Preparing the Arctic: Optimally Locating Aeronautical Search and Rescue Stations along Canada's Northwest Passage

James Adrian Peters

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By: James Adrian Peters

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______________________________ Chair
Dr. Navneet Vidyarthi

______________________________ Examiner
Dr. Navneet Vidyarthi

______________________________ Examiner
Dr. Ahmet Satir

______________________________ Supervisor
Dr. Satyaveer S. Chauhan

Approved by: ______________________________
Dr. Satyaveer S. Chauhan, Graduate Program Director

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Dr. Anne-Marie Croteau, Dean

Date: ______________________________

ABSTRACT

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James Adrian Peters

Although historically ice-covered, the Northwest Passage (NWP)—a maritime corridor located in the Canadian Arctic—has been experiencing melting trends in recent decades. Declining sea ice concentrations would lead to improved navigability along the NWP, suggesting promising opportunities for both domestic and international shippers. With vessel traffic expected to rise, and the lack of emergency response resources currently stationed in the region, Canada would be responsible for equipping its North with a search and rescue (SAR) network that is capable of providing relief to the users of its waterways. Since the Royal Canadian Air Force (RCAF) oversees the majority of SAR activities in Canada, the distribution of its response aircraft throughout the Arctic is crucial in the design of a successful response network. To address these concerns, we formulated the location problem as an integer linear program (ILP) that looked to determine optimal sites for aeronautical SAR stations and the allocation of aircraft so that the weighted primary and secondary coverage of demand points was maximized. To do so, we modelled the response capacities of the RCAF's fleet by designing a set of response functions based on each asset's performance specifications. We analyzed 29 arrangements across two cases: one in which the secondary coverage of demand points was optional (Case A), and another in which it was mandatory (Case B). Using six to seven aircraft, our approach led to three arrangements that would best address SAR concerns in the North: Arrangement 7A which was proposed for Case A, Arrangement 6B for Case B, and Arrangement 7B as a compromise of the two.

Keywords: Search and rescue modelling · Facility location problem · Mathematical optimization · Integer programming · Northwest Passage

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Chapter 1

Introduction

Spanning nearly half the nation's land area, the Canadian Arctic makes for some of the most challenging terrain on which to conduct emergency response operations. Its vastness complicates the process of locating those in distress, while its remoteness makes the time constraint that much more critical—the nearest medical facilities are located in larger settlements, which are scarce in the Arctic. With the area expected to see a rise in maritime traffic in the coming decades, experts suggest that Canada may be responsible for equipping its North with the appropriate response resources. The obstacles present along its Arctic waters hint that such a network must be capable of efficiently meeting the demand while minimizing the risk of casualty; making the optimal placement of assets crucial in its conception.

1.1 Canada's Northwest Passage

Spearheaded by the territories (the Yukon, Northwest Territories, and Nunavut), the Canadian Arctic is the northernmost region of the Americas where the continent tapers off into the Arctic Ocean. Although the majority of the territories lie on the mainland, the rest comprise the nearly 37,000 islands that conglomerate to form the Canadian Arctic Archipelago (CAA). The waterways that separate these islands describe the maritime corridor known as the Northwest Passage (NWP). While its defining routes vary between sources, most authors agree that the NWP primarily serves to connect the North Atlantic and Pacific Oceans through a network of channels and straits. Formally, the Passage begins in Baffin Bay, continues west via two diverging paths that enclose Victoria Island, and ends in the Bering Sea (see Figure 1.1). Some authors expand on this definition by including alternate legs relevant in the context of their research (Liu, Ma, Wang, Wang, & Wang, 2017; Lu, Park, Choi, & Oh, 2014; Sheehan et al., 2021).

Figure 1.1: The main routes and alternate legs of the Northwest Passage. Source: Wright (2018)

The NWP bears many functional similarities to the Northeast Passage (NEP); an Arctic corridor that runs along the northern coasts of Russia and Norway. Much like its counterpart, because of its location and structure, the NWP acts as a natural shortcut between Asian, European, and North American markets. Recognizing this advantage gives rise to potential opportunities in international shipping, as these routes prove to be rather competitive with the current Atlantic-Pacific crossings: the Panama and Suez Canals. The expansive network that runs through the CAA presents equally appealing opportunities for domestic shippers by allowing them to navigate Canada's internal waters to perform several functions—but not without risk.

The harsh sea ice conditions that characterize the Canadian Arctic often pose the largest threat to the viability of commercial shipping through the NWP. Historically, the area was deemed largely unnavigable due to the extensive ice sheets that covered it; but declining ice concentrations have rendered these routes somewhat operable in recent years. According to Liu et al. (2017), certain legs can already be travelled inside a window of 69 to 111 days—typically between July and October—while routes further north still vary significantly in their navigability. Lu et al. (2014) noted that since 1970, global warming has accelerated the melting of Arctic sea ice to an annual average of 74,000 km^2. Climate models suggest that if these trends persist, some sections of the NWP might experience ice-free summers by the second half of the century—forecasted to be ice-free year-round by 2100 (Lu et al., 2014). The improved conditions observed along these waters hint that the benefits of Arctic shipping routes may be more attainable than once believed.

1.2 Opportunities in Navigating the Northwest Passage

Since the turn of the century, the NWP has experienced a spike in vessel traffic, reporting a 66% increase between 2004 and 2015; which correlates to the declining ice concentration (PEW Charitable Trusts, 2016). However, while improving ice conditions do facilitate the navigation of the NWP, they are not the sole driver contributing to maritime activity in the area. Vessel presence in the Arctic can be greatly attributed to two types of commercial shipping: destinational and transit. The former refers to vessels navigating the area to perform local functions, while the latter describes those using the NWP as a shortcut. Although transit shipping is expected gain popularity in the long-run, local operations (ie. resource extraction, community resupplies, and tourism) are more likely to drive shipping trends along the NWP in the coming years (Lajeunesse, 2011; Stephenson et al., 2017).

1.2.1 Destinational Shipping

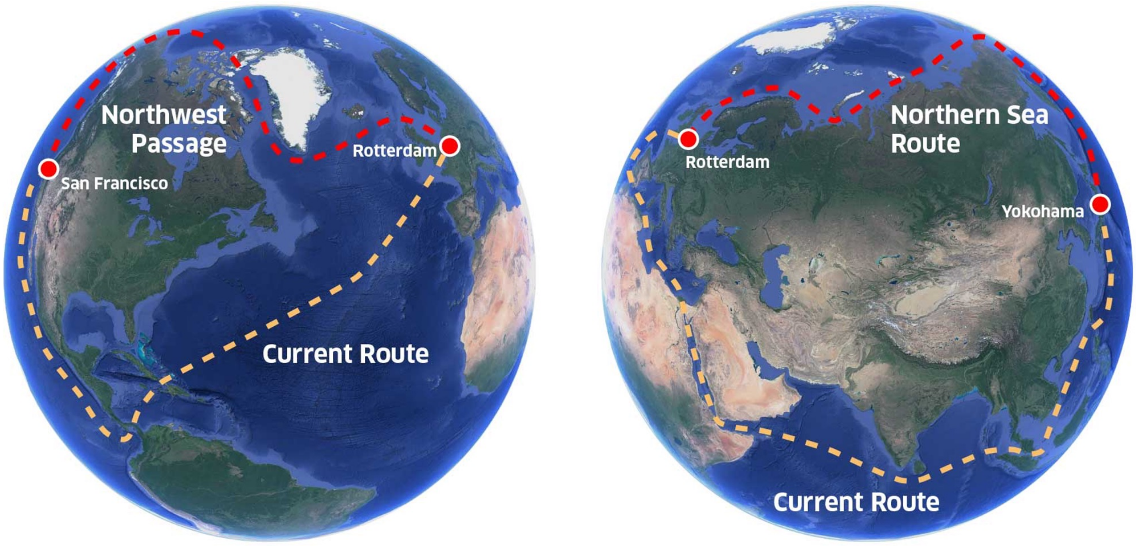
Due to the vastness of Canada's Arctic and the difficulty of accessing its natural resources, many mineral, oil, and gas reserves have gone largely untouched until recently (Lajeunesse, 2011). These deposits could provide lucrative opportunities for those equipped to exploit them, as well as the carriers involved in their distribution to nearby economies. The appeal of the Arctic resource market is fuelled not only by improved shipping conditions, but also by the rise in commodity prices worldwide (Lasserre & Pelletier, 2011).

Also contributing to the region's increased activity is the sudden boom in the Arctic population. While those inhabiting offshore settlements represent only a fraction of the nearly 127,000 Territorians, periodic community replenishments account for a large portion of domestic shipments. With the absence of roads connecting them to the rest of mainland Canada, those inhabiting the CAA have limited access to essentials, making maritime transportation all the more vital. Many communities survive on a limited supply of inventory, enough to sustain them until the next replenishment—which could be months.

The destinational shipping trend that is perhaps most catalyzed by improving sea ice conditions is tourism. While the travel sector represents only a small percentage of the Arctic economy (Exner-Pirot, 2019), it is an area that shows promise for growth in the coming decades. Spotted along the NWP as early as 1984, Arctic cruises have maintained a good reputation for passenger safety; but moving forward, the fate and potential of this trend depends almost entirely on how decision-makers approach the NWP and its many risks (Stewart, Howell, Draper, Yackel, & Tivy, 2007).

1.2.2 Transit Shipping

There is still debate as to when (and whether) merchants will begin using the NWP as an international trade route, but the idea has much potential. Most advantages stem from the NWP's apparent shortness relative to the conventional routes connecting intercontinental markets—like the Panama Canal. With the recent developments in the Arctic, industry experts and researchers are both asking whether efficiency would be improved if an alternate path through the North were considered. To illustrate this, Figure 1.2a compares two routes between San Francisco and Rotterdam: one through the Panama Canal, and the other through the NWP. This contrast is mirrored in Figure 1.2b, wherein a Rotterdam—Yokohama transit is considered via the conventional Suez Canal and the trending Northern Sea Route (NSR), a subset of the NEP. At a glance, both the NWP and NSR appear to be significantly shorter than their counterparts; but just how much more efficient are they?



(a) The Northwest Passage (red) and Panama Canal (yellow) routes in a transit between San Francisco and Rotterdam.

(b) The Northeast Passage (red) and Suez Canal (yellow) routes in a transit between Rotterdam and Yokohama.

Figure 1.2: Comparing the Northwest Passage and Northern Sea Route to their respective alternatives. Source: Discovering the Arctic (n.d.)

Simulated results obtained by Somanathan, Flynn, and Szymanski (2009) showed that when compared to the Panama Canal, ships taking a polar route could accomplish an average of 38% (St. John's—Yokohama) and 13% (New York—Yokohama) more trips per year. These findings were well-aligned with the NWP's hypothesized role as a continental shortcut, reducing travel distances by 33% and 17% in the St. John's and New York cases, respectively (Somanathan et al., 2009). These conclusions draw parallels to the NEP, which supposedly reduces travel distances by up to 40% compared to the Suez Canal route (Solvang, Karamperidis, Valantasis-Kanellos, & Song, 2018). The perceived efficiency gained from adopting a polar route suggests not only shorter lead times, but also reduced operating, fuel, and freight costs, making it attractive to industry decision-makers.

1.3 Challenges of Navigating the Northwest Passage

The true potential of adopting the NWP as a conventional shipping route cannot be fully understood without considering the many challenges that stand in its way. Most apparent are the environmental impacts of operating in such a fragile ecosystem, like the controversial emission of pollutants into the Arctic atmosphere, sure to rise with increased vessel presence (Kong, Jiang, & Ng, 2021). From an economic standpoint, the unpredictable weather conditions could jeopardize the tight schedules on which shipping firms operate, resulting in possible delays and excess costs (Lasserre & Pelletier, 2011). Politically-speaking, the NWP's long debated sovereignty gives rise to questions of legal right to freely navigate these waters (Pharand, 2007). However, with safety at the forefront of Arctic shipping concerns, the biggest challenges stem from the many hazards along the NWP's waters. Poor visibility, severe weather patterns, and drifting sea ice all present themselves as obstacles for ships navigating the Arctic. In fact, some ice floes are found to possess enough mechanical strength to bring a vessel to a halt (Haas & Howell, 2015) or penetrate its hull—putting passengers and crew at risk of injury or death.

The NWP is often compared to the pioneering NSR due to the similar function it serves, environment in which it operates, and conditions to which it is exposed. The difference, however, is that Russia's NSR is better equipped to overcome the obstacles of Arctic shipping; characterized by its developed port infrastructure (Benz, Münch, & Hartmann, 2021) and extensive emergency response network (VanderBerg, 2018). As a result, the route has seen an increase in transit shipping traffic, reporting several thousand trips since 2017, compared to the NWP's 59 in the same time frame (Benz et al., 2021). The gravitation toward a polar shipping route in the East could lend itself as a blueprint for how Canada chooses to approach their own; especially with regards to passenger safety and risk mitigation.

1.3.1 The Demand for Emergency Response

Currently, there is a lack of response capacities in the Canadian Arctic, making its waters even more risky to navigate (Lasserre & Pelletier, 2011). With the expected rise in traffic along the NWP in the coming decades, experts recommend that Canadian policy-makers develop a plan to equip the North with the appropriate resources (Pharand, 2007). Some researchers argue that these allocations be made toward icebreakers and helicopters to create safer waterways and permit quicker response (Lasserre, Beveridge, Fournier, Têtu, & Huang, 2016), while others suggest that a focus on permanent regional units serving multiple functions would be most practical (Shadwick, 2020). Regardless of the approach, an improved emergency response network in the Arctic would greatly minimize the risk of transiting the NWP, as the strategic placement of such resources would allow responders to meet the demand more efficiently than currently possible.

1.4 Search and Rescue in Canada

Search and rescue (SAR) is defined as the emergency response process for locating and retrieving distressed persons, and transporting them to medical attention and safety (Yoo, Goerlandt, & Chircop, 2020). These tasks range in complexity, from the recovery of those stranded in remote areas to the evacuation of crew and passengers aboard a sinking ship. With the establishment of the National SAR Program in 1986, these operations have developed into a cooperative effort led by the Department of National Defence (DND) and the Department of Fisheries and Oceans Canada (DFO), through the Royal Canadian Air Force (RCAF) and the Canadian Coast Guard (CCG), respectively (Pierotti, 2018).

1.4.1 Who is Responsible Search and Rescue in Canada?

In Canada, the CCG and RCAF oversee all maritime and aeronautical SAR operations. Since all federal SAR operations fall under the jurisdiction of the DND, maritime SAR incidents are jointly coordinated between the CCG and RCAF, while aircraft-related incidents are the responsibility of the RCAF alone. Ground cases are usually tasked to provincial or municipal bodies, such as local police forces (Manning & Gold, 2018). When a distress call is placed, the delegation of resources is managed by one of three Joint Rescue Coordination Centers (JRCC), depending on the location and nature of the emergency (Fisheries and Oceans Canada, 2009). Together, their jurisdiction spans the nation's entire land and sea area; with JRCCs Victoria, Trenton, and Halifax responsible for Western, Central, and Eastern Canada, respectively (see Figure 1.3). Occupying the largest search and rescue region (SRR) and most of the Arctic, JRCC Trenton spans five provinces and two territories for a total coverage of 11 million km^2. With the expected increase in Arctic activity, Trenton's capacities in the North are often questioned.

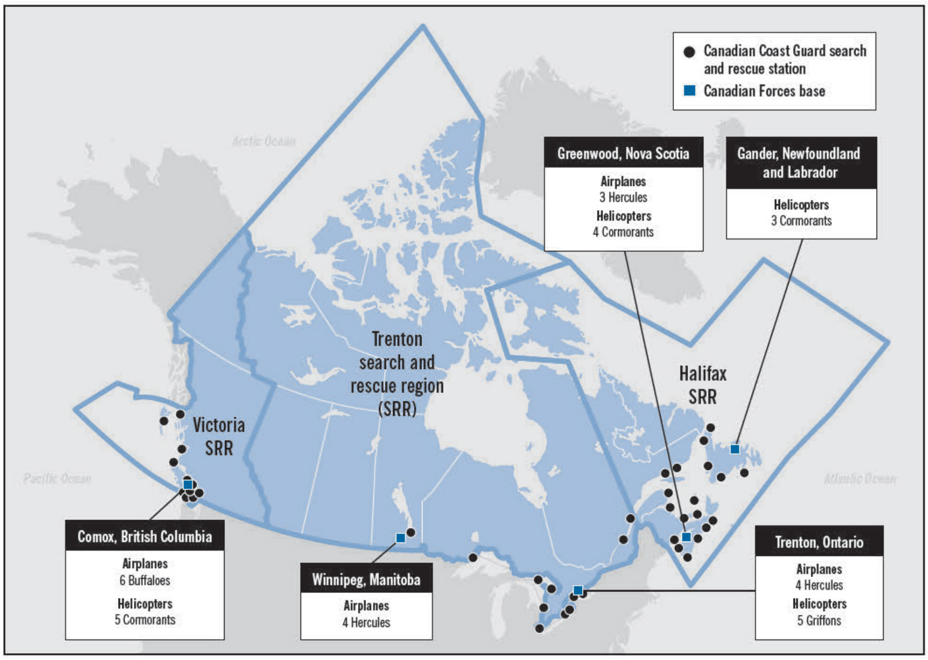


Figure 1.3: Canada's Joint Rescue Coordination Centers. Source: Pierotti (2018)

1.4.2 The Distribution of SAR Resources in the Arctic

With emergency calls varying in nature, scale, and severity, the Canadian North must be well-equipped with the appropriate assets for responding to any incoming request. These resources include aircraft and seacraft, their crews, and the survival specialists who perform the rescue tactics (known as SAR-Techs). On the aviation side, the RCAF operates a versatile fleet serving many SAR functions: short- and long-range helicopters are used in more tactical retrieval missions, while fixed-wing planes are used for transporting larger groups and equipment across greater distances (Government of Canada, 2020). Operated by the CCG, maritime assets include patrol vessels, SAR lifeboats, and icebreakers which serve to break-down concentrated ice patches (Fisheries and Oceans Canada, 2009).

Canada's SAR assets are distributed across its many military bases and coast guard stations, most of which are located in British Columbia, Ontario, and the Maritimes; areas of high population density that are more likely to require SAR. That being said, with the exception of the CCG's Rankin Inlet (Nunavut) Inshore Rescue Boat (IRB) station, the Canadian Arctic is void of year-round SAR bases. While the coast guard's icebreakers are deployed seasonally (usually between June and November) and are capable of providing some SAR relief in the area, the RCAF depends entirely on its fleets stationed in the south to respond to demand in the Arctic (Manning & Gold, 2018). As a result, it could take response teams between two and eight hours to arrive at the incident before even beginning their rescue operations (Manning & Gold, 2018; Pierotti, 2018); which could be the difference between life and death in critical scenarios.

1.4.3 The RCAF's Fleet of SAR Aircraft

As of 2022, the Canadian Air Force operates four types of aircraft to conduct SAR missions: two helicopters, and two fixed-wing airplanes (see Figure 1.4). This fleet is well-equipped for servicing the Arctic's challenging environment; helicopters are versatile and require little space to conduct their rescues, while planes can travel greater distances and transport larger groups.

(a) CH-146 Griffon

(b) CH-149 Cormorant

(c) CC-295 Kingfisher

(d) CC-130H Hercules

Figure 1.4: Search and rescue aircraft currently operated by the RCAF. Source: Government of Canada (2020)

The SAR helicopters used include the CH-146 Griffon and the CH-149 Cormorant. The former, a short-range tactical chopper, is equipped with a hoist for extracting distressed individuals from challenging terrain or harsh waters. Although its capacity is limited to about eight passengers—or six stretchers—the Griffon's ability to provide quick relief to those located in areas of limited access makes it a great asset in Arctic rescue missions. The Cormorant, on the other hand, is a long-range helicopter used almost exclusively for SAR. Like the Griffon, the Cormorant is equipped with an extraction hoist, but can carry almost twice as many passengers—with room for up to 12 stretchers. Both helicopters are capable of conducting SAR operations aerially, without landing, making them ideal for incidents occurring at sea or on-board vessels.

With greater response ranges and capacities than the helicopters, the fixed-wing aircraft operated by the RCAF consist of the CC-295 Kingfisher and the CC-130H Hercules. First acquired in 2019, the Kingfisher is the most recent addition to Canada's SAR fleet. Part of a government plan to replace the CC-115 Buffalo—which served over 50 years—the final (sixteenth) Kingfisher is expected to be delivered in 2022. This plane is perfect for responding to Arctic incidents because of its size, range, and ability to operate in almost all weather conditions. The largest of the fleet, the Hercules, can carry close to 80 passengers and is able to takeoff and land on unpaved terrain. With a range spanning beyond the Canadian Arctic region, this plane's biggest advantage is its ability to rescue large groups in the most remote areas.

1.4.4 Positioning SAR Assets

In Canadian SAR planning, two methods are used for determining where SAR facilities should be positioned and how response assets should be allocated. The CCG employs the Risk-Based Analysis of Maritime Search and Rescue Delivery (RAMSARD) approach, a six-step risk management framework that seeks to identify significant maritime risks, evaluate the effectiveness of current SAR capacities, and analyze alternative strategies and configurations that could help mitigate such risks (Canadian Coast Guard, 2017). In contrast, the RCAF allocates its resources according to historical SAR incidents (Manning & Gold, 2018).

Research has shown that SAR missions involving water are less likely to end successfully than those conducted on land—naming drowning as a significant factor (Adams et al., 2007). Thus, placing permanent SAR assets along an already risky NWP could greatly help reduce the severity of maritime emergencies in the Canadian Arctic. In fact, recommendation 1(a) of the 2018 SAR Report of the Standing Committee on Fisheries and Oceans states that "the Canadian Coast Guard establish additional primary search and rescue stations in the Canadian Arctic to meet the growing demand in areas where marine activity is forecasted to increase" (Manning & Gold, 2018). With the RCAF's fleet currently in full use, reassigning response aircraft to other service regions may be infeasible (Manning & Gold, 2018). Both the forecasted increase in vessel traffic and navigability along the NWP suggest that the planning of Canada's Arctic SAR network and distribution of its assets should be considered sooner rather than later.

1.5 Location Problems

Location problems describe a subgroup of classically-defined mathematical problems concerning the optimal distribution, allocation, and placement of resources within a space. According to ReVelle and Eiselt (2005), location problems consist of four essential elements: (1) demand points, or customers, whose locations are assumed to be known, (2) service points, or suppliers, whose locations must be determined, (3) the space in which demand and service points are located, and (4) some metric that describes the distance between them. The facility location problem (FLP) attempts to determine the optimal arrangement of service facilities so that some given set of requirements is satisfied.

1.5.1 Gaps in the SAR Facility Location Literature

The literature surrounding modern formulations of the FLP date back to the early 20th century. Since then, numerous approaches have emerged for solving such problems, with mathematical modelling being at the forefront. These methods have been adapted for addressing concerns in emergency response operations, network design, and resource allocation across the globe. Search and rescue FLPs, in particular, have been studied extensively in Turkish (Başdemir, 2004; Karatas, Razi, & Gunal, 2017), Chinese (Jin, Wang, Song, & Gao, 2021; Xi, Ye, Yao, & Zhao, 2013), American (Chan, Mahan, Chrissis, Drake, & Wang, 2008; Hornberger, Cox, & Lunday, 2021), and Indonesian (Hadi et al., 2021) settings, among others. However, despite rising international interest, little research has focused on SAR resources in polar regions; more specifically, the Canadian Arctic. Although some authors studied multinational SAR efforts within the Arctic Circle (Shan & Zhang, 2019; VanderBerg, 2018), they mostly observed the problem on a macroscopic scale, focusing less on the Canadian Arctic and the NWP. In fact, to our knowledge, only two studies sought to address issues in SAR capacities in Canada: Nguyen and Ng (2000) who considered the problem nationwide, and Akbari, Eiselt, and Pelot (2018) who focused on the Maritimes.

In order to address the literature gaps, we must recognize the recent environmental changes occurring throughout Canada's Arctic, more specifically, along its waters. Numerous sources agree that the NWP's feasibility as a shipping lane depends largely on its declining sea ice concentrations; a consistent trend observed in the literature since the late-1970s (Chen, Kang, Guo, Xu, & Zhang, 2021; Corbett et al., 2010; Lu et al., 2014). However, the NWP's potential as a trade route and improvements in its navigability have only been explored and discussed in the past decade, which could explain the lack of research concerning SAR operations in the region. Such developments suggest promising avenues for researchers studying the placement and allocation of SAR resources in Arctic Canada—which may, in turn, assist policy- and decision-makers.

1.6 Overview of the Research

This thesis aims to determine the optimal distribution of SAR resources required to provide adequate response coverage to the Canadian Arctic. By considering the current state of SAR in Canada, as well as the assets used in response operations, we seek to locate potential sites for aeronautical SAR stations and allocate the appropriate aircraft to each. This is done through a developed methodological framework that employs geographical information systems (GIS) and mathematical programming in the modelling of a SAR FLP for Canada's North.

1.6.1 Structure of the Thesis

We begin this thesis by addressing the current state of the literature surrounding location problems and SAR network planning (Chapter 2). Then, we proceed by detailing the methods used to carry out this study (Chapter 3). We continue by presenting the main findings of the experiment (Chapter 4), followed by an analysis and interpretation of the results (Chapter 5). This thesis concludes with a brief summary of the contributions, limitations, and departures of the research (Chapter 6).

Chapter 2

Literature Review

The study of location problems (known as location science, or location theory) dates back to the 17th century, when its earliest formulations were found in the works of mathematicians Pierre de Fermat and Evangelista Torricelli (Perreur, 1998). Although the foundational concepts were studied centuries prior, most sources agree that location science as we know it was first popularized by German economist Alfred Weber in 1909 (Farahani & Hekmatfar, 2009)—with many also crediting Wilhelm Launhardt for publishing identical findings in 1882 (Puu, 2009). In his interpretation of the problem, *Über den Standort der Industrie* (Theory of the Location of Industries), Weber considered the spatial placement of a warehouse such that its total distance from each demand point was minimized and costs were reduced (Farahani & Hekmatfar, 2009; Fearon, 2002). Weber then applied his model to real-world markets, demonstrating that location science was not just theory, but practice that could be applied to address logistical concerns in industry (Fearon, 2002).

Since then, the location problem has become a heavily-researched topic in the fields of applied mathematics, industrial engineering, and operations management. Researchers have also expanded on the traditional, warehouse-focused problems by studying the FLP in other contexts, such as the placement of dam sites (Jozaghi et al., 2018), fire stations (Ming, Richard, & Zhu, 2021), and infectious waste disposals (Wichapa & Khokhajaikiat, 2017), to name a few. According to recent trends in the literature surrounding location science, one particular area has been of growing interest to operational researchers: the FLP's application to emergency response networks (Li, Zhao, Zhu, & Wyatt, 2011).

2.1 An Overview of Location Models

Location problems are often formulated as mathematical programming problems, which form the basis for most spatial optimization models. Mathematical expression allows for the FLP to be represented in terms of its many parameters and decision variables, so that constraints are satisfied and objectives are met. Although traditional location problems were formulated almost exclusively as integer linear programs (ILP) or mixed-integer linear programs (MILP) (Toregas, Swain, ReVelle, & Bergman, 1971), researchers over the past few decades have found ways to address uncertainty (Hornberger et al., 2021) and incorporate expert opinion (Farahani & Asgari, 2007) in their formulations. Some of the more comprehensive FLP research focuses on the approaches and algorithms used to solve problems containing elements of non-linearity (Vidyarthi & Jayaswal, 2014) and stochasticity (Contreras, Cordeau, & Laporte, 2011).

That said, there is no general formulation nor solution which can be applied to all FLPs. In fact, the approach taken by researchers is largely dependent on the nature and objective of the stated problem. For example, in the emergency FLP literature, some authors sought to minimize the number of facilities required to respond to all demand points (Yao, Zhang, & Murray, 2019), while others looked to minimize operating costs and response times (Jin et al., 2021). Although both of these cases considered the underlying objective of determining optimal facility placements, they were formulated quite differently. The former, which focused on obtaining a sufficient level of demand coverage, was described by a covering model; while the latter, which considered the weighted distances between demand points and facilities, was described by a distance model. Since this thesis revolves around mathematical modelling in FLPs, we will discuss the relevant literature surrounding covering models in Section 2.2, distance-based models in Section 2.3, and others of note which contribute to the research area in Section 2.4. We conclude the chapter with Section 2.5, where we discuss considerations that might be made in emergency response FLPs.

2.2 Covering Models

In most logistics networks, facilities operate within a specified range to service their customers. This means that those outside this range must be serviced by another location, if at all. In the context of location problems, we say that a customer is *covered* if they are within range of some facility; in other words, the service point is a *cover* for the demand point (Church & Gerrard, 2003). This concept forms the basis for covering models, which seek to distribute facilities in a way that optimizes the service level (or coverage) of demand points in a given space. Although covering models share many similarities with one another, the literature surrounding location problems tends to classify them as one of two types based on the nature of their objectives: set covering location models (SCLM) and maximal covering location models (MCLM) (Church & Gerrard, 2003). These two formulations are discussed in Sections 2.2.1 and 2.2.2, respectively.

2.2.1 Set Covering Location Models (SCLM)

The SCLM is a type of covering model that attempts to optimally place the minimum number of facilities required to cover all demand points. One of the earliest known formulations of the model was developed by Toregas et al. (1971), where it was used in the siting of emergency facilities. Some authors expanded on this definition by accounting for operating costs, thus, redefining the objective to minimize cost (Boonmee, Arimura, & Asada, 2017).

Since it was first introduced, the SCLM and its many applications have been documented extensively in the literature; especially in emergency response contexts. Hadi et al. (2021) successfully developed a covering model that minimized building and operating costs of maritime SAR stations, and allocated each naval fleet to a service region.

Similar in nature to SAR operations, fire station FLP applications—which also place an emphasis on sufficient demand coverage—were studied. Due to the time-sensitive nature of fire emergencies, fire station placement problems often require an entire service area to be covered; a constraint that can be achieved with the SCLM. One of three models used by Wang, Xu, Sun, and Lan (2021) was the SCLM, which helped determine optimal sites for urban fire stations. The model's performance was then evaluated across two scenarios: one which considered existing fire station locations, and one which did not. Aktaş, Özaydın, Bozkaya, Ülengin, and Önsel (2013) also examined these scenarios, among others, in their cost-minimizing model based on historical fire incidents. In a similar application, Yao et al. (2019) took the set covering model one step further by incorporating a second objective function that looked to minimize the weighted travel distance between demand points and proposed fire stations. The bi-objective model—supported by GIS mapping—yielded Pareto-optimal solutions which were then analyzed under the same two scenarios as above.

There are, however, limitations to the SCLM in an emergency FLP context. Firstly, the model's requirement of total coverage may be unattainable, depending on the number of resources available for allocation (Aktaş et al., 2013). To offset this, some researchers found it useful to supplement their SCLM with elements borrowed from other facility location models; like Yao et al. (2019), who employed a weighted distance function as their secondary objective to concentrate stations in areas of higher risk. Furthermore, requiring that all demand points be covered may not always be necessary; certain decision-makers might prefer to optimize their coverage of a given area using limited resources. As a result, some researchers have found it relevant to explore such covering models; particularly, the MCLM, which does not require total coverage.

2.2.2 Maximal Covering Location Models (MCLM)

Unlike its counterpart, the MCLM does not require that all demand points be covered by the chosen facilities. Instead, the MCLM seeks to determine the arrangement that maximizes the coverage of demand points given a limited number of available facilities.

This model, first proposed by Church and ReVelle (1974), has appeared frequently in the literature surrounding location problems. More specifically, it has seen many applications in emergency networks, where response resources are often limited. Nguyen and Ng (2000) employed the MCLM in their optimal placement of Canadian SAR stations; the model was based on historical incidents and accounted for a mixed fleet of aircraft. Başdemir (2004) provided an extension to the MCLM which considered logistical, geographical, and weather factors in the determination of optimal locations. To account for the fact that some sites were better suited than others for accommodating SAR facilities, they developed a qualitative indexing system that assigned a score to each candidate location. This allowed the model to generate an optimal solution that also met some basic regional requirements. In a case study focusing on large-scale medical emergencies, Jia, Ordóñez, and Dessouky (2007) modified the coverage constraint, requiring high risk demand points to be serviced by multiple response facilities. Akbari et al. (2018) introduced multiple resource types in their MCLM, and looked to maximize the percentage of primarily covered demand regions. Li et al. (2011) conducted a literature review of covering models applied to emergency response FLPs; highlighting the SCLM and MCLM, as well as extensions, like the double standard model (DSM) and maximum expected covering location model (MEXCLM).

Fire station location problems have also seen extensive use of the MCLM. Şen, Önden, Gökgöz, and Şen (2011) successfully combined objectives from both covering models into a bi-objective formulation that sought to minimize total setup and operating costs, while also maximizing service area coverage. Their model considered four types of fire stations, each varying in service capacity and cost, and incorporated the appeal of certain locations with an "attractiveness" factor. Zhou and Li (2013) presented an extension to the MCLM that was capable of providing multiple coverage to communities experiencing a high historical incidence of fires. Ming et al. (2021) considered a probabilistic approach that modelled road traffic over various time periods, as well as its impact on fire truck response times and service coverage.

Zarandi, Davari, and Sisakht (2011) studied solution approaches to the MCLM, comparing the genetic algorithm (GA) to the commercial solver CPLEX. They found that, while the GA approach does not reach optimality in all cases (like CPLEX does), it performs fairly well across various problem sizes, with errors consistently below 2%. Moreover, they noted that as problem sizes increase, CPLEX run times increase significantly, whereas the GA solution times remain fairly constant. They suggest that this trade-off between exact solutions and run times can render the GA beneficial when used alongside other algorithms, such as simulation.

2.3 Distance-Based Models

As mentioned, location problems vary in nature, differing not only in the parameters considered, but also in the objectives sought after by decision-makers. While the covering models discussed in Section 2.2 address concerns in service coverage, they do not explicitly account for the distances between facilities and demand points. In the context of emergency response networks, covering models ensure that demand points *can* be serviced by facilities within range, but do not necessarily consider *how long* it takes to provide such services. Thus, some researchers have turned to distance-based models. These models seek to determine the optimal arrangement of resources so that demand-facility distances—and consequently, response times—are minimized. Two types of distance models are frequently mentioned in the FLP literature and applied to emergency contexts: P-median models (PMM) and P-center models (PCM), which will be discussed in Sections 2.3.1 and 2.3.2, respectively.

2.3.1 P-Median Models

The PMM, sometimes called the the minisum model, seeks to minimize the total weighted distance between P facilities and all demand points in a network. A basis for the PMM was first introduced by Hakimi (1964), along with a proof for determining the absolute median of a weighted graph. The absolute median (often simply called the "median") is defined as the point in a metric space whose weighted distance from all other points is minimal (Hakimi, 1964).

Hakimi's concept of medians has since seen applications in the location science literature. Pirkul (1989) explored a variation of the median model with primary and secondary coverage requirements. Based on Weiszfeld's algorithm, Baskar and Xavior (2021) developed an iterative approach that optimally placed maritime service facilities among a group of demand points; the selected sites described geographic medians.

Median models appear to be fitting for emergency response applications of the FLP, where a network's success is largely dependent on response times. In fact, some of the research discussed in Section 2.2 explored covering models that had median elements integrated into their formulations, which allowed for both coverage levels and response times to be considered. This was the case with Wang et al. (2021), where SCLM and MCLM models were used alongside the PMM in determining fire station locations; together, the results from the three models were used to select the ideal sites. Like in their covering model, Jia et al. (2007) employed a constraint in their median model that required demand points of higher risk to be assigned to several servicing locations. Alongside a MCLM, Akbari et al. (2018) developed a PMM that minimized the weighted mean response time while considering multiple facility types. The weight, in this case, was represented by the frequency of incidents having occurred within a given range.

Focusing on helicopter SAR response networks, Karatas et al. (2017) developed an ILP formulation of the PMM which looked to minimize the total time required to respond to emergency incidents. The model considered four types of aircraft, each with their own set of response ranges, speeds, and types of incidents they can service. In addition to determining the locations and number of helipads required, the model allocated a fleet of aircraft to each facility. The authors also made a contribution to the stochastic FLP literature by considering two factors of uncertainty: weather conditions and equipment failure, which were modelled using simulation. Jin et al. (2021) expanded further on the base PMM's objective function by developing a bi-objective model that looked to minimize mean response times, as well as investment costs. Since the model was designed to place dynamic (non-stationary) service points, a multi-objective plant growth simulation algorithm (MO-PGSA) was adopted to solve the formulation. Xi et al. (2013) added a response time constraint to their PMM to ensure that each demand point could be serviced inside an appropriate window. A variable neighborhood search (VNS) algorithm was developed to help solve the model in question.

2.3.2 *P*-Center Models

Adjacent to the PMM, the P-center model (PCM) attempts to minimize the maximum distance between demand points and service facilities. Also known as the minimax model, the foundational theory behind the PCM was developed by Hakimi (1964) in exploring the concepts of absolute medians and centers (Biazaran & Seyedinezhad, 2009).

In a previously mentioned case study, Jia et al. (2007) analyzed the effectiveness of a center model in locating response facilities for large-scale emergencies. When compared to the MCLM and PMM, the PCM approach generated a solution that was less balanced in covering demand points; which, in practice, could result in a greater risk of loss. Yang and Liu (2015) explored the center model in a stochastic FLP, where travel times were defined as fuzzy random variables. They developed three P-center models that could be used to convert the original formulations into their stochastic equivalents, and designed a new solution algorithm: the parametric decomposition-based hybrid tabu search (PD-HTS).

Relative to the SCLM, MCLM, and PMM, the PCM appears to be used less frequently in the emergency response literature. Whereas covering and median models consider overall network performance and individual customer-facility nodes, respectively, center models define optimality as being the *best* worst-case scenario. As a result, it is often used as a “risk guarantee” for the furthest a response unit may be required to travel to service some demand point (Boonmee et al., 2017). Thus, the PCM can be rather limited in solving emergency FLPs. Some deficiencies mentioned in the literature include: the model’s potential for an unbalanced or insufficient coverage of demand points (Jia et al., 2007), and its inability to determine the optimal number of sited facilities—P must be established beforehand (Shan & Zhang, 2019).

2.4 Other Models Used in Emergency Response FLPs

Although the models most relevant to this study were outlined in Sections 2.2 and 2.3, other approaches found in the literature made significant contributions to the study of emergency FLPs—as well as to the inspiration of this thesis—and are worth mentioning.

Popular in location problems, multi-criteria decision-making (MCDM) approaches weigh input from decision-makers in their determination of facility arrangements. When used alongside optimization, MCDM models generate spatially-optimal solutions that are also practical for its users. Farahani and Asgari (2007) integrated MCDM techniques into a set covering model to help site facilities within a military logistics network. The five-step method incorporated a popular decision-making approach—Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)—to quantify expert judgement, while binary and quadratic programming were used in the selection of optimal sites. Wichapa and Khokhajaikiat (2017) explored another MCDM approach—the Analytic Hierarchy Process (AHP)—in the placement of waste disposals across Northeast Thailand. To account for uncertainty, a fuzzy AHP goal programming (FAHP-GP) technique was developed; the AHP phase helped determine the weights to be used in the location model. Alongside GIS mapping, Jozaghi et al. (2018) compared TOPSIS to AHP in a case study exploring dam site selection approaches.

Recognizing that each facility location model, on its own, shows some deficiency, Shan and Zhang (2019) developed the set double-covering median model (SCDMM): a comprehensive formulation that sought to address gaps in the FLP literature by combining the coverage constraints of the SCLM, the minimized nodal distances of the PMM, and the building and operating cost considerations of the double-covering location model (DCLM). The model's practicality was demonstrated in a case study about the allocation of Arctic SAR bases; particularly, areas of high-level risk.

2.5 Considerations in Emergency Response FLPs

As mentioned at the beginning of the chapter, when formulating any FLP, it is important to properly define the problem's four essential elements: demand points, candidate facility locations, the space in which they are located, and a distance metric (ReVelle & Eiselt, 2005).

In many emergency applications of the FLP, the locations of historical SAR incidents have been used as demand points (Nguyen & Ng, 2000). While past incidents can be useful for modelling future scenarios, two limitations should be considered. Firstly, for a large enough dataset, using all occurrences as individual demand points could be excessive, especially for those significantly close to one another. To address this issue, some authors (Jin et al., 2021; Razi & Karatas, 2016) adopted clustering techniques. These approaches seek to aggregate local incidents into unique groups where one point, called the "centroid", acts as the demand point for each cluster. The second limitation is that historical incident distributions do not always accurately represent future demand; although they can be a good predictor. Using a GIS software, Akbari et al. (2018) applied a kernel density estimation procedure to simulate stochasticity in future SAR demand. Karatas et al. (2017) took a more probabilistic approach for simulating uncertainty in SAR incidents, assuming annual demand to be Poisson distributed. Hornberger et al. (2021) addressed both limitations by first using a clustering technique for historical occurrences, and then applying a Poisson distribution to model the stochasticity of demand.

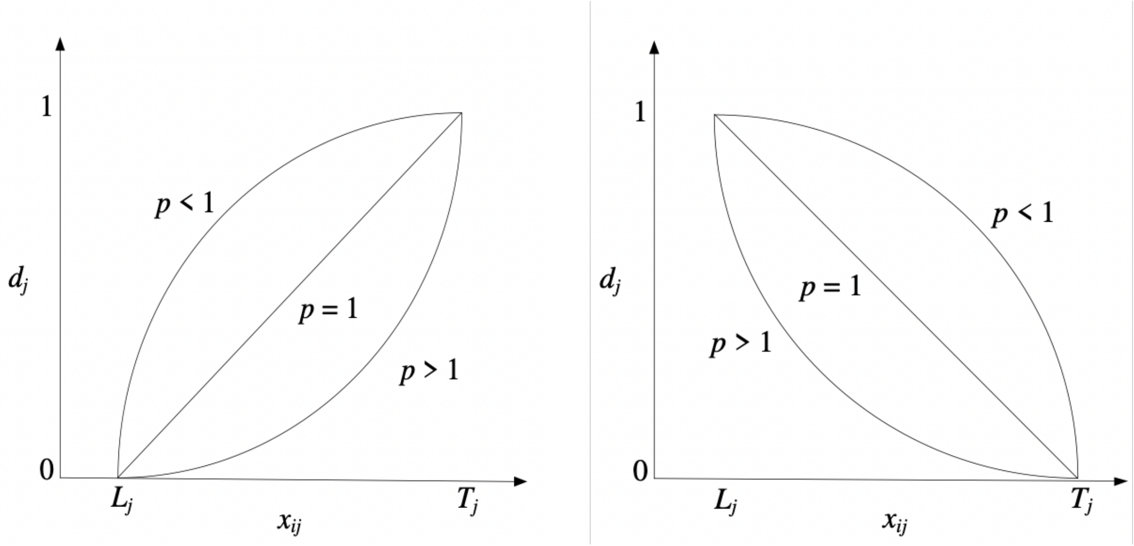
Like demand, candidate locations have been defined in a number of ways throughout the emergency FLP literature. In maritime SAR applications, candidate sites have been defined as coastal settlements (Hadi et al., 2021) and remote islands (Jin et al., 2021) capable of accommodating the construction of naval berths. In an assessment of Arctic SAR capacities, Shan and Zhang (2019) defined the set of candidate sites as cities or towns in the region of study which had existing airports, ports, and hospitals. Depending on the nature of the problem and its level of detail, SAR stations can either be placed in areas with or without the required infrastructure. In some cases (Akbari et al., 2018; Yao et al., 2019), researchers have considered existing facilities in their models, while looking to optimize the placement of new ones. The interested reader may also refer to the Port Impact Value (PIV), an index developed by VanderBerg (2018) to assess the quality of Arctic ports with respect to frequently-cited criteria, such as: closeness to natural resource deposits, proximity to major shipping routes, and the accessibility of alternative transportation.

The third component, the metric space, describes the bounded Cartesian or geographical area in which demand and service points interact. Depending on the scale and objectives of the FLP, the space may be segmented into sub-regions (Hornberger et al., 2021) or observed as one single region (Yao et al., 2019). Hornberger et al. (2021), for example, divided the SAR area into 15 zones, each represented by a unique incident distribution; allowing regions of, say, greater population density to behave differently under uncertainty than those of low density. Several FLPs consulted throughout the literature (Akbari et al., 2018; Karatas et al., 2017) also used grids to segment their metric spaces, which helped identify regions of greater risk.

Defining an appropriate distance metric is also necessary when formulating an emergency response FLP. The distance metric is a measure that describes the amount of space between demand points and the servicing facilities. The most trivial metric used in graphical FLPs is Euclidean distance. Other metrics, such as the Haversine distance—which measures the distance between two points on the Earth's surface—have been used in large-scale geospatial FLPs involving coordinates (Baskar & Xavior, 2021). Applying weights, such as cost (Jin et al., 2021) or risk level (Yao et al., 2019), may be appropriate in certain contexts. In SAR FLP applications, where response speed plays a critical role in safety and risk reduction, distance metrics may be converted into response times. One way of accomplishing this is by expressing response time as a function of travel distance over response speed; an approach taken by Karatas et al. (2017) in an aeronautical SAR network with four helicopter types. Both Jin et al. (2021) and Akbari et al. (2018) integrated the time metric into their formulations of maritime SAR FLPs, which each considered a mixed fleet of response vessels.

2.5.1 Desirability Functions

First introduced by Harrington (1965), desirability functions serve to transform some observation variable into a unitless desirability index. Ranging from 0 to 1, an index of 0 describes an unacceptable outcome, while an index of 1 represents the ideal. By adjusting certain parameters, the functions can be modified to align with the problem's objectives: they can be designed to increase or decrease with the observation variable, as well as vary in slope (see Figure 2.1). Desirable outcomes are more difficult to attain in convex functions (denoted by the "$p > 1$" curves in Figure 2.1) since the curves become steeper as they approach a desirability index of 1. Concave functions (denoted by the "$p < 1$" curves), on the other hand, become flatter as they tend to higher indices, and are therefore more inclusive in their definition of desirability. One function of particular interest to researchers is the Harrington desirability function (Trautmann & Weihs, 2006). Expressed as a double exponential function, the curve becomes convex as it approaches low desirability and concave as it approaches high desirability.



(a) Increasing, "larger the better" desirability function

(b) Decreasing, "smaller the better" desirability function

Figure 2.1: Different types of desirability functions. Source: Karande and Chatterjee (2018)

A useful technique for assessing alternatives in decision-making, desirability functions have been explored in the literature surrounding multi-criteria optimization, with particular applications to industrial processes (Pal & Gaur, 2018), quality control (Quirante, Sebastian, & Ledoux, 2012), and facility location (Karande & Chatterjee, 2018). To our knowledge, they have not yet been used in location problems involving transportation, let alone SAR operations.

Chapter 3

Methodology

This research seeks to determine optimal locations for aeronautical SAR stations and the distribution of response aircraft throughout the Canadian Arctic. The problem can be formulated as a FLP with demand points based on historical incidents and predefined candidate locations capable of siting the SAR infrastructure and assets.

We proposed a two-phase methodological framework that was carried out over five stages. The Preparation Phase served to obtain the parameters that would be used in the optimization model, and consisted of three stages: Geospatial Analysis (Stage 1), Aeronautical SAR Operations Modelling (Stage 2), and Response Function Design (Stage 3). Stage 1 was done in the GIS software QGIS and looked to define the geographical study region, obtain the demand points, and compute relevant distances. In Stage 2, the RCAF's SAR aircraft were studied and used to build the response functions in Stage 3.

The Results Phase consisted of the two final stages: the Model Formulation (Stage 4) and the Solution Approach & Sensitivity Analysis (Stage 5). Here, solutions were obtained and analyzed across two cases: with optional and mandatory secondary coverage, Cases A and B, respectively. In Stage 4, we formulated the FLP mathematically as an ILP. In Stage 5, the model was coded and solved in CPLEX using the parameters obtained from the Preparation Phase. Subsequent analyses of the solutions were performed to determine the most optimal arrangements for stations and aircraft.

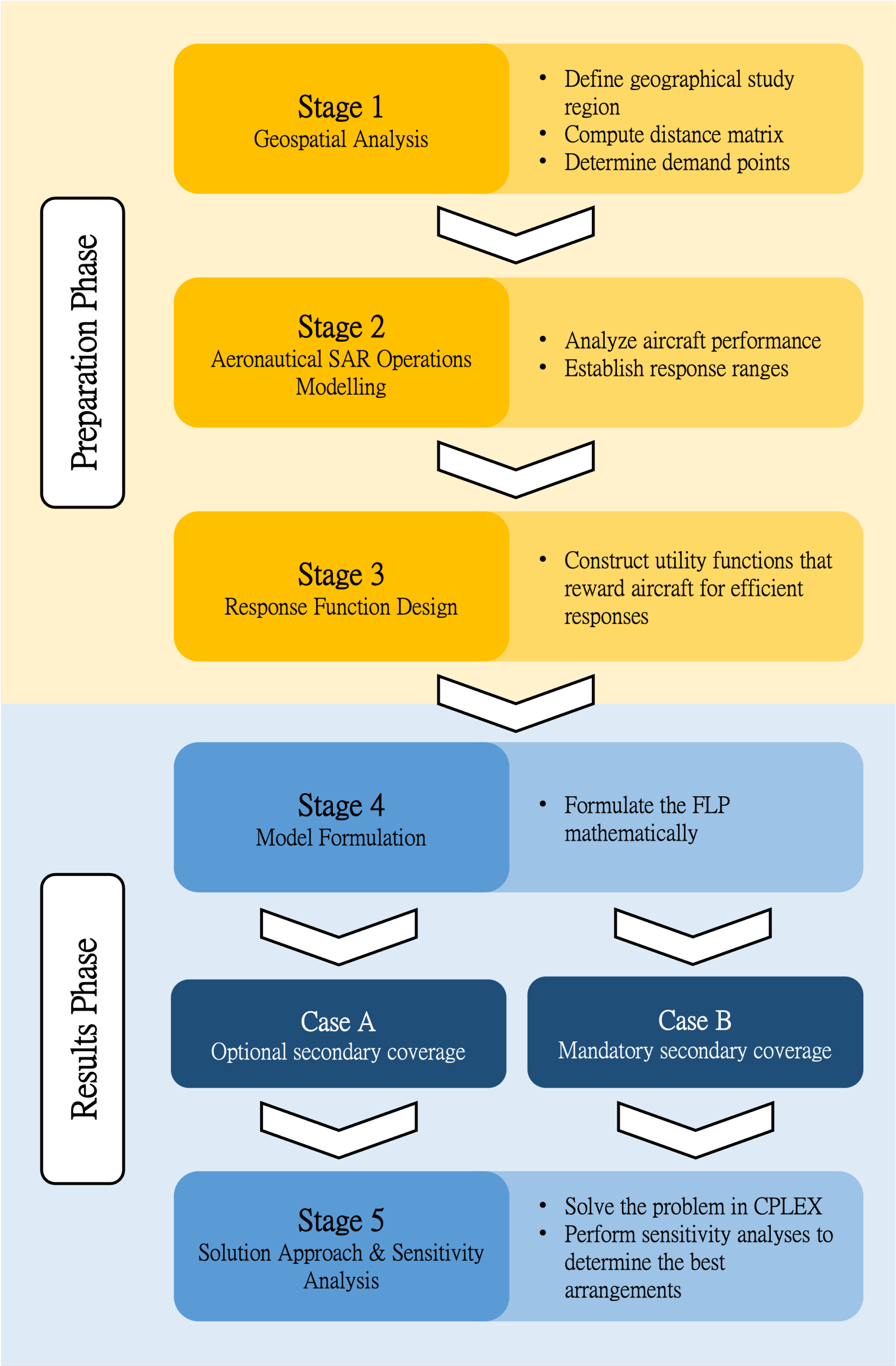


Figure 3.1: The two-phase methodological framework.

In this chapter, we describe the approach taken to achieve the thesis objectives, providing a detailed outline of the methods in Sections 3.1 through 3.5.

3.1 Stage 1: Geospatial Analysis

The National Topographic System (NTS), a method used by Natural Resources Canada, was implemented to define the boundaries of our study area. This cartographic technique segments the country into square regions (or cells) using three grids of varying scale: 1:1,000,000 (1:1M), 1:250,000 (1:250k), and 1:50,000 (1:50k). The most macroscopic of the three, the 1:1M grid, divides the country into cells measuring 8 degrees in longitude by 4 degrees in latitude, with each denoted by a three-digit label. These cells are then segmented into 16 smaller ones, labelled “A” to “P”, which gives the 1:250k grid. The 1:50k grid is then obtained by dividing the 1:250k cells into 16 areas, and assigning each a label from “1” to “16”. Together, the labels from each grid generate a unique alphanumeric index that refers to a specific square region in Canada. For example, the green area in Figure 3.2 can be described by the index “082O12” since it lies in cell “082” on the 1:1M grid, cell “O” on the 1:250k grid, and cell “12” on the 1:50k grid. Regions in the high Arctic differ slightly in their labelling and size.

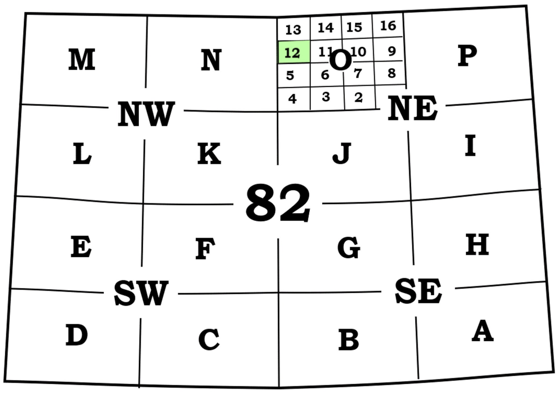


Figure 3.2: An NTS grid shown on three different scales. Source: McGoldrick (2020)

Canada’s NTS boundaries range between the 48th and 144th meridians west (48°W and 144°W) and north of the 40th parallel north (40°N). The region considered in this study was defined by the NTS boundaries for the Canadian Arctic—which included all points between 56°W and 144°W, and north of 60°N. This area encompassed the entirety of the Territories, as well as the northernmost parts of Quebec and Labrador. Once the space was established, a 1:250k NTS grid of the study region was imported into QGIS along with the set of historical incident locations. Together, the NTS grid and incidents helped obtain two important parameters in the formulation: the demand weights, and the demand points. Using QGIS's "count points in polygon" function, the number of incidents occurring within each NTS grid cell were computed. These frequencies represented the demand weights used in the model, to be denoted w_i. A clustering function was used to compute the mean coordinates (or centroid) of each NTS region. The centroids were taken to be the demand points, i, in the formulation. Candidate SAR stations, j, were predetermined. The final geospatial parameter obtained in QGIS was the distance matrix, which gave the distances, d_{ij}, between each pair of demand points i and candidate locations j in the network. Distances were expressed in kilometers.

3.2 Stage 2: Aeronautical SAR Operations Modelling

In order to design a network based on Canadian SAR aircraft, we first needed to understand their response capabilities. As mentioned in Chapter 2, the RCAF operates a fleet of four different aircraft for SAR operations: the Griffon, Cormorant, Kingfisher, and Hercules. These assets vary in type, range, and speed; all factors which were to be considered in the model. Table 3.1 presents the details and performance specifications of the fleet.

Each aircraft of type-k was defined by a maximum range, $r_{k(max)}$, describing the furthest one-way distance it could travel. Since aircraft were assumed to return to their respective stations following a task, the response ranges, r_k, were taken to be 45% of the maximum. This meant that each aircraft had 90% of its total range available for travelling between stations and incidents, with a 10% buffer for uncertainty. Their trajectories were assumed to be linear. Furthermore, inspired by Nguyen and Ng (2000), the response ranges represented the radii of an aircraft's "service region" centered at some SAR station j (see Figure 3.3). Each aircraft could therefore respond to any demand point within its service region.

Table 3.1: Performance specifications of SAR aircraft used by the RCAF.

Aircraft	**Griffon** ($k = 1$)	**Cormorant** ($k = 2$)	**Kingfisher** ($k = 3$)	**Hercules** ($k = 4$)
Aircraft type	Helicopter	Helicopter	Fixed-wing plane	Fixed-wing plane
Maximum range (km), $r_{k(max)}$	656	1,018	4,815	7,222
Response range (km), r_k	295	458	2,167	3,250
Maximum speed (km/h), $v_{k(max)}$	260	280	482	556
Response speed (km/h), v_k	234	252	434	500
Reaction time (h), $t_{k(react)}$	0.33	0.33	0.67	1
Transit time (h), $t_{k(trans)}$	1.26	1.82	4.99	6.50
Maximum response time (h), $t_{k(max)}$	1.59	2.15	5.66	7.50

In addition to range, each aircraft was characterized by a maximum speed, $v_{k(max)}$. Although SAR tasks are time-sensitive, aircraft rarely reach top speed for safety reasons. Thus, each asset's response speed, v_k, was taken to be 90% of its maximum.

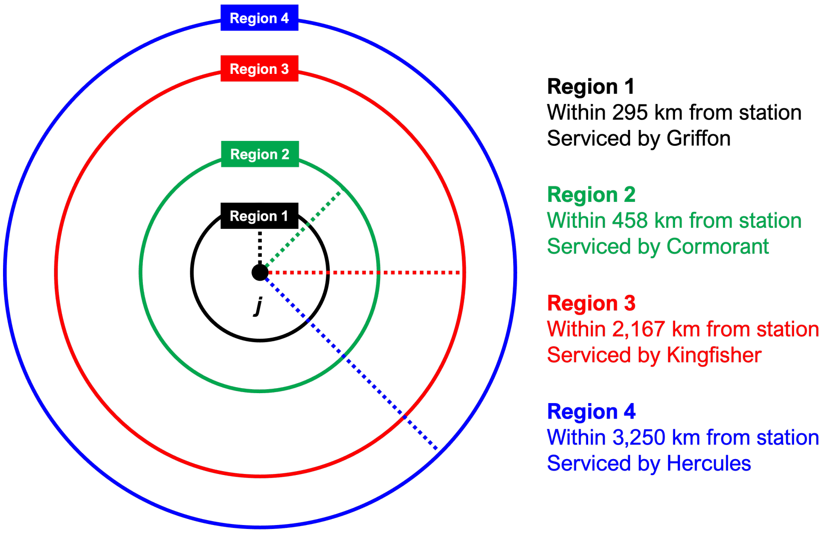


Figure 3.3: Diagram showing the response ranges and service regions for each aircraft, relative to some station j.

Reaction time—the period between an aircraft's assignment to an incident and its departure—was also considered in the model. Denoted $t_{k(react)}$, these were assumed to be 0.33 hours for both helicopters, 0.67 hours for the Kingfisher, and 1 hour for the Hercules; since large planes require more preparation before takeoff. Transit time, $t_{k(trans)}$, described the time required to travel from the station to the rescue location. Like in the literature, this was computed by taking the response range over response speed. The upper bound of each aircraft's response time, denoted $t_{k(max)}$, was expressed as the sum of their reaction and transit times. This described the theoretical maximum time required to service some point within range of type-k aircraft, and was computed using Equation (3.1).

$$t_{k(max)} = t_{k(trans)} + t_{k(react)} = r_k/v_k + t_{k(react)} \tag{3.1}$$

A similar expression was used to find the individual response times between demand point i and station j using aircraft of type-k, denoted t_{ijk}. Given the distance, d_{ij}, between i and j, response time was computed using Equation (3.2).

$$t_{ijk} = d_{ij}/v_k + t_{k(react)} \tag{3.2}$$

These metrics were integral to the response function design and model formulation, discussed in Sections 3.3 and 3.4, respectively.

3.3 Stage 3: Response Function Design

To account for the RCAF's mixed SAR fleet in our model, we constructed four aircraft-specific response functions. Three criteria were established to guide us in developing functions that would meet the study objectives. Firstly, the functions were to be generally-defined so that model-users could adapt them to their own applications. Secondly, the functions were to reward the appropriate use of response assets; meaning the allocation of short-range aircraft to local demand and long-range aircraft to distant demand. In other words, the response functions should penalize the allocation of long-range aircraft to nearby incidents, and instead, incentivize the siting of close-range aircraft for responding to such cases. Lastly, the functions were to be designed in a way that each aircraft would be most appealing within its own response region. As depicted in Figure 3.3, this meant that the Griffon should be the favored asset in Region 1, the Cormorant between Regions 1 and 2, the Kingfisher between Regions 2 and 3, and the Hercules beyond Region 3. In Sections 3.3.1 and 3.3.2, we outline the general procedure for obtaining the response functions.

3.3.1 The Harrington Desirability Function

The proposed response functions were based on the Harrington desirability function (Trautmann & Weihs, 2006)—an exponential curve that outputs a desirability index, d, between 0 and 1 based on some observation variable, x. To design the response curves, we first began with the general Harrington desirability function, as described by Equation (3.3).

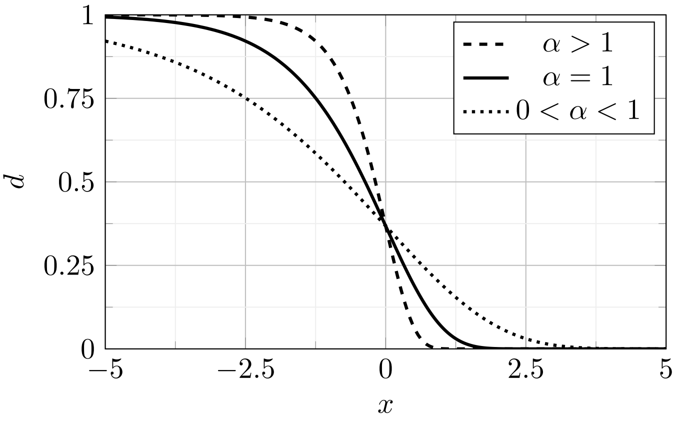
$$d = \exp(-\exp(\beta + \alpha x)) \tag{3.3}$$

The shape of this curve could be adjusted by manipulating two parameters: the sloping constant, α, and the shifting constant, β. The former impacts the curve's steepness, while the latter controls its position on the horizontal axis (see Figure 3.4).

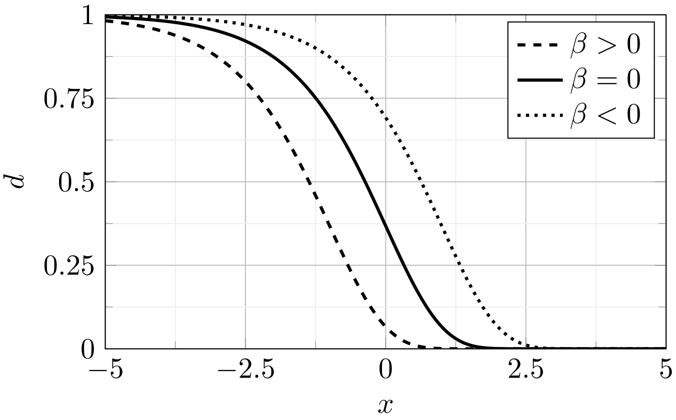
The parameters x and d were rewritten to represent response time, t_{ijk}, and "response level", f_{ijk}, respectively. Response level described how ideal an aircraft was for responding to demand within a given window of time. Values of f_{ijk} could be computed for any arrangement in the network; that is, any demand point i being serviced by SAR station j using aircraft of type-k. Since our model was formulated as a maximization problem, the response functions were designed to diminish exponentially with response time, and thus, optimal response levels were those nearest 1.

In order to construct n unique response functions, we required sloping and shifting constants that were specific to each aircraft of type-k, denoted α_k and β_k, respectively. The general form of the proposed response functions are given by Equation (3.4).

$$f_{ijk} = \exp(-\exp(\beta_k + \alpha_k t_{ijk})) \qquad \forall k \in 1, \ldots, n \tag{3.4}$$



(a) Sloping constant, α



(b) Shifting constant, β

Figure 3.4: Effects of manipulating the sloping constant, α, and shifting constants, β, for a decreasing Harrington desirability function.

3.3.2 Obtaining the Aircraft-Specific Response Functions

To construct the response curves, we began by establishing the sloping constants, α_k, which described an aircraft's range. Short-range assets were assigned larger constants resulting in curves that steepened with response time, while long-range assets were assigned smaller constants resulting in curves that flattened (as shown earlier in Figure 3.4a). In context, this meant that short-range aircraft—which could not travel far—were consistently rewarded for their use in local operations. On the other hand, long-range aircraft—which could cover a much greater area—were penalized locally, but rewarded when responding to demand in areas that could not be reached with short-range assets.

Let us assume that, in the general case, n aircraft types were considered in the model. For simplicity, say they were arranged in increasing order of their maximum response times (ie. $t_{1(max)} < t_{2(max)} < \cdots < t_{n(max)}$). The sloping constant for the aircraft with the shortest range, α_1, was determined by dividing the greatest upper bound on response times by the number of SAR aircraft being considered in the model, as given by Equation (3.5)

$$\alpha_1 = \frac{t_{n(max)}}{n} \tag{3.5}$$

Then, an iterative procedure based on relative response ranges was used to determine the others (ie. for $k = 2, \ldots, n$). The formula is described by Equation (3.6).

$$\alpha_k = \alpha_{k-1}(r_{k-1}/r_k) \qquad \forall k \in 2, \ldots, n \tag{3.6}$$

This approach allowed the sloping constants to be proportional to one another based on the response ranges, while also accounting for the number of functions being designed. For example, if more than four different aircraft were used in the network, the initial sloping constant, α_1, would be smaller. This would result in sloping constants that are closer together, generating response functions that behave more similarly.

As shown in Table 3.1, the upper bounds for each aircraft's response times were known; theoretically, an aircraft of type-k could respond to an incident inside a window of $t_{k(max)}$ hours. Thus, each aircraft's function was assigned a minimum response level, $f_{k(min)}$, based on the desirability of its window. Since faster response times are ideal, aircraft with stricter windows were generally assigned higher $f_{k(min)}$ values.

By inputting the parameters $f_{ijk} = f_{k(min)}$ and $t_{ijk} = t_{k(max)}$ into the general response function (Equation (3.4)), we obtain Equation (3.7).

$$f_{k(min)} = \exp(-\exp(\beta_k + \alpha_k t_{k(max)})) \tag{3.7}$$

We then solved for the shifting constants, β_k, using Equation (3.8). This procedure was repeated for each aircraft type, $k \in \{1, \ldots, n\}$, producing n unique response functions.

$$\beta_k = \ln(-\ln(f_{min})) - \alpha_k t_{max} \tag{3.8}$$

3.4 Stage 4: Model Formulation

The location problem for siting SAR bases and aircraft in the Canadian Arctic was formulated as an ILP. Expressed as a maximization problem, our model sought to optimize the weighted primary and secondary response coverage of all demand points in the network given a set of constraints. The model assumptions are summarized in Table 3.2.

Table 3.2: Model assumptions made in the ILP formulation.

Assumption	**Description**
(i)	Response aircraft depart from and return to the SAR station to which they are assigned.
(ii)	Reaction times are assumed to be constant, as specified in Table 3.1.
(iii)	Each aircraft has a response range that is 45% of its maximum range, and travels at a response speed that is 90% of its maximum speed.
(iv)	Response aircraft follow a linear trajectory between SAR stations and demand points, travelling at the constant response speeds specified in Table 3.1.
(v)	Candidate SAR stations can site up to four aircraft, depending on runway length (we assume this to be one aircraft for every 0.5 km of runway length).
(vi)	Each demand point must be covered by one primary SAR station and servicing aircraft.
(vii)	The same aircraft cannot be used to provide primary and secondary coverage to some demand point.
(viii)	Secondary stations must not provide the same weight of coverage as primary stations in the model (we assume secondary coverage to be weighted half as much as primary coverage, ie. $\lambda = 0.5$).

The formulation of the mathematical model and notation (sets, indices, variables, and parameters) are presented below.

$$
\begin{aligned}
\text{maximize} \quad & Z = \sum_{k\in K}\sum_{j\in J}\sum_{i\in I} f_{ijk} w_i X_{ijk} && && (3.9)\\
& \quad + \sum_{k\in K}\sum_{j\in J}\sum_{i\in I} \lambda f_{ijk} w_i x_{ijk} && && \\
\text{subject to} \quad & \sum_{k\in K}\sum_{j\in J} X_{ijk} = 1 && \forall i \in I && (3.10)\\
& \sum_{k\in K}\sum_{j\in J} x_{ijk} \le 1 && \forall i \in I && (3.11)\\
& X_{ijk} + x_{ijk} \le 1 && \forall i \in I, j \in J, k \in K && (3.12)\\
& d_{ij} X_{ijk} \le r_k y_{jk} && \forall i \in I, j \in J, k \in K && (3.13)\\
& d_{ij} x_{ijk} \le r_k y_{jk} && \forall i \in I, j \in J, k \in K && (3.14)\\
& \sum_{k\in K}\sum_{j\in J} y_{jk} \le N && && (3.15)\\
& z_j \le \sum_{k\in K} y_{jk} \le c_j z_j && \forall j \in J && (3.16)\\
& X_{ijk} \in \{0,1\} && \forall i \in I, j \in J, k \in K && (3.17)\\
& x_{ijk} \in \{0,1\} && \forall i \in I, j \in J, k \in K && (3.18)\\
& y_{jk} \in \{0,1\} && \forall j \in J, k \in K && (3.19)\\
& z_j \in \{0,1\} && \forall j \in J && (3.20)
\end{aligned}
$$

where: Sets:

$I = \{1, \ldots, n\}$: Set of demand points;

$J = \{1, \ldots, m\}$: Set of candidate SAR stations;

$K = \{1, 2, 3, 4\}$: Set of aircraft types;

Indices:

i : Demand point i;

j : Candidate SAR station j;

k : Aircraft of type-k;

Decision variables:

Z : Objective value;

X_{ijk} : Primary coverage of i being serviced by j using k (1 if so; 0 otherwise);

x_{ijk} : Secondary coverage of i being serviced by j using k (1 if so; 0 otherwise);

y_{jk} : Allocation of k to j (1 if so; 0 otherwise);

z_k : Status of j (1 if selected; 0 otherwise);

Parameters:

f_{ijk} : Response value of i being serviced by j using k;

w_i : Regional incident weight of i;

d_{ij} : Distance between i and j (in km);

r_k : Response range of k (in km);

c_j : Aircraft capacity of j;

N : Number of aircraft to be allocated;

λ : Secondary response function factor.

The objective function, as given by Equation (3.9), seeks to maximize the total weighted primary and secondary response coverage. Equation (3.10) ensures that each demand point is primarily covered by one SAR station, while Equation (3.11) makes that requirement optional for secondary coverage. Equation (3.12) ensures that the primary and secondary coverage received by some demand point comes from different response assets. Equations (3.13) and (3.14) respectively ensure that all demand points are within range of the primary and (if necessary) secondary SAR stations to which they are assigned. Equation (3.15) limits the total number of aircraft to be allocated. Equation (3.16) limits the number of aircraft allocated to station j to no more than its capacity if the station is selected, and zero otherwise. Equations (3.17) through (3.20) restrict the decision variables to binary values.

It should be noted that the above formulation was that used in Case A, where secondary coverage is optional. The formulation of the Case B model, for mandatory secondary coverage, can be easily obtained by replacing Equation (3.11) by (3.21).

$$\sum_{k \in K} \sum_{j \in J} x_{ijk} = 1 \qquad \forall i \in I \tag{3.21}$$

The objective function, Equation (3.9), can also be re-expressed in terms of response time through Equation (3.4). The expanded form is given in Equation (3.22).

$$\begin{aligned} Z = & \sum_{k \in K} \sum_{j \in J} \sum_{i \in I} \exp(-\exp(\beta_k + \alpha_k t_{ijk})) w_i X_{ijk} \\ & + \sum_{k \in K} \sum_{j \in J} \sum_{i \in I} \lambda \exp(-\exp(\beta_k + \alpha_k t_{ijk})) w_i x_{ijk} \end{aligned} \tag{3.22}$$

Ultimately, the proposed model provided extensions to the SCLM, MCLM, and PMM by borrowing elements from each. Like the SCLM, our formulation required that every demand point be serviced by at least one SAR station—two, if possible. It also looked to maximize this service coverage for a limited number of response assets; a defining property of the MCLM. Lastly, by incorporating the diminishing response functions, quicker response times were incentivized and minimal travel distances optimal. This describes a similar objective to the PMM, which, despite being expressed as a minimization problem, looks to optimize weighted distances across the network.

3.5 Stage 5: Solution Approach & Sensitivity Analysis

Having developed the ILP, the final step was to collect and analyze the results. The model was first coded in CPLEX and the required parameters were imported. Solutions were obtained by controlling for the number of aircraft to be allocated: we observed all optimal arrangements for $N \in 1, \ldots, 15$. Hereafter, the N^{th} arrangement (ie. that which allocates N aircraft) will be referred to as "Arrangement NA" in Case A and "Arrangement NB" in Case B.

In addition to the value of the objective function, Z, the solution determined the candidate locations to be selected (z_j), the aircraft they should base (y_{jk}), and the demand points they should service (X_{ijk}, x_{ijk}). This procedure was performed for both Case A and Case B, where they were analyzed independently and in contrast to one another.

3.5.1 Selection Criteria

All of the observed arrangements will be optimal for a given number of allocated aircraft, N. In order to provide sensible recommendations on the placement of SAR resources in the Arctic, we should avoid solutions that simply distribute the most aircraft, returning an absurdly high objective value. In theory, policy-makers *could* allocate dozens of aircraft to the North; and it would produce a more desirable objective value than an arrangement with, say, five aircraft. But this approach is unrealistic. Thus, we have proposed a selection criteria that allows us to generate a reasonable set of recommended arrangements.

For the selection process, we considered the marginal percent increase in objective values for each arrangement relative to the previous (ie. that which allocates one less aircraft). This was evaluated separately in both Cases A and B, wherein the first arrangement to fall below a 5% improvement of the previous solution was chosen. Surrounding arrangements were also considered, and those which may be of interest to policy-makers were added to the set of recommended arrangements.

Chapter 4

Results

Having developed a methodological framework for modelling Canada's Arctic SAR capacities, we then proceeded to collect and analyze the solutions to the FLP model. In this chapter, we discuss the data (Section 4.1) and response functions (Section 4.2) used for this study, as well as the main findings (Section 4.3).

4.1 Description of the Data

Here, we describe the datasets used to define our demand points and candidate locations; as outlined in Sections 4.1.1 and 4.1.2, respectively.

4.1.1 Demand Points

The demand points used in the case study were obtained from Canada's Transportation Safety Board (TSB) "Occurrence Table" dataset. Reporting all incidents filed through the TSB's Marine Safety Information System (MARSIS) between 1975 and 2021, the dataset recounted the details of accidents involving vessels in Canadian waters. Ranging from vessel damage (ie. ships running aground, sinking, or capsizing) to hazards compromising passenger safety (ie. persons overboard, missing, injured, or deceased), the complete dataset contained 82,762 entries. Once multiples were removed, the set was reduced to 43,968 unique cases. Next, only incidents within the area of study were considered, limiting the set to only 628 entries. One final cleaning of the data was performed to remove duplicate events that were reported in the exact same location on the same day, leaving 622 occurrences in the dataset.

These incidents were then imported into QGIS along with an NTS grid of scale 1:250k. All incidents located within the same grid cell were clustered together and the mean coordinates were computed. The resulting centroids for each region were taken as the 172 demand points used in the study, as mapped in Figure 4.1. The regional incident frequencies represented the weights, w_i, used in the model.

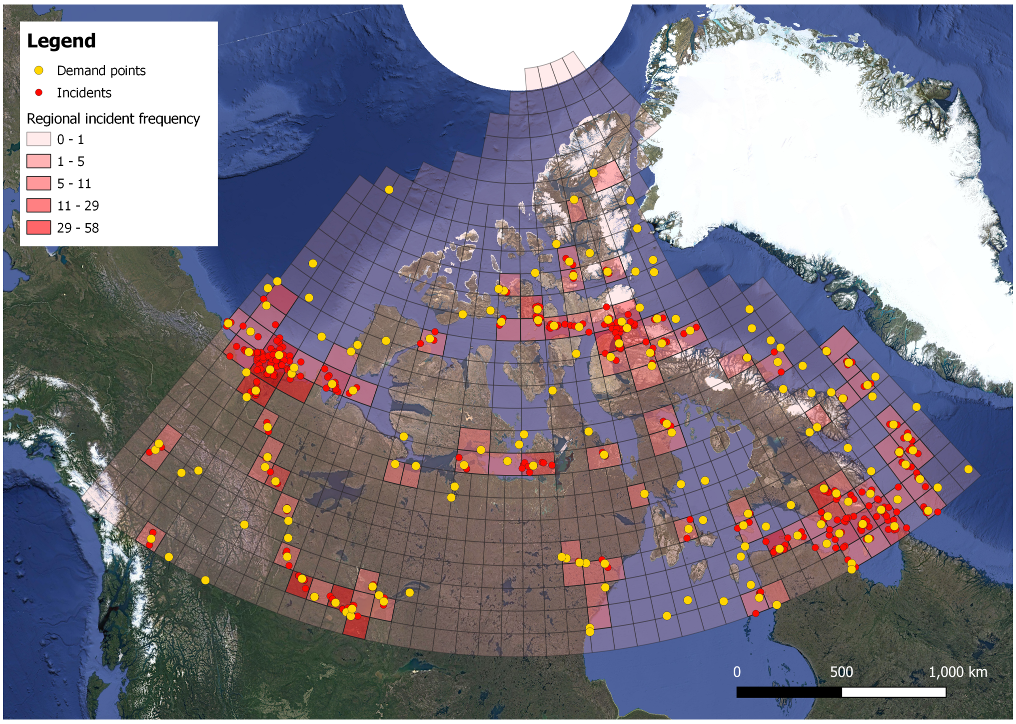


Figure 4.1: Map of incidents and demand points.

4.1.2 Candidate Locations

Since the model was designed for locating aeronautical SAR stations, existing aerodromes and airports in the Canadian Arctic were considered as candidate sites. The primary source for obtaining these facilities was a North American and Arctic Defence and Security Network (NAADSN) report (Bouchard, 2020) listing all civilian aeronautical infrastructure in the Territories. The document listed both private and government-operated locations; but since SAR operations fall under federal jurisdiction, only the latter were considered. The report provided the coordinates of the aerodromes, which were used in computing demand-facility distances, d_{ij}, as well as runway lengths, which were used to determine the capacity of each station, c_j. Runways shorter than 0.5 km were taken to site at most one aircraft, those between 0.5 and 1 km to site at most two, those between 1 and 1.5 km to site at most three, and those equal to or exceeding 1.5 km to site up to four.

The aerodromes obtained from the NAADSN report were further supplemented by the literature analyzing Arctic infrastructure; particularly VanderBerg (2018), who mentioned two Quebec airports that would subsequently be added to the set of candidate sites. Other articles that discussed some of the locations used in this study include Sheehan et al. (2021) and Shan and Zhang (2019). The final list of candidate SAR stations consisted of 84 locations across four provinces and territories: Quebec (2), the Northwest Territories (28), Nunavut (27), and the Yukon (27). These locations are mapped in Figure 4.2 and a complete list of candidate locations is given in Appendix A.

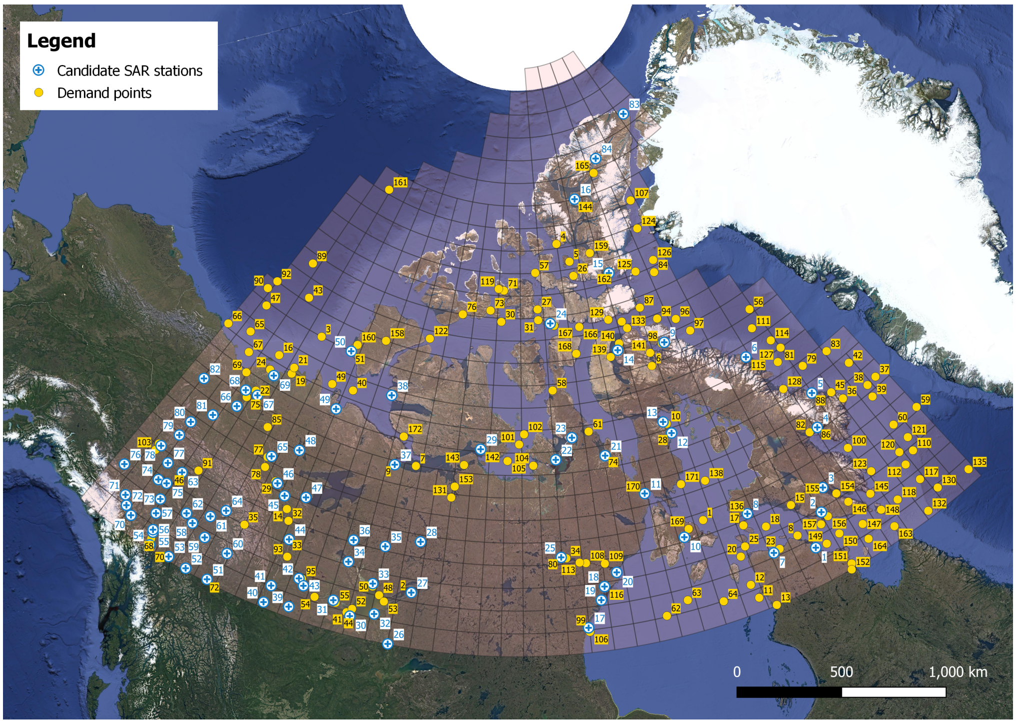


Figure 4.2: Map of demand points and candidate SAR stations.

4.2 Response Functions Designed for this Study

Our location problem considered four SAR aircraft types. We began by determining the sloping constant for the type-1 (Griffon) aircraft using Equation (3.5). This yielded $\alpha_1 = 1.875$. Using Equation (3.6), we obtained the sloping constants $\alpha_2 = 1.2077$, $\alpha_3 = 0.25525$, and $\alpha_4 = 0.17019$, for the Cormorant, Kingfisher, and Hercules, respectively.

For this study, we said that a 1.59 hour response from the Griffon was 90% ideal, a 2.15 hour response from the Cormorant was 80% ideal, a 5.66 hour response from the Kingfisher was 30% ideal, and a 7.5 hour response from the Hercules was only 10% ideal. In other words, we took minimum response levels of $f_{1(min)} = 0.9$, $f_{2(min)} = 0.8$, $f_{3(min)} = 0.3$, and $f_{4(min)} = 0.1$. Using the procedure outlined in Section 3.3.2, we obtained the four desired response functions, as expressed by Equations (4.1) to (4.4), respectively.

$$f_{ij1} = \exp(-\exp(-5.23161 + 1.875t_{ij1})) \tag{4.1}$$

$$f_{ij2} = \exp(-\exp(-4.09649 + 1.2077t_{ij2})) \tag{4.2}$$

$$f_{ij3} = \exp(-\exp(-1.25908 + 0.25525t_{ij3})) \tag{4.3}$$

$$f_{ij4} = \exp(-\exp(-0.44239 + 0.17019t_{ij4})) \tag{4.4}$$

These response functions are graphed in Figure 4.3 along with the maximum response times for each—as represented by the dashed lines. It should be noted that the proposed response functions follow the criteria outlined in the beginning of Section 3.3: they are generally expressed, penalties are least severe when assets are used appropriately, and each aircraft's response curve is greatest within its respective region.

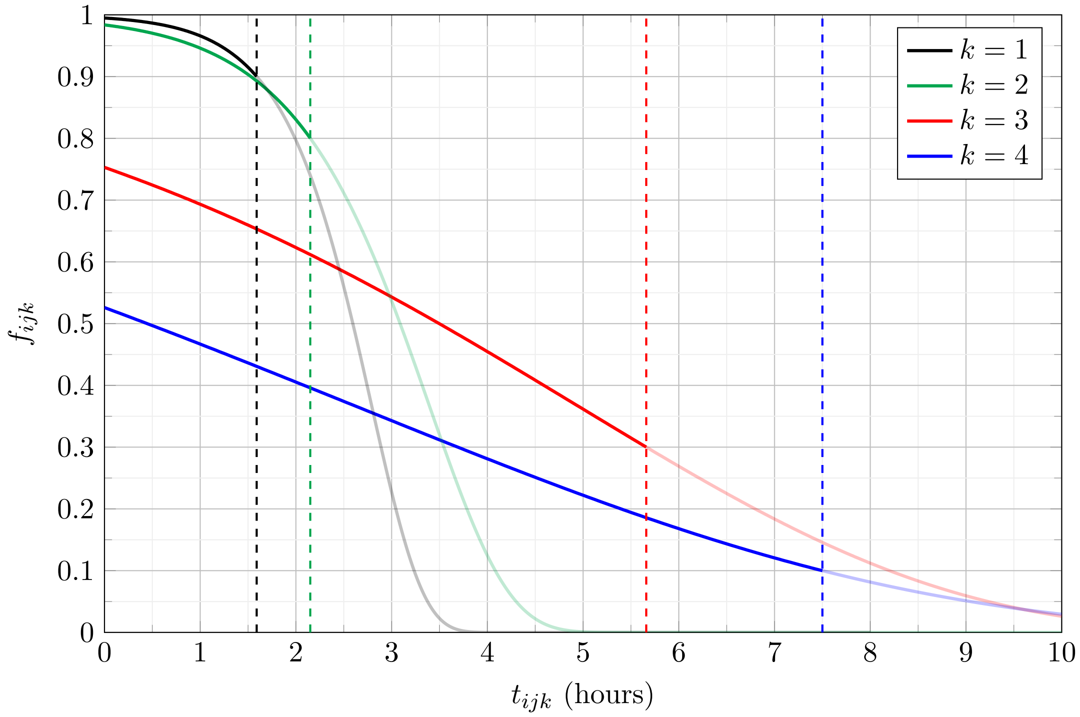


Figure 4.3: The four aircraft-specific response functions designed for this study.

4.3 Results from the Model

In this section, we present the results from the model. We discuss Case A with the optional secondary coverage constraint in Section 4.3.1, and Case B with the mandatory secondary coverage constraint in Section 4.3.2. In Section 4.3.3, we compare the two by discussing the surrounding solutions.

4.3.1 Case A: Optional Secondary Coverage

In Case A, we studied arrangements under optional secondary coverage. Solutions were obtained for allocations of up to 15 aircraft, where the model determined the optimal placement and distribution of such assets.

Observing Figure 4.4, we first note that the objective value, Z, increases with each additional aircraft. The marginal percent increase in Z is largest at 53.65% in Arrangement

2A, since the allocation of a second aircraft introduces secondary coverage to the network. Beyond the allocation of two aircraft, the objective function increases at a significantly slower rate: from 18.65% when a third is added, to less than 3% when we consider eight or more.

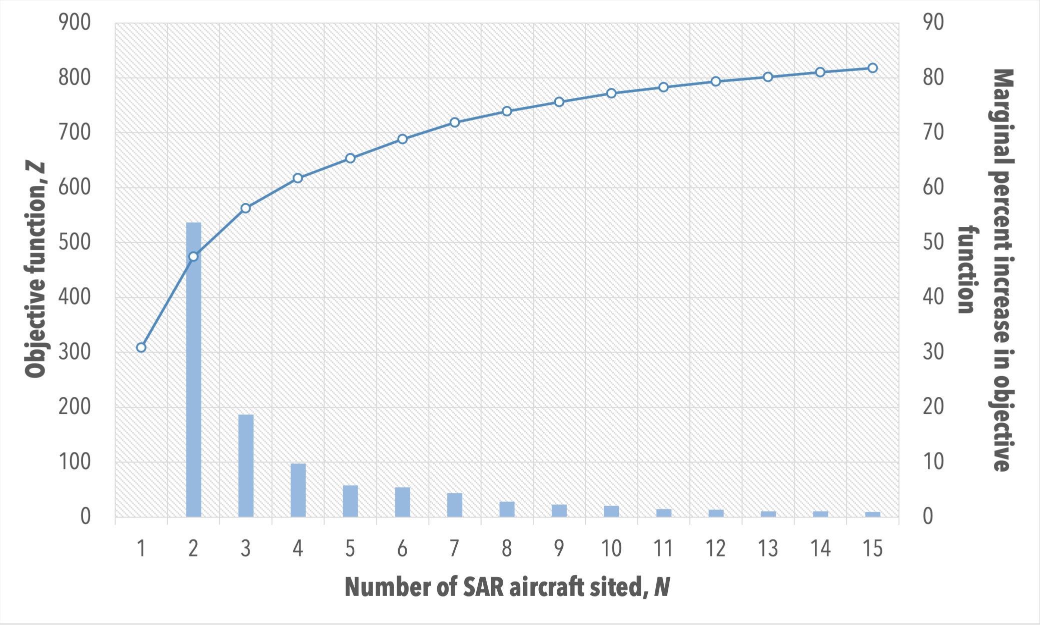


Figure 4.4: Objective function and its percent increase versus the number of SAR stations being allocated in Case A.

It is also worth mentioning that, since secondary coverage is optional in Case A, total double coverage (denoted DC% in Table 4.1) of all demand points only occurs once 11 aircraft are stationed. Before that, the highest percentage of demand points receiving double coverage is 97.09% in Arrangement 3A. Despite not being mandatory, secondary coverage is still rather high in Case A, ranging between 87.79% and 100%—with the obvious exception of 0% when only one aircraft is sited. This suggests that the RCAF's fleet can provide significant coverage of Arctic demand points, so long that at least two aircraft are used.

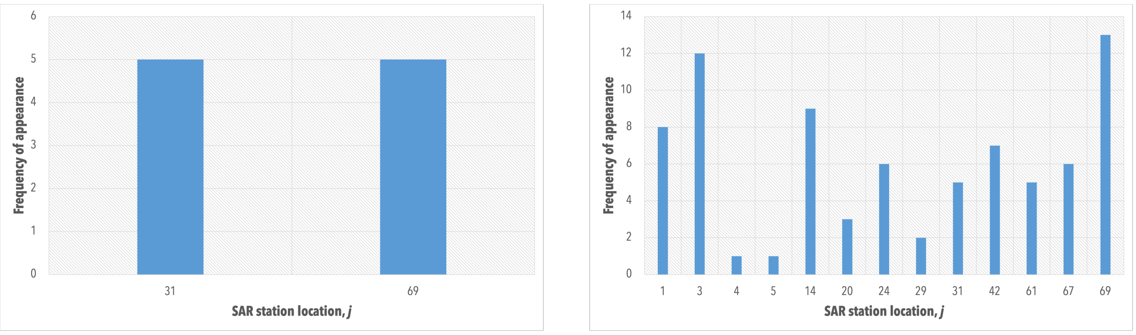
Table 4.1 shows the optimal arrangements of stations and aircraft for the Case A solutions. It is apparent that the Griffon, Cormorant, and Kingfisher are all found to be optimal at some point in the solutions, while the Hercules is never mentioned. Although the Hercules is faster and has a greater response range than the rest of the fleet, the

Kingfisher was capable of covering all demand points with optimal response levels. We also see that the model suggests maintaining at least two Kingfishers in the network at all times, while using helicopters to fill other openings. Since planes operate wider service regions, the two-to-three Kingfishers ensure that remote locations can receive basic coverage, while also acting as a secondary responder to points that are serviced primarily by the helicopters. Of the three aircraft types found throughout the solutions, the Cormorant appears most frequently. In fact, as of Arrangement 3A, each additional asset is chosen to be a Cormorant; this continues until Arrangement 11, where the Griffon is first introduced.

Table 4.1: Optimal distribution of SAR aircraft across candidate station locations for the Case A solution.

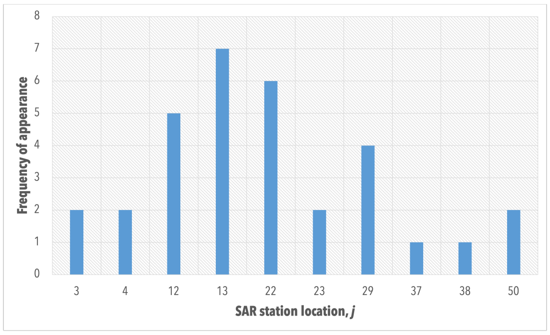
				Candidate SAR stations, *j*			
Arr.	***N***	***Z***	**DC%**	Griffon	Cormorant	Kingfisher	Hercules
1A	1	308.620	0.00			22	
2A	2	474.200	97.09			23, 29	
3A	3	562.620	93.02		69	12, 29	
4A	4	617.410	87.79		3, 69	13, 37	
5A	5	653.150	93.02		3, 67, 69	13, 29	
6A	6	688.590	96.51		3, 42, 67, 69	12, 23	
7A	7	718.880	94.19		3, 14, 42, 67, 69	3, 22	
8A	8	739.020	93.60		1, 3, 14, 42, 67, 69	13, 29	
9A	9	755.980	96.51		1, 3, 14, 31, 42, 67, 69	13, 22	
10A	10	771.560	96.51		1, 3, 14, 24, 31, 42, 67, 69	12, 22	
11A	11	782.860	100.00	31, 69	1, 3, 14, 24, 42, 61, 69	12, 22	
12A	12	793.220	100.00	31, 69	1, 3, 4, 14, 24, 42, 61, 69	12, 22	
13A	13	801.540	100.00	31, 69	1, 3, 14, 20, 24, 31, 61, 69	4, 13, 38	
14A	14	810.100	100.00	31, 69	1, 3, 14, 20, 24, 29, 31, 61, 69	4, 13, 50	
15A	15	817.800	100.00	31, 69	1, 3, 5, 14, 20, 24, 29, 31, 61, 69	3, 13, 50	

Observing the frequency trends displayed in Table 4.5, several locations emerge as desirable candidates for aeronautical SAR stations. The short-ranged Griffon only appears to be recommended for two locations: 31 (Fort Providence) and 69 (Tuktoyaktuk). The Cormorant shows much more diversity in its siting; with locations 1 (Kangiqsujuaq), 3 (Iqaluit), 14 (Arctic Bay), and 69 appearing in at least eight arrangements. Meanwhile, four locations appear to be well-suited in siting the Kingfishers: 12 (Hall Beach), 13 (Igloolik), 22 (Gjoa Haven), and 29 (Cambridge Bay).



(a) Griffon ($k = 1$)

(b) Cormorant ($k = 2$)



(c) Kingfisher ($k = 3$)

Figure 4.5: Optimal candidate locations and their frequency of appearance in Case A solutions, by aircraft.

Following the selection criteria outlined in Section 3.5.1, we conclude that the optimal setup in this case is Arrangement 7A. This solution is the first to fall below a 5% marginal increase—improving upon Arrangement 6A by 4.399%. With an objective value of 718.88, this arrangement provides double coverage to 94.19% of demand points, for a total of 162 regions. As shown in Table 4.1, this solution requires seven aircraft: five Cormorants at candidate locations 3, 14, 42 (Fort Simpson), 67 (Inuvik), and 69, and two Kingfishers at locations 3 and 22. This calls for the siting of six SAR stations across Nunavut (3, 14, and 22) and the Northwest Territories (42, 67, and 69).

As shown in Figure 4.6, the Kingfishers are capable of covering (almost) the entire study region; the plane found at station 22 can provide basic coverage to any demand point, while the one found at station 3 can cover a large portion of the east. We also note that the five Cormorants are scattered throughout the region, concentrated in areas of high historical demand, as was shown in Figure 4.1. In fact, a high density of incidents occurring in the northwest corner of the mainland Arctic prompted the model to site two Cormorants less than 150 kilometers apart, at locations 67 and 69. This configuration also appears in Arrangements 5A through 10A.

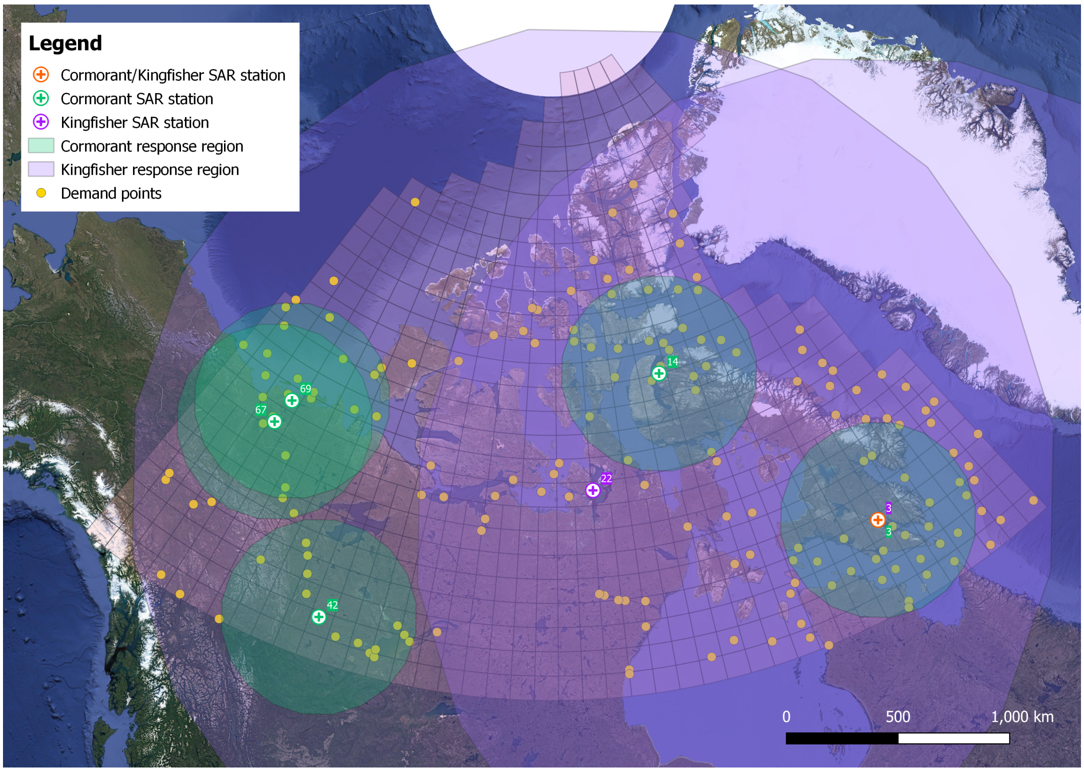


Figure 4.6: Arrangement 7A ($N = 7$).

4.3.2 Case B: Mandatory Secondary Coverage

In Case B, we explored optimal arrangements under a mandatory secondary coverage constraint. In other words, here, all demand points required service from a primary responding aircraft and a secondary, which provided backup coverage. Since at least two aircraft were required to meet these conditions, we observed the configurations allocating 2 to 15 assets.

We note that the objective values in Figure 4.7 follow a similar trend to those found in Figure 4.4, in that they both increase with each additional aircraft. The objective value is most affected by the addition of a third asset, improving upon Arrangement 2B by 18.77%. Similar to those in Case A, this increase occurs at a decreasing rate—reaching less than 1% marginal improvement when 15 aircraft are considered in the model.

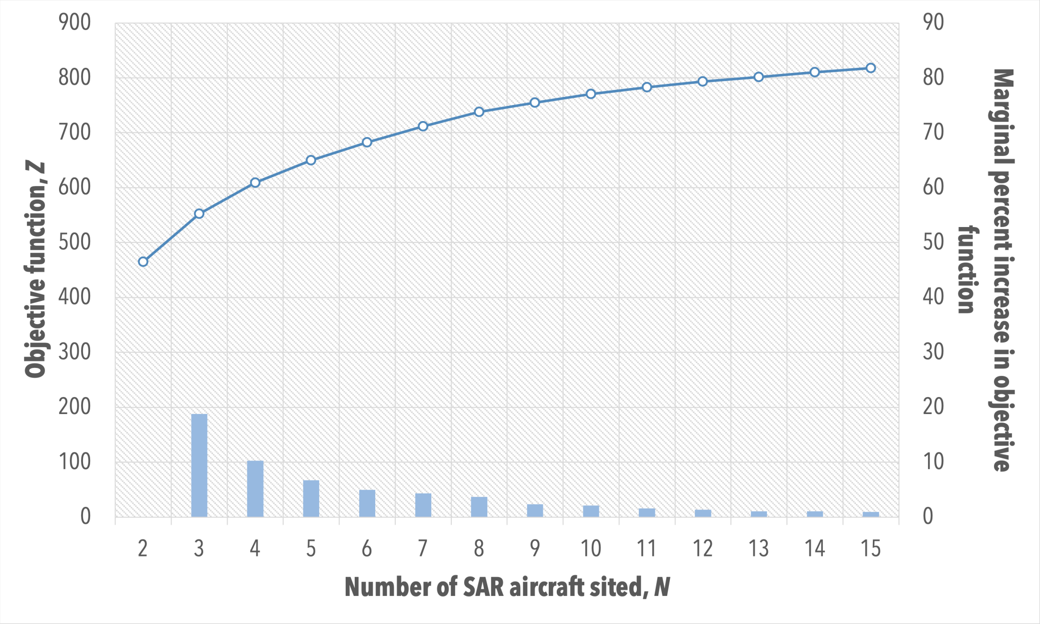


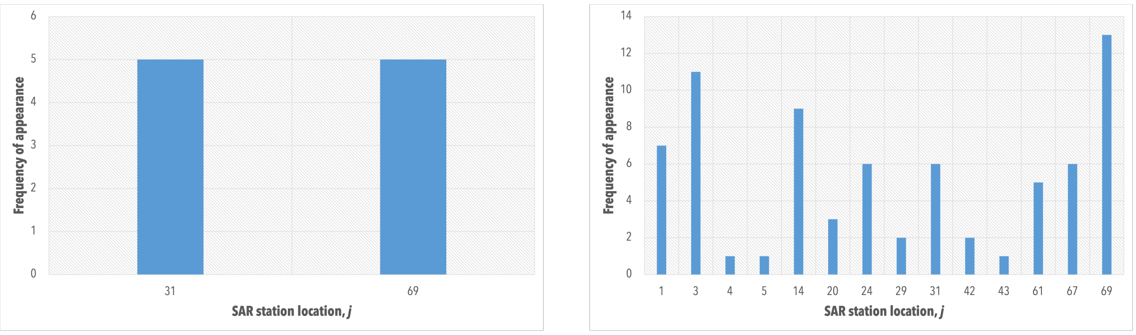
Figure 4.7: Objective function and its percent increase versus the number of SAR stations being allocated in Case B.

Studying the solutions more closely in Table 4.2, we notice once again that the Hercules is not optimal, and the arrangements depend exclusively on the Griffon, Cormorant, and Kingfisher. This presents many parallels between the two cases. As seen earlier, Arrangement 2A achieved 97.09% double coverage using only two Kingfishers located at stations 23 (Taloyoak) and 29 (Cambridge Bay); Arrangement 2B demonstrates that 100% coverage is possible by simply relocating station 29 to 22. This is seen across various solutions, suggesting that Case A arrangements can be as little as one relocation away from total coverage—of course, at the expense of a reduced objective value. We also see that at least two Kingfishers are kept in the network at all times; although more solutions suggest the allocation of three to ensure that the secondary coverage constraint is met. It is also worth noting that Arrangements 11A through 15A are identical to their Case B equivalents, since they provide total double coverage.

Table 4.2: Optimal distribution of SAR aircraft across candidate station locations for the Case B solution.

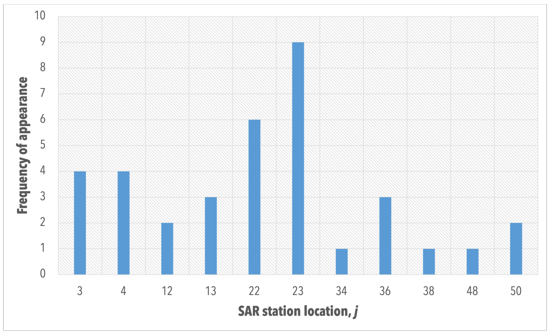
			Candidate SAR stations, *j*			
Arr.	$\boldsymbol{N}$	$\boldsymbol{Z}$	Griffon	Cormorant	Kingfisher	Hercules
2B	2	465.090			22, 23	
3B	3	552.420		69	22, 23	
4B	4	609.000		69	3, 23, 48	
5B	5	649.790		3, 67, 69	22, 23	
6B	6	682.210		3, 43, 67, 69	22, 23	
7B	7	711.660		3, 14, 67, 69	3, 23, 34	
8B	8	737.730		3, 14, 31, 67, 69	3, 23, 36	
9B	9	754.750		1, 3, 14, 31, 67, 69	4, 23, 36	
10B	10	770.540		1, 3, 14, 24, 31, 67, 69	4, 23, 36	
11B	11	782.860	31, 69	1, 3, 14, 24, 42, 61, 69	12, 22	
12B	12	793.220	31, 69	1, 3, 4, 14, 24, 42, 61, 69	12, 22	
13B	13	801.540	31, 69	1, 3, 14, 20, 24, 31, 61, 69	4, 13, 38	
14B	14	810.100	31, 69	1, 3, 14, 20, 24, 29, 31, 61, 69	4, 13, 50	
15B	15	817.800	31, 69	1, 3, 5, 14, 20, 24, 29, 31, 61, 69	3, 13, 50	

When comparing the trends in Figure 4.8 to those in Figure 4.5, we observe no difference in the Griffon's suggested locations. The Cormorant's siting in stations 1, 3, 14, and 69 appear about as frequently in Case B as they did in Case A. In contrast, we notice a significant drop in the optimality of location 42, which appears only twice throughout the Case B solutions—as opposed to seven times in Case A. Perhaps the most significant changes resulting from the mandatory secondary coverage constraint are in the Kingfishers' siting. Some stations which came up frequently in the Case A solutions, such as 12 and 13, saw a decrease in their appearance throughout Case B; others, like location 29, were dropped altogether. In contrast, we did notice a spike in the siting of other candidate locations for the Kingfisher, namely: locations 3, 4 (Pangnirtung), and 23. Location 22 appeared as frequently here as it did in Case A.



(a) Griffon ($k = 1$)

(b) Cormorant ($k = 2$)



(c) Kingfisher ($k = 3$)

Figure 4.8: Optimal candidate locations and their frequency of appearance in Case B solutions, by aircraft.

Applying the same selection criteria as in Case A, we determine that the suggested setup here is Arrangement 6B. Improving upon Arrangement 5B by 4.989%, this solution yields an objective value of 682.21 and provides total primary and secondary coverage to all 172 demand points in the model. From Table 4.2, we note that this arrangement requires six aircraft: four Cormorants at candidate locations 3, 14, 67, and 69, and two Kingfishers at locations 22 and 23. In turn, this arrangement calls for the opening of six SAR stations: four in Nunavut (3, 14, 22, and 23) and two in the Northwest Territories (67 and 69). This solution provides 100% secondary coverage using one less Cormorant and the same amount of Kingfishers as the suggested Arrangement 7A for the previous case. The selected locations are also similar; both share stations 3, 14, 67, and 69 for the Cormorant, and station 22 for the Kingfisher.

Arrangement 6B is presented in Figure 4.9. Here, we note that the two Kingfishers are placed at the center of the study region, less than 150 kilometers from one another.

With their expansive response ranges, the planes can therefore provide optimal primary and secondary coverage to remote demand points that cannot be reached by helicopter.

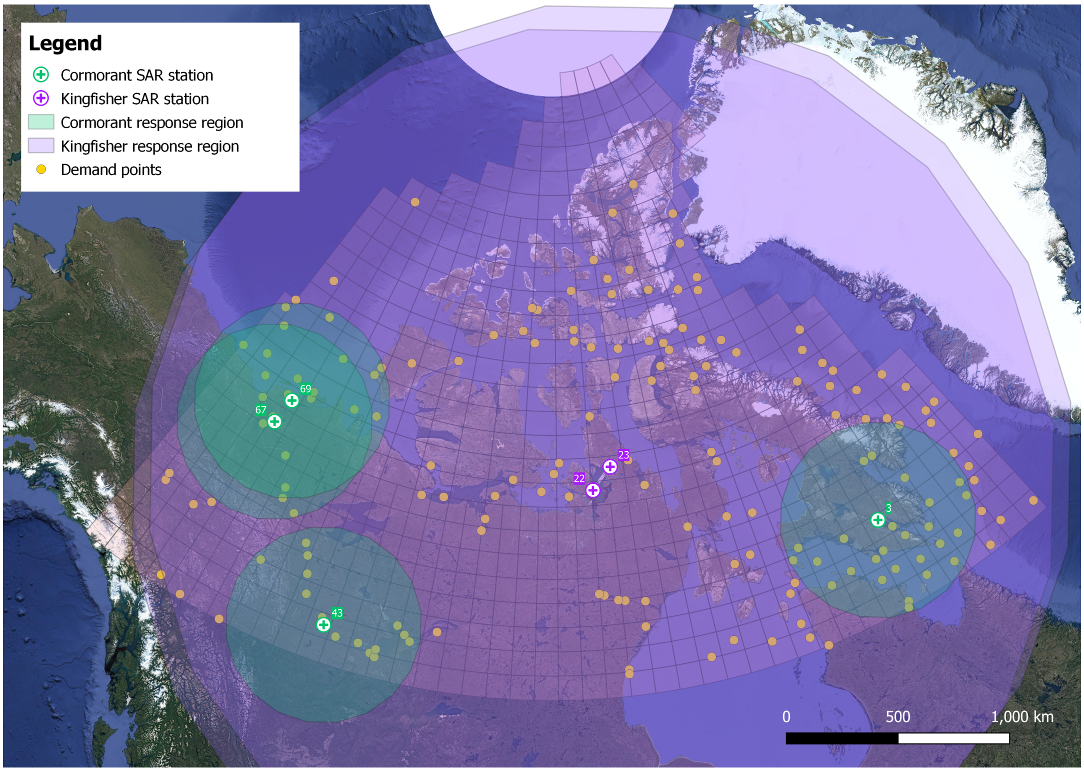


Figure 4.9: Arrangement 6B ($N = 6$).

4.3.3 A Compromising Solution

The selection criteria applied to Cases A and B determined that the suggested distribution of SAR stations and assets should follow Arrangements 7A and 6B, respectively. Between the two, we see a trade-off: Arrangement 7A returns a greater objective value at the expense of achieving only 94.19% secondary coverage, whereas Arrangement 6B returns a lower objective value, but provides total secondary coverage using fewer assets. It may therefore be appealing to explore Arrangement 7B, which uses the same number of aircraft as Arrangement 7A while also achieving total secondary coverage, like Arrangement 6B. Although it allocates one more aircraft than Arrangement 6B, it improves the solution by 4.317%, yielding an objective value of 711.66—only a 1% drop from that in Arrangement 7A.

Unlike its Case A counterpart, this setup calls for four Cormorants in candidate locations 3, 14, 67, and 69, and three Kingfishers in locations 3, 23 and 34 (Whatì). As a result, it requires the siting of six SAR station at locations 3, 14, 23, 34, 67, and 69 (see Figure 4.10). While this solution was not determined using the selection criteria, it can lend itself as a compromise between Arrangements 7A and 6B, and should be considered in discussion.

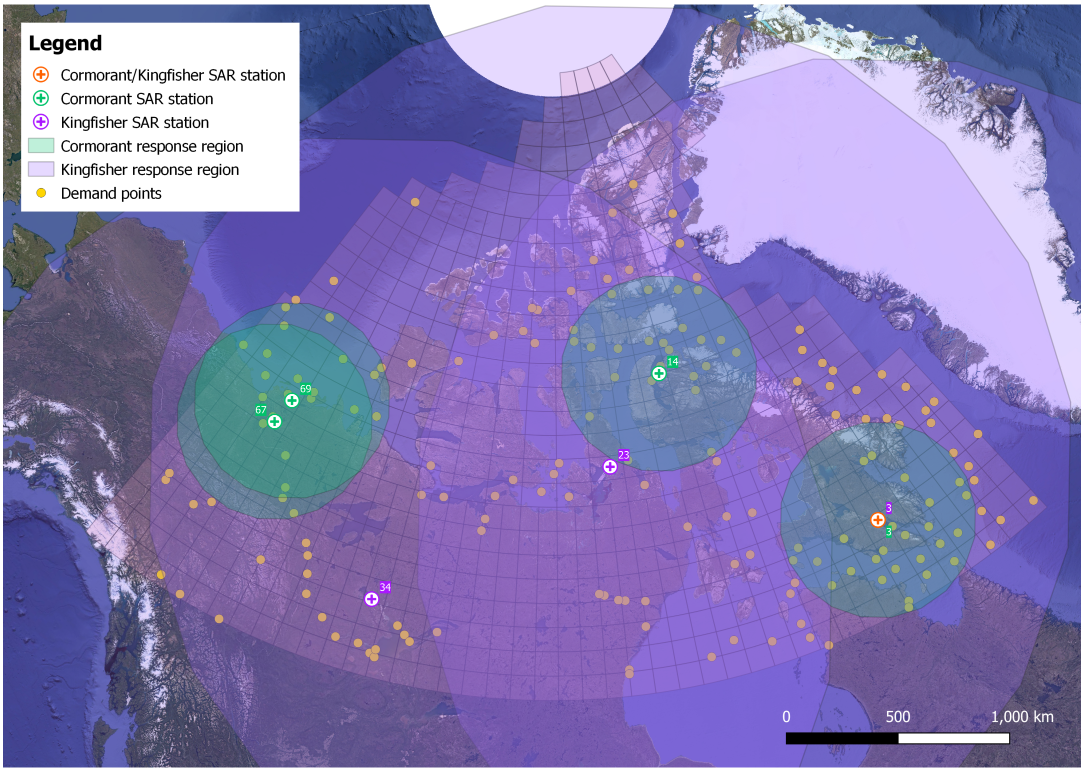


Figure 4.10: Arrangement 7B ($N = 7$).

Chapter 5

Discussion of Findings

In the previous chapter, we collected 29 optimal arrangements across both optional and mandatory secondary coverage constraints; Cases A and B, respectively. Here, we interpret the findings (Section 5.1) and discuss their implications on SAR in Canada (Section 5.2).

5.1 Interpretation of the Results

Selection criteria were applied to determine the arrangements that might be of interest to decision-makers. This yielded three desirable solutions to the SAR station location problem: Arrangement 7A was proposed for Case A, Arrangement 6B for Case B, and Arrangement 7B was recommended as a compromise of the two.

The three arrangements outlined in Table 5.1 each had advantages and disadvantages. Using seven aircraft, Arrangement 7A scored the highest objective value of the proposed solutions at 718.88, but provided secondary coverage to only 94.19% of demand points. While Arrangement 6B did generate a lower objective value than Arrangement 7A, it provided total secondary coverage using only six assets. Lastly, in recognizing the trade-off between Arrangements 7A and 6B, we proposed the inclusion of Arrangement 7B, which used seven aircraft and gave total secondary coverage. Furthermore, it maintained a relatively high objective value of 711.66, which is over 4% more than that of Arrangement 6B and only 1% less than that of Arrangement 7A.

Table 5.1: The three recommended arrangements.

	Arrangement 7A	**Arrangement 6B**	**Arrangement 7B**
Objective value, Z	718.88	682.21	711.66
Secondary coverage (%)	94.19	100	100
Cormorant locations, j	3, 14, 42, 67, 69	3, 43, 67, 69	3, 14, 67, 69
Kingfisher locations, j	3, 22	22, 23	3, 23, 34
Advantages	Higher Z	Total secondary coverage, fewer assets	Higher Z, total secondary coverage
Disadvantages	More assets, partial secondary coverage	Lower Z	More assets

Although these arrangements differ slightly in their distribution of assets, they do offer some insight into what candidate sites might be of interest to policy-makers. Since the Cormorant was favored in local operations, the aircraft saw many allocations to areas of high historical incidence; around demand points that were heavily weighted in the model. Among these were the regions surrounding Tuktoyaktuk and Iqaluit (see Figure 5.1). It made sense to see such a large number of past incidents in these two areas: located at the NWP's opening, Iqaluit is the largest (and only) city in Nunavut, and Tuktoyaktuk is an important Arctic port located at the route's end. With the critical location of these port communities, and the abundance of incidents having occurred there in the past, it follows that these two regions should receive adequate coverage. This inference was supported by our recommended solutions, as all three called for the siting of a Cormorant at stations 3 (near Iqaluit), and 67 and 69 (both in the area surrounding Tuktoyaktuk). This was also the case for the demand points located in Lancaster Sound, another important leg of the NWP. One of the local candidate sites, station 14, was deemed optimal for the Cormorant in Arrangements 7A and 7B. The region surrounding the Great Slave Lake in Figure 5.1 was another area of dense historical demand. This prompted Arrangements 7A and 6B to allocate a helicopter to the nearby stations 42 and 43, respectively. It should be noted that the four areas labelled in Figure 5.1 represent the areas which historically experienced a great frequency of maritime incidents. As a result, we see the model's consistent allocation of the Cormorant as a primary responder to these regions.

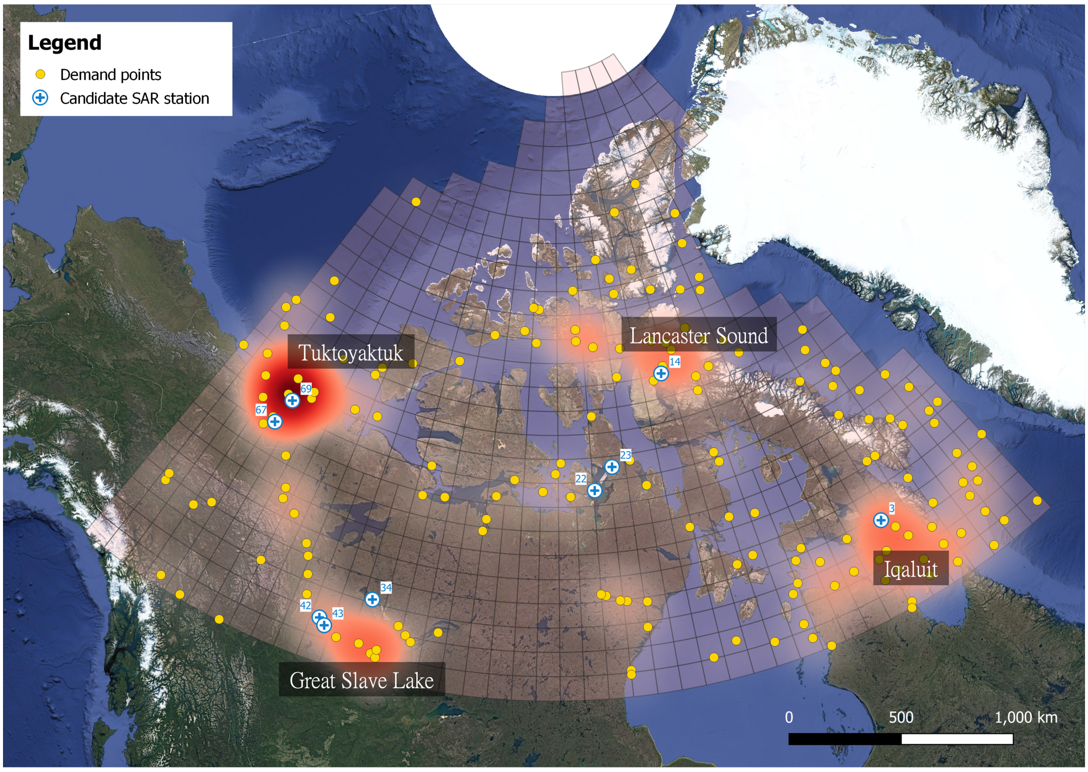


Figure 5.1: Heat map of historical incident locations with demand points and stations selected in the set of recommended arrangements.

Two general areas emerged as important sites for the long-ranged Kingfishers. The first was once again candidate station 3, located in the Iqaluit region; the station was assigned both a Cormorant and Kingfisher in Arrangements 7A and 7B. This strategy permits the helicopter—more restricted in its service range—to act as a primary responder to nearby demand. At the same time, the plane serves as a secondary asset for those local demand points, as well as a primary covering to those which could not be reached by helicopter. Although station 3 is situated in the southeast corner of the study region, the placement of a Kingfisher here is essential to servicing the east Arctic, which accounts for nearly 75% of demand points. Another area that saw increased Kingfisher sitings was station 22 (and the nearby 23), appearing in each of the three recommended arrangements at least once. Unlike the other areas of interest, these stations were not surrounded by dense clusters of historical incidence. These candidate sites played a crucial role in the arrangements since they were located at the geographic center of the study region. When sited at locations 22 and 23, the Kingfishers, with their expansive range, were capable of covering all demand points. This established the sited planes as a fundamental basic covering, capable of providing primary service to remote areas inaccessible by helicopter, and secondary coverage in support of primary response operations.

5.2 Impacts on the Canadian SAR Network

Since no year-round aeronautical SAR assets are currently stationed in the Canadian Arctic, the placement of even one aircraft in the area could play a major role in the improvement of navigational safety along the NWP. Thus, our results have relevant implications toward Canadian SAR planning, particularly in its addressing of two current issues: the vastness of SRRs, and the uneven distribution of SAR stations.

As described in the earlier chapters, we recall that three JRCCs manage SRRs across the country: Victoria, Trenton, and Halifax. In addition to covering the provinces, the JRCCs are collectively responsible for providing SAR support to the Arctic: JRCC Victoria services the Yukon, JRCC Trenton services the Northwest Territories and most of Nunavut, and JRCC Halifax services the southern half of the Baffin Island. Occupying the largest SRR by area, Trenton is responsible for most of the CAA—and by extension, the NWP. As a result of increased traffic, a larger burden would be expected to befall Trenton in its Arctic responsibilities; based on our sample, roughly 70% of demand points lie within its SRR. Relative to the other JRCCs, Trenton's excessive jurisdiction in the North could affect its capacities in the rest of mainland Canada, where it still occupies the largest region of operation. Since our study considered all points north of the 60th parallel, the proposed solutions could help redistribute SAR responsibilities in the North, allowing current JRCCs to focus instead on provincial demand. Policy-makers could use our findings to redefine the SRR boundaries by adding a new Arctic SRR controlled by its own JRCC. The red area in Figure 5.2 describes the study region relative to the existing SRRs, and could lend itself as an example for the redefined SAR jurisdiction.

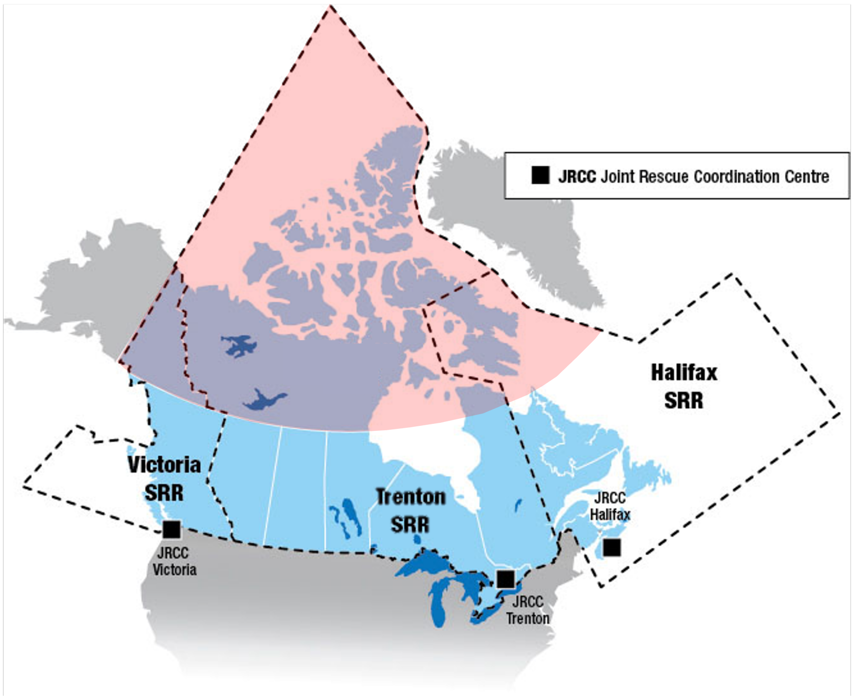


Figure 5.2: Existing search and rescue regions and the area considered in this study. Source: Ministry of National Defence (2013)

Within each region, the RCAF presently operates five bases: Comox in the Victoria SRR, Winnipeg and Trenton in the Trenton SRR, and Gander and Greenwood in the Halifax SRR. Canada's SAR fleet is distributed across these bases, most of which are located in southern Canada close to the American border. As a result, SAR assets are often hours away from Arctic demand, which could present problems with the area's expected rise in activity. The three recommended arrangements called for the siting of SAR aircraft such that they could most effectively cover areas expecting the most SAR support. These solutions differ from the five existing RCAF stations in that they are not centralized. Rather than allocate all aircraft to one or two stations (consult Figure 1.4), our arrangements scattered the response assets across the region. According to our model, this strategy is most optimal in covering the Arctic as it assigns short-ranged helicopters in areas of concentrated demand, and positions longer-ranged aircraft in a way that they can cover a higher volume of incidents—including areas that require SAR support less frequently.

It should also be noted that the current arrangement of SAR aircraft across the five

RCAF bases (Comox, Winnipeg, Trenton, Gander, and Greenwood) does not satisfy the constraints of our model. When assessing this in QGIS and CPLEX, we found that the distance between demand point 161 and each of the five existing bases exceeds 3,250 km (the response range of the most capable aircraft, the Hercules). Since our model requires the primary coverage of *all* demand points, and demand point 161 cannot be serviced by any of the existing locations, the model generates no solution. On the basis that the current distribution of aeronautical SAR assets do not meet the requirements of this model, we conclude that our three recommended arrangements improve upon Canada's current response capacities in the Arctic.

Overall, this research is intended to assist Canadian policy- and decision-makers in the placement of SAR stations and the distribution of aircraft along the NWP. With changes rapidly occurring in the North, Canada's implementation of an actionable SAR plan is critical.

Chapter 6

Conclusion

Recent trends in the literature surrounding the NWP's potential as a shipping route suggest that its feasibility relies on how Canadian decision-makers choose to establish an Arctic SAR presence. With the current lack of permanent response aircraft stationed in the North, the placement of aeronautical SAR bases and allocation of the RCAF's response fleet are crucial in the development of such a network. While emergency response applications of the location problem have been studied extensively in the past, few researchers have considered how such approaches can be used to address concerns in Canada's own SAR capacities.

In this research, we looked to fill this gap in the SAR FLP literature by developing a five-stage methodology that helped determine optimal arrangements of aeronautical SAR stations and aircraft throughout the Canadian Arctic. Using GIS software, our approach used geospatial mapping to define the study region and compute relevant distances. Then, we studied the RCAF's existing SAR fleet (the CH-146 Griffon, CH-149 Cormorant, CC-295 Kingfisher, and CC-130H Hercules) and their performance specifications. Each aircraft's response potential was modelled in our design of four Harrington desirability functions. The FLP was then expressed mathematically as an integer linear program which looked to maximize the weighted coverage of Arctic demand points through primary and secondary response assets. The proposed ILP combined elements from the SCLM, MCLM, and PMM. Two cases of the model were studied: Case A considered optional secondary coverage, while Case B required the mandatory secondary coverage of all points of interest. The model was then solved in CPLEX for all allocations of up to 15 aircraft. The solutions were evaluated across both Cases A and B, where sensitivity analyses helped determine three recommended arrangements.

The results suggested that Arrangements 7A, 6B, and 7B would be best-suited for providing SAR coverage to the Canadian Arctic. Of the three, Arrangement 7A yielded the highest objective value (718.88) by allocating five Cormorants (to stations 3, 14, 42, 67, and 69) and two Kingfishers (to stations 3 and 22). Arrangement 6B had an objective value of 682.21 and provided total secondary coverage while allocating only six aircraft: four Cormorants (to stations 3, 42, 67, and 69) and two Kingfishers (to stations 22 and 23). Arrangement 7B, which allocated four Cormorants (to stations 3, 14, 67, and 69) and three Kingfishers (to stations 3, 23, and 34), was taken as a compromise between Arrangements 7A and 6B since it provided secondary coverage to all demand points while maintaining a relatively high objective value (711.66). We concluded that each of these optimal arrangements would appropriately address Canada's SAR concerns along a developing NWP. The results were intended to guide policy- and decision-makers in the planning of an Arctic SAR network, particularly by identifying regions of strategic importance, as well as mathematically-optimal sites for SAR stations and aircraft.

Our findings also had significant implications regarding the current state of SAR in the Arctic. Firstly, the research addressed the uneven distribution of SAR responsibility in Canada's North by demonstrating how the addition of a new SAR region that focuses exclusively on Arctic demand might be in the best interest of decision-makers. The arrangements obtained from our model also suggested that a less centralized approach be taken in allocating the aircraft. Instead of concentrating the fleet across one or two bases per JRCC (as currently), our findings showed that the placement of several stations throughout the region would be most optimal. More specifically, we infer that Cormorants be located in areas of high historical incidence, while Kingfishers be allocated more centrally to provide service to the greatest volume of demand.

6.1 Limitations

There are some limitations to the research, some of which stem from the data that was used for the study. Firstly, demand points were based on a list of past incidents and accidents involving vessels, as reported through the TSB's MARSIS platform. While historical occurrence *may* be a good indicator for future demand, it does not necessarily account for areas that *will* experience the need for SAR resulting from the region's expected increase in navigability. While we would have liked to consider the forecasted SAR demand—or even past SAR incidents reported with the RCAF—the TSB dataset was the best option available at the time of study. Moreover, the dataset did not provide any information on crew sizes or the number of passengers aboard each vessel. Thus, our model relied on the assumption that each aircraft could service a distressed vessel, regardless of how many people were on-board. This is certainly a limitation to our research, as each aircraft has a different capacity; helicopters can transport significantly less individuals than the larger fixed-wing planes.

Another limitation to the study was that it did not consider the costs of acquiring and operating such aircraft, nor the maintenance and construction costs associated with the SAR station facilities. With economic incentive being at the forefront of the NWP's potential as a shipping route, it may be worth assessing whether the economic benefits of Arctic transport justify the investments required to develop SAR infrastructure in the North and operate the necessary resources. As Canada's budget would certainly play a role in its planning of an Arctic SAR network, the costs of obtaining the aircraft, staffing the crew, and maintaining the facilities would all be worth considering in future departures.

Lastly, there are situational factors (ie. poor flying conditions, aircraft failure, and overwhelming demand) that were not considered in the model. These are real-world issues that could affect the success of SAR operations; however, the area currently experiences little activity. Thus, some potential SAR issues—like receiving multiple distress calls at the same time—are of less priority than having an established Arctic presence. Nevertheless, these are concerns that should certainly be assessed in the future, and can be an appealing avenue for future researchers studying stochastic FLPs.

6.2 Departures

As one of the first pieces of literature to address Arctic SAR capacities and the allocation of response aircraft along the NWP, this thesis may act as a springboard for future researchers. In terms of the formulation of the FLP as an integer program, researchers may wish to explore a model that addresses the limitations of this research; more specifically, one that considers aircraft passenger capacities and incorporates operating and maintenance costs. A bi-objective model that seeks to maximize primary and secondary coverage while minimizing setup costs could lend itself as a promising starting point for future researchers.

It may also be of interest to researchers in healthcare logistics to explore this location problem in its interaction with medical facilities. In extreme cases, distressed individuals may require more medical attention than can be provided by a SAR-Tech. A network that coordinates transportation between demand points and hospitals into its design could make sizeable contributions to the creation of safer waterways in the Canadian North.

Perhaps the most appealing avenue for future research is the consideration of expert judgement through MCDM techniques—like AHP or TOPSIS—and how those results compare to our mathematical approach. Since the design of an Arctic SAR network would be a collaborative effort between several facets of the Canadian government, it would be beneficial to consider policy- and decision-makers' opinions in its planning. Such techniques would also open the door for researchers to consider the valuable opinions of those who might be most affected by the increase in economic activity along the NWP—namely the Indigenous communities of the Canadian Arctic.

Appendix A

List of Candidate SAR Stations

j	**Location**	**Terr.**	**Lat. (°N)**	**Lon. (°W)**	**Operator**	c_j
1	Kangiqsujuaq	QC	61.588471	71.929805	Kativik Regional Govt.	3
2	Kimmirut	NU	62.847990	69.875978	Govt. of Nunavut	2
3	Iqaluit	NU	63.757014	68.546477	Govt. of Nunavut	4
4	Pangnirtung	NU	66.145157	65.712405	Govt. of Nunavut	2
5	Qikiqtarjuaq	NU	67.545785	64.033698	Govt. of Nunavut	3
6	Clyde River	NU	70.485827	68.517005	Govt. of Nunavut	3
7	Salluit	QC	62.179256	75.667039	Kativik Regional Govt.	3
8	Cape Dorset Harbor	NU	64.230651	76.526212	Govt. of Nunavut	3
9	Pond Inlet	NU	72.691094	77.966878	Govt. of Nunavut	3
10	Coral Harbor	NU	64.193102	83.359482	Govt. of Nunavut	4
11	Naujaat	NU	66.522097	86.226302	Govt. of Nunavut	3
12	Hall Beach	NU	68.776251	81.243482	Govt. of Nunavut	4
13	Igloolik	NU	69.365572	81.818825	Govt. of Nunavut	3
14	Arctic Bay	NU	73.006669	85.048339	Govt. of Nunavut	3
15	Grise Fiord	NU	76.425766	82.908904	Govt. of Nunavut	2
16	Eureka	NU	79.995081	85.817606	Environment Canada	3
17	Arviat	NU	61.098120	94.072178	Govt. of Nunavut	3
18	Rankin Inlet	NU	62.810202	92.113519	Govt. of Nunavut	4
19	Whale Cove	NU	62.240060	92.597848	Govt. of Nunavut	3
20	Chesterfield Inlet	NU	63.347155	90.731643	Govt. of Nunavut	3
21	Kugaaruk	NU	68.534554	89.809694	Govt. of Nunavut	4
22	Gjoa Haven	NU	68.635611	95.850751	Govt. of Nunavut	3
23	Taloyoak	NU	69.546181	93.576440	Govt. of Nunavut	3
24	Resolute	NU	74.716846	94.969292	Govt. of Nunavut	4
25	Baker Lake	NU	64.298846	96.077498	Govt. of Nunavut	3
26	Fort Smith	NT	60.020221	111.961978	Govt. of NWT	4
27	Łutselk’e	NT	62.418150	110.681928	Govt. of NWT	2
28	Ekati	NT	64.699168	110.614755	Govt. of NWT	4
29	Cambridge Bay	NU	69.107929	105.137774	Govt. of Nunavut	4

j	**Location**	**Terr.**	**Lat. (°N)**	**Lon. (°W)**	**Operator**	c_j
30	Hay River	NT	60.839850	115.783381	Govt. of NWT	4
31	Fort Providence	NT	61.319033	117.606198	Dept. of Transportation	2
32	Fort Resolution	NT	61.180659	113.689811	Govt. of NWT	3
33	Yellowknife	NT	62.468820	114.443312	Govt. of NWT	4
34	Whatì	NT	63.131995	117.246219	Govt. of NWT	2
35	Wekweètì	NT	64.190682	114.076433	Govt. of NWT	2
36	Gamèti	NT	64.111638	117.346829	Govt. of NWT	2
37	Kugluktuk	NU	67.816899	115.144740	Govt. of Nunavut	4
38	Ulukhaktok	NT	70.763007	117.806494	Govt. of NWT	3
39	Sambaa K'e	NT	60.441219	121.245940	Govt. of NWT	3
40	Fort Liard	NT	60.235947	123.470198	Govt. of NWT	2
41	Nahanni Butte	NT	61.030008	123.388333	Govt. of NWT	2
42	Fort Simpson	NT	61.760186	121.236854	Govt. of NWT	4
43	Jean Marie River	NT	61.521390	120.622429	Govt. of NWT	2
44	Wrigley	NT	63.209954	123.437181	Govt. of NWT	3
45	Tulita	NT	64.909742	125.570873	Govt. of NWT	3
46	Norman Wells	NT	65.281195	126.797660	Govt. of NWT	4
47	Deline	NT	65.210956	123.435767	Govt. of NWT	3
48	Colville Lake	NT	67.021437	126.129086	Govt. of NWT	3
49	Paulatuk	NT	69.360765	124.076301	Govt. of NWT	3
50	Sachs Harbor	NT	71.993668	125.242462	Govt. of NWT	3
51	Watson Lake	YU	60.116888	128.824379	Govt. of Yukon	4
52	Pine Lake	YU	60.103028	130.933740	Govt. of Yukon	2
53	Teslin	YU	60.173041	132.743283	Govt. of Yukon	4
54	Carcross	YU	60.173881	134.697732	Govt. of Yukon	2
55	Whitehorse (Nielsen)	YU	60.712689	135.0705781	Govt. of Yukon	4
56	Whitehorse (Cousins)	YU	60.811508	135.1823781	Govt. of Yukon	2
57	Braeburn	YU	61.485550	135.777852	Govt. of Yukon	2
58	Ross River	YU	61.970710	132.424895	Govt. of Yukon	4
59	Finlayson Lake	YU	61.691635	130.773893	Govt. of Yukon	2
60	Hyland	YU	61.524031	128.269771	Govt. of Yukon	3
61	Twin Creeks	YU	62.619286	131.270740	Govt. of Yukon	2
62	Faro	YU	62.207475	133.375680	Govt. of Yukon	3
63	Mayo	YU	63.616731	135.869159	Govt. of Yukon	3
64	Macmillan Pass	YU	63.176383	130.20283	Govt. of Yukon	1
65	Fort Good Hope	NT	66.240632	128.648757	Govt. of NWT	3
66	Fort McPherson	NT	67.407200	134.861015	Govt. of NWT	3
67	Inuvik	NT	68.303920	133.483704	Govt. of NWT	4
68	Aklavik	NT	68.222976	135.005681	Govt. of NWT	2
69	Tuktoyaktuk	NT	69.433066	133.026140	Govt. of NWT	3
70	Haines Junction	YU	60.789283	137.546244	Govt. of Yukon	4
71	Burwash Landing	YU	61.370916	139.040932	Govt. of Yukon	4
72	Silver City	YU	61.029066	138.406983	Govt. of Yukon	2
73	Carmacks	YU	62.110437	136.180057	Govt. of Yukon	4
74	Fort Selkirk	YU	62.768262	137.384865	Govt. of Yukon	2

j	**Location**	**Terr.**	**Lat. (°N)**	**Lon. (°W)**	**Operator**	c_j
75	Pelly Crossing	YU	62.837234	136.52537	Govt. of Yukon	3
76	Beaver Creek	YU	62.410207	140.869000	Govt. of Yukon	3
77	McQuesten	YU	63.606415	137.567436	Govt. of Yukon	2
78	Dawson City	YU	64.042886	139.128302	Govt. of Yukon	4
79	Chapman Lake	YU	64.903840	138.277614	Govt. of Yukon	2
80	Ogilvie River	YU	65.674807	138.115780	Govt. of Yukon	2
81	Eagle Plains	YU	66.490895	136.575360	Govt. of Yukon	2
82	Old Crow	YU	67.570254	139.839555	Govt. of Yukon	4
83	Alert	NU	82.517841	62.2811382	Military (DND)	4
84	Tanquary Fiord	NU	81.407929	76.841243	Parks Canada	3

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