# Assessing the Impact of Infrastructure on Arctic Operations

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## *ABSTRACT*

*With the loss of ice coverage in the Arctic, access to Canadian territorial waters such as the North West Passage is becoming feasible over a wider area and time span. As a result, shipping through the area is expected to grow, increasing the likelihood of Canadian Armed Forces (CAF) domestic operations in the region. We present analytical work on the effect of sparse logistical infrastructure on military operations in the Canadian Arctic region undertaken as part of an effort to inform Department of National Defence infrastructure investment decisions. The relative response capability of the CAF was assessed using major maritime disaster scenario involving a large cruise ship. We examine the transportation and logistics component of the problem using a mixed-integer programming capacitated vehicle routing model. Factors considered include the current CAF force deployment and response posture, transit to forward operating locations, vehicle capacity, fuel requirements, degradation of the medical state of the evacuees over time, and triage decisions at loading time. The model was applied over all feasible combinations of forward operating locations and a grid of incident locations to assess performance over the entire region and to measure the impact of procedural and infrastructure changes.*

## 1.0 INTRODUCTION

Canada's Arctic region is an important theme in Canada's defence policy. This importance is expected to grow over time, given that climate change, advancements in technology, etc. will increase the region's accessibility, resulting in greater activity from a variety of sectors, including commercial ventures, research, and tourism. [1] In turn, the frequency and significance of incidents, such as search and rescue, natural and man-made disasters, etc., to which the Canadian Armed Forces (CAF) will be called upon to respond is expected to rise accordingly.

Regardless of the incident type, infrastructure in Canada's Arctic plays a vital role in the CAF ability to project its forces within the region. Given the sparseness of Canadian Arctic infrastructure, its vulnerability to the impacts of climate change, and the high cost of its construction and maintenance, having an understanding of the impact Canadian Arctic infrastructure investment/divestment decisions on the CAF operations is paramount.

In order to make a comprehensive assessment of a decision's impact, an analytical approach that employs multiple scenarios and/or factors should be used. For example:

- Ewing et al. [2] used multiple-objective decision analysis to determine the value of infrastructure to the Unites States Army and an installation portfolio model to develop the starting point to identify potential unit realignments and base closures;
- Mason and Kerzner [3] developed measures of effectiveness, covering operational impact, infrastructure condition and efficiency, and economic impact, to gauge the value of major infrastructure sites and

employed a consensus ranking method to create a prioritized list of infrastructure sites to be considered for divestment;

- Caron et al. [4] used multi-criteria decision analysis to identify advantageous operational hub locations and combinations in Canada's Arctic region;
- Lambert et al. [5], within the context of the Afghanistan National Development Strategy, used a scenario-informed multi-criteria approach to prioritize major infrastructure investments in Afghanistan's Nangarhar province.

While such approaches are preferred, in this study we elected to use a single-scenario based approach. This was selected based on numerous discussions with the study's sponsor—Canadian Joint Operations Command J5 staff—during which they expressed their interest with studying the CAF ability to implement CONPLAN LENTUS in Canada's Arctic due to logistical limitations.[1] Furthermore, CJOC J5 staff choose a Major Maritime Disaster (MAJMAR) scenario for two primary reasons: first, from a logistical perspective it is a high demand scenario; and second, the CAF's response to a MAJMAR in Canada's Arctic has not been studied in detail.[2]

With this scope in mind, this paper's main contribution is a methodology that provides insights into the impact of Canadian Arctic infrastructure investment/divestment decisions on the CAF ability to respond to a MAJMAR scenario within Canada's Arctic region. It accomplishes this by: first, identifying existing geospatial gaps in the CAF ability to respond as well as expected scenario outcomes; and second, by comparing these results with those in which an infrastructure investment/divestment is implemented. Whereas the former provides a baseline assessment, the latter explores the impact of a decision in terms of changes in both geospatial gaps and regions in which the CAF may still respond, but the scenario's outcomes differ. While the methodology is presented in the context of a MAJMAR, it is applicable to a range of scenarios involving transportation or evacuation of people, including major air disasters, natural disasters, and humanitarian crises.

The remainder of this paper is organized as follows. Section 2 describes the methodology used in the study; in particular, it describes the MAJMAR scenario in which the methodology is demonstrated, how the scenario's evacuees' medical state and the CAF response are modelled, and how the impacts of infrastructure investment/divestments are quantified. Next, Section 3 presents an application of the methodology. Section 4 provides a brief discussion of the methodology's limitations, and lastly Section 5 summarizes this work.

## 2.0 METHODOLOGY

This report investigates how the infrastructure is in the Northern Area of Responsibility (AoR), defined in Chan and Rempel [10] as the region of Canadian territory north of 55ºN, can be used to support an operations. A fictitious scenario is developed in order to examine some possible courses of action by the CAF. This section details the selected scenario with reasons, and describes two models that were used to evaluate the CAF ability to respond to that scenario. In Section 3, a representative divestment option is compared to the current baseline infrastructure.

[1] CONPLAN LENTUS is concerned with aid to the civil power and is typically invoked to deal with emergencies and disasters. From a logistical perspective, the largest likely military response to a LENTUS event in Canada's Arctic involves an Immediate Response Unit (IRU) of approximately 500 persons, with associated equipment, plus an unspecified number of military aircraft.

[2] The CAF response to a MAJMAR scenario in Canada's Arctic was discussed by Boileau et al. [6], however their work focused on equipment and human physiology. Poitras [7] also discussed the CAF response to a maritime scenario in Canada's Arctic; however, the scenario involved two individuals. In addition, while not in the Canadian Arctic, a response to a MAJMAR scenario Canada's Pacific SAR region has been studied previously. [8,9]

Per [10], infrastructure is defined for this study as ``the permanent installations required for military purposes" or ``the resources (such as buildings or equipment) required for an activity." In this case specifically that infrastructure which may be used to support air, land and/or sea force projection and sustainment in the Northern AoR. We further define ``Canadian Arctic waters" in accordance with the region used in the 2014 Fall Report to Parliament of the Commissioner of the Environment and Sustainable Development, Chapter 3–Marine Navigation in the Canadian Arctic [11], as reproduced in Figure 2-1.

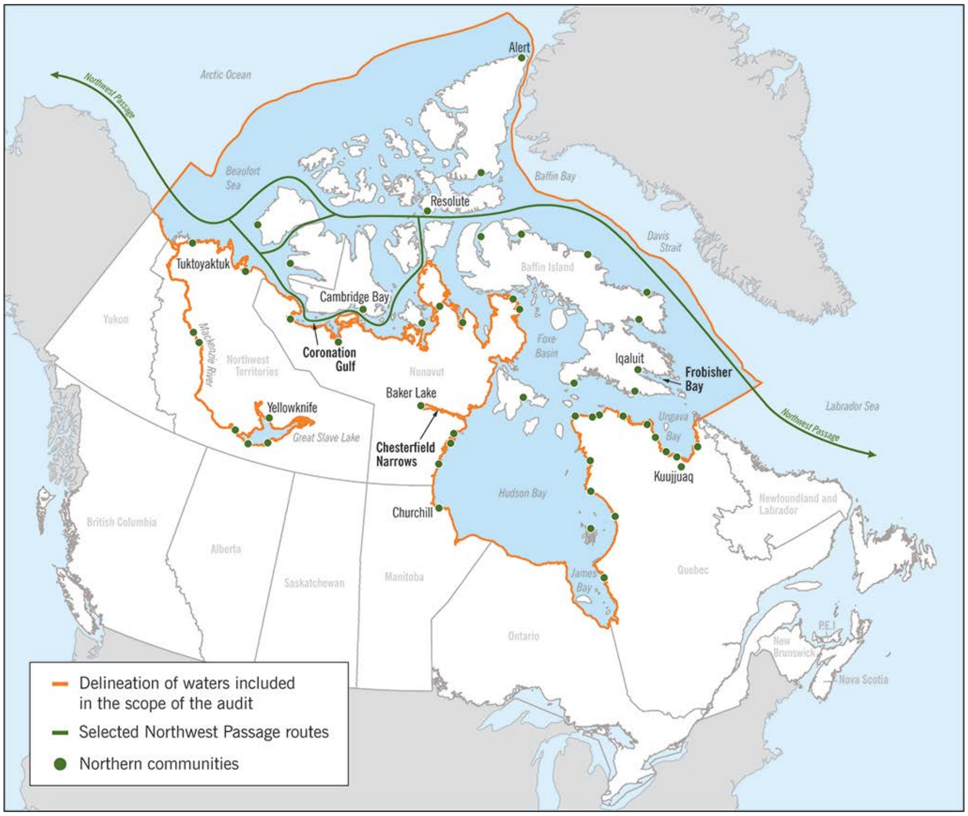


**Figure 2-1: Canadian Arctic waters, as defined in the 2014 Fall Report to Parliament of the Commissioner of the Environment and Sustainable Development. Graphic sourced from [11].**

## 2.1 Scenario

The scenario selected for this work is a major maritime disaster (MAJMAR) in the Arctic involving a cruise ship. Although it is fictitious, the idea of a large cruise ship sailing across the Northwest Passage (NWP) in the Canadian Arctic Archipelago is not. [12] Even in warm waters, significant maritime accidents have happened and called for a mass evacuation with heavy casualties. A notable example is the case of the *Costa Concordia* in 2012. [13, 14] When a large cruise ship encounters an accident in the Arctic region [15], it becomes more dangerous and challenging to mount a rescue and evacuation operation, as was the case with the *Viking Sky* off the coast of Norway in 2019. [16, 17] Hydrographic data for the Canadian Arctic is inadequate across most of the region. [11] That a cruise ship venturing off the main shipping lanes to view the scenery could experience some sort of mishap is well within the realm of imagination. This work depicts such a scenario, which was approved by CJOC staff prior to beginning modelling efforts.

In the scenario, the *Gemstone Tranquility*, a cruise ship travelling through the NWP during the summer, suffers a catastrophic incident that renders the ship uninhabitable, forcing the evacuation of the ship. Possible causes for such an event are running aground or striking ice, which causes the ship to take on water and lose power. Given the size and capacity of *Gemstone Tranquility*, the Canadian Coast Guard (CCG) maintains a constant communication with its crew. [18] It is assumed that the Joint Rescue Coordination Centre (JRCC) is contacted almost immediately after the evacuation decision was made, either via the CCG or directly by *Gemstone Tranquility*.

The following is a list of high-level assumptions for the scenario that are used to build the model and conduct the analysis in the remainder of this report.

1. Although the CCG is the lead agency for the response to maritime disasters [19], the CCG and JRCC will ask the CAF to assist due to the magnitude of the event;

2. The scenario takes place during the summer in August. In general, this is the month with the greatest freedom of navigation due to ice melt. A single reference position at 71.9°N, 96.0°W is used to set day length and temperature range. The length of daylight here in mid-August is 19 hours[3] [20] and the temperature is between 0°C and 5°C[4] [21];

3. The total number of passengers and crew aboard the ship is 2000. All persons aboard are present and accounted for – that is, there are no missing persons;

4. The CCG's Search and Rescue Units (SRUs) are too far away from the event location [22] and do not have the capacity to carry 2000 people. The CAF are asked to rescue the evacuees from immediate danger and to transport them to a location in the South. Only CAF assets and resources are used;

5. The distress signal was sent at midnight. Everybody on the ship starts the evacuation process at that time, and the CAF starts organising the rescue and evacuation operation at the same time; and

6. Rotary-wing (RW) aircraft are used to bring the evacuees from the incident site to a location from which fixed-wing (FW) aircraft will transport them to a location in the South. At least one location with an airfield suitable for a CC130J and within the operational range of the RW aircraft is selected to act as a transportation hub and temporary shelter for the evacuees.

## 2.2 Problem definition and modelling

For the CAF, this scenario immediately becomes a problem of logistics: 2000 persons must be extricated from a difficult situation far from the bases of the most relevant CAF assets. To do this, the CAF must first deploy RW aircraft from their Main Operating Bases (MOBs) to a suitable FOL within range of the incident location. The distances involved and the distribution of airfields are such that deployment to the FOL may take many legs and several days to complete.

The helicopters will require a large quantity of fuel for the evacuation operation, which must be assumed to be unavailable at the FOL unless otherwise specified. This must be transported to the FOL by \Royal Canadian Air

[3] The number of daylight hours affects the maximum duration of operations under visual flight rules (VFR).

[4] The weather conditions strongly influence the rate at which the evacuees' health degrades.

Force (RCAF) FW transports, principally CC130J Hercules. The evacuees that are moved from the incident site to the FOL must then be moved to southern Canada for medical care and repatriation. At the same time, the CAF personnel required to operate and maintain the RW aircraft at the FOL, to assist and care for the evacuees, and to co-ordinate the operation. Both the evacuees and the military personnel will require additional supplies of all sorts. These personnel and supplies must also be moved to the FOL on the same FW transports that are moving the fuel and the evacuees. All the while, the victims that have not yet been evacuated are exposed to the difficult conditions of the Arctic without adequate sustenance, housing or sanitation, which will inevitably lead to illness and generally declining health among them. Thus, the most crucial aspects of this problem are

- The deployment of RW aircraft to the FOL;
- The representation of the medical condition of the evacuees over time; and
- The modelling of the transportation network that moves all of these persons and supplies.

We consider each of these aspects below. As the point of scenario is to save lives, the measures of performance (MOPs) for a given CAF response and infrastructure configuration are be based on or incorporate the number of survivors. The MOPs are discussed in Section 2.3.3.

### 2.2.1 CAF response

CJOC OR&A provided CJOC J5 North with a list of required input data; an enumeration of the military personnel and assets that would be allocated to deal with this scenario, and certain relevant information on the capabilities of the assets. CJOC J5 North responded after consultation with 1 Canadian Air Division and with the Joint Forces Air Component Command (JFACC), which holds the primary responsibility for air asset tasking. The maximal response, as laid out by 1 Canadian Air Division, would involve 2 CH149, 8 CH147, either 2 CC130J *or* 1 CC177, and 500 CAF personnel drawn from the IRU, RCAF and supporting units. In practice, the CC130Js can land at more locations than the CC177 and so are used more often in the analysis below. Depending on other operational commitments at the time of the scenario, it may not be possible to allocate this many aircraft; it is very unlikely that more aircraft could be assigned to this operation.

### 2.2.2 Deploying helicopters to forward operating locations

The deployment of CH147 from 1 Wing Petawawa and CH149 from 9 Wing Gander or 19 Wing Comox to an arbitrary point requires a consideration of several factors: (a) item the range of the helicopter, (b) the location of airports to act as waypoints between the origin and the destination, (c) the availability of necessary services at the waypoints, fuel being the most important, and (d) the requirement to obey crew rest rules and flight regulations in the Flight Operations Manual. [23] This version of the shortest-path problem has been solved separately for each helicopter type and FOL used in this report. The resulting deployment times were used as input parameters to the optimization model.

### 2.2.3 Logistic network model

Two models were developed for this study, a simulation model [24] and an optimization model. [25] Each of them describes the transportation network imagined for the CAF response to the scenario, including

- The locations of the incident site, the chosen FOL and the rear echelon location(s) in southern Canada (principally Canadian Forces Base (CFB) Trenton);

- The RCAF RW and FW aircraft assigned, accounting for the speed, range, fuel consumption rate and capacity of each aircraft to carry fuel, supply and persons in various medical states;
- The movement of evacuees southward on those aircraft and the transportation of supplies and CAF personnel northward; and
- The need for fuel to be present at the FOL for helicopter operations and the consumption of that fuel by operations.

The models were developed concurrently at the beginning of the study. The simulation model was used to verify the results of the optimization model and to test assumptions. Once the optimization model was assessed to be working correctly by producing results consistent with the simulation model, the optimization model was then applied across all feasible combinations of selected FOLs and an incident site grid.

### 2.2.4 Representation of the medical state of evacuees

Because the quality of CAF response to the scenario is measured in terms of the number of survivors, their medical condition must be considered to make a valid assessment. Transportation modelling is discussed above. As the representation of the evacuees' health has a strong effect on the modelling outcomes, this section discusses the medical condition of the evacuees and how it is affects and is represented in the two models.

In this study, an evacuee's medical condition is not modelled in detail because it involves numerous factors such as cause of injury, severity, first aid, age, medical history and so on. For the purposes of the study, an evacuee's medical condition affects only their life expectancy from that point in time and the amount of space they will require on an aircraft. An evacuation triage system similar to the Simple Triage and Evacuation (START) system [26] is adopted in this study. It divides the evacuees into five categories from the uninjured, colour-coded as white, to the terminally injured or deceased who were colour-coded as black. The other three categories were for the ones who required immediate treatment (red), early treatment (yellow), and only routine treatment (green). The CAF triage system [19] is substantially similar to the START system, with the addition of a sixth category, grey, for missing persons. Since our assumptions above preclude the existence of missing persons[5], we ignore this category. The triage state in which one is in dictates his or her evacuation priority. Under Canadian Standard Operating Procedure (SOP) the patients in the red triage state have the highest priority followed in order by yellow, green and white triage states. This SOP is relaxed in the optimization model. The standard practice of the air SRU leaves those in the black triage state at the scene, which is adopted here as well. We further assume that patients in the red and yellow triage states are on stretchers.

#### *2.2.4.1 Initial conditions and triage states*

This study assumes that the medical condition of the evacuees deteriorates only gradually over time before arriving at a southern city that had adequate medical facilities. As a result, their corresponding triage state moves one level from white to green, or green to yellow, and so on. Patients in the yellow triage state may only change to the red triage state and may not go directly to the black triage state. The simulation model and the optimization model approaches for handling the transition are found in [24] and [25] respectively.

At the start of the evacuation, 100 people are injured with different treatment requirements. We assume that 30 of them required immediate treatment (i.e. in the red triage state), another 30 require early treatment (yellow triage

[5] Given the environmental conditions of the region, anyone who goes missing during the evacuation of a ship is effectively already dead.

state) and the last 40 injured evacuees are in the green triage state. The initial counts are tabulated in Table 1-1. The initial number of injured evacuees is inspired by the Costa Concordia disaster that happened 140 km from Rome, Italy in 2012. [14] The Italian cruise ship, which had 4252 people on board (over three thousand were passengers), ended up having 32 death and 64 people injured. [27] Hence, an initial set of 100 injured people is deemed reasonable for a MAJMAR in a cold, remote and isolated environment.

**3 Table 1-1: Properties of the five triage states**

| Triage State | Required Treatment | Initial Count | On Stretcher? | Mean time in state [h] | |
|---|---|---|---|---|---|
| | | | | At event site | At FOL |
| White | None (uninjured) | 1900 | No | 120 | 160 |
| Green | Routine | 40 | No | 48 | 64 |
| Yellow | Early | 30 | Yes | 8 | 10.67 |
| Red | Immediate | 30 | Yes | 1.5 | 2 |
| Black | None (deceased) | 0 | Not applicable | ∞ | ∞ |

#### *3.2.4.1 Medical state transition rates*

In order to model the effects of exposure on victims that have not yet been evacuated, a medical professional was consulted for some rule-of-thumb estimates of how long a person would stay in a particular triage state under various environmental conditions and levels of care. [28] These are found in Table 1-1. In accordance with our assumptions, these are the mean times than a person would spend in the indicated state before progressing (deteriorating) to the next worse state. If there is no intervention, a person will always eventually transition from white to green, green to yellow, yellow to red, and finally red to black.

The red triage state at the event node is modelled after a person having a heart attack. The American Heart Association recommends fewer than 90 minutes from the symptoms begin to the opening of the blocked artery. [29] The eight hours of average transition period for the yellow triage state patients at the scene is the average value of 4.5[6] and 12[7] hours from the onset of symptoms for treating stroke patients. Those in the yellow triage state are presumably pneumonia patients. Within two days after the start of symptoms, neuraminidase inhibitor as a treatment is recommended to the viral pneumonia patients by Ruuskanen et al [31]. Finally, it is assumed that the healthy evacuees would catch a common cold or influenza in five days because they stay close to one another in a confined area at the event node. The other average transition times at the FOL node and on board of an aircraft are simply multiples of the baseline averages at the event node.

The mean state durations in Table 1-1 are almost certainly the greatest source of uncertainty in the absolute accuracy of results for this study. All decisions and measures of performance within the models are directly tied to these times and should be validated prior using this study to make detailed decisions regarding triage and evacuation priorities. However, as long as all evacuees at all candidate locations follow the same medical transition process, the mortality rate at a location serves as an indicator to differentiate the usefulness of the candidate locations.

[6] The recommended time within which recombinant tissue plasminogen activator (rtPA) could be effectively used. [30]

[7] Time window for treating ST-segment elevation myocardial infarction (STEMI) patients using endovascular thrombolysis. [30]

#### *3.2.4.2 Optimization model medical state transition matrices*

The optimization model requires a medical state transition matrix that is applied to evacuees at event FOL nodes at the end of every day. The transition matrix is calculated by simulating the progression of 10 000 000 evacuees through the colour-coded triage states. The data in Table 1-1 are used as the means of exponential distributions in this simulation. The simulation must be used once for each node type. The times are used to build a table of times representing each simulated evacuee's time in the states depending on their initial state. These times are then compared to a time window to determine what fraction of the population ended in which state. It has been assumed that every evacuee has spent 24 hours at their location at the end of each day, for a time window of 24 hours. This is clearly not true, but the formulation of the model does not distinguish individuals, making an assumption necessary overall even if it does not reflect individual situations. The resulting transition matrices that were used for the optimization model runs are found in Table 1-2.

**Table 1-2: Medical state transition matrices used for the optimization model. Rows give the initial state, columns the end state. The values in a row are the probabilities of ending in the corresponding end state given that the evacuee began in the row's state.**

| Event site transition matrix | | End state | | | | |
|---|---|---|---|---|---|---|
| | | White | Green | Yellow | Red | Black |
| Initial state | White | 0.819 | 0.141 | 0.0173 | 0.003 | 0.0195 |
| | Green | 0.0 | 0.606 | 0.111 | 0.0212 | 0.261 |
| | Yellow | 0.0 | 0.0 | 0.0498 | 0.0115 | 0.939 |
| | Red | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 |
| | Black | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 |

| FOL transition matrix | | End state | | | | |
|---|---|---|---|---|---|---|
| | | White | Green | Yellow | Red | Black |
| Initial state | White | 0.861 | 0.116 | 0.0124 | 0.00110 | 0.0103 |
| | Green | 0.0 | 0.687 | 0.116 | 0.0110 | 0.185 |
| | Yellow | 0.0 | 0.0 | 0.105 | 0.0109 | 0.884 |
| | Red | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 |
| | Black | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 |

## 2.3 Generalizing over the AoR

After the two models were developed and tested such that their results aligned within the limitations already stated above, the optimization model (only) was applied to the entire AoR. The definition of the AoR is discussed below in section 2.3.1. The generalization over the region used the optimization model because its run time is significantly lower than the simulation model. The exact run time of the solver depends on the details of the problem, mainly the number of aircraft included and the distances between nodes. A full discussion of the complexity of the problem is found in [25].

An `R` script was written to apply the model over the AoR using the model sweep algorithm given below. [32] The script makes extensive use of the `magrittr`, `tidyverse`, `maps`, `mapproj`, `sp`, `dggridR` and `gurobiR` packages.

Model sweep algorithm:

For each FOL, do the following:

1. Create a separate folder for the input and output files related to this FOL;
2. Look up the helicopter deployment time for this FOL;
3. Find all DGGS cells within range of the helicopters used for the scenario;
4. For each of these cells, do the following:
   a. Create a sub-folder for the input and output files related to this cell;
   b. Create an instance of the optimization model in MPS format for this FOL-cell combination by doing the following:
      i. Copy the common input data files to this folder;
      ii. Create modified versions of the input files that are affected by a change in FOL or cell;
      iii. Create an MPS file from the base optimization model file, incorporating the modified input data;
   c. Load the MPS file into `R` as a Gurobi model object;
   d. Call Gurobi to find a feasible solution to the model.
   e. Modify the model object with the feasible solution as a warm start solution[8];
   f. Call Gurobi to solve the model. Loop until an acceptable stopping condition is met:
      i. If the MIP gap is at or below specified level when the solver ended, exit the loop;
      ii. If the solver ended because the time limit was reached but MIP gap is below 5%, exit the loop;
      iii. Otherwise, update the model object with the best solution and call Gurobi again to solve the model;
   g. Write output to a Gurobi `.sol` file;
   h. Parse the Gurobi `.sol` file using `R` to create an `.RData` file;

After completing all FOL-cell combinations, another `R` script was run to read through all of the folders created, read the `RData` files and read the results of interest into a single `R` data frame. All analysis uses this data frame as its input.

The script was run on an HP Z840 dual-processor workstation, with an Intel® Xeon® E5-2650 v4 motherboard and 16 GB of RAM. This motherboard has two processors each with 12 cores and 24 threads. Total execution time is between 48 and 120 h. The exact time depends on the number of decision variables to be decided; cases with poorer response characteristics solve more quickly because the number of casualties is greater and therefore the number of decisions to be made within the model is smaller. The model is intensive in CPU usage but not memory; only a few gigabytes of memory are needed by the solver.

### 2.3.1 Geographic scope and representation of space

Initially the region considered in the study was limited to the sea and coastal areas around the NWP, due to the scenario and the fact that cruise ships that have transited the Arctic followed this path. Per the request of CJOC

[8] This is not the same as a full warm start including the entire solution tree.

staff during the interim updates on this study, the geographic scope of the study was expanded to include Hudson's Bay. It now corresponds more or less with the Canadian Arctic waters definition in [11].

The Canadian Arctic was discretized into approximately hexagonal regions projected onto the Earth's surface using a geodesic discrete global grid system (DGGS). [33] For this study, a discrete global grid using an Icosahedral Snyder Equal Area projection [34] with hexagonal cells, aperture 3 and resolution 8 (hereafter referred to as ISEA3H8) was created with `dggridR` [35], based on [36]. A DGGS avoids the problem of irregular shapes and areas that arises with grids based on latitude and longitude by tiling the Earth's surface with hexagonal cells of equal area projected onto the WGS84 ellipsoid. The ISEA3H8 DGGS is shown in Figure 2-2. Cells that contain no coastline have been removed due to the nature of the scenario.

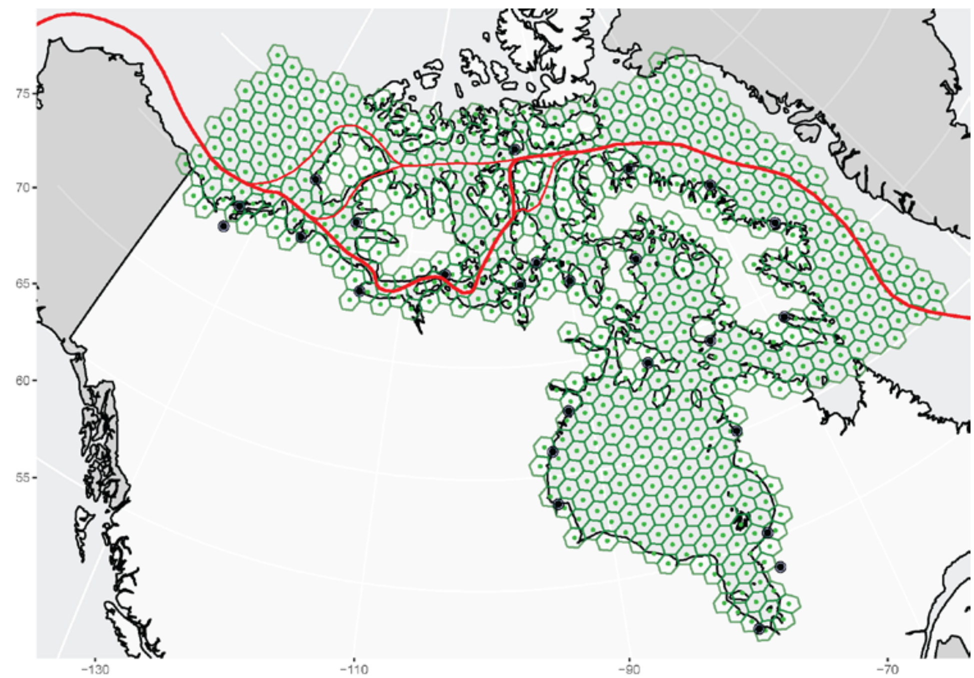


**Figure 2-2: The ISEA3H8 grid used to cover the area of interest. Blue and black dots indicate the location of FOLs. The Northwest Passage is indicated in red.**

Because of the shape of the WGS84 ellipsoid, there is some variation in the shape of the cells in order to keep the area constant. The area of a hexagon is 7774.2 $km^2$, which is equivalent to a circle with a diameter of 99.5 km.

Each of the cells shown in Figure 2-2 is referenced by a unique identifier and is modelled using the location of its centre. The 25 FOLs – the circled black dots shown – are modelled using their actual locations.

### 2.3.2 Weighting of cells

Weights were calculated for each cell in the grid. These were based on two functions taking into account three factors. The first function is the route weight, based on the distance between the cell in question and the nearest point on the NWP line as seen in Figure 2-2. First, the distance between all cell centres in the ISEA3H8 DGGS were calculated. Next, the NWP lines were mapped on the ISEA3H8 grid. Then, for each cell in that line, a weight was calculated for every other cell in the grid using a Cauchy function to create a relative weight using a scaling factor of 250 km.

The second weighting function is a generalized logistic function that increases with distance from a community and decreases with its population. This is a very subjective representation of the ideas that there is some inherent capability of communities to provide assistance in their neighbourhoods, and that larger communities are more capable than smaller ones. This function and its parameters are of course quite arbitrary. They have been selected such that the effect is smaller close to the community and decreases with distance, with almost all effect being lost by about 400 km away regardless of community size. This is intentional; current regulations require lifeboats for ships travelling north to carry 24 h of fuel. An approximate speed of 10 knots would allow them to cover 444 km in that time.

The two weighting functions were multiplied on a by-cell basis to create the final weighting map, as seen in Figure 2-3. While the weighting functions are arbitrary, this map already shows some interesting and useful features. It clearly identifies regions where cruise ship traffic might be expected and for which local support is not readily available (under the given assumptions). This map of weights will be used to create measures of performance below.

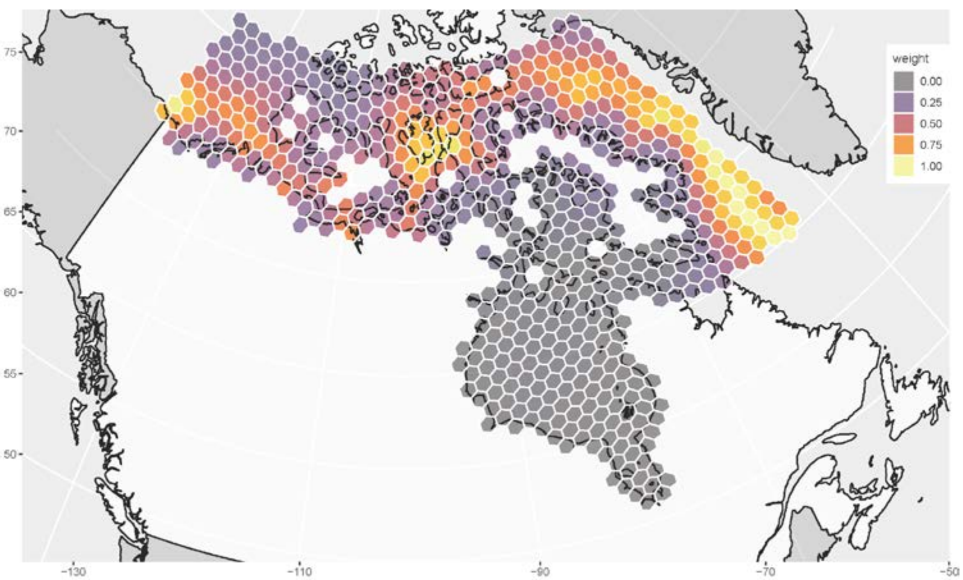


**Figure 2-3: Final weighting of cells in the ISEA3H8 DGGS based on product of the route weights and the community proximity weights**

### 2.3.3 Measures of performance

We define two measures of performance (MOPs) for the analysis of the optimization results. The first and more basic is the number of surviving evacuees in a cell. When analysing the results for a given set of FOLs, each cell is associated with the FOL that performs the best (that is, maximizes the number of survivors) and that number of survivors is taken as the measure for that cell. Because we solve all FOL-cell combinations, there may be more than one result per cell. We save all of these results, as this allows us to see the effect of removing an FOL from consideration.

The second MOP is the risk measure, defined as the product of the number of *casualties* (2000-survivors) and the cell weight value. This applies more importance to the cells that are expected to see traffic and that are far from settlements and devalues the rest. This is the more useful MOP of the two. By accumulating the risk measure by FOL we will see which are most critical to maintaining current effectiveness and also have the greater opportunity for improvement.

## 3.0 EXAMPLE APPLICATION

All numerical results have been removed from the following figures and discussion. Due to the assumptions made during the modelling process, it would be unwise to take the numbers at face value as that may create incorrect expectations. The real value of the results is in relating cells and FOLs to one another.

Figure 3-1 shows the number of survivors by cell for the baseline case of the current infrastructure configuration. Cells covering areas with no coastline have been removed. It can be seen that the number of survivors is greatest close to an FOL and decrease with distance. There is an additional gradient in survivors with increasing distance from the main operating bases of the helicopters (CFB Petawawa, Ontario for the CH147 Chinook and either CFB Gander, Newfoundland and Labrador or CFB Comox, British Columbia for the CH149 Cormorant). Some of the cells in Figure 3-1 are empty. These cells are outside of the range of the helicopters considered. The optimization model returns a result of zero survivors here. They have been left out of the colour scale to avoid obscuring the information in the remaining cells.

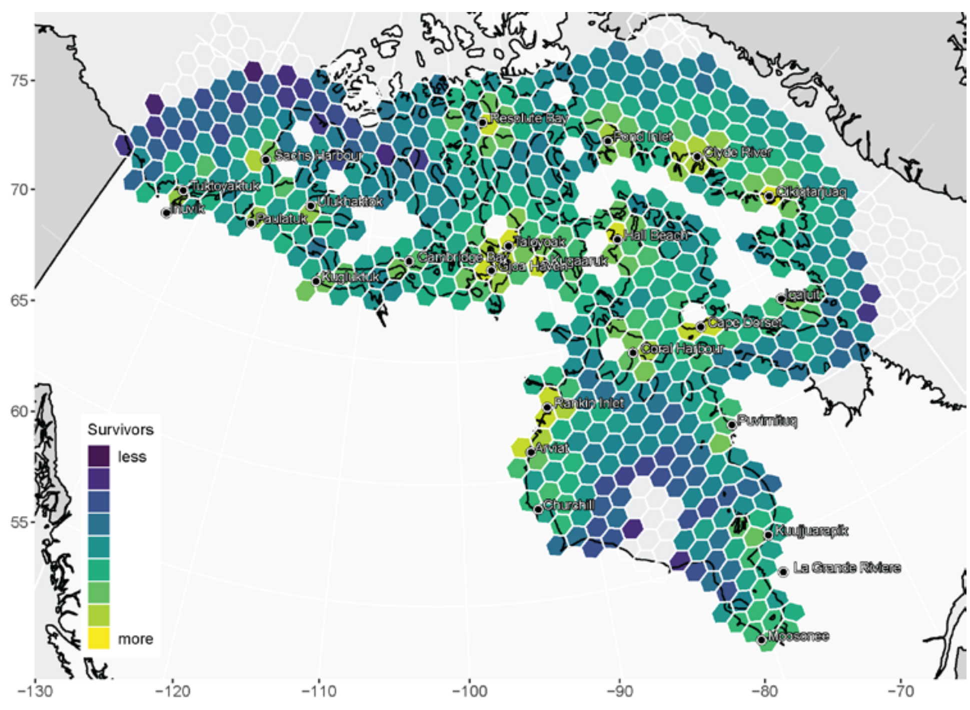


**Figure 3-1: Map of survivors as a function of the incident location. The result shown for a cell is the best achieved among all FOLs in range of the cell. Empty cells are out of helicopter range or landlocked.**

Multiplying the number of casualties (the counterpart of the results shown in Figure 3-1) by the cell weights found in Figure 2-3 results in the risk measure MOP. This is shown in Figure 3-2. As before, empty cells are outside of helicopter range and are excluded to make a more readable figure. This figure shows three concentrations of risk: the far west of the AoR, from the American border to just west of Sachs Harbour; around Peel Sound and the

Franklin Strait along the Cambridge Bay – Resolute Bay axis, around the upper centre of the map; and from Lancaster Sound east of Resolute Bay down through Baffin Bay and into the Davis Strait (between Baffin Island and Greenland). These are the regions of greatest concern under the current assumptions.

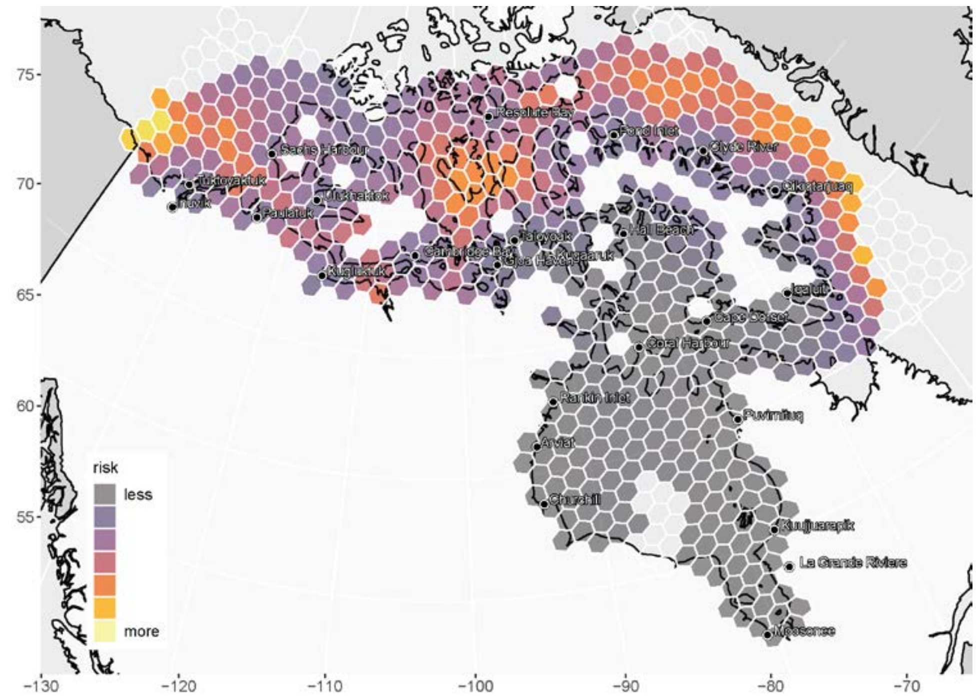


**Figure 3-2: Risk measure by cell. The measure is defined as the product of the number of casualties and the cell weight. The result shown for a cell is the best achieved among all FOLs in range of the cell. Empty cells are out of helicopter range or are landlocked.**

The risk measure can be grouped by FOL to give an indication of which FOLs are more likely to be used to respond to a MAJMAR and also the quality of that response. Figure 3-3 shows the mean risk measure by FOL plotted against the number of cells attributed to that FOL. FOLs that are located in the upper right of the graph are "at-risk" FOLs, more likely to experience MAJMARs to which they cannot respond well while also serving a large area. Comparing Figures 3-2 and 3-3, it can be seen that most of the at-risk FOLs are located in the north-east quadrant of Figure 3-2.

The main objective of the study was to develop a methodology to assess the impact of infrastructure investments and divestments. Because we solved the model for all FOL-cell combinations, not just the best ones, it is simple to assess the effect of a site divestment. First we sum the risk measure over all FOLs for the baseline situation. Next, we remove each FOL in turn and reassign each cell to the next best FOL. In some cases, there is no other FOL that can serve that cell. We then sum the risk measure MOP again. The difference between the baseline sum and the current sum for the removed FOL is the penalty for the removed FOL. This is shown for all FOLs in Figure 3-4, in order of decreasing penalty. Under the given cell weights, the region served by Resolute Bay in the Vaseline infrastructure configuration is the most sensitive to loss or divestment, followed by Qikiqtarjuq, Iqaluit, Pond Inlet, Clyde River, and Sachs Harbour. These locations are the six rightmost points in Figure 3-3. Further investigation shows that the global risk measure is most sensitive to these locations because they have the most cells without redundant coverage – if any one of these is removed, there are many cells that have no backup location or which are very poorly served by those backup locations.

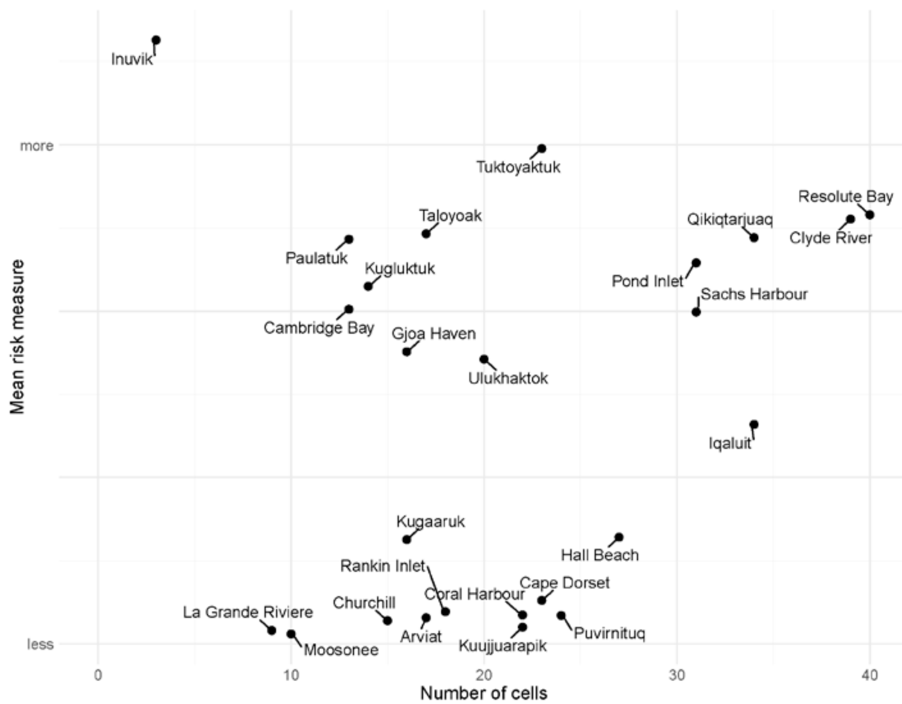


**Figure 3-3: The mean risk measure for an FOL as a function of the number of cells for which that FOL maximizes the number of survivors.**

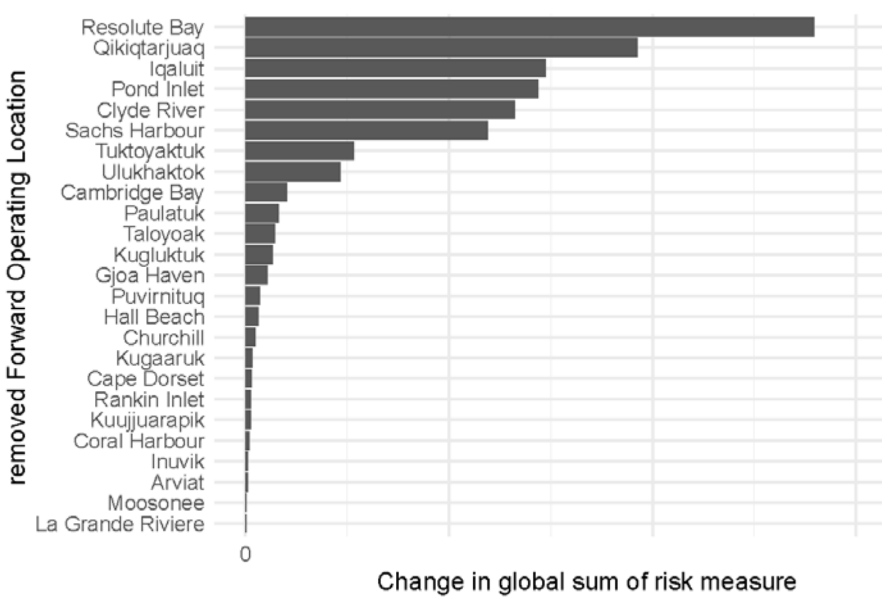


**Figure 3-4: The increase in the global sum of the risk measure if a particular FOL is removed.**

Applying the methodology to other infrastructure investment/divestment decisions requires more effort because the algorithm must be applied a second time rather than simply exploiting the underlying data structure of the baseline results.

## 4.0 DISCUSSION

The mixed integer-linear programming model does not contain as much detail about infrastructure or capabilities as desired. Some factors are suitable for implementation in a pure mathematical optimization model, but may require a departure from strictly integer-linear programming. Significant factors or capabilities that could be accounted for in an optimization model framework are

- Model the effects of CCG and Royal Canadian Navy (RCN) ships;
- Runway load limits on the combined mass of aircraft and cargo by airfield;
- Caps on ramp space and basing that restrict the maximum-on-ground aircraft and also the number of aircraft that can be based at an airfield;
- Airfield capabilities such as de-icing equipment and instrument landing aids;
- Storage capacity for fuel and supplies, and shelter for personnel and evacuees. The latter could also be expanded to include the available electrical supply, water supply and sewage disposal capacity; and
- Modelling of fuel and supply consumption by evacuees and military personnel with penalties for shortfalls.

Other relevant factors are stochastic in nature and are less amenable to a pure optimization approach. Because of this they have not been included. Two principle ones are the effects of weather and the random nature of equipment failures. The current default assumption for the scenario is that the weather is clear and dry for the duration of the analysis period, a dubious assumption at best. Poor weather would worsen the health prognosis for the evacuees and hinder the evacuation effort. Similarly, it is currently assumed that all aircraft can be made serviceable within the allotted turn-around times built into the model and input data. It would be more realistic to create a service/failure model that inserts breakdowns into the solution process at random intervals.

Related to the concept of adding stochastic events is the fact that the current optimization model has complete knowledge of the future; it knows exactly how decisions made on day 1 will affect all subsequent days. Stochastic or approximate dynamic optimization could be used to achieve a more realistic decision process wherein choices must be made with imperfect knowledge, including the weather and breakdown effects, but also randomizing the survival outcomes of individual evacuees.

Solution time is an issue for this methodology. Complete solution of all FOL-cell combinations can take up to a week or more with the reported hardware configuration. Adding features as described above will increase this further. Future applications of the methodology should consider using a lower resolution DGGS to reduce the number of FOL-cell combinations examined, or restrict the area of interest, depending on the type of infrastructure decision under consideration.

## 5.0 CONCLUSION

We have demonstrated a methodology to assess the impact of infrastructure investment and divestment decisions on the CAF response to MAJMAR scenario in Canada’s Arctic. Although the we used a MAJMAR scenario, the method is applicable to other scenarios which include transportation or evacuation of individuals, such as natural disasters, humanitarian crises and major air disasters. Applying it to more general military scenarios is possible with changes to the underlying model.

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