



Optimal RSOM-hub Locations for Northern Operations

A MAJAID Scenario Analysis

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Abstract

This paper presents an analysis of a Reception, Staging and Onward Movement hub (RSOM-hub) concept to support Canadian Forces Major Air Disaster (MAJAID) operations in the North and provides insights into the optimal RSOM-hub locations. RSOM-hubs are permanent or temporary staging bases for cross-loading between strategic and tactical lift during military deployment and sustainment operations. In this study, performance measures were formulated to assess the effectiveness and the responsiveness of different RSOM-hub options to support MAJAID deployments. A simulation-based optimization model was also developed to determine the optimal number and locations of hubs in the North. The model was considered in a multi-objective framework and solution trade-offs were determined through an exhaustive search methodology. An illustrative scenario and associated data were used to simulate deployment lift to various MAJAID locations and to demonstrate the methodology. Sensitivity analysis was conducted to examine the impact of different operational parameters on hub performance and optimal locations. The study indicated that the optimal number of RSOM-hubs for MAJAID operations in the North would be two, corresponding to Iqaluit and Yellowknife.

Résumé

Ce document présente une analyse du concept de plaque tournante pour l'accueil, le stationnement transitoire et le mouvement vers l'avant (plaque tournante du RSOM) à l'appui des opérations nordiques des Forces canadiennes (FC) en cas de catastrophe aérienne (CATAIR), et donne un aperçu des emplacements les plus indiqués pour l'installation de la plaque tournante du RSOM. Les plaques tournantes du RSOM sont des zones d'étape utilisées pour la répartition de la charge de travail entre le transport stratégique et tactique durant les déploiements militaires et les opérations de maintien en puissance. Au cours de cette étude, les mesures de rendement ont été établies en vue d'évaluer l'efficacité et la capacité à réagir des différentes options de plaque tournante du RSOM à l'appui des déploiements en cas de CATAIR. Un modèle d'optimisation par simulation a également été élaboré afin de déterminer le choix optimal relatif au nombre et aux emplacements des plaques tournantes dans le Nord. Le modèle a été évalué en tenant compte de multiples objectifs et le choix de la solution a été fait à l'aide d'une méthodologie de recherche exhaustive. Un scénario a été utilisé, aux fins d'illustration, pour simuler le transport vers divers endroits dans le cadre de déploiements effectués en situation de CATAIR et pour démontrer la méthodologie. Une analyse de sensibilité a été effectuée afin d'évaluer l'impact des différents paramètres opérationnels sur le rendement et l'emplacement optimal de la plaque tournante. L'étude a révélé qu'idéalement, pour appuyer les opérations nordiques en cas de CATAIR, deux plaques tournantes du RSOM seraient nécessaires et devraient être installées à Iqaluit et Yellowknife.

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Executive Summary

Optimal RSOM-hub location for Northern operations – a MAJAID scenario analysis

Ahmed Ghanmi; DRDC CORA TM 2011-122; Defence R&D Canada – CORA;
August 2011.

Introduction

To examine the support requirements for future Canadian Forces (CF) deployments in the North, Canadian Operational Support Command (CANOSCOM) has initiated the Northern Lines of Communication (NORLOC) project. The aim of NORLOC is to develop the logistics requirements and to identify mitigation strategies for improving the deployability and sustainability of assets in response to potential events in the North. One of the strategies being examined by CANOSCOM for NORLOC would be the establishment of Reception, Staging and Onward Movement hubs (RSOM-hubs) at different Northern airfields. RSOM-hubs are permanent or temporary staging bases for cross-loading between strategic and tactical lift during deployment and sustainment operations. They can also be used for pre-positioning deployable packages required for response to potential events in the North.

To develop and implement the RSOM-hub concept, CANOSCOM has identified a number of potential Northern airfields and has requested operational research support to facilitate better decisions concerning the selection of efficient RSOM-hub locations. Preliminary studies were conducted to examine the RSOM-hub concept effectiveness for Northern operations and to provide insights into the optimal hub locations. Following these studies, CANSOCOM requested a further examination of the RSOM-hub location optimization problem using a Major Air Disaster (MAJAID) scenario.

Methodology

The objective of this study is to analyze RSOM-hub locations for supporting MAJAID operations in Northern Canada. Three performance measures (response time, lift cost avoidance and hub capacity) were formulated to assess the effectiveness and the responsiveness of different RSOM-hub options. A simulation-based optimization model was also developed to determine the optimal number and locations of RSOM-hubs. The model was considered in a multi-objective framework and solution trade-offs were determined through an exhaustive search methodology. An illustrative scenario involving one strategic lift aircraft (CC-177) and two tactical helicopters (CH-146) was used to simulate MAJAID deployment lift to various Northern locations. Illustrative flight tracks were also used to determine the probability of MAJAID events at a given location in the North (defined as location weighting factor). Different RSOM-hub options were examined and optimal locations for maximizing the average relative cost avoidance or minimizing the average relative response time were determined for single and multiple RSOM-hub solutions. Solution trade-offs involving different objectives were also investigated and discussed. Sensitivity analysis was performed to explore the impact of key model parameters and assumptions on the optimal solution and RSOM-hub performance.

Results

The study indicated that the RSOM-hub concept could offer potential cost avoidance and response time reduction on deployment lift for MAJAID operations in the North and could be a potential strategy for improvement of the CF domestic support capability. For a single RSOM-hub solution, Yellowknife would be the time effective RSOM-hub location. From a cost avoidance perspective, Iqaluit would be the optimal hub location. Both airfields have the required capability and resources (e.g., fuel, maintenance) for supporting strategic lift aircraft (CC-177) and tactical helicopter (CH-146) operations. For a multiple RSOM-hub solution, the analysis indicates that the optimal number of RSOM-hubs would be two, corresponding to Iqaluit and Yellowknife, when response time and cost avoidance are both considered.

The sensitivity analysis indicated that the optimal RSOM-hub solution would be sensitive to the location weighting factor. For example, the time-effective hub location would be Yellowknife for a track-based location weighting factor and would be Whitehorse for a constant location weighting factor (uniform probability distribution). It also indicated that the distance adjustment factor (i.e., variable to take into consideration additional distance to reach refuelling stops) and the helicopter operational parameters (flying rate, speed and number of sorties) would not affect the optimal locations for a two RSOM-hub solution.

Recommendations

The study is a first research attempt to explore the RSOM-hub problem for MAJAID operations in the North. It used an illustrative scenario to demonstrate the methodology for analyzing the effectiveness of the RSOM-hub concept and the optimal hub locations. Following this study, it is recommended that:

- Yellowknife and Iqaluit should be considered as potential RSOM-hub locations to support Northern MAJAID operations.
- Further Northern scenarios, such as response to maritime or natural disaster, should be investigated to determine the optimal RSOM-hub locations for a range of potential responses in the North. The logistics requirements for each scenario should be identified. As well, consideration of other departments and agencies should be included in the scenario.
- Particular attention should be given to the location weighting factor as the optimal RSOM-hub solution is sensitive to this parameter. For MAJAID operations, flight tracks would be used for evaluating the probability of a MAJAID at a given location in the North. In this study, as illustrative data is used to demonstrate the methodology. Updated and complete data of flight tracks should be gathered and analyzed for future studies.
- Given the lack of detailed information about the capabilities at the different airfield options, illustrative airfield capacity values were used in the study. An assessment of the airfield capacity should be performed using multi-criteria decision analysis and further analysis should be conducted with realistic data.
- In the analysis, the tactical airlift was simulated using the CH-146 Griffon. Further analysis should be conducted using different helicopter options, such as the CH-147 Chinook.

Sommaire

Optimal RSOM-hub location for Northern operations – a MAJAID scenario analysis

Ahmed Ghanmi; DRDC CORA TM 2011-122; R & D pour la défense Canada – CARO; août 2011.

Introduction

Afin d'étudier les besoins de soutien des Forces canadiennes (FC) en matière de déploiements nordiques futurs, le Commandement du soutien opérationnel du Canada (COMSOCAN) a entrepris le projet sur les voies de communication nordiques « Lignes de communication du Nord » (NORLOC). Le but du projet NORLOC est de définir les besoins en matière de logistique et de développer des stratégies d'atténuation des risques afin d'améliorer la capacité de déploiement et de soutien des ressources en cas d'événements dans le Nord. Une des stratégies que considère le COMSOCAN pour les NORLOC est l'installation de plaques tournantes pour l'accueil, le stationnement transitoire et le mouvement vers l'avant (plaques tournantes du RSOM) sur différents terrains d'aviation nordiques. Les plaques tournantes du RSOM sont des zones d'étape utilisées pour la répartition de la charge de travail entre le transport stratégique et tactique durant les déploiements militaires et les opérations de maintien en puissance. Elles peuvent également être utilisées pour installer à l'avance des unités prêtes à être déployées en cas d'événements dans le Nord.

Afin de développer le concept de plaque tournante du RSOM et de le mettre en œuvre, le COMSOCAN a choisi un certain nombre de terrains d'aviation dans le Nord canadien; pour ce faire, il a demandé l'appui de la division de la recherche opérationnelle afin de faciliter la prise de décision concernant le choix d'emplacements favorables pour ces installations. Des études préliminaires ont été effectuées afin d'évaluer la capacité du concept de plaque tournante du RSOM à appuyer les opérations nordiques et de donner un aperçu des emplacements les plus indiqués pour l'installation de la plaque tournante. Une fois ces études effectuées, COMSOCAN a demandé que la question du choix de l'emplacement de la plaque tournante du RSOM soit examinée de plus près en ayant recours à un scénario de catastrophe aérienne (CATAIR).

Méthodologie

Cette étude a pour objet d'étudier les emplacements de la plaque tournante du RSOM à l'appui des opérations effectuées dans le Nord canadien en cas de CATAIR. Trois mesures de rendement (le temps de réponse, l'évitement de coûts de transport et la capacité de la plaque tournante) ont été établies en vue d'évaluer l'efficacité et la capacité à réagir des différentes options de plaque tournante du RSOM. Un modèle d'optimisation par simulation a également été élaboré afin de déterminer le choix optimal relatif au nombre et aux emplacements des plaques tournantes du RSOM. Le modèle a été évalué en tenant compte de multiples objectifs et le choix de la solution a été fait à l'aide d'une méthodologie de recherche exhaustive. Un scénario prévoyant l'utilisation

d'un aéronef de transport stratégique (CC177) et de deux hélicoptères tactiques (CH146) a été utilisé, aux fins d'illustration, pour simuler le transport dans le cadre de déploiements visant à répondre à des situations de CATAIR à différents endroits dans le Nord. Des données historiques sur les vols ont été utilisées en vue de déterminer la probabilité qu'une CATAIR se produise dans une région nordique particulière (ce qui est défini comme le facteur de pondération relatif à l'emplacement). Différentes options pour les plaques tournantes du RSOM ont été examinées et les meilleurs emplacements, à l'égard de l'évitement de coûts maximal ou du temps de réponse relatif minimal, ont été déterminés pour des configurations simples et multiples de plaques tournantes. Les différentes solutions visant les divers objectifs ont également été étudiées et ont fait l'objet de discussions. Une analyse de sensibilité a été effectuée afin d'examiner l'incidence des principaux paramètres du modèle ainsi que les hypothèses émises à l'égard de la solution optimale et le rendement de la plaque tournante du RSOM.

Résultats

L'étude a révélé que le concept de plaque tournante du RSOM pourrait contribuer à éviter des coûts et engendrer une réduction du temps de réponse dans le cadre de déploiements à l'appui des opérations nordiques menées en cas de CATAIR et qu'il pourrait constituer une stratégie visant à améliorer la capacité de soutien des FC au pays. Pour une configuration simple de plaques tournantes, Yellowknife serait l'emplacement qui procure les meilleurs avantages à l'égard du temps de réponse. En ce qui concerne l'évitement des coûts, Iqaluit serait l'emplacement privilégié. Ces deux terrains d'aviation ont la capacité et les ressources nécessaires (carburant, maintenance) pour appuyer l'exploitation de l'aéronef de transport stratégique (CC177) et l'hélicoptère tactique (CH146). Pour ce qui est de la configuration de plaque tournante multiple, l'analyse a révélé que, à l'égard du temps de réponse et de l'évitement des coûts, le nombre optimal de plaques tournantes du RSOM serait de deux et leur emplacement respectif serait Yellowknife et Iqaluit.

L'analyse de sensibilité a révélé que la meilleure solution à l'égard de la plaque tournante du RSOM dépendrait du facteur de pondération relatif à l'emplacement. Par exemple, l'emplacement procurant les meilleurs avantages en ce qui a trait au temps de réponse serait Yellowknife pour un facteur de pondération relatif à l'emplacement axé sur les données historiques de vol, mais serait Whitehorse pour un facteur constant de pondération relatif à l'emplacement (distribution uniforme de la probabilité). Elle a également révélé que le facteur de variation de la distance (variable qui prend en considération la distance additionnelle à couvrir pour l'avitaillement) et les paramètres opérationnels de l'hélicoptère (les activités aériennes et la vitesse de l'aéronef et le nombre de décollages) n'auraient aucune incidence sur le choix du meilleur emplacement dans le cas d'une solution prévoyant deux plaques tournantes du RSOM.

Recommandations

La présente étude est la première tentative du COMSOCAN visant à analyser la question de la plaque tournante du RSOM dans le cadre des opérations nordiques en cas de CATAIR. Elle utilise un scénario, aux fins d'illustration, afin de démontrer la méthodologie utilisée pour déterminer l'efficacité du concept de plaque tournante et les meilleurs emplacements pour son installation. À la suite de cette étude, les recommandations suivantes sont formulées :

- Yellowknife et Iqaluit devraient être considérés comme emplacements possibles pour l'installation d'une plaque tournante du RSOM à l'appui des opérations nordiques en cas de CATAIR.
- D'autres scénarios nordiques devraient être étudiés afin de déterminer les emplacements optimaux permettant de réagir à une gamme d'événements se produisant dans le Nord. Les exigences en matière de logistique pour chacun des scénarios devraient être cernées.
- Une attention particulière devrait être accordée au facteur de pondération relatif à l'emplacement étant donné que le choix du meilleur emplacement pour installer une plaque tournante du RSOM en dépend. Dans le cas d'opérations visant à répondre à des situations de CATAIR, des données historiques sur les vols seraient utilisées en vue de déterminer la probabilité qu'une CATAIR se produise dans une région nordique particulière. Cependant, des données à jour et complètes devraient être collectées et analysées.
- Compte tenu du manque de renseignements détaillés concernant les capacités des différents terrains d'aviation considérés, des valeurs de capacité fictives ont été utilisées dans cette étude. Une évaluation de la capacité des terrains d'aviation devrait être effectuée en utilisant une technique d'analyse décisionnelle multicritères et une analyse plus approfondie des données réelles devrait être menée.
- Au cours de l'analyse, la simulation du transport tactique était fondée sur le CH146 Griffon. Une analyse plus approfondie devrait être menée en envisageant l'utilisation d'autres appareils comme le CH147 Chinook.

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1 Introduction

1.1 Background

The Canadian government has raised awareness of Northern sovereignty as well as prospects for greatly increased economic activity in the North as a result of natural resources development, commercial transportation and tourism activities. These activities will place additional burdens on infrastructure, security, law enforcement, and human capital and could involve the transformation of governance in the North. Indeed, the region is the site of one quarter of Canada's remaining discovered petroleum and one half of the country's estimated potential resources. It also holds the sea passage between Asia and Europe known as the Northwest Passage. The opening of the Northwest Passage route would increase shipping activities in the area and would raise concerns over shipping regulations, environmental degradation and potential events in the Arctic (e.g., resurgence of conflict over resources). Establishing and maintaining an increased federal presence in the North would require future deployments of the Canadian Forces (CF) to address specific scenarios.

Potential Northern scenarios that would require the CF's involvement could include humanitarian aid, search and rescue, evacuation operations, natural disaster assistance, etc. To quickly and effectively respond to these scenarios, the CF would need to improve its personnel and equipment readiness for deployment in the North. This includes education and training of military personnel to work in the Arctic environment as well as the pre-positioning of specific equipment and supplies for rapid deployment and sustainment [14].

To examine the support requirements for the CF deployments in the North, Canadian Operational Support Command (CANOSCOM) has initiated the Northern Lines of Communication (NORLOC) project. The aim of NORLOC is to develop the logistics requirements and to identify mitigation strategies for improving the deployability and sustainability of CF assets in response to potential events in the North. One of the strategies being examined by CANOSCOM for NORLOC would be the establishment of Reception, Staging and Onward Movement hubs (RSOM-hubs) at different Northern airfields [1]. RSOM-hubs are permanent or temporary staging bases for cross-loading between strategic and tactical lift during deployment and sustainment operations. They can also be used for pre-positioning deployable packages required for response to potential events in the North. Deployable packages to support Northern operations could include an arctic feeding, shelter and ablution camp that would permit the operation of a small camp for helicopters, basic medical support and transit quarters for personnel moving through the RSOM-hub.

To develop and implement the RSOM-hub concept, CANOSCOM has identified a number of potential RSOM-hub locations in Northern Canada and has requested operational research support to facilitate better decisions concerning the selection of efficient RSOM-hub locations. Preliminary studies [2, 3, 4] were conducted to examine the RSOM-hub concept effectiveness for Northern operations and to provide insights into the optimal hub locations. These studies used a generic deployment scenario to demonstrate the concept and illustrate the methodology. Following these studies, CANOSCOM requested a further examination of the RSOM-hub

location optimization problem using a Major Air Disaster (MAJAID) scenario. MAJAID operations require quick response times and involve airlift deployments for short durations.

1.2 Objective

The objective of this study is to analyze RSOM-hub locations for supporting MAJAID operations in Northern Canada. The paper develops performance measures and models to determine the time- and cost-effective hub locations for MAJAID operations.

1.3 Problem Description

The RSOM-hub location optimization problem can be viewed as a particular case of the general facility location problem, which consists of locating a number of facilities in a distribution system to route traffic flows. The problem can be stated as follows: Given a set of potential RSOM-hubs (Northern airfields) with their respective capacities (e.g., fuel, runway characteristics, infrastructure) and a number of potential deployment locations (the Northern region is divided into grid cells with the centre of each cell represents a deployment location), determine the optimal number and locations of RSOM-hubs in order to minimize the average deployment lift time and/or cost. Note that the RSOM-hub problem is not a pure hub location optimization problem as there is no quadratic hubbing concept and no allocation necessary [5].

Unfortunately, facility location problem has been demonstrated to be a nondeterministic polynomial-time hard (NP-hard) problem [6]. Different problem variants using various topological assumptions have been studied, including capacitated or uncapacitated facility location models (i.e., limited or unlimited facility capacity), static or time dynamic location models (i.e., fixed or time dependent demand), deterministic or stochastic models (i.e., known or unknown demand), and p -location models (i.e., p is the maximum number of facilities to locate). A comprehensive literature review of the discrete facility location problem can be found in [5]. The RSOM-hub problem can be viewed as a discrete (pre-selected sites), uncapacitated (i.e., unlimited capacity), and static (fixed demand) facility location problem with a stochastic demand location. The demand location corresponds to the geographical locations of the MAJAID event and can be represented by a probability distribution function.

1.4 Report Structure

This report is organized in five sections. The next section examines the concept of deployment for a MAJAID response and discusses the potential RSOM-hub locations in Northern Canada. The subsequent section presents the formulation of performance measures and mathematical models to determine optimal RSOM-hub locations for MAJAID operations. The fourth section presents an analysis of the RSOM-hub performance and optimal locations, including sensitivity analysis. Concluding remarks are found in the penultimate section.

2 Concept of Deployment

This section presents an overview of the RSOM-hub concept, identifies the potential RSOM-hub locations for Northern operations and discusses the concept of deployment for a MAJAID scenario using RSOM-hubs.

2.1 RSOM-hub Concept

The RSOM concept has been developed by the North Atlantic Treaty Organization (NATO) to control, coordinate and deconflict the deployment of multinational forces [7]. More specifically, RSOM is the phase of the military deployment that transitions units, personnel, equipment and materiel from arrival at Port of Debarkation (POD) to their final destinations. It encompasses the movement and transportation, logistics support and force protection operations. It also involves the establishment of intermediate staging bases along the deployment lines of communications to facilitate the transition between strategic and tactical movements.

As defined in [7], the main RSOM operations are:

- *Reception*: The process of receiving, offloading, marshalling and transporting personnel, equipment and materiel from strategic or operational lift through sea, air, or land transportation PODs. Reception is the most critical stage of the RSOM operation. It begins with the arrival of deploying forces, equipment and sustainment into a POD and concludes with the relocation of force into staging areas.
- *Staging*: The process of assembling, temporary holding, and organizing of arriving personnel, equipment and materiel into formed units, as they prepare for onward movement. Deploying forces have limited mission capability and may not be self-sustainable during staging. Provision of facilities, sustainment, life support and protection must be ensured until deploying units achieve their mission. The staging process starts with the arrival of personnel, equipment and sustainment and concludes with the onward movement.
- *Onward Movement*: The process of moving units, personnel and accompanying materiel from reception facilities and staging areas to final destinations. Onward Movement may be multimodal and require unit reassembly in the final destination. Onward Movement is complete when the different elements reach the final destination.

While the RSOM-hub concept is mainly developed for expeditionary forces, it is being considered by the CF for domestic operations, particularly for Northern operation deployments. RSOM-hubs would improve logistics distribution effectiveness and responsiveness for Northern operations. Domestic RSOM-hubs can be viewed as permanent or temporary staging bases for cross-loading between strategic and tactical lift during deployment and sustainment operations and for pre-positioning deployable packages required for response to potential events in the Arctic. Deployable packages to support Northern operations could include an arctic feeding, shelter and ablution camp that would permit the operation of a small camp for helicopters, basic medical support and transit quarters for personnel moving through the RSOM-hub [1].

2.2 Hub Location Options

As the deployment of MAJAID assets would be conducted by airlift, several Northern airfields are considered as potential RSOM-hub locations. The choice of airfield is determined largely by the requirement that the runway be sufficiently long and strong to accommodate the CC-177 aircraft. Figure 1 depicts the locations of the different Northern airfields and Annex A presents their main characteristics (e.g., runway length). Among these airfields, CANOSCOM has identified the following locations as future potential RSOM-hubs (red dots): Iqaluit, Yellowknife, Whitehorse, Rankin Inlet, Inuvik, Resolute, Clyde River and Alert. It should be noted that the airfields at Resolute and Alert will require development and remediation before the CC-177 can be accommodated. The remaining airfields (small dots) can accommodate the runway requirements of the CC-130 aircraft (but not the CC-177) and would be used as a Forward Support Bases (FSB) for sustaining Northern operations.

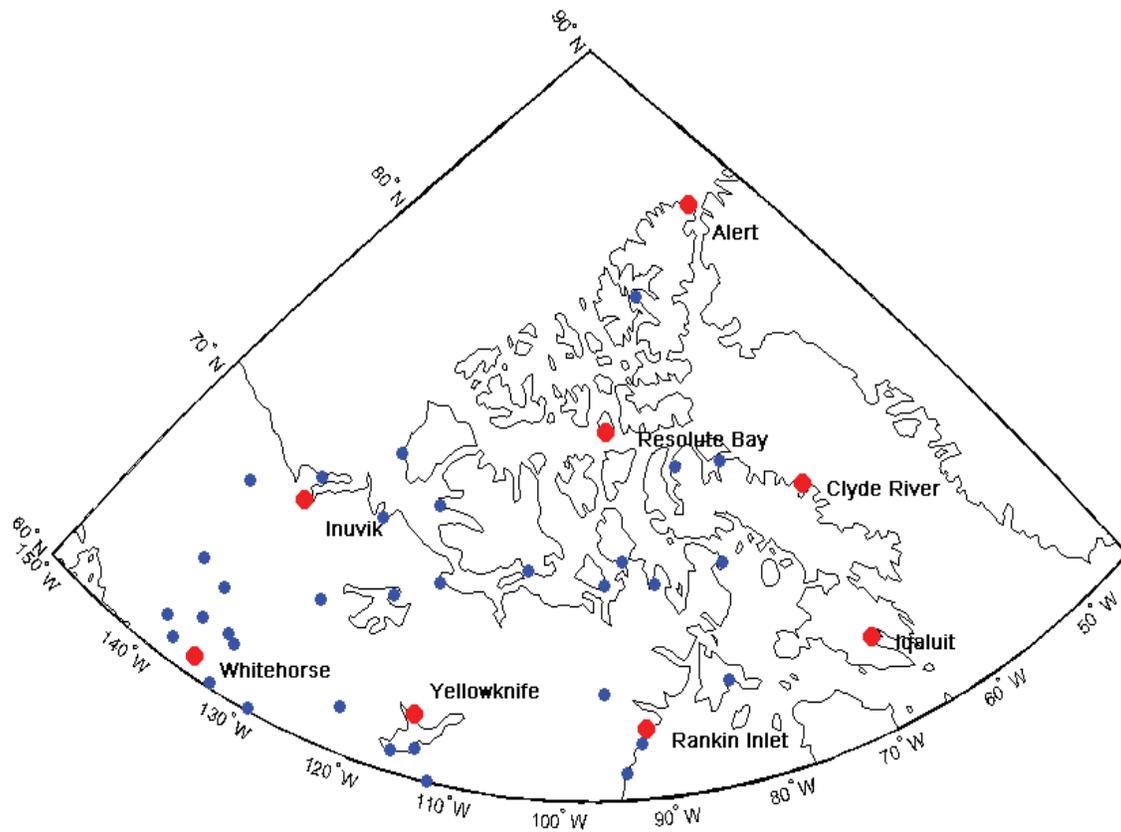


Figure 1: Northern airfields and potential RSOM-hub locations

2.3 MAJAID Response

Based on the Canada Command CONPLAN 10250/10 MAJAID¹, the CF would respond to a MAJAID scenario in the North in two stages [14]:

- *Initial Responders.* Composed of a search and rescue team, an airborne support group with two CH-146 Griffon helicopters (or possibly one CH-147 Chinook), a health support section, a joint task force support element, an airlift control element, and a MAJAID command element. They would deploy within hours of notification and are configured to conduct operations over a 72-hour period. Their primary role would likely be a rescue and may be augmented by elements of the Canadian Rangers and Joint Task Force North resources already in the North.
- *Follow-on Forces.* After 72 hours, follow-on forces could be deployed to conduct post rescue operations. While this aspect does not appear to have been developed yet, it seems likely that such follow-on forces might consist of the Vanguard Company of an Immediate Reaction Unit battalion, which would conceivably have the role of assisting with the tasks of body recovery and site cleanup.

Given that the information about the structure and the requirements of the follow-on forces is not available, the analysis focuses on the deployment of the initial responders. A concept of deployment using RSOM-hubs is being developed by CANOSCOM (Figure 2):

- A strategic lift aircraft (CC-177) would be used to move personnel and two helicopters (CH-146 Griffon) from Trenton to a given RSOM-hub. The helicopters would be self-deployed from Petawawa (main base), disassembled and loaded in the aircraft at Trenton. From a response time perspective, the CC-130 aircraft would not be effective for the deployment of the helicopters as the time required to disassemble a CH-146 in order to load in a CC-130 would be 24 hours (seven hours for the CC-177). The CC-130 aircraft would be used for the movement of MAJAID kits, personnel and sustainment packages to either RSOM-hubs or the closest FSB to the scenario location.
- At the hub, the helicopters would be reassembled, tested and self-deployed to the event location. Alternatively, the helicopters could fly directly to the event location if it is close to Petawawa².
- The helicopters would be used to conduct evacuation operations from the event location to the closest FSB. Depending on the scenario scale, multiple trips of the helicopters could be used to complete the movement.
- Upon completion of the evacuation operations, the helicopters would fly back to the hub for redeployment (or fly back to Petawawa).

Note: It is assumed that refuelling stops would be available in the North for refuelling the helicopters during tactical lift operations.

¹ Canada Command, CONPLAN 10250/10 MAJAID, "Response to a Major Air Disaster (DRAFT), May 2010.

² Refuelling stops might be required to refuel the helicopter.

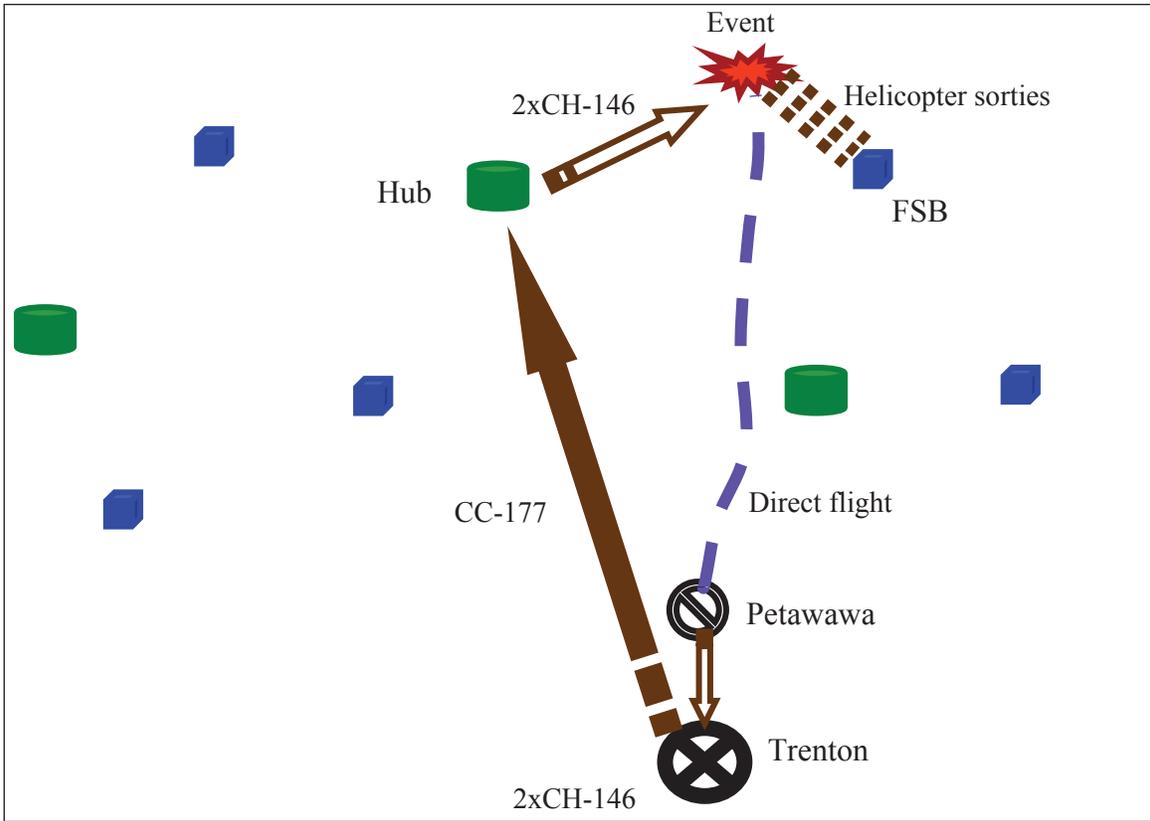


Figure 2: Concept of deployment using RSOM-hubs

3 Hub Location Model

In the section, performance measures were developed to assess the effectiveness and the responsiveness of different RSOM-hubs. A hub location optimization model was also formulated to determine optimal hub locations for a MAJAID scenario.

3.1 Performance Measures

In this paper, three performance measures were developed for the selection of RSOM-hubs for MAJAID operations in the North: *Response time*, *Lift cost avoidance*, *Airfield operational capacity*. The following assumptions are considered for the development of the performance metrics:

- A deployment scenario to a MAJAID location in Northern Canada (latitude $\geq 60^\circ$) is considered. Various deployments were simulated by dividing the Northern region into different potential MAJAID locations.
- RSOM-hubs are established at different Northern airfields. All hubs can accommodate the CC-177 aircraft. All airfields can be used as FSBs.
- It is assumed that at least one CC-177 aircraft is available for the movement at the event time for the strategic lift between Trenton and the RSOM-hubs.
- It is assumed that at least two helicopters (CH-146) are available for the deployment at the event time for the tactical lift between the RSOM-hubs and the deployment location.
- Given its limited range, refuelling stops would be required for the helicopter lift. It is assumed that refuelling locations are available in the North³.
- Great circle distance is used to estimate the airlift time of the aircraft, neglecting issues such as the weather effects, etc.

Let n be the number of RSOM-hubs, i ($i = 1, \dots, n$) the index of an individual hub, m the number of deployment locations, j ($j = 1, 2, \dots, m$) the index of an individual deployment location, p the number of FSBs, and k ($k = 1, 2, \dots, p$) the index of an individual FSB. Let v_a be the aircraft speed (km/h), r_a the aircraft hourly flying cost (\$/h), v_h the helicopter speed (km/h), r_h the helicopter hourly flying cost (\$/h). Let d_i be the great circle distance between Trenton and hub i , d_0 the distance between Petawawa and Trenton, d_{ij} the great circle distance between hub i and location j , and d_{kj} the great circle distance between FSB k and location j . Let ℓ be the helicopter preparation time (h) that includes the time required for disassembling and loading the helicopter at Trenton, and the time required for unloading, reassembling and testing the helicopter at a given hub. Let f_{ij} be the helicopter refuelling time (h) for the lift between hub i and location j and f_{kj} be refuelling time (h) for the lift between FSB k and location j .

³ The hubs and the FSBs would be used as refuelling stops for the helicopter.

3.1.1 Response time

The main performance measure for a MAJAID scenario would be the response time. Response time is defined as the total time required for deploying the equipment and personnel of the MAJAID initial response team from Petawawa (through Trenton) to the event location, following the movement notification. It includes (Figure 3) the helicopter self-deployment time from Petawawa to Trenton, the strategic lift time from Trenton to a given RSOM-hub (including the helicopter preparation time) and the tactical lift time from the hub to the deployment location (including the helicopter refuelling service time). It also includes the time required to conduct the rescue operations from the event location to the closest FSB (by definition only the first helicopter sortie is considered in the response time calculation).

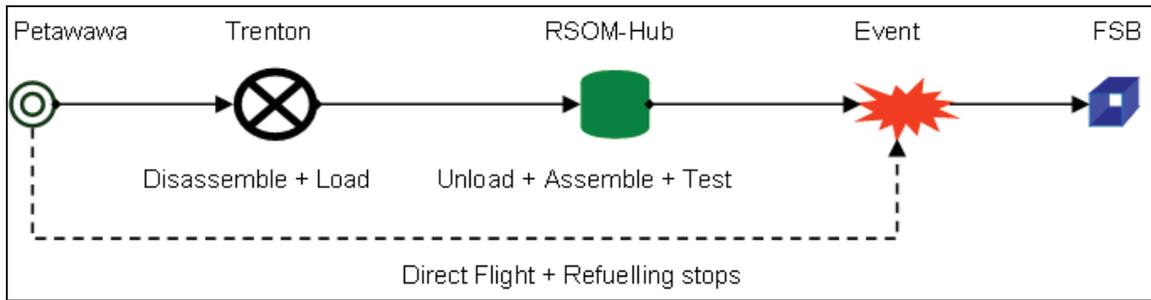


Figure 3: Response time components

The response time (T_{ij}) for location j using hub i ($i \geq 1$) is given by:

$$T_{ij} = \frac{d_0}{v_h} + \ell + \frac{d_i}{v_a} + \frac{\beta_{ij} d_{ij}}{v_h} + f_{ij} + \min_k \left(\frac{\beta_{kj} d_{kj}}{v_h} + f_{kj} \right) \quad (1)$$

Where β_{ij} ($\beta_{ij} \geq 1$) is an adjustment factor to take into consideration the additional distance between hub i and location j required to reach fuelling stops for refuelling the helicopter (refuelling stops are not necessarily close to the helicopter route). Refuelling stops are required when traveled distances exceed the helicopter range. Given the lack of data (e.g., location of refuelling stops), a distance adjustment factor of ($\beta_{ij} = 1$) will be used for all hubs and FSBs.

The response time (T_{0j}) for location j using a direct flight from Petawawa is given by:

$$T_{0j} = \frac{\beta_{0j} d_{0j}}{v_h} + f_{0j} + \min_k \left(\frac{\beta_{kj} d_{kj}}{v_h} + f_{kj} \right) \quad (2)$$

Where d_{0j} is the great circle distance between Petawawa and location j , β_{0j} is the distance adjustment factor for the helicopter direct flight between Petawawa and location j and f_{0j} is the

refuelling service time for the helicopter direct flight between Petawawa and location j . The optimal response time (T_j) for location j is the minimum lift time over all hubs, including the direct flight from Petawawa ($i = 0$).

$$T_j = \min_i (T_{ij}) \quad (3)$$

The average response time (\overline{RT}), weighted by a normalized weighting factor for location j ($0 \leq w_j \leq 1$), is calculated as follows:

$$\overline{RT} = \sum_{j=1}^m w_j T_j \quad (4)$$

The location weighting factor (w_j) represents the probability of an event that occurs at location j and requires a CF response. For MAJAID scenarios, historical air traffic flights were used to determine the probability of an event at a given location in the North.

Refuelling service time

While refuelling stops would not be required for the strategic lift between Trenton and the RSOM-hubs (i.e., the distances between Trenton and the hubs are within the range of the CC-177 aircraft), refuelling stops might be required for the tactical lift between the hubs and the deployment locations, depending on the location distance and the helicopter maximum range. To determine the total refuelling service time, the number of refuelling stops should first be calculated. It is also important to note that the maximum range is applicable to situations where the helicopter deploys from a site with fuel to another site with fuel. For the purpose of this analysis, it is assumed that the deployment locations have no fuel; therefore the last leg of the traveled distance should be less than half of the maximum range (R) to allow the helicopter to return to the previous refuelling stop (Figure 2).

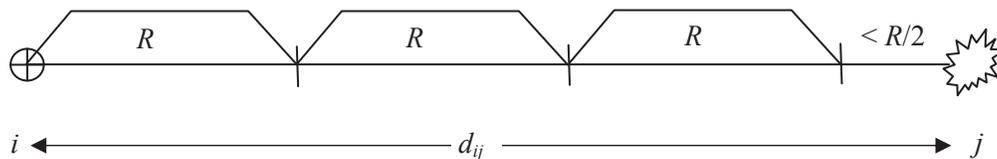


Figure 4: Helicopter refuelling stops

Taking into consideration the fuel restriction at destination, The total refuelling service time (f_{ij}) for a helicopter with a range (R) traveling a distance (d_{ij}) between hub i and deployment location j (one way) can be formulated as follows [2]:

$$f_{ij} = \begin{cases} 0 & ; d_{ij} < \frac{R}{2} \\ \alpha \left\lfloor \frac{d_{ij}}{R} + \frac{1}{2} \right\rfloor & ; d_{ij} \geq \frac{R}{2} \end{cases} \quad (5)$$

where $\lfloor \cdot \rfloor$ is the floor operator and α is the average refuelling service time for one stop.

3.1.2 Lift cost avoidance

The other performance measure that could be used for the selection of hub locations, in addition to response time, is the lift cost avoidance. The lift cost avoidance is defined as the total lift cost that could potentially be avoided if the movement is conducted through the RSOM-hub (hub-based lift) instead of the helicopter direct lift from Petawawa. The total lift cost from Petawawa to a given deployment location (round trip) through an RSOM-hub is the sum of the cost for the strategic lift between Trenton and the hub (assuming one sortie only) and the cost for the tactical lift between the hub and the deployment location. The cost of the helicopter movement between the event location and the FSB is not considered in the total lift cost calculation as it does not affect the cost avoidance (i.e., common to both the hub-based lift and the direct lift methods).

Assuming that the helicopters return from the FSB after their mission, the total lift cost for the direct flight (K_j^0) from Petawawa to the event location j (round trip) can be written as follows:

$$K_j^0 = 2b r_h \frac{\beta_{0j} d_{0j}}{v_h} \quad (6)$$

Where b is the number of helicopters. For the hub-based method, the optimal lift cost (K_j^1) for location j (round trip) is the minimum lift cost over all hubs:

$$K_j^1 = \min_i \left(2b r_h \frac{d_0}{v_h} + 2r_a \frac{d_i}{v_a} + 2b r_h \frac{\beta_{ij} d_{ij}}{v_h} \right) \quad (7)$$

For some event locations (e.g., close to Petawawa), the direct lift method would be more cost-effective than the hub-based lift and the overall optimal lift cost (K_j) for location j would be:

$$K_j = \min(K_j^0, K_j^1) \quad (8)$$

The lift cost avoidance for a given deployment location is the difference between the hub-based lift cost and the direct flight lift cost. The average relative cost avoidance (\overline{RCA}), weighted by the location weighting factor ($0 \leq w_j \leq 1$) is calculated as follows:

$$\overline{RCA} = \sum_{j=1}^m w_j \left(1 - \frac{K_j}{K_j^0} \right) \quad (9)$$

3.1.3 Airfield operational capacity

The airfield operational capacity is a measure of the level of capability and resources available at a given airfield. Subject Matter Experts (SMEs) have identified the following criteria for assessing an airfield operational capacity for Northern operations:

- *Fuel Availability*: assesses the capacity of the community at the airfield location to supply fuel for outside requirement.
- *Runway Characteristics*: assesses the quality (e.g., paved, gravel) and characteristics (e.g., length, width) of the airfield runway.
- *Infrastructure Capability*: assesses the availability of the necessary infrastructures (e.g., lodging facilities) next to the airfield.
- *Maintenance Capability*: assesses the availability of contractual support from the community as well as the availability of aircraft/helicopter maintenance and handling equipment at the airfield.

The multi-criteria decision analysis methodology will be used to assess the operational capacity of the different airfield options. The methodology requires SMEs to weight the importance of the decision criteria and to score each airfield for each criterion. Once the weighting and the scoring processes are completed, the capacity scores for each airfield option are averaged over all SMEs and rolled-up using the weighted-sum method to determine a single airfield operational capacity score. The weighted-sum method, which is also known as weighted linear combination, is a simple and most often used multi-criteria decision technique. The method evaluates the capacity score (u_i) of airfield option i based on the weighted average using the following formula:

$$u_i = \sum_{c=1}^C \lambda_c s_{ic} \quad ; \quad \forall i \quad (10)$$

Where s_{ic} is the score of airfield option i with respect to criterion c , C is the number of criteria, and λ_c is the relative weight of criterion c .

The above performance measures will be used in the objective function of an optimization model to determine the optimal RSOM-hub locations. Depending on whether the objective is to minimize the average response time, maximize the average relative cost avoidance or maximize the average airfield operational capacity, the optimal RSOM-hub locations could be different. The response time measure minimizes the weighted average response time over all destinations. It will be biased towards reducing the response time of the most distant deployments since it considers time in the absolute sense. The cost avoidance measure maximizes the weighted fractional savings relative to the direct lift from Petawawa over all destinations. Hence, it will tend to favour

having arrangements that lead to a distribution of small savings over a large number of total deployment locations. The airfield operational capacity is a static performance measure that looks at the airfield resources and infrastructure requirements for Northern operations—it does not consider the geographical location of the airfields. A multi-objective optimization approach will be formulated to explore the problem solution space involving all three performance measures.

3.2 Hub Location Optimization Model

The RSOM-hub problem can be viewed as a discrete facility location model. Three sub-models have been developed to determine the optimal hub locations for MAJAID operations in the North: *Time-effective*, *Cost-effective* and *Multi-objective optimization*. The models were formulated as binary integer (linear) programs.

3.2.1 Time-effective sub-model

The time-effective sub-model determines the optimal RSOM-hub locations that minimize the weighted average response time over all deployments as follows:

$$\text{Minimize } \overline{RT} = \sum_{j=1}^m w_j \left[\sum_{i=1}^n x_i \left(\frac{d_0}{v_h} + \ell + \frac{d_i}{v_a} \right) + \sum_{i=0}^n x_{ij} \left(\frac{\beta_{ij} d_{ij}}{v_h} + f_{ij} \right) + \sum_{k=1}^p y_{kj} \left(\frac{\beta_{kj} d_{kj}}{v_h} + f_{kj} \right) \right]$$

subject to:

$$\sum_{i=0}^n x_{ij} = 1 \quad ; \quad \forall j \quad (a)$$

$$\sum_{i=1}^n x_i \leq H \quad (b)$$

$$x_i u_i \geq u_s \quad ; \quad \forall i \quad (c)$$

$$x_i \geq x_{ij} \quad ; \quad \forall i, j \quad (d)$$

$$x_i, x_{ij}, y_{kj} \text{ binary} \quad (e)$$

where x_i is a decision variable for the optimal hub location ($x_i = 1$ if hub i is in the optimal set, 0 otherwise), x_{ij} is a decision variable to indicate whether hub i ($i = 0$ for Petawawa) is used for the deployment to location j ($x_{ij} = 1$) or not ($x_{ij} = 0$), y_{kj} is a decision variable to indicate whether FSB k is used for the deployment to location j ($y_{kj} = 1$) or not ($y_{kj} = 0$), u_s is the threshold airfield capacity score and H is the maximum number of hubs to locate.

Constraint (a) is a demand constraint to ensure that each deployment location is assigned one hub (including Petawawa). Constraint (b) specifies the maximum number of hubs to locate. Constraint (c) ensures that if a hub is selected it should satisfy a minimum capacity performance requirement established by SMEs. Constraint (d) is a facility location constraint to indicate that if a hub is assigned to a location then the hub is activated. Constraint (e) is a variable domain constraint.

3.2.2 Cost-effective sub-model

The cost-effective sub-model determines the optimal RSOM-hub locations that maximize the weighted average relative cost avoidance over all deployments as follows:

$$\text{Maximize } \overline{RCA} = \sum_{j=1}^m w_j \left(1 - \frac{\sum_{i=1}^n x_i \left(b r_h \frac{d_0}{v_h} + r_a \frac{d_i}{v_a} \right) + \sum_{i=0}^n x_{ij} b r_h \frac{\beta_{ij} d_{ij}}{v_h}}{b r_h \frac{\beta_{0j} d_{0j}}{v_h}} \right)$$

subject to:

$$\sum_{i=0}^n x_{ij} = 1 \quad ; \quad \forall j \quad \text{(a)}$$

$$\sum_{i=1}^n x_i \leq H \quad \text{(b)}$$

$$x_i u_i \geq u_s \quad ; \quad \forall i \quad \text{(c)}$$

$$x_i \geq x_{ij} \quad ; \quad \forall i, j \quad \text{(d)}$$

$$x_i, x_{ij} \text{ binary} \quad \text{(e)}$$

3.2.3 Multi-objective sub-model

The cost- and time-effective sub-models determine the optimal RSOM-hub locations using single objectives. In practice, cost and time are not the only decision criteria for consideration in the selection of RSOM-hubs. For political (e.g., regional development) and operational (e.g., proximity to a seaport) reasons, decision makers may not consider the cost (or time) effective solution. As such, different solution trade-offs need to be investigated using multi-objective optimization to provide decision makers with a number of effective solution options. The multi-objective model considers all three objectives: minimizing the weighted average response time, maximizing the weighted average relative cost avoidance, and maximizing the average airfield capacity performance. This can be formulated as follows:

$$\text{Minimize } \overline{RT} \text{ , Maximize } \overline{RCA} \text{ and Maximize } \overline{U} = \frac{1}{n} \sum_{i=1}^n x_i u_i$$

subject to: Constraints (a–e).

For any multi-objective optimization with conflicting objectives, there is no one optimal solution, but rather a set of possible solutions that trade off the objective values. This concept is captured formally by the notion of Pareto efficiency [8]. A solution is said to be Pareto efficient (or Pareto optimal) if any other solution's scores are worse in at least one of the objectives. If an assignment of decision variables is not Pareto optimal, some other assignment can improve one objective without loss in any other objective. The sets of all Pareto optimal solutions comprise the Pareto front of a multi-objective optimization problem. They can be determined by searching the space of possible decision variables assignments in an exhaustive manner.

3.3 Solution Method

Formulating an appropriate model is only one step in analyzing the hub location problem. Another challenge is identifying the optimal solution. Typically, the first approach to finding the optimal solution to location problems is to apply the standard optimization methods such as branch and bound (a typical exhaustive search method that considers all possibilities but reduces the search space by bounding the search tree) or an implicit enumeration (exhaustive search) method. While these methods can be applied to most location models, they are typically only useful on reasonably sized problems. For large location problems, search algorithms such as simulated annealing [9], tabu search [10], and genetic algorithms [11] are usually used to determine a near-optimal solution.

The RSOM-hub models were implemented using MATLAB and optimal solution was determined using an exhaustive search approach. It is important to note that for reasonably sized problems, such as the RSOM-hub location problem (number of hubs = eight), running an exhaustive search can be more effective (in terms of computational speed) than other exact optimization algorithms. To implement the exhaustive search method for the RSOM-hub location problem, a pre-processing algorithm was developed in order to determine the optimal allocation of hubs and the closest FSB to a given deployment location.

4 Hub Locations Analysis

This section presents an analysis of the RSOM-hub performance and optimal locations. Optimal solution was determined using single and multi-objective models developed in Section 3. Sensitivity analysis was conducted to address the impact of model parameters and assumptions on the optimal solution.

4.1 Scenario and Data

For the purpose of this analysis, a baseline scenario involving one CC-177 aircraft and two CH-146 helicopters was considered to simulate MAJAID responses at different Northern locations. The performance characteristics of the assets, provided by CANOSCOM [12], are presented in Table 1. The average helicopter preparation time is ($\ell = 11$ h) and includes the time required for disassembling and loading the helicopter on the CC-177 aircraft in Trenton as well as the time required for unloading, assembling and testing the helicopter at a given hub. A refuelling service time of ($\alpha = 1$) was used for the helicopters. Given the lack of information (refuelling stop locations), a distance adjustment factor of ($\beta = 1$) was assumed. However, sensitivity analysis will be conducted to assess the impact of β on the optimal solution. Sensitivity analysis will also be performed using the CH-147 Chinook (Table 1) instead of the CH-146. The Northern region was divided into $m = 50400$ grid cells; the centre of each cell represents a MAJAID location.

Table 1: Performance characteristics of CC-177, CH-146 and CH-147 Aircraft

| Parameter | CC-177 | CH-146 Griffon | CH-147 Chinook |
|-----------------------------|--------|----------------|----------------|
| Number of required assets | 1 | 2 | 1 |
| Speed (km/h) | 750 | 200 | 220 |
| Flying rate (\$/h) | 20000 | 5000 | 8000 |
| Range (km) | 7600 | 500 | 800 |
| Loading/ Unloading time (h) | 2 | - | - |
| Disassembling time (h) | - | 6 | 3 |
| Reassembling time (h) | - | 2 | 3 |
| Testing time (h) | - | 1 | 1 |
| Refuelling time (h) | - | 1 | 1 |

For a MAJAID scenario, flight tracks are used to determine the location weighting factor (w_j) (i.e., the probability of an event at a given location j). Historical aircraft flight data in the North for four 24 hour days in 2005/2006 [13] were used in the analysis. The specific data provided by NAV Canada are the following: 2005-08-18 (Summer), 2005-11-17 (Fall), 2006-02-16 (Winter), 2006-05-18 (Spring). As an example, the aircraft flight tracks for the August 18, 2005 date are shown in Figure 3 [13]. The number of flights is as follows: 834 Summer flights, 598 Fall flights, 613 Winter flights, 613 Spring flights.

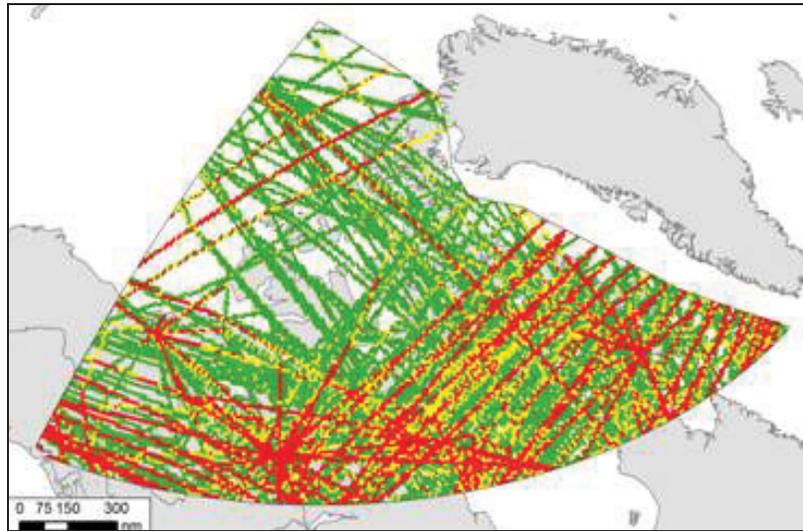


Figure 5: Aircraft flight tracks (18-08-2005)

To determine the density of flight traffic, the four days of flight traffic were mapped onto the different grid cells. The number of flight tracks intersecting each grid cell is calculated and normalized (number of tracks in a grid cell divided by the total number of tracks going through all grid cells) to obtain the location weighting factor that should be normalized. However, this study used NAVCAN radar data only and does not include other hits; therefore the track data is incomplete, particularly for the High Arctic.

For the airfield capacity assessment, CANOSCOM provided general descriptions of the capability and resources available at each airfield option (Annex B). Figure 6 shows a pictorial representation of the airfields capacity, where green indicates that the airfield has the appropriate capability and resources, yellow indicates that the airfield has limited the resources, and red indicates that there is no resource (or marginal) available at the airfield.

Given the lack of detailed information on airfield capacities to conduct multi-criteria decision analysis, illustrative airfield capacity scores (u_i) are used in the analysis to demonstrate the methodology:

$$u_{Iqaluit} = 0.2; u_{Inuvik} = 0.15; u_{Yellowknife} = 0.2; u_{Whitehorse} = 0.2;$$

$$u_{Rankin_Inlet} = 0.08; u_{Clyde_River} = 0.01; u_{Alert} = 0.08; u_{Resolute_Bay} = 0.08$$

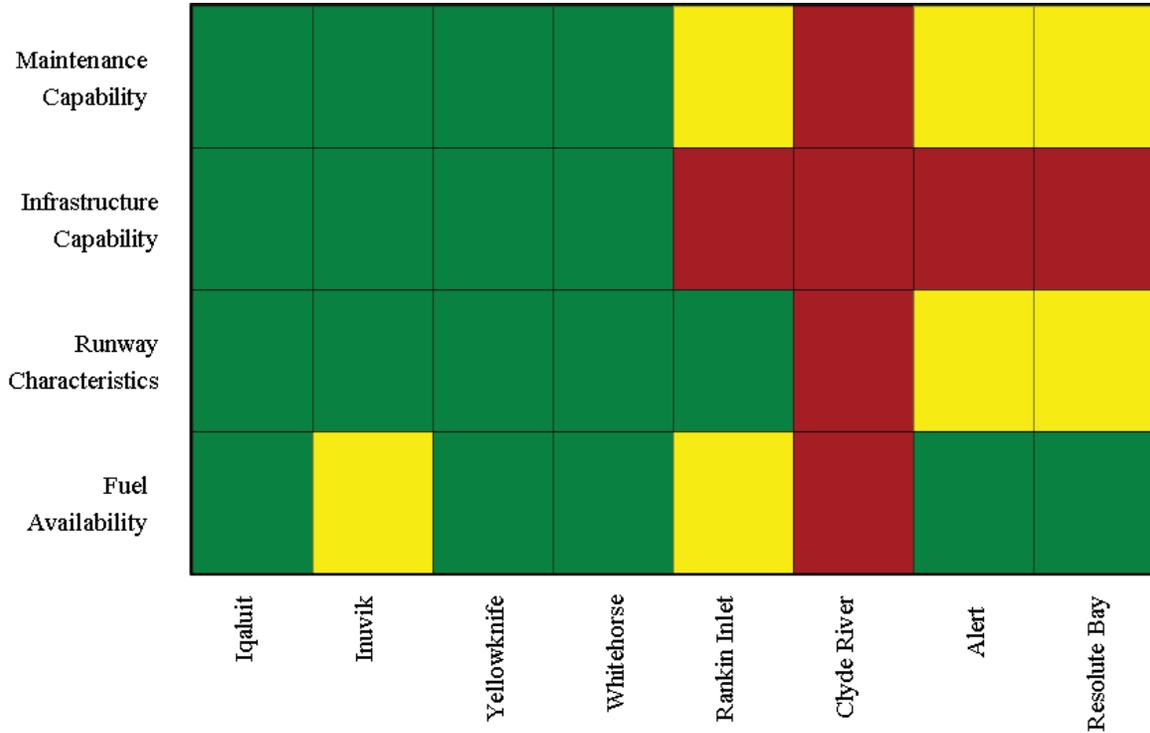


Figure 6: Airfields capacity assessment

4.2 Performance Assessment

The performance of the different potential RSOM-hub locations was analysed and compared. Figure 7 presents the average response time in hours (left scale) and the average relative cost avoidance in % (right scale) of the different hub location options. From a response time perspective, Yellowknife would be the most effective location for MAJAID operations. The average response time (weighted by the location weighting factor) over all deployment destinations would be 23 hours. Whitehorse and Inuvik would be the second and third time-effective locations, respectively. However, the three airfields are located in the northwest region and would not be cost-effective for deployments in the central and east regions of the North. In terms of airfield capacity, both Yellowknife and Whitehorse have sufficient fuel, infrastructure, and maintenance capabilities, and their runways are suitable for CC-177. Inuvik has also sufficient capabilities, except for fuel (limited). The average response times of the remaining airfields are comparable and would about 26.5 hours.

From a cost avoidance perspective, Iqaluit would be the most effective location, followed by Rankin Inlet. Both airfields are located in the centre of the Canadian Northern region and would represent strategic locations for potential RSOM-hubs. Using Iqaluit (or Rankin Inlet), the weighted average relative cost avoidance (over all deployment destinations) would be 34.5% (assuming two helicopters). In terms of airfield capacity, Iqaluit has sufficient fuel, infrastructure, and maintenance capabilities, and its runway is suitable for CC-177. Rankin Inlet has limited fuel and maintenance capability and has no infrastructure capability.

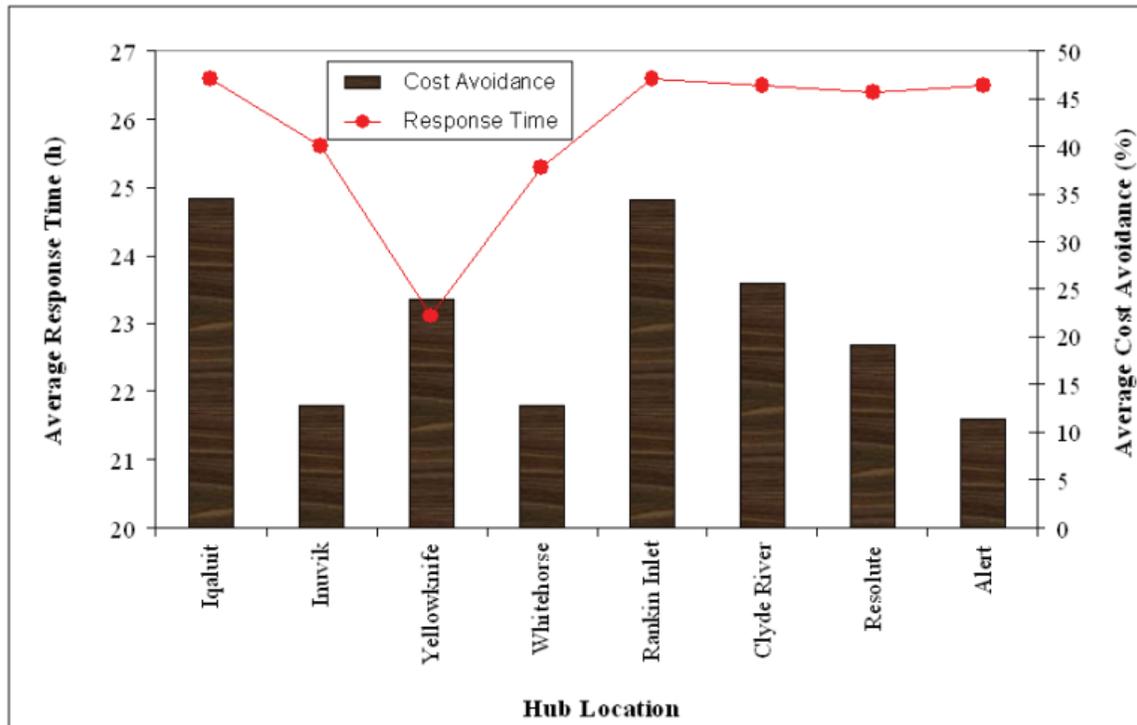


Figure 7: Airfield performance assessment

4.3 Optimal Hub Locations

Optimal hub locations were determined using a single objective optimization approach (i.e., time or cost effective sub-models) for different number of hubs ($H = 1, 2, 3$). Table 2 presents the optimal RSOM-hub locations and the overall performance of the hub system. It indicates that for time effective solution (left part of the table), on average the response time for MAJAID operations would be about 23 hours. With respect to cost effective solution (right part of the table), the relative cost avoidance would be about 35% if RSOM-hubs were implemented in the North. It also indicates that the time and cost effective locations are different for one hub ($H = 1$), two hub ($H = 2$) and three ($H = 3$) hub solutions. In particular, Yellowknife and Whitehorse would be the time-effective locations and Yellowknife and Iqaluit would be the cost-effective locations for a two hub solution. For a three hub solution, Yellowknife and Whitehorse and Alert would be the optimal locations from a response time perspective and Yellowknife and Whitehorse and Iqaluit would be the optimal locations from a cost avoidance perspective. It is important to note that the additional relative cost avoidance and the response time reduction after two hubs

would be marginal. When considering response time and cost at the same time, the overall optimal number of RSOM-hubs for MAJAID operations would be two, corresponding to Iqaluit and Yellowknife.

Table 2: Optimal locations for different number of RSOM-hubs

| # of Hubs | Time effective solution | | | Cost effective solution | | |
|-----------|------------------------------------|-------------------|--------------------|--------------------------------------|-------------------|--------------------|
| | Locations | Response time (h) | Cost avoidance (%) | Locations | Response time (h) | Cost avoidance (%) |
| 1 | Yellowknife | 23.2 | 23.9 | Iqaluit | 26.6 | 34.5 |
| 2 | Yellowknife Whitehorse | 22.7 | 24 | Yellowknife Iqaluit | 23.1 | 34.6 |
| 3 | Yellowknife Whitehorse Alert | 22.5 | 24.1 | Yellowknife Iqaluit Whitehorse | 22.6 | 34.7 |

Figures 8 and 9 present the response time distribution of MAJAID operations for one and two hub solutions, respectively. The minimum response time would be 20 hours and the maximum response time would be 52 hours. In contrast with one hub solution, the response time for a two solution is slightly reduced for locations in the North East region. This can also be confirmed by the results in Table 2, where the average response time is reduced from 23.1 to 22.6 hours for a two hub solution. This means that an additional hub in Iqaluit (after Yellowknife) would not be effective from a response time perspective. Indeed, a direct lift from Petawawa to destinations would be a time-effective option for locations in the North East region.

Figure 10 and 11 present the relative cost avoidance distribution for one and two hub solutions, respectively. The maximum relative cost avoidance is about 50 to 60% and would be around the different FSBs. Significant cost avoidance was observed in the North West and the extreme North regions for both the one hub and the two hub solutions. In these regions, the direct flight from Trenton would require several refuelling services and would not be cost-effective nor time-effective option. There is also an operational risk associated with the availability of refuelling stops in these regions.

The blue region in Figures 10 and 11 indicates locations of marginal cost avoidance. These locations are relatively close to Trenton and the hub-based lift option would not provide significant cost savings with respect to the direct lift option from Petawawa. This is also confirmed by results in Table 2.

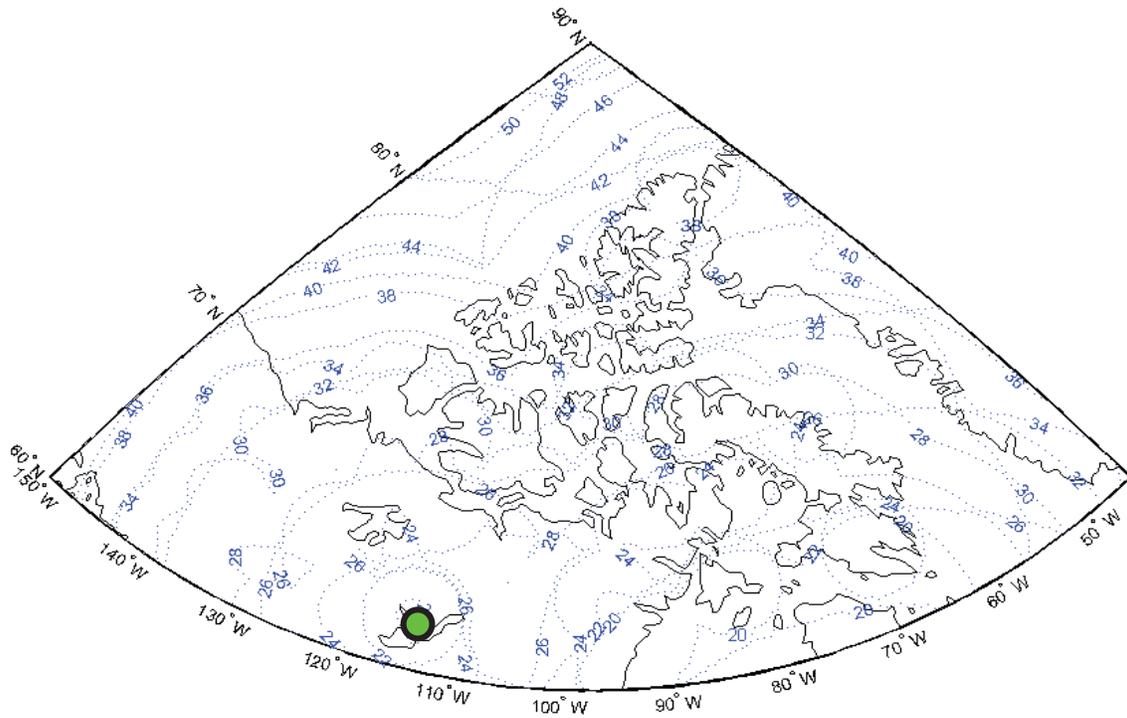


Figure 8: Response time distribution for one hub solution (Yellowknife)

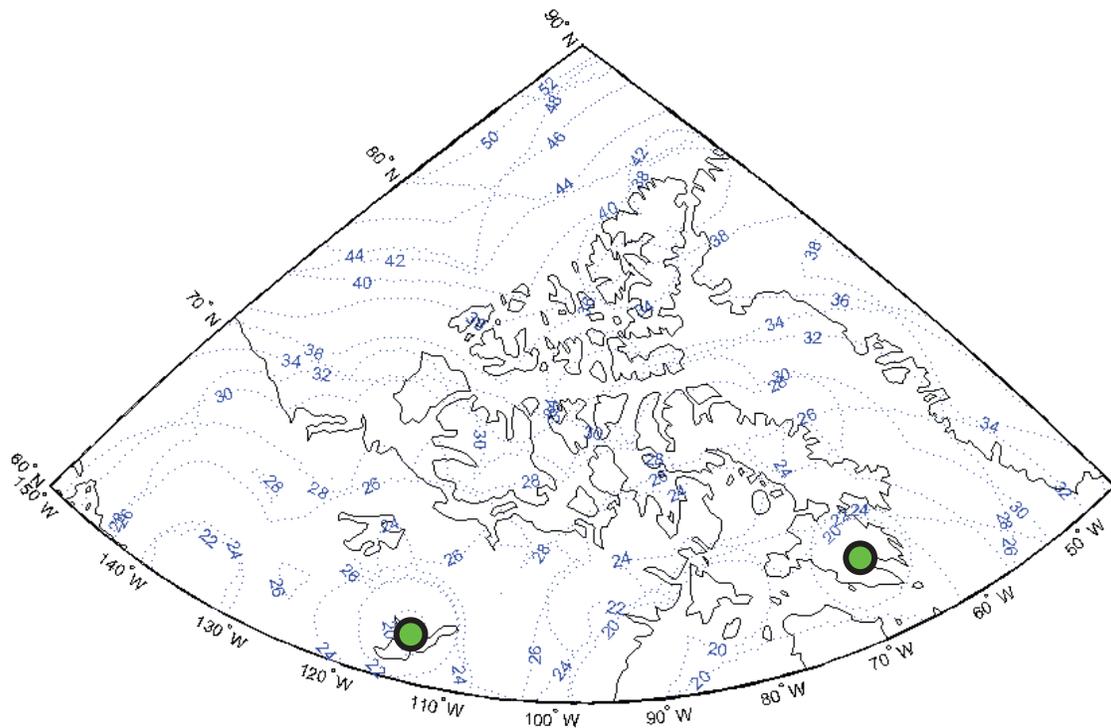


Figure 9: Response time distribution for a two hub solution (Iqaluit, Yellowknife)

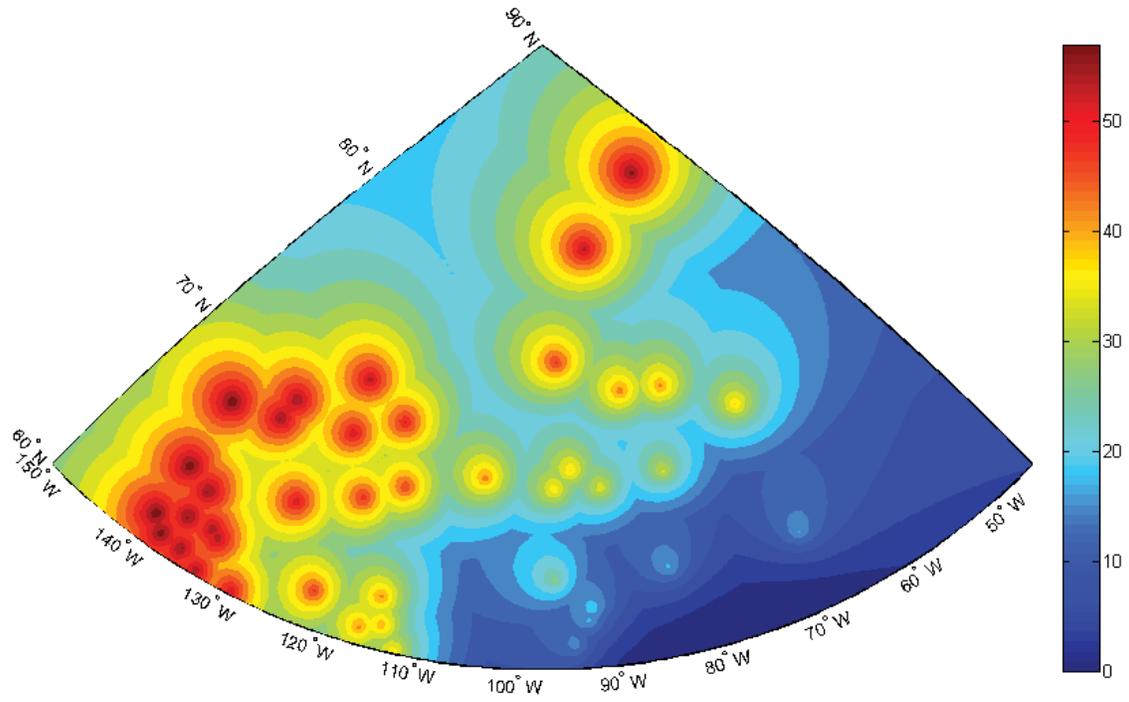


Figure 10: Relative cost avoidance distribution for one hub solution (Iqaluit)

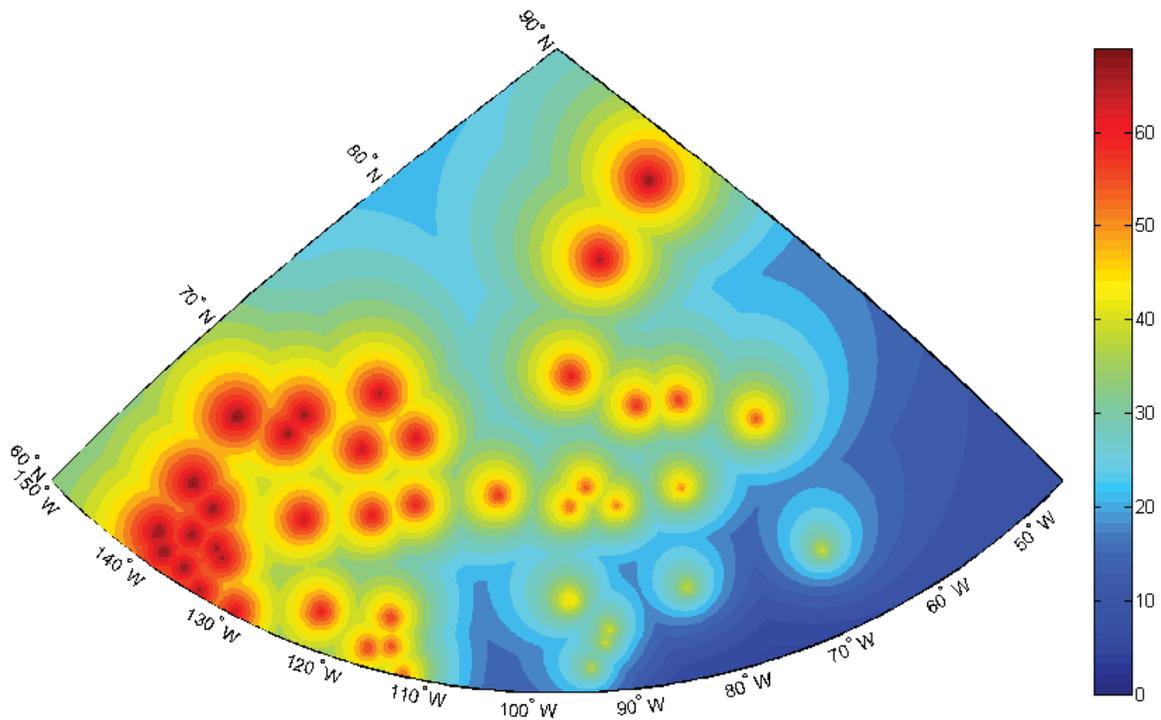


Figure 11: Relative cost avoidance distribution for a two hub solution (Iqaluit, Yellowknife)

4.4 Multi-objective Analysis

Optimal RSOM-hub locations were also determined using a multi-objective optimization approach, taking into consideration the three performance measures (response time, cost avoidance and airfield capacity) developed in Section 3.1. As indicated in Section 4.1, illustrative values of the airfield capacity scores are used to demonstrate the methodology. Figure 12 depicts the performances of different location combinations for a two hub solution. The airfield capacity performance is represented by the color bar (an average capacity score is calculated for each combination). Figure 12 indicates that the time-effective location combination is (Yellowknife, Whitehorse), with a maximum average capacity score of 0.2. While (Iqaluit, Yellowknife) and (Iqaluit, Whitehorse) location combinations have also a maximum average capacity score of 0.2, they are less time-effective than the (Yellowknife, Whitehorse) location combination. As shown in Figure 12, there are many cost-effective location combinations. However, if we take into consideration the airfield capacity performance measure then (Iqaluit, Yellowknife) and (Iqaluit, Whitehorse) would be the most cost-effective combinations. Figure 12 also indicates that the time-effective and the cost-effective location combinations are not necessarily identical.

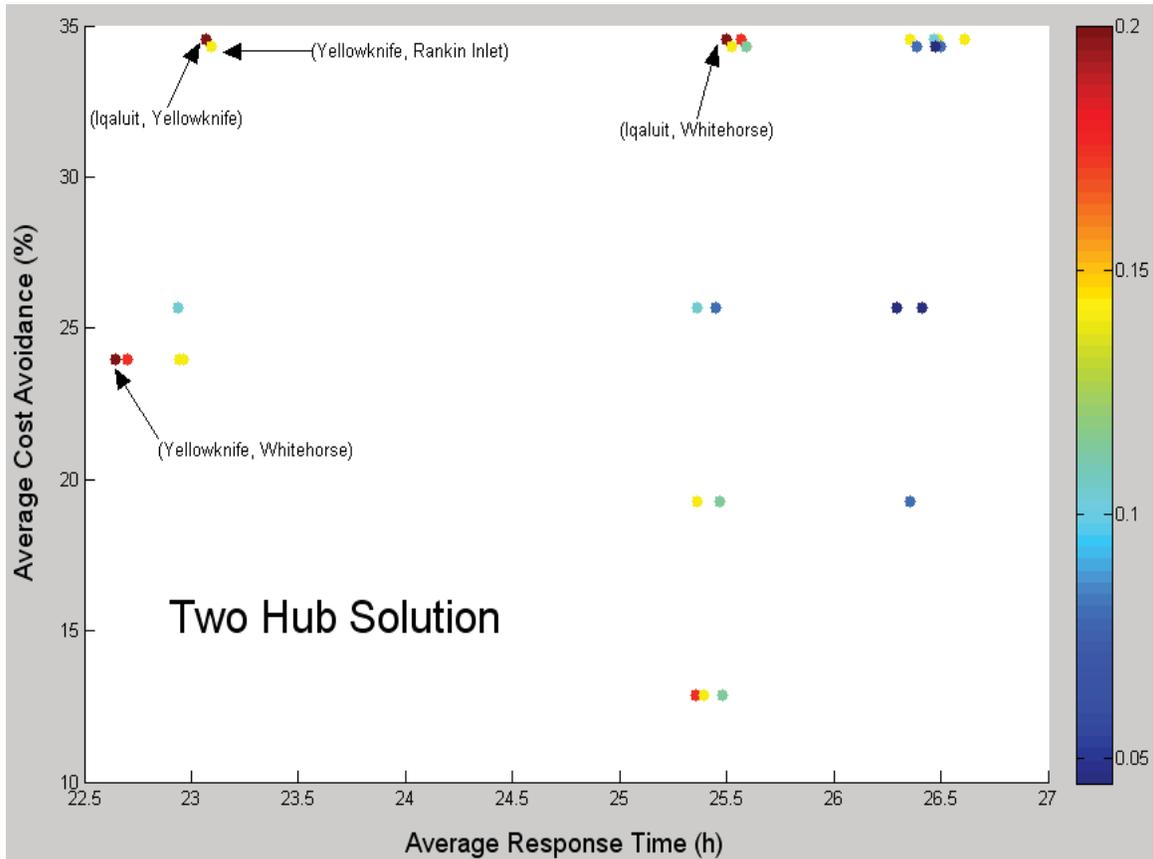


Figure 12: Optimal hub locations for a two hub solution

Figure 13 depicts the performances of different location combinations for a three hub solution. It indicates that there are three time-effective location combinations, namely (Yellowknife, Whitehorse, Alert), (Yellowknife, Whitehorse, Resolute Bay) and (Yellowknife, Inuvik, Alert). As depicted in Figure 13, there are many cost-effective location combinations. However, by taking into consideration all the performance measures, (Iqaluit, Yellowknife, Whitehorse) would be the optimal location combination for a three hub solution.

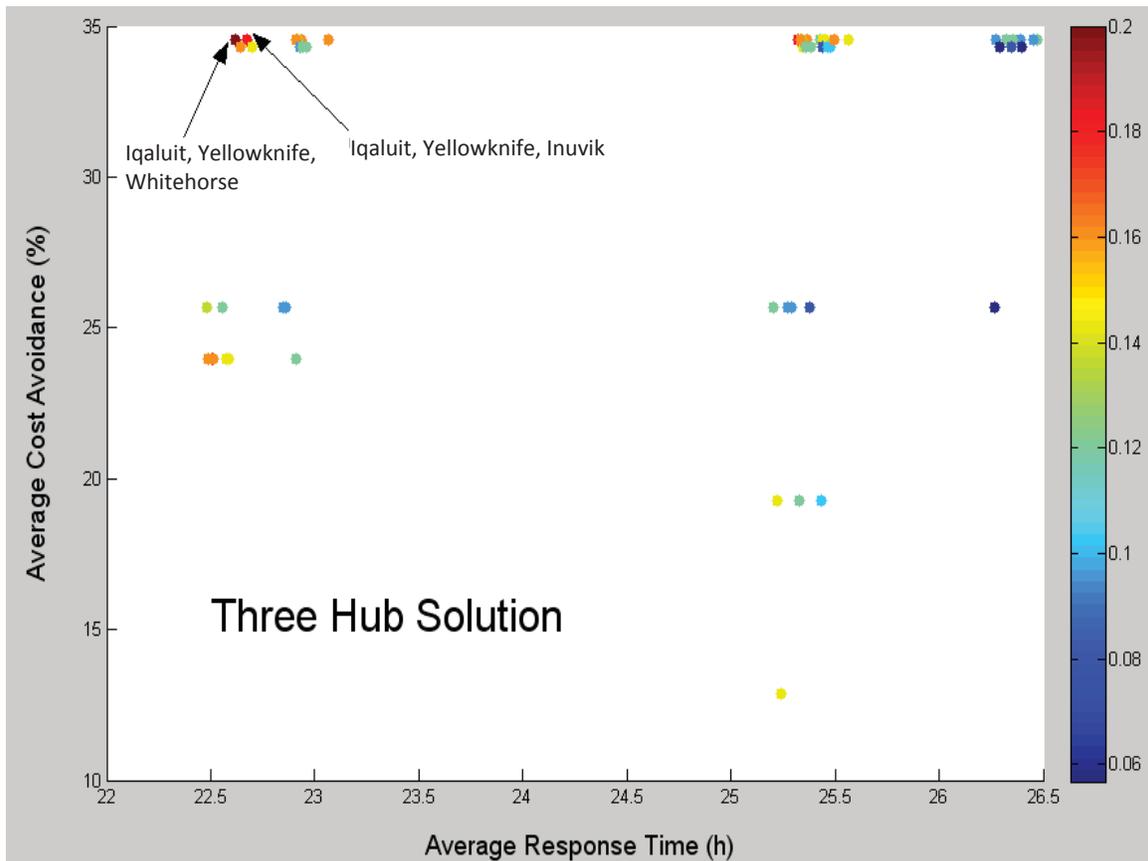


Figure 13: Optimal hub locations for a three hub solution

4.5 Sensitivity Analysis

A sensitivity analysis was conducted to assess the impact of the model parameters and assumptions on the optimal hub locations. While there are many potential areas for detailed sensitivity analysis (e.g., aircraft speed and range, hourly flying cost, etc.), I restricted the analysis to three typical parameters that could impact the optimal hub locations: location weighting factor, distance adjustment factor, and helicopter operational performance (speed, range, and payload). The analysis was conducted for a two hub solution ($H = 2$).

4.5.1 Location weighting factor

In the baseline scenario, historical flight tracks are used to derive the location weighting factor. In this analysis, a constant weigh factor of ($w_j = 1/m$) is used to assess the sensitivity of the optimal hub locations and the hub performance to the location weighting factor. The analysis indicated that the cost-effective hub location would be the same (Iqaluit) as the baseline scenario but the time-effective hub location would be Whitehorse instead of Yellowknife. The average response time is slightly increased and the average relative cost avoidance is slightly reduced with respect to the baseline scenario.

4.5.2 Distance adjustment factor

In the baseline scenario, a distance adjustment factor of ($\beta = 1$) was assumed. In this analysis, the sensitivity of the optimal hub locations and the hub performance to the distance adjustment factor was assessed for different β ($1.0 \leq \beta \leq 1.3$). The analysis indicates that the cost-effective and the time-effective RSOM-hub locations remain the same as the baseline scenario. Thus, the optimal RSOM-hub locations are not noticeably sensitive to the distance adjustment factor. However, the average relative cost avoidance and the average response time are sensitive the distance adjustment factor.

4.5.3 Helicopter operational performance

The impact of the helicopter operational performance is assessed by varying three main parameters, namely hourly flying cost, speed and capacity. This could be, for example, assessing the impact of using the CH-147 instead of the CH-146 on the optimal hub locations.

For the flying cost, let ρ_r be the ratio of the aircraft (CC-177) to helicopter hourly flying costs (for two helicopters). In the baseline scenario, a flying cost ratio of ($\rho_r = 20000/(2*5000) = 2$) is used. In this analysis, the sensitivity of the optimal RSOM-hub locations and the hub performance to the hourly flying cost ratio is assessed for different ρ_r ($1.5 \leq \rho_r \leq 2.5$). The analysis indicates that the cost effective and the time effective RSOM-hub locations remain the same as the baseline scenario but the average relative cost avoidance and the average response time are different.

For the aircraft speed, let ρ_v be the ratio of the aircraft (CC-177) to helicopter cursing speeds. In the baseline scenario, a speed ratio of ($\rho_v = 750/200 = 3.5$) was used. In this analysis, the sensitivity of the optimal RSOM-hub locations and the hub performance to the speed ratio is assessed for different ρ_v ($3.0 \leq \rho_v \leq 4.0$). The analysis indicates that the cost effective and the time effective RSOM-hub locations remain the same as the baseline scenario but the average relative cost avoidance and the average response time are different.

The helicopter capacity parameter is examined by varying the number of required sorties between the FSBs and the event locations. As the number of helicopter sorties would be the same of the hub-based support option and the direct lift option, the average relative cost avoidance would not be affected by the number of helicopter sorties. Similarly, by definition only the first helicopter sortie is considered in the response time calculation, thus the average response time would not be affected by the number of helicopter sorties. Therefore, the optimal hub locations would not be sensitive to the number of helicopter sorties.

5 Conclusions and Recommendations

This paper presents an analysis of the RSOM-hub concept to support MAJAID operations in Northern Canada and provides insights into the optimal RSOM-hub locations. Three performance measures (response time, lift cost avoidance and hub capacity) were formulated to assess the effectiveness and the responsiveness of different RSOM-hub options. A simulation-based optimization model was also developed to determine the optimal number and locations of RSOM-hubs. The model was considered in a multi-objective framework and solution trade-offs were determined through an exhaustive search methodology. An illustrative scenario involving one strategic lift aircraft (CC-177) and two tactical helicopters (CH-146) was used to simulate MAJAID deployment lift to various Northern locations. Illustrative flight tracks were used to determine the probability of MAJAID events at a given location in the North (defined as location weighting factor). Different RSOM-hub options were examined and optimal locations for maximizing the average relative cost avoidance or minimizing the average relative response time were determined for single and multiple RSOM-hub solutions. Solution trade-offs involving different objectives were also investigated and discussed. Sensitivity analysis was performed to explore the impact of key model parameters and assumptions on the optimal solution and RSOM-hub performance.

The study indicated that the RSOM-hub concept could offer potential cost avoidance and response time reduction on deployment lift for MAJAID operations in the North and could be a potential strategy for improvement of the CF domestic support capability. For a single RSOM-hub solution, Yellowknife would be the time effective RSOM-hub location. From a cost avoidance perspective, Iqaluit would be the optimal hub location. Both airfields have the required capability and resources (e.g., fuel, maintenance) for supporting strategic lift aircraft (CC-177) and tactical helicopter operations. For a multiple RSOM-hub solution, the analysis indicates that the optimal number of RSOM-hubs would be two, corresponding to Iqaluit and Yellowknife, when response time and cost avoidance are both considered.

The sensitivity analysis indicated that the optimal RSOM-hub solution would be sensitive to the location weighting factor. For example, the time-effective hub location would be Yellowknife for a track-based location weighting factor and would be Whitehorse for a constant location weighting factor (uniform probability distribution). It also indicated that the distance adjustment factor (i.e., variable to take into consideration additional distance to reach refuelling stops) and the helicopter operational parameters (flying rate, speed and number of sorties) would not affect the optimal locations for a two RSOM-hub solution.

The study is a first research attempt to explore the RSOM-hub problem for MAJAID operations in the North. It used an illustrative scenario to demonstrate the methodology for analyzing the effectiveness of the RSOM-hub concept and the optimal hub locations. Following this study, it is recommended that:

- Yellowknife and Iqaluit should be considered as potential RSOM-hub locations to support Northern MAJAID operations.
- Further Northern scenarios, such as response to maritime or natural disaster, should be investigated to determine the optimal RSOM-hub locations for a range of potential responses

in the North. The logistics requirements for each scenario should be identified. As well, consideration of other departments and agencies should be included in the scenario.

- Particular attention should be given to the location weighting factor as the optimal RSOM-hub solution is sensitive to this parameter. For MAJAID operations, flight tracks would be used for evaluating the probability of a MAJAID at a given location in the North. In this study, as illustrative data is used to demonstrate the methodology. Updated and complete data of flight tracks should be gathered and analyzed for future studies.
- Given the lack of detailed information about the capabilities at the different airfield options, illustrative airfield capacity values were used in the study. An assessment of the airfield capacity should be performed using multi-criteria decision analysis and further analysis should be conducted with realistic data.
- In the analysis, the tactical airlift was simulated using the CH-146 Griffon. Further analysis should be conducted using different helicopter options, such as the CH-147 Chinook.

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Annex A Northern Airfields

Annex A presents the list of the Northern airfield locations and their characteristics. The last two columns of the table indicate if the airfield is suitable for the aircraft (1) or not (0).

Table 3: Northern airfield locations and their characteristics

| Airfield | Lat | Long | Runway Length (feet) | Runway Width (feet) | Surface | CC130 | CC177 |
|--------------------|-------|---------|----------------------|---------------------|---------|-------|-------|
| Aklavik | 68.22 | -135 | 3000 | 75 | Gravel | 0 | 0 |
| Alert | 82.52 | -62.28 | 5500 | 150 | Gravel | 1 | 0 |
| Arctic Bay | 73.04 | -85.15 | 1500 | 50 | Gravel | 0 | 0 |
| Arviat | 61.08 | -94.07 | 4000 | 100 | Gravel | 1 | 0 |
| Baker Lake | 64.28 | -96.07 | 4200 | 100 | Gravel | 1 | 0 |
| Burwash | 61.37 | -139.03 | 5005 | 100 | Gravel | 1 | 0 |
| Cambridge Bay | 69.03 | -105.13 | 5000 | 150 | Gravel | 1 | 0 |
| Cape Dorset | 64.23 | -76.53 | 3980 | 100 | Gravel | 0 | 0 |
| Carcross | 60.17 | -134.7 | 2200 | 75 | Gravel | 0 | 0 |
| Carmacks | 62.11 | -136.18 | 5000 | 100 | Gravel | 1 | 0 |
| Chesterfield Inlet | 63.34 | -90.71 | 3600 | 100 | Gravel | 0 | 0 |
| Clyde River | 70.49 | -68.52 | 3500 | 100 | Gravel | 0 | 0 |
| Coral Harbour | 64.18 | -83.35 | 5000 | 100 | Gravel | 1 | 0 |
| Dawson City | 64.03 | -139.12 | 5007 | 100 | Gravel | 1 | 0 |
| Eureka | 79.98 | -85.8 | 4802 | 150 | Gravel | 1 | 0 |
| Faro | 62.2 | -133.37 | 4000 | 100 | Gravel | 1 | 0 |
| Fort Good Hope | 66.24 | -128.65 | 3000 | 98 | Gravel | 0 | 0 |
| Fort McPherson | 67.41 | -134.86 | 3500 | 100 | Gravel | 0 | 0 |
| Fort Providence | 61.32 | -117.61 | 2998 | 100 | Gravel | 0 | 0 |
| Fort Resolution | 61.17 | -113.68 | 4000 | 100 | Gravel | 1 | 0 |
| Fort Simpson | 61.75 | -121.23 | 6000 | 146 | Asphalt | 1 | 1 |
| Fort Smith | 60.02 | -111.95 | 6000 | 200 | Asphalt | 1 | 1 |
| Gjoa Haven | 68.63 | -95.85 | 4400 | 100 | Gravel | 1 | 0 |
| Great Bear Lake | 66.7 | -119.72 | 5197 | 100 | Gravel | 1 | 0 |
| Grise Fiord | 76.43 | -82.91 | 1950 | 75 | Gravel | 0 | 0 |
| Haines Junction | 60.79 | -137.55 | 5000 | 100 | Gravel | 1 | 0 |
| Hall Beach | 68.77 | -81.23 | 5220 | 150 | Gravel | 1 | 0 |
| Hay River | 60.83 | -115.77 | 6000 | 150 | Asphalt | 1 | 1 |
| Igloodik | 69.36 | -81.82 | 3800 | 100 | Gravel | 0 | 0 |
| Inuvik | 68.3 | -133.47 | 6000 | 150 | Asphalt | 1 | 1 |
| Iqaluit | 63.75 | -68.53 | 8600 | 200 | Asphalt | 1 | 1 |
| Kimmirut | 62.85 | -103.5 | 1900 | 75 | Gravel | 0 | 0 |
| Kugaaruk | 68.53 | -89.8 | 5000 | 100 | Gravel | 1 | 0 |
| Kugluktuk | 67.82 | -115.14 | 5500 | 100 | Gravel | 1 | 0 |

| | | | | | | | |
|----------------|-------|---------|------|-----|---------|---|---|
| Lutselk`e | 62.42 | -110.68 | 2998 | 100 | Gravel | 0 | 0 |
| Mayo | 63.6 | -135.87 | 4856 | 100 | Gravel | 1 | 0 |
| Nanisivik | 72.97 | -84.6 | 6400 | 150 | Gravel | 1 | 0 |
| Norman Wells | 65.27 | -126.78 | 5997 | 150 | Asphalt | 1 | 1 |
| Old Crow | 67.57 | -139.83 | 4900 | 100 | Gravel | 1 | 0 |
| Pangnirtung | 66.15 | -65.71 | 2920 | 100 | Gravel | 0 | 0 |
| Paulatuk | 69.35 | -124.07 | 4000 | 100 | Gravel | 1 | 0 |
| Pelly Crossing | 62.83 | -136.58 | 3305 | 75 | Gravel | 0 | 0 |
| Pond Inlet | 72.68 | -77.97 | 4000 | 100 | Gravel | 1 | 0 |
| Qikiqtarjuaq | 67.55 | -64.03 | 3800 | 100 | Gravel | 0 | 0 |
| Rae / Edzo | 62.77 | -116.08 | 3372 | 98 | Gravel | 0 | 0 |
| Rankin Inlet | 62.8 | -92.1 | 6000 | 150 | Asphalt | 1 | 1 |
| Repulse Bay | 66.52 | -86.22 | 3400 | 100 | Gravel | 0 | 0 |
| Resolute Bay | 74.72 | -94.97 | 6500 | 200 | Gravel | 1 | 0 |
| Ross River | 61.97 | -132.42 | 5113 | 100 | Gravel | 1 | 0 |
| Sachs Harbour | 71.98 | -125.23 | 4000 | 100 | Gravel | 1 | 0 |
| Sanikiluaq | 56.54 | -79.25 | 3800 | 100 | Gravel | 0 | 0 |
| Taloyoak | 69.53 | -93.57 | 4020 | 100 | Gravel | 1 | 0 |
| Teslin | 60.17 | -132.73 | 5000 | 100 | Gravel | 1 | 0 |
| Trout Lake | 56.5 | -114.72 | 2500 | 60 | Gravel | 0 | 0 |
| Tuktoyaktuk | 69.43 | -133.02 | 5000 | 150 | Gravel | 1 | 0 |
| Tulita | 64.91 | -125.57 | 3000 | 100 | Gravel | 0 | 0 |
| Ulukhaktok | 70.75 | -117.8 | 4300 | 100 | Gravel | 1 | 0 |
| Watson Lake | 60.1 | -128.82 | 5500 | 150 | Asphalt | 1 | 1 |
| Wekweeti | 64.19 | -114.08 | 3000 | 75 | Gravel | 0 | 0 |
| Wha Ti | 63.14 | -117.25 | 2991 | 100 | Gravel | 0 | 0 |
| Whale Cove | 62.24 | -92.6 | 4000 | 100 | Gravel | 1 | 0 |
| Whitehorse | 60.7 | -135.07 | 9497 | 150 | Asphalt | 1 | 1 |
| Yellowknife | 62.45 | -114.43 | 7500 | 150 | Asphalt | 1 | 1 |

Annex B Northern Airfield Capacities

Annex B presents a general assessment of the airfield capacities.

1. Iqaluit:

- a. Fuel: The community has a capacity to supply fuel for outside requirement.
- b. Runway: 8,600' X 200' Paved runway
- c. Infrastructure capacity: All necessary infrastructures are available from the community. DND does have ownership of a FOL / PAB facilities next to the airport.
- d. Maintenance capacity: Contractual support available from the community. Aircraft MHE equipment are readily available at the airport up to 10 Ton forklift

2. Inuvik:

- a. Fuel: The community has a limited capacity to supply fuel outside their annual requirement.
- b. Runway: 6,000' X 150' Paved runway
- c. Infrastructure capacity: All necessary infrastructures are available from the community. DND does have ownership of a FOL / PAB facilities next to the airport.
- d. Maintenance capacity: Contractual support available from the community. Aircraft MHE equipment are readily available at the airport up to 5 Ton forklift

3. Yellowknife:

- a. Fuel: The community has a capacity to supply fuel outside their annual requirement.
- b. Runway: 7,500' X 150' Paved runway
- c. Infrastructure capacity: All necessary infrastructures are available from the community. DND does have ownership of a FOL / PAB facilities next to the airport.
- d. Maintenance capacity: Contractual support available from the community. Aircraft MHE equipment are readily available at the airport up to 10 Ton forklift

4. Whitehorse:

- a. Fuel: The community has a capacity to supply fuel outside their annual requirement.
- b. Runway: 9,500' X 150' Paved runway
- c. Infrastructure capacity: All necessary infrastructures are available from the community. DND does have ownership of Det Yukon HQ building and Boyle Barrack Cadet Camp 12 Km from the airport site.
- d. Maintenance capacity: Contractual support available from the community. Aircraft MHE equipment are readily available at the airport up to 5 Ton forklift

5. Rankin Inlet:

- a. Fuel: The community has a limited capacity to supply fuel outside their annual requirement.
- b. Runway: 6,000' X 150' Paved runway.
- c. Infrastructure capacity: Very limited infrastructure within the community. DND does have ownership of a FOL / PAB facilities next to the airport and a Early Warning System Radar site.
- d. Maintenance capacity: Very limited contractual support from the community. Aircraft MHE equipment are readily available at the airport up to 5 Ton forklift

6. Clyde River

- a. Fuel: The community has very limited capacity to supply fuel outside their annual requirement.
- b. Runway: 3,500' X 100' Soft surface (Gravel)
- c. Infrastructure capacity: Very limited infrastructure within the community.
- d. Maintenance capacity: Very limited contractual support from the community. Aircraft MHE equipment are limited with a 2 ton forklift capacity.

7. Resolute Bay

- a. Fuel: The community has a capacity to supply fuel outside their annual requirement.
- b. Runway: 6,500' X 200" Soft surface (gravel)
- c. Infrastructure capacity: Very limited infrastructure within the community. Borek Hangar available for rental. DND does have ownership of a small storage facility through 17 W.
- d. Maintenance capacity: Very limited contractual support from the community. Aircraft MHE equipment are readily available at the airport up to 10 Ton forklift

8. Alert

- a. Fuel: The community has a capacity to supply fuel outside their annual requirement.
- b. Runway: 5,500' X 150' Soft surface (gravel)
- c. Infrastructure capacity: Very limited infrastructure within the community. DND does have ownership of a town site for logging and feeding.
- d. Maintenance capacity: DND support for maintenance requirement but no contractual support from the community with very limited hangar space. Aircraft MHE equipment are readily available at the airport up to 10 Ton forklift

List of Abbreviations/Acronyms

| | |
|----------|--|
| CANOSCOM | Canadian Operational Support Command |
| CF | Canadian Forces |
| DND | Department of National Defence |
| DRDC | Defence Research Development Canada |
| FSB | Forward Support Base |
| Lat | Latitude |
| Long | Longitude |
| MAJAID | Major Air Disaster |
| NATO | North Atlantic Treaty Organization |
| NORLOC | Northern Lines of Communication |
| NP-hard | Nondeterministic Polynomial-time Hard |
| POD | Port of Debarkation |
| RSOM | Reception, Staging and Onward Movement |
| SME | Subject Matter Expert |

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This paper presents an analysis of a Reception, Staging and Onward Movement hub (RSOM-hub) concept to support Canadian Forces Major Air Disaster (MAJAID) operations in the North and provides insights into the optimal RSOM-hub locations. RSOM-hubs are permanent or temporary staging bases for cross-loading between strategic and tactical lift during military deployment and sustainment operations. In this study, performance measures were formulated to assess the effectiveness and the responsiveness of different RSOM-hub options to support MAJAID deployments. A simulation-based optimization model was also developed to determine the optimal number and locations of hubs in the North. The model was considered in a multi-objective framework and solution trade-offs were determined through an exhaustive search methodology. An illustrative scenario and associated data were used to simulate deployment lift to various MAJAID locations and to demonstrate the methodology. Sensitivity analysis was conducted to examine the impact of different operational parameters on hub performance and optimal locations. The study indicated that the optimal number of RSOM-hubs for MAJAID operations in the North would be two, corresponding to Iqaluit and Yellowknife.

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Airlift; NORLOC; RSOM-hub, Facility Location

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