using the Breadth-First Search (BFS) method (Kozen, 1992), and the total distance of each is computed. Next, the Dijkstra algorithm identifies the shortest route, while the average separation of alternative paths from this shortest route is calculated (Silveira, Teixeira, & Soares, 2019). Routes within a predetermined separation range are filtered, ranked, and the top two alternatives are selected. Where necessary, additional refueling stations are integrated into these routes. Finally, each path is validated against operational constraints (e.g., fuel capacity, weather conditions) before the results and associated metrics are exported to Excel for further analysis (see Figure 6).

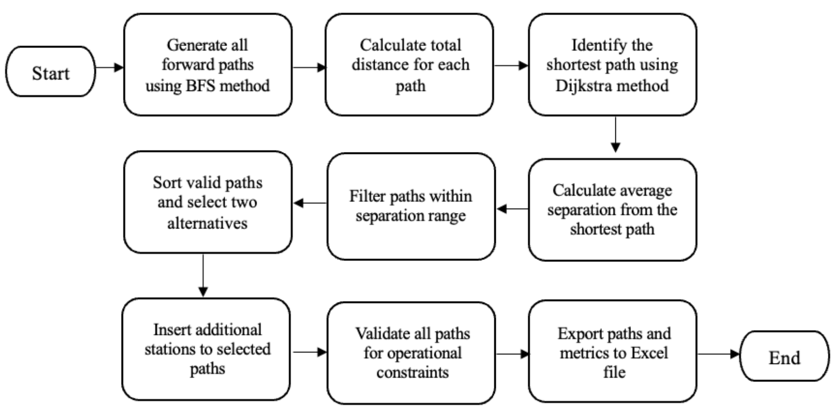

Figure 6. Flowchart for Search and Rescue (SAR) Path Selection and Optimization Process

Forward-Only Path Exploration

The BFS algorithm is configured to consider only routes that progress toward the incident site, eliminating detours that would increase travel distance and thereby enhancing computational efficiency.

Fuel Management

Fuel capacity and consumption rates are integrated into the BFS process. Routes that require more fuel than available are discarded, and when fuel levels near their limit, the algorithm identifies reachable refueling stations to incorporate feasible stops.

Helicopter Speed and Range

The framework accounts for the maximum speed and operational range of the CH-149, ensuring that all identified routes are viable under real-world conditions, even when environmental factors may reduce effective range (see Figure 7).

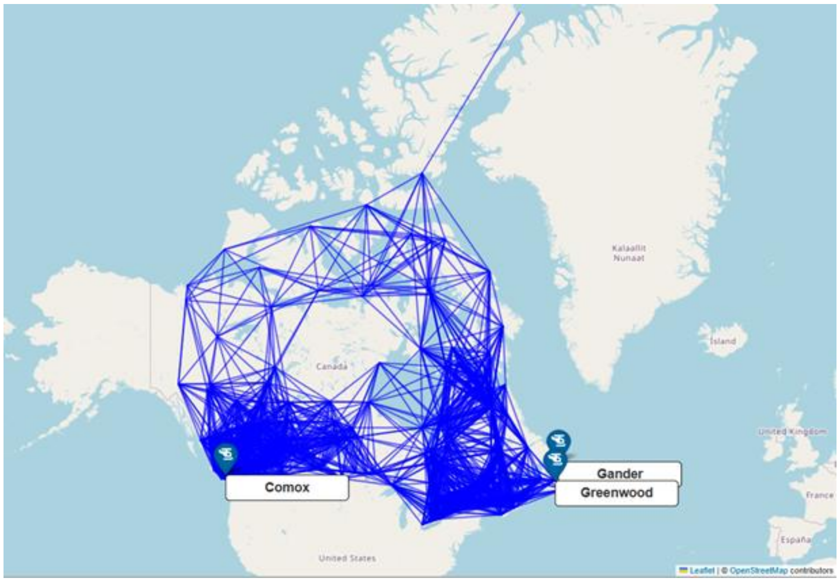

Figure 7. Network of feasible rescue paths

Refueling Strategy

For long-distance missions, the algorithm resets fuel capacity at designated refueling stations, simulating realistic multi-leg search and rescue (SAR) operations in remote Arctic regions where refueling infrastructure is limited (see Table 3 for key helicopter parameters).

Table 3. Helicopter parameters

Parameters	Values	Units
Passenger capacity	12	people
Helicopter range	1143	km
Fuel tank capacity	4000	kg
Fuel critical level	600	kg
Refueling time	30	mins
Maximum speed	241	km/h

By embedding these constraints into the BFS framework, the methodology produces a realistic network of potential routes. This network serves as a robust foundation for subsequent analysis of travel and rescue times, ultimately supporting informed decision-making in emergency response scenarios (see Figure 7).

Given the structured approach, the model can generate over 8,000 possible routes for a single incident, which is computationally intensive. To mitigate this, a local optimization strategy is applied. A local optimum is defined as a route that is the best within a specific neighborhood of the solution space (Lourenço, Martin, & Stützle, 2003). Based on expert recommendations—such as those noted by Fernandes (2024) in sea-based incident analyses—helicopter SAR missions typically prioritize the shortest route.

After constructing the complete network, the shortest path is determined using the Haversine method, which accurately calculates distances while accounting for the Earth's curvature (Rezania Azdy & Darnis, 2020). A modified Dijkstra algorithm then refines this shortest route, while alternative paths are generated by selecting those that maintain an average separation of 100 to 300 kilometers from it. This range provides operational flexibility in the event of unexpected obstacles, adverse weather, or refueling challenges. The final selection process balances spatial distance and feasibility constraints to ensure each route can be executed in practice. Figures 8 and 9 illustrate sample routes from each base to an incident location, demonstrating how the algorithm selects both the shortest and backup paths while considering refueling and operational requirements.

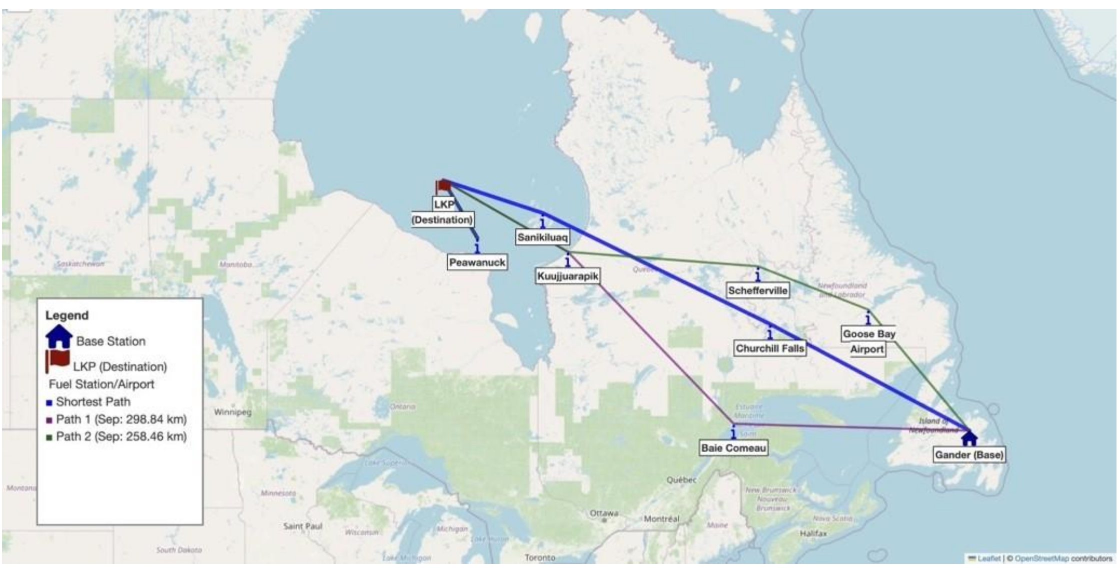

Figure 8. SAR Route from Gander Base to Destination

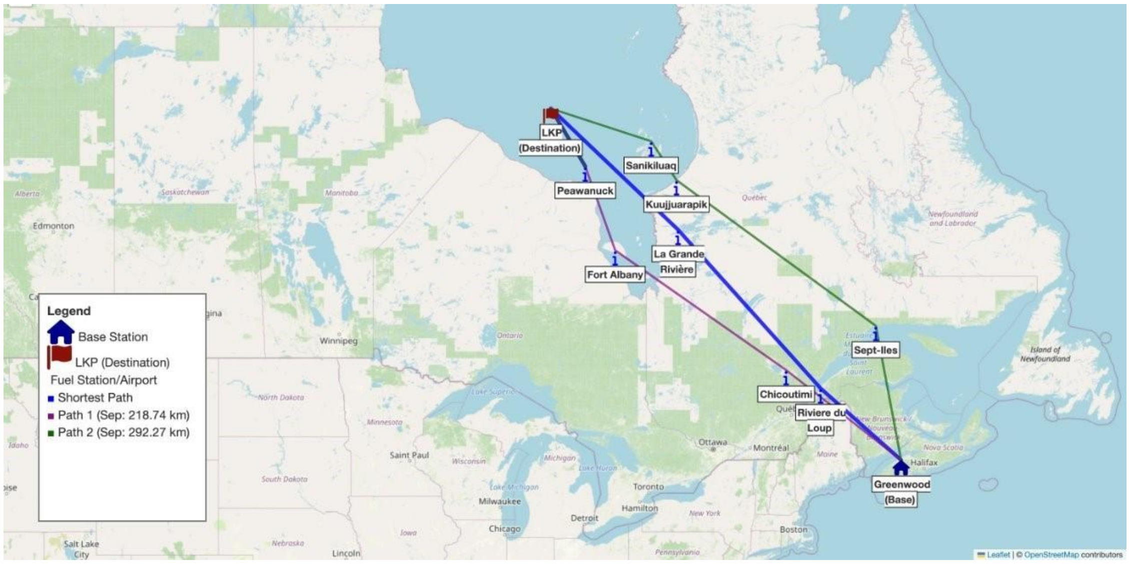

Figure 9. SAR Route from Greenwood Base to Destination

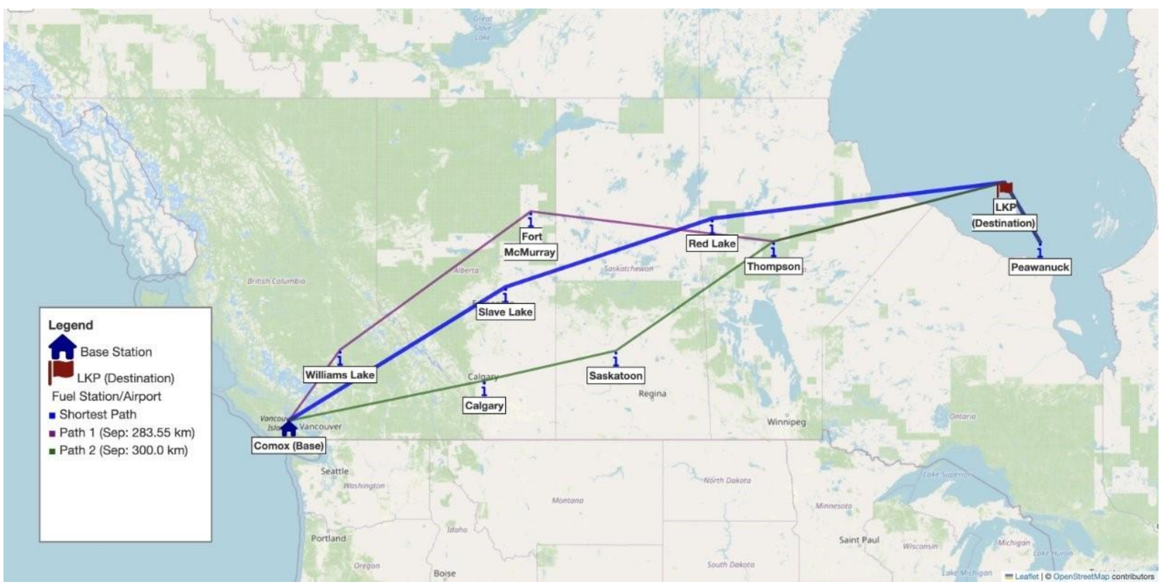

Figure 10. SAR Route from Comox Base to Destination

On average, generating and optimizing alternative routes for a single incident site—while incorporating refueling constraints and weather overlays—takes approximately 10 to 20 minutes for each incident location when executed on a multi-core processor (16-core, 64GB RAM) using parallelized Python code.

Phase three

Phase three evaluates weather conditions along three selected helicopter rescue paths. It begins by getting three paths defined in the phase two, then dividing all arcs into 100 km segments and storing their coordinates. Weather conditions are checked for all coordinates at each timestamp, and a model consisting of so-called F-U-N (Favorable, Unfavorable, No-go) criteria is applied to assess weather thresholds for each factor, as explained in the next subsection. The model is then executed for every location in one timestamp of Spire's environmental data to determine if the path is viable under current weather conditions. Finally, all details for each path, including weather assessments and model outputs, are saved in an Excel file for further analysis, see Figure 11.

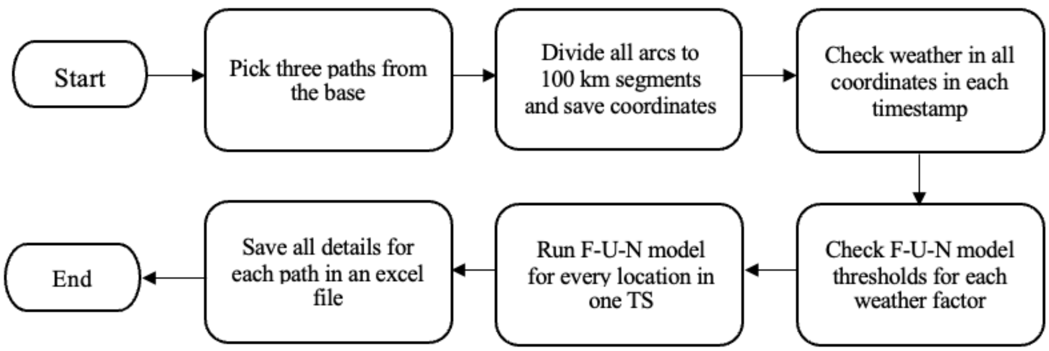

Figure 11. Weather Analysis Workflow for Search and Rescue (SAR) Route Evaluation

Integrating Weather data into SAR Helicopter Mission Planning

In Phase 3, we apply a model that integrates meteorological data, helicopter performance constraints, and predefined flight paths (see phase two) to evaluate the viability and transit speed of helicopter missions under diverse weather conditions. The data workflow begins with the collection of station coordinates and the extraction of key atmospheric variables such as temperature, precipitation type, and wind parameters from the GRIB files, as described in phase one. This approach captures both temporal fluctuations and spatial gradients, see Figure 11.

Each route is divided into 100-km segments to balance the need for detailed weather data with computational efficiency. For a given timestamp (e.g., "2018-01-01 at 00:00"), the model queries the meteorological conditions for every segment along all potential paths simultaneously. Once the conditions for all segments are recorded at that timestamp, the process is repeated for a subsequent timestamp (e.g., "2018-01-01 at 01:00"), and so on. This sequential evaluation across different timestamps allows the model to capture a complete hourly cycle for each segment.

For any given incident, this procedure generates nine distinct paths (three from each base), with hourly weather data compiled over an entire month. The process is repeated for 930 potential incident sites in the Canadian Arctic using two years of historical data (2018 and 2019), thereby producing a comprehensive spatiotemporal dataset.

The Helicopter Environmental Operability (HEO) model (Fernandes, 2024) is then employed to assess the effect of weather on SAR helicopter missions. Developed from expert interviews and validated through a workshop, this model considers critical factors including visibility, precipitation (including freezing rain and thunderstorms), air temperature, and wind speed. It categorizes weather effects on the Cormorant helicopter into two main groups: conditions that prevent takeoff or landing, and conditions that affect speed, fuel consumption, and overall range.

To determine operational feasibility, the F-U-N (Favorable–Unfavorable–No-Go) RCAF Helicopter Environmental Operability Model (RHEO) model is adopted (Fernandes, 2024). Expert-derived thresholds, depicted in Figure 12 with corresponding threshold values, classify each weather parameter as favorable, unfavorable, or no-go for SAR helicopter flight, take-off, and landing. These classifications ensure that the four key weather factors are accurately categorized in line with practical SAR operations.

System limits	Favourable	Unfavorable	No-go
Wind (knots)	None or tailwind	headwind	55 knots
Air temperature (C)	>=0	5 visible moisture	-43
Visibility (miles)	>0.5	-	0.5 mile for landing and take off
Precipitation	None	-	Freezing precipitation/thunderstorms

Figure 12. RHEO model – thresholds for each weather factor

The HERO model defines "Unfavorable" weather as conditions that do not completely prevent flight but degrade performance. Specifically, temperature and wind are marked as unfavorable due to their impact on speed and fuel efficiency, while precipitation and visibility are classified strictly as either Favorable or No-go since they directly determine flight feasibility. These validated thresholds are integrated into the Maximum Expected Time of Rescue – Helicopter Transit (METR-HT) calculations.

For example, when temperatures drop below 5°C with visible moisture, pilots activate the anti-icing system—requiring the auxiliary power unit and increasing fuel consumption by 15–20%. Consequently, the model conservatively assumes a 20% increase in fuel consumption, and pilots typically reduce speed by 10% to counteract efficiency losses from low temperatures and air density changes.

Figure 12 illustrates that if any of the four parameters, i.e. wind, precipitation, temperature, or visibility, is classified as "No-go," the overall condition is set to "No-go." If none are "No-go" but at least one is "Unfavorable," the overall condition is deemed "Unfavorable." Only when all parameters are "Favorable" does the helicopter proceed without delay. When multiple factors are unfavorable, the model applies the delay from the most impactful one, ensuring that the most restrictive weather limitation governs operability (Fernandes, 2024).

Phase four

In the ongoing development of Phase 4 of the overall SAR helicopter model, a combination of mathematical modeling and simulation is employed. Specifically, discrete event and Monte Carlo simulation are used to capture the dynamic and variable nature of SAR helicopter missions. The proposed model represents the mission as a sequence of discrete events: receiving distress calls, dispatching the helicopter, refueling, searching for survivors, hovering and hoisting, and dropping people off at a safe location Zarrin Mehr et al. (2023) used the flow chart in Fig. 13 to present the steps of the process. By breaking the overall operation into these discrete steps, the simulation can systematically handle critical decision points (e.g., whether to stop for refueling) and incorporate probabilistic logic to reflect real-world complexities.

Through multiple simulation runs, the model captures a broad range of possible SAR outcomes, enhancing its ability to reflect the unpredictability of actual operations. Once the simulation is executed, it identifies which of the nine candidate paths offers the shortest overall travel time, considering slower speeds in unfavorable conditions and delays at refueling stations under no-go conditions. Although the simulation results are still being finalized, preliminary findings are expected to reveal insights such as which seasons yield faster response times, and which areas benefit from greater coverage. Additionally, the model aims to estimate the time it takes for helicopters to reach incident locations. These outcomes can be valuable for supporting strategic planning by the Canadian Coast Guard and Armed Forces, especially as maritime traffic and incident risks continue to rise in the Arctic.

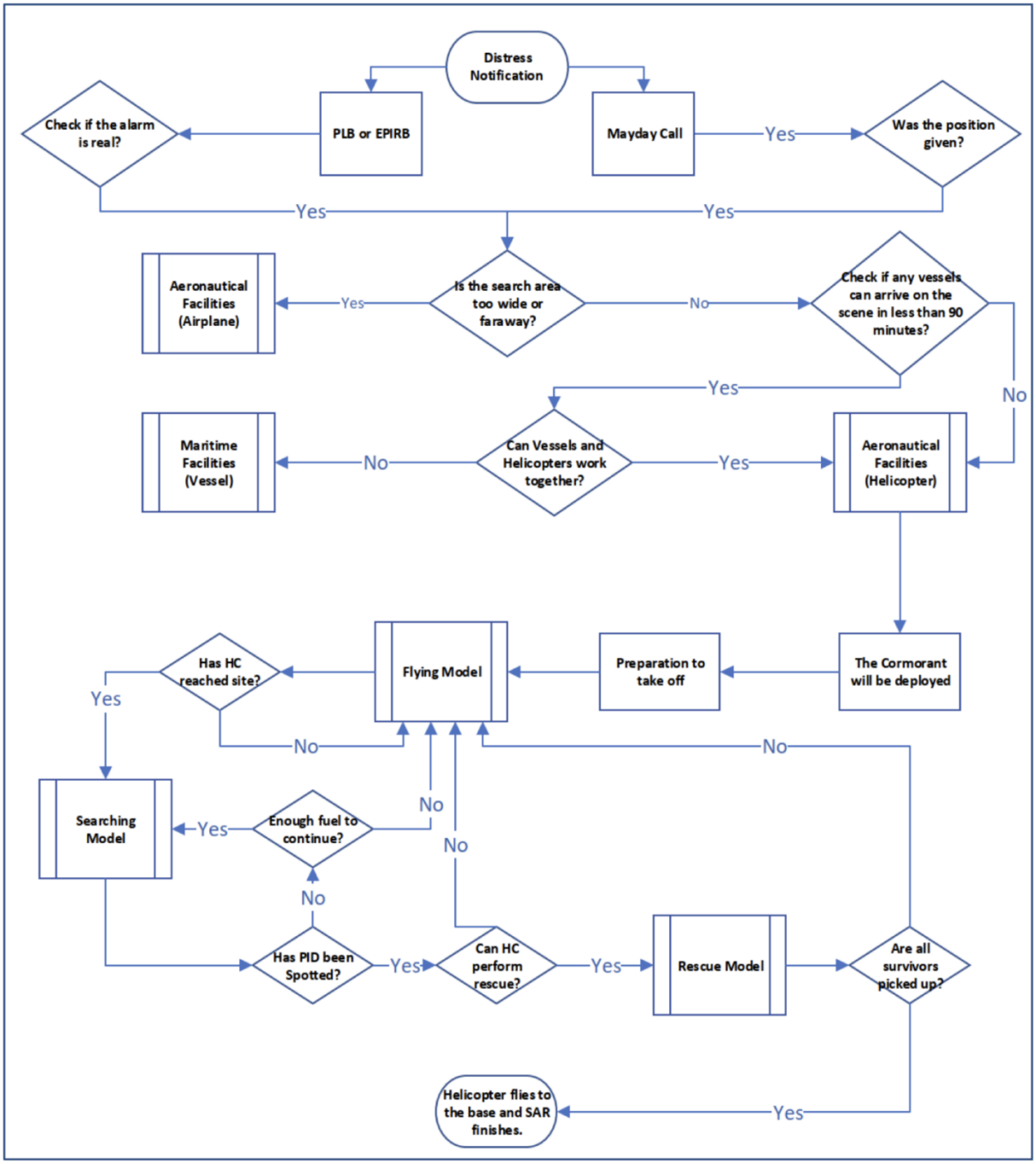

Figure 13. Simplified SAR Operation Flow Chart for Helicopters (Zarrin Mehr, 2023)

Current Status

At this stage, model development and parameter calibration are ongoing. Future work involves extending the simulation runs to cover additional incident scenarios, validating the model outputs against selected real-world mission data, and refining the logic that governs key decision points.

Once finalized, this comprehensive modeling framework will help SAR planners and local community SAR responders obtain systematic insights in plausible SAR helicopter response times, with possible future use to optimize overall resource allocation to improve mission effectiveness. The focus of this analysis will specifically focus on the maximum expected helicopter SAR travel time to Northern communities and SAR rescue times in locations across the Arctic. Variations in the availability of SAR assets will be investigated to understand the implications for travel and rescue times, e.g. for cases where only two bases of Fig. 7 have a helicopter available. Future work will also assess the implications of using different helicopter or air asset types than the Cormorant CH-19 considered here, as their different operational ranges, fuel capacity, and operability and speed in different weather conditions can lead to different travel and rescue times.

Model Implementation

The model is being implemented in Python programming language, using data from multiple Canadian SAR databases and leveraging Monte Carlo sampling to capture variability in weather severity, detection probabilities, fuel consumption, and other operational factors. Discrete event simulation ensures that all mission elements from dispatch timing to final survivor hand-off are treated in a systematic, time-sensitive manner. By integrating these approaches, the framework aims to quantify mission success probabilities, highlight potential bottlenecks, and suggest avenues for refining SAR protocols under diverse and challenging conditions.

Discussion

Although the final Monte Carlo analysis is still in development, preliminary simulations have already yielded valuable insights into the structure and sensitivity of the discrete event model. Trial runs confirm that the flow of events, from distress notification and helicopter dispatch to survivor retrieval and subsequent drop-off at a safe location, functions as expected within the simulation environment. Notably, preliminary tests confirm that weather checks performed every 100 km play a pivotal role in shaping the route selection, occasionally causing delays or reroutes when forecasted conditions exceed defined thresholds.

These early observations also indicate that refueling stops and weather-driven diversions can introduce substantial variation in total mission times, suggesting that the model effectively captures key operational challenges and sources of uncertainty in helicopter SAR operations. Nonetheless, a rigorous statistical evaluation of these effects will only be possible once comprehensive Monte Carlo experiments are completed.

Limitation

A current limitation of our model is that incident site locations are assumed to be evenly distributed across the Arctic grid, rather than being weighted based on historical SAR call data. This was due to limited access to granular incident location datasets. As a result, the representativeness of simulated demand scenarios may be constrained. Incorporating empirically derived distributions of SAR incidents would further enhance the model's operational realism and accuracy, and we identify this as an important direction for future work.

CONCLUSION

This article focuses on the development of a strategic planning framework for optimizing helicopter-based SAR operations in the Canadian Arctic, addressing the region's extreme weather, vast distances, and logistical constraints. By integrating path network optimization, discrete-event simulation, and Monte Carlo methods, the model enables informed decision-making by evaluating multiple rescue routes under varying meteorological and operational conditions. The incorporation of detailed weather data ensures that SAR helicopters can adapt to changing conditions while maintaining mission feasibility. Preliminary results underscore the impact of adverse weather and refueling constraints on response times, emphasizing the need for proactive planning and resource allocation. As the model undergoes further validation and refinement, it will provide valuable insights to SAR coordinators, local community SAR responders and policymakers, aiding in the development of efficient deployment strategies. Ultimately, this research strengthens the long-term strategic planning of Arctic SAR operations, enhancing overall preparedness and community resilience in remote environments**.**

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REFERENCES

Akbari, A., Pelot, R., & Eiselt, H. A. (2018). A modular capacitated multi-objective model for locating maritime search and rescue vessels. Multiple Objective Optimization, 267, 3–28. https://doi.org/10.1007/s10479-017-2593-1

Jessica Cucinelli, Floris Goerlandt, Ronald Pelot. (2023). Exploring risk governance deficits of maritime Search and Rescue in Canada, Marine Policy, Volume 149, 105511, ISSN 0308- 597X, https://doi.org/10.1016/j.marpol.2023.105511

Stoddard, M. A., Pelot, R., Goerlandt, F., & Etienne, L. (2024). Making sense of marine-based search and rescue response time using network analysis. In A. Chircop, F. Goerlandt, R. Pelot, & C. Aporta (Eds.), Area-based management of shipping (pp. 219-237). Springer. https://doi.org/10.1007/978-3-031-60053-1_12

Ash, J. Flying against the clock – risk management and resilience in Arctic search and rescue and casualty evacuation flights. Saf. Extreme Environ. 5, 79–89 (2023). https://doi.org/10.1007/s42797-023-00071-x

International Maritime Organization. (1979). International Convention on Maritime Search and Rescue (SAR). https://www.imo.org/International-Convention-on-Maritime-Search-and-Rescue-(SAR).aspx

Arctic Council. (2011). Agreement on cooperation on aeronautical and maritime search and rescue in the Arctic. http://hdl.handle.net/11374/531

Kikkert, P., Pedersen, C. A., & Lackenbauer, P. W. (2023). Mitigating the tyranny of time and distance: Community-based organizations and marine mass rescue operations in Inuit Nunangat. In *Shipping in Inuit Nunangat* (pp. 182–210). Brill. https://doi.org/10.1163/9789004508576_010

Funston, B. (2014) Emergency Preparedness in Canada's North: An Examination of Community Capacity. Northern Canada Consulting

Kennedy, A. (2013). Evaluating Exposure Time until Recovery by Location.

Kikkert, P., & Lackenbauer, P. W. (2019). Canada's Arctic and Northern policy framework: A roadmap for the future. *Arctic yearbook*, *10*.

Karatas, M., Razi, N., & Gunal, M. M. (2017). An ILP and simulation model to optimize search and rescue helicopter operations. *Journal of the Operational Research Society*, *68*(11), 1335-1351. https://doi.org/10.1057/s41274-016-0154-7.

Zarrinmehr, M. M. (2023). A Macro-Scale Generalized Search and Rescue (SAR) Model for the Coastal Regions of Eastern Canada and the Arctic. 2023 Offshore Technology Conference DOI 10.4043/3248.

Stoddard, M., Pelot, R., Etienne, L., & Goerlandt, F. (2024). On Calculating the Ice RiskAdjusted Estimated Time of Arrival for Polar Class Ships.\.

Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F. J. W., Brown, R., Bhatt, U. S., Euskirchen, E. S., Romanovsky, V. E., Walsh, J. E., Overland, J. E., Wang, M., Corell, R. W., Meier, W., & Wout, B. (2019). Key indicators of Arctic climate change: 1971–2017. *Environmental Research Letters, 14*(4), 045010. https://doi.org/10.1088/1748-9326/aafc1b

Mathisen, H. (2017, February). *How search and rescue works in Canada's most inhospitable clime.* Up Here. Retrieved from https://uphere.ca/articles/crisis-team

Kikkert, P., & Lackenbauer, P. W. (2021). Search and rescue, climate change, and the expansion of the coast guard auxiliary in Inuit Nunangat/the Canadian Arctic. *Canadian Journal of Emergency Management, 1*(2). Retrieved from https://cdnjem.ca/wp-content/uploads/2021/07/CJEM-Vol1-No2-Kikkert-and-Lackenbauer.pdf

Kikkert, P., Quigley, J., Belton, I., Brown, R., Ennis, K. A., Goerlandt, F., ... & Wright, G. (2023, June). Addressing the challenges to search and rescue operations caused by ice conditions in Nunavut, Canada. In *27th International Conference on Port and Ocean Engineering under Arctic Conditions*.

Bliss, L. C., & Hu, F. S. (2025, February 7). *Tundra*. *Encyclopedia Britannica*. https://www.britannica.com/science/tundra

Kruke, B. I., & Auestad, A. C. (2021). Emergency preparedness and rescue in Arctic waters. *Safety Science, 136*, 105163. https://doi.org/10.1016/j.ssci.2021.105163

Qi, X., Li, Z., Zhao, C., Zhang, Q., & Zhou, Y. (2023). Environmental impacts of Arctic shipping activities: A review. *Ocean & Coastal Management*, *232*, 106936. https://doi.org/10.1016/j.ocecoaman.2023.106936

Chen, Q., Lau, Y.-Y., Ge, Y.-E., Dulebenets, M. A., Kawasaki, T., & Ng, A. K. Y. (2021). Interactions between Arctic passenger ship activities and emissions. *Transportation Research Part D: Transport and Environment*, *99*, 102925. https://doi.org/10.1016/j.trd.2021.102925

Benz, L., Münch, C., & Hartmann, E. (2021). Development of a search and rescue framework for maritime freight shipping in the Arctic. *Transportation Research Part A: Policy and Practice, 152*, 54-69. https://doi.org/10.1016/j.tra.2021.07.006

Chircop, A. (2007). Climate change and the prospects of increased navigation in the Canadian Arctic. *WMU Journal of Maritime Affairs, 6*(2), 193–205. https://doi.org/ 10.1007/BF03195114

Tseng, P. H., & Pilcher, N. (2017). Assessing the shipping in the Northern Sea Route: a qualitative approach. *Maritime Business Review*, *2*(4), 389-409. https://doi.org/10.1108/MABR-06-2017-0013

Solski, J. J. (2013). New developments in Russian regulation of navigation on the Northern Sea route. *Arctic Review on Law and Politics*, *4*(1), 90-119.

Borch, O. J., & Batalden, B. M. (2014). Business-process management in high-turbulence environments: the case of the offshore service vessel industry. *Maritime Policy & Management*, *42*(5), 481–498. https://doi.org/10.1080/03088839.2014.913816

Takei, Y. Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic: an assessment. *Aegean Rev Law Sea* 2, 81–109 (2013). https://doi.org/10.1007/s12180-013-0026-9

Ford, J., & Clark, D. (2019). Preparing for the impacts of climate change along Canada's Arctic coast: The importance of search and rescue. *Marine Policy*, *103*, 103662. https://doi.org/10.1016/j.marpol.2019.103662

Christensen, R. E., Ottosen, C. I., Sonne, A., Noernberg, B. (2021). Search and rescue helicopters for emergency medical service assistance: A retrospective study. *American Journal of Emergency Medicine, 46*, 342–349. https://doi.org/10.1016/j.amj.2021.03.001

Abi-Zeid, I., & Frost, J. R. (2005). SARPlan: A decision support system for Canadian search and rescue operations. *European Journal of Operational Research*, *162*(3), 630–653. https://doi.org/10.1016/j.ejor.2003.10.029

Jian, T., Kejun, Z., Haixiang, G., Chengzhu, G., Can, L., & Shuwen, Z. (2018). Using auction-based task allocation scheme for simulation optimization of search and rescue in disaster relief. *Simulation Modelling Practice and Theory*, https://doi.org/10.1016/j.simpat.2017.12.014

Kandel, R., & Baroud, H. (2023). A data-driven risk assessment of Arctic maritime incidents: Using machine learning to predict incident types and identify risk factors. *Reliability Engineering & System Safety, 236*, 109779. https://doi.org/10.1016/j.ress.2023.109779

Spire Global. (n.d.). *Weather & climate.* Spire. Retrieved [date], from https://spire.com/weather-climate/

Python Software Foundation. (2024). *Python (Version 3.11.5) [Computer software]*. https://www.python.org

Esri. (2024). *ArcGIS Pro (Version 3.1) [Computer software]*. Environmental Systems Research Institute. https://www.esri.com

Silveira, P., Teixeira, A. P., & Soares, C. G. (2019). AIS based shipping routes using the Dijkstra algorithm. The International Journal on Marine Navigation and Safety of Sea Transportation, 13.

Kozen, D. C. (1992). Depth-first and breadth-first search. In The design and analysis of algorithms. Texts and Monographs in Computer Science. Springer. https://doi.org/10.1007/978-1-4612-4400-4_4

Lourenço, F., Martin, O. C., & Stützle, T. (2003). Iterated local search. In F. Glover & G. Kochenberger (Eds.), Handbook of metaheuristics (pp. 363–397). Springer. https://doi.org/10.1007/978-1-4419-9466-4_10

SAR Course 49. (n.d.). *The Canadian SAR system*. SAR Course 49. Retrieved February 9, 2025, from https://sarcourse49.wordpress.com/the-canadian-sar-system/

Government of Canada. (n.d.). *CH-149 Cormorant*. Royal Canadian Air Force. Retrieved February 9, 2025, from https://www.canada.ca/en/air-force/services/aircraft/ch-149.html

Government of Canada. (n.d.). *Cormorant mid-life upgrade*. Department of National Defence. Retrieved February 9, 2025, from https://www.canada.ca/en/department-national-defence/services/procurement/cormorant-mid-life-upgrade.html

Rezania Azdy, & Darnis, F. (2020, April). Use of Haversine formula in finding distance between temporary shelter and waste end processing sites. Journal of Physics: Conference Series, 1500(1), 012104. https://doi.org/10.1088/1742-6596/1500/1/012104

Fernandes, I. de A. (2024). Estimating maximum expected time of rescue: Focusing on helicopter rescue to marine incidents in the Canadian Arctic *Arctic* (T hesis, Dalhousie University). Dalhousie University Library.

Mostaghimi, K. (2024). *Estimating maximum expected time of rescue: Focusing on transit time of marine resources to incidents in the Canadian Arctic* (Thesis, Dalhousie University). Dalhousie University Library.