Airships for military logistics heavy lift

A performance assessment for Northern operation applications.

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Abstract

An airship is a self-propelled lighter-than-air aircraft with directional control surfaces. Unlike an airplane, the lift for an airship is generated aerostatically by the buoyancy of a lifting gas. Airships are being considered by the Canadian Forces (CF) as potential platforms to address deficiencies in logistics transportation to support Northern operations. Airships could provide a cost-effective point-to-point delivery capability and could mitigate several limitations (e.g., infrastructure requirements) associated with other forms of transport. This paper presents an assessment of the airship capability for logistics heavy lift in support of CF Northern operations. Performance measures were developed to assess the effectiveness and the responsiveness of the airship lift. A Monte Carlo simulation framework was also developed to simulate various logistics lift scenarios. A sensitivity analysis was conducted to address the impact of different operational parameters on the airship lift effectiveness. The study indicates that airships could potentially improve the sustainability of CF Northern operations. Significant potential cost avoidance and response time reduction could be realized on sustainment lift by using airships versus fixed and rotary wing aircraft.

Résumé

Un dirigeable est un automoteur plus léger que l'air avec un système de direction. Contrairement à un aéronef, l'élévation d'un dirigeable est générée aérostatiquement par la flottabilité d'un gaz de levage. Les dirigeables sont considérés par les forces canadiennes (FC) comme un véhicule de transport potentiellement capable de corriger les lacunes logistiques enregistrées dans leurs opérations du Nord. Avec une importante capacité de charge et une livraison directe à des endroits sans infrastructures, ces dirigeables constitueraient une solution sécuritaire, souple et efficace qui permettrait d'atténuer plusieurs limitations et exigences associées aux autres moyens de transport. Ce document présente une évaluation de la capacité des dirigeables à appuyer les opérations des FC dans le transport du matériel lourd vers le Nord. Des mesures de performance ont été élaborées pour évaluer l'efficacité et la réactivité des dirigeables. Un cadre de simulation de Monte Carlo a également été développé pour simuler différents processus de livraison vers le Nord Canadien. Une analyse de sensibilité a été menée pour analyser l'impact des différents paramètres de fonctionnement sur l'efficacité des dirigeables. L'étude montre que les dirigeables pourraient améliorer la viabilité des opérations nordiques des FC. Des réductions importantes dans les coûts du transport et dans le temps de réponse pourraient être réalisées si les dirigeables étaient employés dans ces opérations.

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Executive summary

Airships for military logistics heavy lift: A performance assessment for Northern operation applications

Ahmed Ghanmi; Abderrahmane Sokri; DRDC CORA TM 2010–011; Defence R&D Canada – CORA; January 2010.

Background

To maintain its sovereignty over its Northern region, Canada will need to develop enforcement and surveillance capabilities for the Arctic. In particular, a logistics heavy lift capability would be required to support the deployment and sustainment of the Canadian Forces (CF) in remote austere environments in the North. While the CF has procured a fleet of CC-177 and CC-130J aircraft for strategic and tactical lift respectively, these assets can land only in a few Northern airfields due to the runway requirements.

Airships are being considered by the CF as possible platforms to address deficiencies in logistics heavy lift for Northern operations. An airship, also known as a dirigible, is a self-propelled lighter-than-air aircraft with directional control surfaces. Unlike an airplane, the lift for an airship is generated aerostatically by the buoyancy of a lifting gas. Airships could provide a cost-effective point-to-point delivery capability and could mitigate several limitations (e.g., infrastructure requirements) associated with other forms of transport.

Operational research request

Canadian Operational Support Command (CANOSCOM) has identified that airships are potential options for logistics heavy lift and has requested an Operational Research study to assess the cost effectiveness, time responsiveness, and operational limitations of airship lift for Northern operations.

Methodology

This study examines the airship capability for military logistics heavy lift in support of CF Northern operations. Performance measures were developed to assess the cost effectiveness and the time responsiveness of the airship lift. A Monte Carlo simulation framework was developed to simulate the airship logistics lift cost and time for different deployments in Northern Canada. Various deployment locations were examined by dividing the Northern region into different potential deployment areas. A sensitivity analysis was conducted to address the impact of different operational parameters on the airship lift effectiveness and responsiveness. A qualitative assessment of the airship capability was also provided to highlight the operational limitations and the requirements of airship lift for Northern operations.

Conclusions

The study indicates that airships could potentially improve the sustainability of CF Northern operations. Depending on the deployment location, potential cost avoidances of up to 60% would be realized on the sustainment lift by using airships instead of the current transportation approach. The lift response time would also be significantly reduced, particularly for regions located far from the Northern airfields. However, as theoretical data on airship technical performance were used for the analysis (airships are still in the scale model prototype phase and their operating data are determined using computer simulations), these operational performances might be different in reality.

In addition to the cost avoidance and the response time reduction, airships would have the potential to significantly reduce fuel consumption and greenhouse gas emissions, which would confer substantial environmental benefits. Indeed, airships rely primarily on buoyant gas to keep their mass aloft and consequently require little direct energy to create lift. While the main focus of the analysis has been on the airship lift cost effectiveness and time responsiveness for military logistics heavy lift, an examination of the airship fuel consumption data indicated that up to 50% of carbon emission could potentially be avoided with airships, depending on the deployment location.

Recommendations

Following this study, it is recommended that:

1. The CF should consider airship technologies to address deficiencies in logistics transportation to support Northern operations. Airships could provide a cost-effective point-to-point delivery capability, mitigate several limitations (e.g., infrastructure requirements) associated with other modes of transport and potentially improve the sustainability of Northern operations. Airships could operate under Northern environmental conditions for most of the year (e.g., 10 months) and could be used in most geographical locations in the North.

2. The CF should also consider airships for tactical logistics lift. Freight could be moved by fixed-wing aircraft to a Northern airfield or by ships to a Northern seaport and then lifted by tactical airship to the final destination.

3. CANOSCOM should examine the operational requirements for using airships in Northern operations. In particular, the requirements for infrastructure, de-icing, ground handling, refuelling, forward operating base locations and intermodal transfer need to be investigated.

4. CANOSCOM should examine the different options for contracting airship services, including long term lease and time charter options and determine the appropriate option for domestic operations. This requires a better understanding and an analysis of future logistics lift requirements.

5. Further analysis should be undertaken to address other aspects of the airship logistics heavy lift, particularly for expeditionary operations. In addition, studies should be initiated into other uses for airships such as surveillance, communication, power generation, and security applications.

Sommaire

Emploi de dirigeables pour le transport militaire de charges lourdes : Évaluation du rendement dans le contexte des opérations dans le Nord

Ahmed Ghanmi; Abderrahmane Sokri; RDDC CARO TM 2010–011;
Recherche et développement pour la défense Canada – CARO; Janvier 2010.

Contexte

Afin de maintenir sa souveraineté dans la partie nord de son territoire, le Canada devra acquérir des moyens de surveillance et d'application de la loi pour l'Arctique. En particulier, il lui faudrait un moyen de transport de charges lourdes pour soutenir le déploiement et le maintien en puissance des Forces canadiennes (FC) dans les espaces éloignés et inhospitaliers du Nord. Les FC on fait l'acquisition d'une flotte d'avions CC177 et CC130J pour répondre à leurs besoins stratégiques et tactiques, respectivement, mais ces appareils ne peuvent se poser qu'à quelques aérodromes du Nord en raison de la longueur de piste dont ils ont besoin.

Les FC envisagent de recourir aux dirigeables pour remédier aux lacunes en matière de transport de charges lourdes aux fins des opérations dans le Nord. Un dirigeable est un aérostat autopropulsé plus léger que l'air muni de commandes de direction. Contrairement à ce qui est le cas d'un avion, la portance d'un dirigeable est d'origine aérostatique et elle est due à la poussée hydrostatique d'un gaz de sustentation. Les dirigeables constitueraient un moyen rentable de livraison point à point et élimineraient plusieurs contraintes (p. ex., l'infrastructure nécessaire) liées à d'autres formes de transport.

Demande de recherche opérationnelle

Le Commandement du soutien opérationnel du Canada (COMSOCAN) a établi que les dirigeables représentent une solution éventuelle pour assurer le transport de charges lourdes et il a demandé une étude opérationnelle afin d'évaluer la rentabilité et les limites opérationnelles du transport par dirigeable dans le cadre des opérations dans le Nord, ainsi que les délais d'exécution avec ce mode de transport.

Méthodologie

La présente étude porte sur l'emploi de dirigeables pour assurer le transport de charges lourdes à l'appui d'opérations des FC menées dans le Nord. Nous avons défini des critères de rendement afin d'évaluer la rentabilité du transport par dirigeable et les délais d'exécution avec ce mode de transport. Nous avons utilisé une simulation Monte Carlo pour examiner le coût du transport logistique par dirigeable et les délais d'exécution correspondants dans différents déploiements dans le Nord canadien. L'étude a porté sur divers lieux de déploiement et, pour cela, nous avons divisé le Nord en zones de déploiement potentielles. Nous avons fait une analyse de sensibilité pour cerner les effets de divers paramètres opérationnels sur l’efficacité et la souplesse du transport par dirigeable. Nous avons aussi fait une évaluation qualitative des capacités du dirigeable afin de mettre en lumière les limites opérationnelles et les exigences de ce moyen de transport dans le contexte des opérations dans le Nord.

Conclusions

L’étude montre que les dirigeables pourraient améliorer la soutenabilité des opérations des FC dans le Nord. Selon le lieu de déploiement, il serait possible de réduire le coût du transport de soutien jusqu’à 60 p. 100 en utilisant des dirigeables au lieu des moyens de transport actuels. Les délais de transport seraient eux aussi grandement raccourcis, surtout dans les régions situées loin des aérodromes du Nord. Cependant, comme des données théoriques sur les performances techniques des dirigeables ont été employées dans l’analyse (on en est encore à utiliser des maquettes prototypes de dirigeable, et les données sur leur fonctionnement sont définies au moyen de simulations informatiques), les performances opérationnelles risquent d’être différentes dans la réalité.

Outre que les dirigeables permettraient de réduire les délais de transport et les coûts, ils contribueraient sans doute à une diminution de la consommation de carburant et des émissions de gaz à effet de serre, ce qui représenterait un avantage environnemental considérable. En effet, les dirigeables tirent leur sustentation principalement de gaz de gonflement, et il leur faut donc peu d’énergie directe pour engendrer la portance. L’analyse a principalement porté sur la rentabilité du transport par dirigeable et sur les délais d’exécution du transport militaire de charges lourdes, mais un examen des données sur la consommation de carburant de ces appareils a montré que ceux-ci permettraient d’obtenir une réduction des émissions de carbone pouvant aller jusqu’à 50 p. 100, selon le lieu de déploiement.

Recommandations

À la suite de cette étude, nous formulons les recommandations suivantes :

1. Les FC devraient envisager de recourir aux dirigeables pour remédier aux lacunes relatives au transport logistique nécessaire au soutien des opérations dans le Nord. Les dirigeables pourraient constituer un moyen rentable de livraison point à point, éliminer plusieurs contraintes (p. ex., les exigences infrastructurelles) liées à d’autres modes de transport et améliorer la soutenabilité des opérations dans le Nord. Les dirigeables pourraient fonctionner dans les conditions environnementales arctiques pendant la majeure partie de l’année (10 mois) et presque partout dans le Nord.

2. Les FC pourraient aussi employer les dirigeables dans un rôle de transport tactique : le fret pourrait être transporté par avion jusqu’à un aérodrome du Nord, ou par bateau jusqu’à un port maritime du Nord, puis acheminé par dirigeable tactique jusqu’à sa destination finale.

3. Le COMSOCAN aurait avantage à examiner les exigences opérationnelles liées à l’utilisation de dirigeables dans le Nord, notamment en ce qui concerne l’infrastructure, le dégivrage, le service au sol, le ravitaillement en carburant, l’emplacement des bases d’opérations avancées et les transferts intermodaux.

4. Le COMSOCAN devrait examiner différentes options en ce qui concerne l'adjudication de contrats d'utilisation de dirigeables, y compris des baux à long terme et l'affrètement à temps, et choisir l'option convenant le mieux aux opérations intérieures. Pour cela, il faut mieux comprendre et analyser les besoins à venir en matière de transport logistique.

5. Il convient de mener d'autres analyses sur d'autres aspects du transport de charges lourdes par dirigeable, notamment aux fins des opérations de forces expéditionnaires. En outre, il faut amorcer des études sur d'autres rôles que pourraient assumer les dirigeables, par exemple la surveillance, les communications, la production d'énergie et la sécurité.

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1. Introduction

…But the North needs new attention. New opportunities are emerging across the Arctic, and new challenges from other shores. Our government will bring forward an integrated northern strategy focusing on strengthening Canada's sovereignty, protecting our environmental heritage, promoting economic and social development, and improving and devolving governance, so that northerners have greater control over their destinies…

Speech from the Throne October 16, 2007 [1]

1.1 Background

Northern Canada, colloquially the North, is the vast northernmost region of Canada variously defined by geography and politics. The term refers to the three territories under the jurisdiction of the federal government: Yukon, the Northwest Territories and Nunavut. The region is characterised by its low population density (Figure 1) and presents many challenges in terms of surveillance, regulation, and infrastructure development.

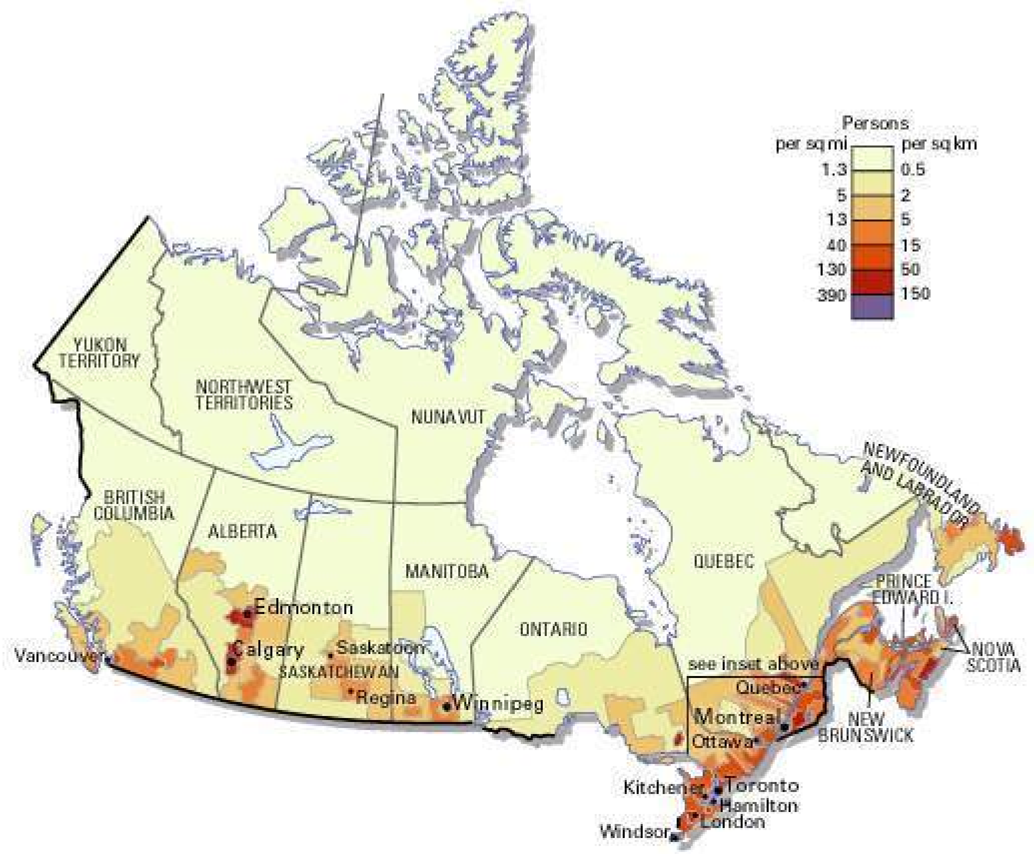

Figure 1: Population density in Canada

Northern Canada has been particularly sensitive to climate change over the past 30 years. Recent scientific evidence suggests that the average area covered by sea ice has decreased by about 8% and the average thickness of sea ice has decreased by about 10 to 15% over this period [2]. These environmental changes are generating opportunities for economic development and scientific research activities in the Northern region. 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) [3].

To maintain its sovereignty over its Northern region, Canada will need to develop enforcement and surveillance capabilities for the Arctic. In particular, a logistics heavy lift capability would be required to support the deployment and sustainment of the Canadian Forces (CF) in remote austere environments in the North. While the CF has procured a fleet of four CC-177 aircraft for strategic lift, these assets can land in only a few Northern airfields due to their runway requirements. In addition, the Arctic lacks a road infrastructure network that can effectively connect the north to the south as shown in Figure 2.

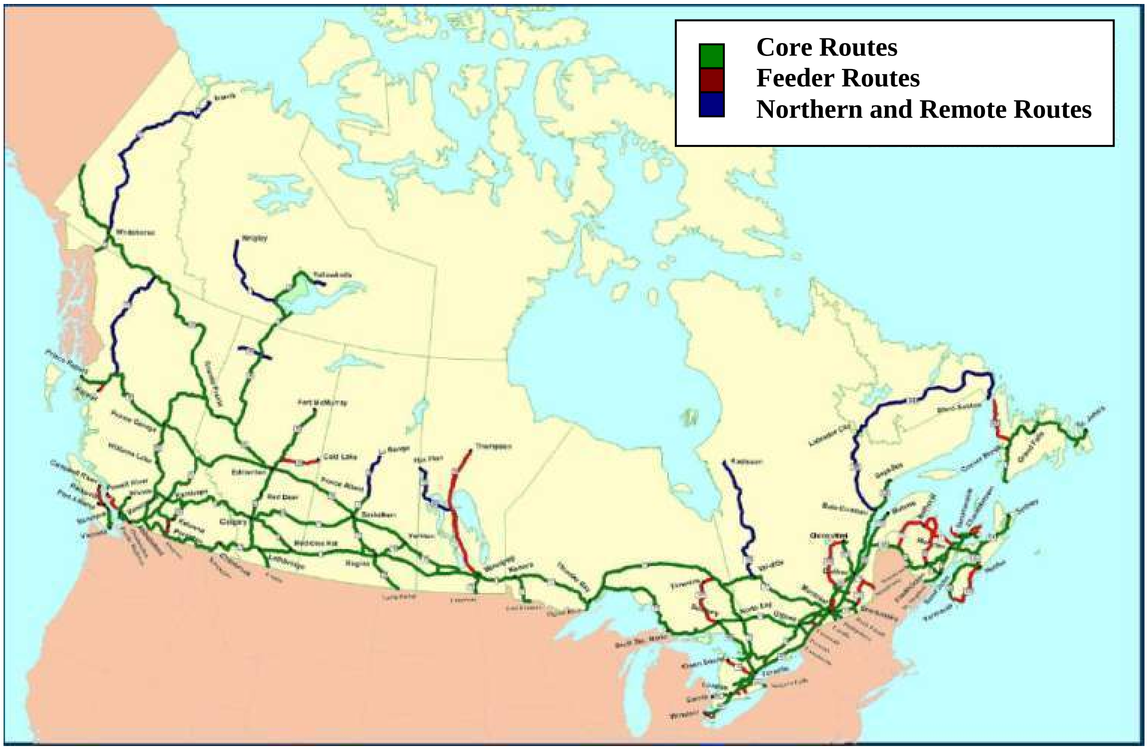

Figure 2: National highway system in Canada as of December 2007

Lighter-Than-Air (LTA) airships (Figure 3) are being considered by the CF as possible platforms to address deficiencies in logistics heavy lift for Northern operations, to address national surveillance requirements over large remote areas, and to extend high bandwidth communications to the Arctic [4]. An airship, also known as a dirigible, is an aerostatic vehicle that can be steered and propelled through the air using rudders and propellers or other thrust. Unlike aerodynamic aircraft (e.g., fixed-wing aircraft and helicopters) which produce lift by moving a wing through the air, aerostatic aircraft (e.g., airships) stay aloft by filling a large cavity with a lifting gas (e.g., Helium). In military applications, LTA can be used for tactical or strategic logistics lift during deployment and sustainment operations. Further descriptions of LTA airships are discussed in Section 2.

Figure 3: Lighter-than-air airship

1.2 Aim

The Canadian Operational Support Command (CANOSCOM) has identified airships as one of the potential options that could be used as an affordable and flexible (in terms of landing infrastructure requirement) capability for logistics heavy lift in the Arctic. This study aims to analyze the airship logistics lift effectiveness and responsiveness in support of Northern operations for CANOSCOM.

1.3 Literature review

While the study of strategic airlift and sealift problems has spawned several noteworthy papers in the open literature, airship lift problems have received comparatively little attention due to the lack of technical and operational performance data. Indeed, modern heavy lift airships are currently in the scale model prototype phase and their operational parameters are estimated using computer simulations. Gazder and Rajkumar [5] conducted a comparative cost analysis of airships and helicopters as alternative modes of passenger transportation in Uttaranchal, India. They developed a methodology for estimation of direct operating costs of airships and helicopters and used two 5-seater non-rigid airships and two 5-seater helicopters for the analysis. The study indicated that helicopters would have better payload capability at all operating altitudes and lower overall annual operating cost than airships. Indeed, even though airships are much more fuel-efficient than helicopters, their annual operating costs are still significantly higher than helicopters due to the initial investment for ground support infrastructure.

Prentice *et al* [6] examined the niche market for airships and discussed the inherent advantages and disadvantages of the airship mode of transportation. They developed an economic model to evaluate the cost effectiveness of heavy lift airships. They analyzed two potential airship lift applications: a long-haul airship service for the transport of pineapple and papaya between Hawaii and North America and a short-haul airship service for the transport of goods and passengers to remote Northern communities in Canada. The study indicated that airships would be a potential cost-effective mode of transport particularly for logistics heavy lift to remote areas such as Northern Canada.

Newbegin [7] conducted a quantitative analysis of the use of airships for deploying US Army forces in a theatre of operations. He considered three typical deployment scenarios for the analysis (strategic airlift of an interim brigade combat team to Southeast Asia, strategic airlift of an armoured cavalry regiment to the Middle East, intra-theatre airlift of a Helicopter battalion) and compared the airship lift cost and time with various strategic lift aircraft such as the C-17 and the C-5 aircraft. The study indicated that while airships have a slight edge in total deployment time, they have an advantage in deployment cost as they burn much less fuel to accomplish the mission. Gordon and Holland [8] conducted a qualitative assessment of the operational requirements and effectiveness of airship strategic lift for deployed operations for the US Air Force. They indicated that airships could potentially be used for strategic and tactical deployment lift of expeditionary operations. Prentice and Thomson [9] conducted an economic evaluation of using a new generation of cargo carrying airships to support northern mining operations. They developed an economic model to analyze fuel transportation costs for a cluster of mines located in the North West Territories. They considered a generic airship that could carry 84 tonnes of fuel or general freight and conducted a lift cost analysis. The study indicated that logistics transportation for Northern resources development would be a potential application for which a heavy lift airship could be economically viable, based on reasonable performance assumptions.

In DRDC, different operational research studies have been conducted to address various military logistics lift problems. However, to our knowledge, there is no paper focusing on airship applications. Comeau [10], for example, developed a Strategic Mobility Optimization Model for Lift Capability Analysis (STRATL). The model used a linear optimization routine to allocate cargo to various aircraft and ships under consideration. STRATL was developed for strategic lift concept development. Dickson [11] conducted a study on the examination of the strategic lift capability of aircraft fleets with the potential for acquisition. He examined the fleet sizes (strategic lift capability) required to meet current and projected CF commitments based on representative force structures deployed to typical locations. Scales [12] studied the heavy lift requirements for Major Air Disaster (MAJAID) response in Northern Canada. She evaluated the response times for MAJAID operations using different strategic and tactical airlift assets. Ghanmi and Shaw [13] conducted an analysis of some of the strategic lift options for the CF and developed a simulation framework to study the effectiveness of a variety of pre-positioning options. They also developed an aircraft load allocation optimisation model, using simulated annealing and genetic algorithm methods, to solve multi-objective optimisation problems associated with allocating a set of cargo items across a heterogeneous fleet of available airlift assets [14]. Recently, Ghanmi [15] examined the hub-based support concept for the CF and developed a mathematical model to assess the effectiveness of different hubs and to determine the optimal hub locations for deployed operations. The model was formulated as a discrete facility location problem and was implemented using mixed integer nonlinear programming. He also developed an aircraft routing model to determine the optimal aircraft routes within a network of support hubs [16].

This study examines the airship capability for military logistics heavy lift in support of CF Northern operations. Performance measures were developed to assess the effectiveness and the responsiveness of the airship lift. A Monte Carlo simulation framework was also developed to simulate sustainment lift to various deployment scenarios in Northern Canada using airships. A sensitivity analysis was conducted to address the impact of different operational parameters on the airship lift effectiveness.

1.4 Document structure

This report is organized as follows. Following the introduction, Section 2 provides a detailed description of the airships' state of the art. In Section 3, the airship lift is examined for a typical CF operation in the North, namely Operation Boxtop. Section 4 provides a qualitative assessment of the airship lift capability and requirements. In Section 5, a quantitative analysis is conducted to assess the airship lift effectiveness and responsiveness for logistics heavy lift in support of Northern operations. Concluding remarks and recommendations for future analysis and development are found in the sixth and final Section.

2. Airship – state of the art

This section presents a historical background of the airship technology, discusses the basics, strengths and weaknesses of airship lift and highlights some current commercial airship models.

2.1 Historical perspective

Airships were the first aircraft to make controlled and powered flight. Their development started even before the 20th Century. The most famous airship at that time was the Zeppelin, developed by Ferdinand Zeppelin, a German military officer. Historically, airships were used in different military roles such as bombing, reconnaissance, anti-submarine warfare and ocean surveillance [17]. However, because of their combustible hydrogen lifting gas they quickly became vulnerable to attacks and obsolete for military purposes. Their decline was confirmed by many disasters, including notably the burning of the hydrogen-filled Hindenburg airship in 1937 [18].

For decades, the memory of the Hindenburg catastrophe, as well as technological advances in heavier-than-air flight, trucking, and maritime transport made the large airship seem a slow, cumbersome, and ultimately tragic detour in the history of transportation. In the 21st Century, interest has been renewed in airships due to technological developments in a number of fields including materials science, engines, weather forecasting, avionics and computer assisted design. With improved performance and cost profiles, large airships are being considered again, but for new roles in the movement of commercial general freight, fluids and passengers as well as for some military applications.

Interest in airships has been heightened further by their indirect advantages. These vehicles could mitigate several negative externalities associated with other forms of transport. Concerns about port, road, and airport congestion, and evidence of climate change have caused all nations to reconsider their transportation systems. The inherent fuel efficiency of airships is a further economic incentive. Currently, several firms in different countries are developing research prototypes and commercial airships. The creation of a new mode of transport can have profound economic effects. Improved service and lower transportation costs can stimulate new commodity flows, industrial activity and create new trade routes.

2.2 Airship basics

For logistics heavy lift, an airship has obviously different operating characteristics than an aircraft. Some operating characteristics are better, some are not, and some are just different. In order to understand the capabilities and limitations of airships, certain basic principles must be understood.

2.2.1 Aerostatic versus aerodynamic lift

Unlike an airplane for which lift is generated aerodynamically, the lift required for an airship to leave the ground is produced aerostatically by the buoyancy of the lifting gas in the surrounding air. The difference between the two lift forms is that aerodynamic lift costs horsepower and fuel in the form of induced drag, which is roughly proportional to the lift required. This is in addition to parasitic drag—so-called because it does not provide anything useful, like lift—which varies with the square of the velocity of the aircraft and explains why higher speeds require significantly more thrust. Aerostatic lift, on the other hand, has no induced drag component. The vehicle is lifted by the buoyancy of the lifting gas and what the engines must do is overcome parasitic drag to move the vehicle through the air. The two lifting gases historically used in airships are hydrogen and helium. Hydrogen is less dense so it has slightly more lift, about 70 pounds per 1000 cubic feet of gas versus 65 for helium. It is also considerably less expensive.

2.2.2 Rigid, semi-rigid and nonrigid airships

From a structural viewpoint, airships are classified in three categories, rigid, semi-rigid and nonrigid. Rigid airships have rigid frames containing multiple, non-pressurized gas cells or balloons to provide lift. They do not depend on the internal pressure of the lifting gas to maintain their shape. Rigid airships are much more expensive to produce than the nonrigid variety primarily because of the complexity of the aluminum hull structure. Rigid airship programs ended after successive technical failures of several experimental tests and no rigid airships have been built since the 1930s. Semi-rigid airships require internal pressure to maintain their shape but have extended, usually articulated keel frames running along the bottom of the envelope to distribute suspension loads into the envelope and allow lower envelope pressures.

Nonrigid airships are the only airship types constructed today. Their shape is maintained by slight pressurization of the lifting gas inside the envelope. The typical lifting gas is helium. The biggest drawback of nonrigid airships is the limitation in size by the strength of the fabric used in the envelope. Even though it is only slightly pressurized, the larger a nonrigid airship gets the greater the stress on the fabric even if the internal pressure remains constant. Nonrigid airships are currently used for many military applications such as maritime surveillance, border patrol, anti-drug trafficking, pollution control, photographic mapping, oceanographic research and hydrographic surveys. Commercial and military heavy lift applications of nonrigid airships are being investigated.

2.2.3 Pressure Height

As discussed in [8], when an airship climbs the lifting gas within it expands as atmospheric pressure decreases. The lifting gas must be allowed to expand for two reasons. First, to try to contain it under increasing pressure would put unnecessary stress on the envelope. Although an airship may appear to be highly pressurized, the pressure inside the envelope is maintained only slightly above ambient pressure to maintain its structural integrity. Second, because the pressure and density of the atmosphere decreases with altitude, as the airship climbs the lifting gas must continue to provide the same amount of buoyant lift and must be allowed to expand to displace additional ambient air. In a nonrigid airship, this is accomplished by incorporating separate, smaller envelopes called ballonets within the main envelope. The ballonets are filled with ambient air and expand and contract opposite the lifting gas. Before takeoff the ballonets are filled with air and the rest of the envelope with helium. As the airship rises and the helium expands within the main envelope, air in the ballonets is released into the atmosphere and the ballonets contract.

The pressure height of the airship, which is generally the maximum operational ceiling, is the altitude at which the ballonets are completely emptied of air and helium fills the main envelope. When the airship descends and the helium contracts the ballonets are refilled with atmospheric air to compensate for the shrinking helium and maintain the same relative pressure and total volume of gas within the main envelope. The design pressure height of an airship is important because it determines the proportion of total envelope volume allocated to air in the ballonets—more air means greater pressure height, but it also means less of the main envelope is allocated to helium at takeoff, which means less lift.

2.2.4 Buoyancy compensation

Another aspect of airship operations that is not technically obvious is buoyancy compensation [8]. When an airship takes off with neutral buoyancy the aerostatic lift produced by the helium is equal to the total weight of the vehicle—the combined weight of the structure, payload, and fuel. As fuel is burned en route, however, the total weight of the airship decreases but the aerostatic lift remains the same. If nothing is done, over time the ship will gain significant positive buoyancy. As this is undesirable from both a control and structural viewpoint, the airship must have a mechanism for buoyancy compensation. Hydrogen-filled airships simply vented excess hydrogen into the atmosphere to compensate for the weight of fuel burned. This was an acceptable solution because hydrogen was both inexpensive and easily generated wherever the airships were scheduled to land and refuel. Not so for helium, which is considerably more expensive and cannot always be generated locally. Helium-filled airships are constructed with an apparatus on the engine exhaust to condense and recover the water it contains. The water is then stored to compensate for the weight of fuel burned. While a seemingly elegant solution to the en route buoyancy compensation problem, the water recovery apparatus is heavy, sometimes unreliable, and the condensers mounted on the skin of the airship add drag. While the equipment has improved over time, the water recovery problem as a whole remains a challenge of helium-inflated airships.

The other aspect of the buoyancy compensation problem occurs when cargo is offloaded at destination. If an airship arrives at a destination with neutral buoyancy and offloads its cargo load, it immediately has excess lift. For an airship in commercial operations this is addressed by onloading equivalent ballast, either outbound cargo, water, or both, as the inbound cargo is removed. It can be problematic for a military airship however, as there is often no outbound cargo during a buildup at a forward operating base.

2.2.5 Hybrid aircraft

Addressing the destination buoyancy compensation problem when ballast is not available is one of the main reasons driving examination of the Hybrid Aircraft (HA). A HA is an airship in which significant lift is provided both aerostatically and aerodynamically. While all airships generate and make use of a small amount of aerodynamic lift, it is generally only to address minor buoyancy issues en route. The cylindrical fuselage of a conventional airship is optimized for volumetric efficiency of the lifting gas and low parasitic drag, not to generate lift, and airships typically take off and land with close to neutral buoyancy. A true HA is designed to take off and land heavier than air, but makes use of aerostatic lift to give part of the weight of the vehicle a free ride. The elegance of a HA is that it may be designed so the apportionment of aerostatic and aerodynamic lift can completely address the buoyancy compensation problem. En route, as fuel is burned, the angle of attack of the HA (essentially the degree to which it is flying nose up) is reduced proportionally so less aerodynamic lift is generated and total lift remains the same as the gross weight of the vehicle reduces due to fuel burned (the aerostatic lift also remains the same during the flight). When the HA arrives at its destination with a small amount of fuel remaining and the cargo is unloaded, it will still be slightly heavy and not require ballast because the aerostatic lift is only lifting the structure. With this added flexibility come several penalties. First, because the HA always operates heavier-than-air (but partially, not like a fixed-wing aircraft), it cannot take off or land vertically or hover. Second, because of the induced drag generated by the aerodynamic component of lift, a HA is less efficient than a pure airship. However, it can still be considerably more efficient than an airplane.

2.3 Comparison with other transport modes

Each mode of transport has unique logistical strengths and weaknesses and service advantages that dictate its uses. Figure 4 presents conceptual lift cost and time tradeoffs for comparison of different transportation modes. Conventional air transport is the greyhound of intercontinental commerce. Its great speeds are purchased in terms of limited cargo capacities and high costs per unit of weight. Marine transport is slower than any other mode despite technological advances. The advantages of marine transport are high capacity, long range, and low cost per unit of weight. Both airplanes and ships require infrastructures for cargo transshipment. Airships are relatively fast compared to ships, cheaper than aircraft and have voluminous cargo holds and sufficient endurance for long distance flights. Like conventional marine transport, airships are subject to significant economies of scale. Large airships could have tonne-mile freight costs ($/tonne × mile) much lower than fixed-wing air freight.

For the lift service, airships can overfly ocean-land boundaries and conduct intermodal transfers at non-congested internal gateways. Such intermodal transshipments can be performed with minimal infrastructure. Transfers are not tied to geographic features, such as coastlines, because airships do not require extensive landing facilities. Airships are capable of delivering door-to-door service for large indivisible loads, but in most cases, regular freight would be combined with truck and intermodal rail for final delivery. Airships can operate across rough terrain with less developed surface transport infrastructures. With the exception of higher mountain ranges, physical barriers of topography impose few limitations on airships. Airships can travel over land or sea, and can thrive in tropical or frigid air masses. Consequently, they can serve remote road-less land masses or island archipelagoes equally well as the more developed and populated continental areas.

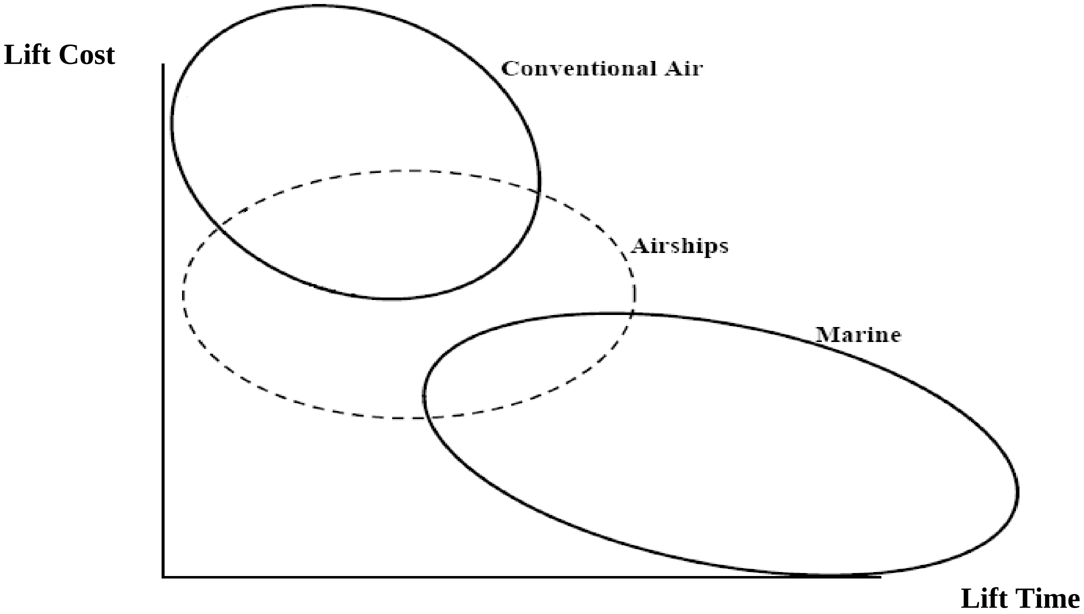

Figure 4: Lift cost and time trade-off for different transportation

2.4 Airship models

Several airship models are being developed for logistics heavy lift applications. However, the development and the commercialization of these airships are currently facing many challenges, particularly for the investment capital. Indeed, customers are still sceptical about operating or servicing airships and are not yet ready to invest in this technology. The most important development in airships for logistics heavy lift has been undertaken by the following manufacturers.

Advanced Technology Group (ATG): Based at Cardington in the United Kingdom, the ATG has been developing a logistics heavy lift airship model using lighter-than-air and air-cushioned hovercraft technologies. The vehicle, known as SkyCat[1], will be built in different lift sizes, namely the SkyCat 20, 50 and 200 with payload capacities of 20, 50, and 200 tonnes, respectively. Its speed will range from 150 to 180 km/h, depending on the model size. SkyCat is a non-rigid hybrid airship with a laminated fabric envelope. The vehicle can be configured as a passenger airship, an ultra heavy cargo ship and as an airborne surveillance platform. Military applications include tactical and strategic airlift, a command, control, computers and information platform, mine countermeasures, airborne early warning and anti-surface warfare.

SkyHook International: The Canadian Alberta-based SkyHook International has signed a teaming agreement with Boeing to develop a commercial airship model for tactical logistics heavy lift. The vehicle, known as the SkyHook Jess Heavy Lifter (JHL)[2], is a hybrid vehicle that combines helicopter rotor systems with a neutrally buoyant airship. Designed to lift a 40-ton slung payload over a 200-mile range, the JHL-40 is being aimed initially at transporting heavy equipment for the oil industry in the Canadian Arctic and Alaska, avoiding the need to build roads in remote areas. The JHL-40 will use a helium-filled airship envelope to carry the vehicle's empty weight, and four Chinook helicopter rotor systems to lift the payload. Still in the engineering stage, the first SkyHook airship is expected to fly in 2014.

Lockheed Martin: The Lockheed Martin Corporation has been developing an experimental aerostatic/aerodynamic airship model for military logistics heavy lift applications, known as the P-791[3]. The P-791 is a very large hybrid lift vehicle being developed for the US Air Force for the deployment of up to 500 tonnes of equipment and supplies across international distances. The vehicle may also be used for extended range airborne patrol and intra-theatre support and re-supply. However, the P-791 model appears to be essentially identical in design to the SkyCat model. Indeed, both models use similar design concepts and the two programs might be related. The maiden flight of the P-791 was in 2006.

CargoLifter AG: Based in Germany, CargoLifter AG was created to offer logistical services through point-to-point transport of heavy and outsized loads. This service was based on the development of a heavy lift airship, the CL160[4], designed to carry payloads weighing up to 160 tonnes to a range of up to 10,000 km. The CL160 is a semi-rigid vehicle in which the envelope is not stretched over a rigid structure but has a keel which is attached to the bottom of the envelope and distributes the weight of the payload along the length of the envelope. For financial reasons, the status of the CL160 development remains uncertain. However a small scale experimental airship has already been developed and had its first flight in 1999.

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[1] www.worldskycat.com
[2] www.skyhookint.com
[3] www.military-heat.com
[4] www.cargolifter.com

3. Operation Boxtop sustainment lift analysis

In this section, the airship lift is examined for a typical CF operation in the North: Operation Boxtop. Operation Boxtop is the resupply operation for the Canadian Forces Station Alert (CFS Alert). The sustainment lift of Operation Boxtop is analyzed with the airship lift and compared with the current lift approach using fixed wing CC-130 flights.

3.1 CFS Alert

CFS Alert is a CF signals intelligence intercept facility located in Alert, Nunavut on the northeastern tip of Ellesmere Island at approximately 800 km from the geographic North Pole. The station's mission is: to maintain signals intelligence collection and geolocation facilities in support of the Canadian cryptologic program; to maintain radio frequency direction finding facilities in support of SAR and other programs; and to provide support services to other organizations (e.g., Environment Canada weather services, arctic scientific research activities, etc.).

Currently, CFS Alert has a full-time strength of approximately 70 military personnel, divided into the following sections: Administration, Operations, Construction Engineering, Transport, Supply, Food Services and Medical Services. Environment Canada also maintains an upper air meteorological service at CFS Alert. Every spring, once the daylight period arrives, the complement of personnel increases proportionately as Station replenishment, new construction projects, and preventive maintenance activities get under way. To support the CFS Alert activities, the CF established Operation Boxtop to replenish the station with fuel and freight.

3.2 Operation Boxtop

Boxtop is the biannual resupply of CFS Alert. Using the United States Air Force Base at Thule in Greenland as a staging point, for two to three weeks every spring (Boxtop I) and fall (Boxtop II), the Canadian Air Force operates day and night to fly fuel and supplies to the Alert station. Historically, a typical Boxtop operation moved over 500 tonnes of equipment and supplies and more than 1,000,000 litres of fuel into CFS Alert. While the fuel is usually sourced in Greenland, the equipment is shipped to Greenland by sealift from Montreal. The airlift is usually conducted from Thule to Alert using a fleet of CC-130 aircraft. The great circle distance between Thule and Alert is about 700 km and on average 120 CC-130 sorties are usually performed for each Boxtop operation[5].

In addition to Operation Boxtop, a weekly sustainment flight from Trenton to Alert is conducted by CC-130 to transport perishable supplies. These flights usually move food, medical supplies as well as CF personnel rotating through CFS Alert. On average, 15 tonnes (average payload of CC-130) of perishable supplies are moved every week to CFS Alert. In the future, Operation Boxtop could be expanded to resupply—in addition to CFS Alert—all northern locations including Resolute Bay. Other military operations and exercises in the North such as Operation Nanook (annual joint exercise of Canada's Maritime Command and the Canadian Coast Guard to train for disaster and sovereignty patrols in the Arctic) would also require logistical support lift.

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[5] http://www.thule.af.mil

3.3 Sustainment lift analysis

This section compares the airship lift cost using SkyCat-50 with the aircraft lift cost using CC-130 for Operation Boxtop. The performance characteristics of the assets are presented in Table 1.

Table 1: Performance characteristics of CC-130 and SkyCat-50

Performance Characteristics	CC-130	SkyCat-50)
Speed (km/h)	500	180
Range (km)	4500	2000
Lift rate ($/h)	8000	5000
Lift time between Trenton and Alert (Distance = 4000 km)	8	22.5
Lift time between Trenton and Thule (Distance = 3750 km)	7.5	21

Aircraft lift cost

Assuming an airlift time of three hours (round trip) between Thule and Alert, the total lift time of Operation Boxtop (I and II) using CC-130 would be:

Aircraft Positioning
Cost in Thule = Lift rate × hours per sortie (round trip from Trenton to Thule)
= 8000 × 15
= $120,000

Boxtop Airlift Cost = Lift rate × number of sorties × hours per sortie × 2 (Boxtop I and II)
= 8000 × 120 × 3× 2
= $5.76 million

The airlift cost for the routine sustainment flight from Trenton to Alert is calculated as follows:

Routine Airlift Cost = Lift rate × number of sorties × hours per sortie (round trip)
= 8000 × 52 × 16
= $6.66 million

The total airlift cost for the CFS Alert sustainment operation would be $12.54 million per year.

Airship lift cost

Consider a 50 tonne payload airship (e.g., SkyCat-50) for the resupply of CFS Alert. Using the SkyCat manual, the hourly flying rates and speed of the airship are estimated to $5000 and 180 km/h, respectively (Table 1). The range of the airship is about 2000 km, which exceeds the return trip distance between Alert and Thule (one refuelling stop is required). The airship flying time (round trip) between Alert and Thule would be 7 hours. With a 50 tonne payload, the number of sorties required for the airship to lift the Boxtop logistics requirements would be 40 (the airship payload is about three times the CC-130 payload). The total airlift cost for the Boxtop Operation using a 50 tonne airship would be:

Airship positioning
Cost in Thule = Lift rate × hours per sortie (round trip from Trenton)
= 5000 × 42
= $210,000

Boxtop Airship Cost = Lift rate × number of sorties × hours per sortie × 2 (Boxtop I and II)
= 5000 × 40 × 7 × 2
= $2.8 million

For the routine sustainment lift, the number of sorties required for the airship to move supplies between Trenton and Alert would be 18 sorties (about 1/3 of the number of CC-130 sorties). However, as sustainment flights would be every three weeks, perishable food would be problematic. Given the distance between Alert and Trenton, the airship flying time would be at least 22.5 hours (excluding refuelling times) or 45 hours for a round trip. The routine airship lift cost would be:

Routine Airship Cost = Lift rate × number of sorties × hours per sorties
= 5000 × 18 × 45
= $4.05 million

The total sustainment lift cost for CFS Alert using a 50 tonne airship would be $7.06 million per year, which would give a potential annual cost saving of $5.48 million compared to CC-130 lift.

It is important to note that the analysis does not include the cost of positioning the airship in Trenton nor the sealift cost for the movement of supplies to Thule (the sealift cost is common to both modes of transport). In addition, the analysis used theoretical performance characteristics (lift rate, speed, etc.) of a particular airship and the calculated cost savings could vary with different airship options.

Discussion

The above analysis provides an assessment of the airship lift capability for a particular Northern military scenario (Operation Boxtop). As part of the Canada First Defence Strategy, CF are required to increase their presence in the North and better respond to incidents and potential challenges to Canada’s sovereignty. Therefore, it is expected that the level of CF activities (e.g., training, surveillance, search and rescue, etc.) in the North will increase and the requirements for logistics lift will also increase. These activities would not necessarily all be in the same location (e.g., Alert) but rather across the North. Section 5 will provide an assessment of the airship lift capability for various deployment locations in the North.

The lift cost is not the only criterion to assess the operational performance of a transportation capability. Other operational parameters such as response time, environmental impact (e.g., greenhouse gas emissions), survivability, etc. should also be included in the capability assessment. In the next section, a qualitative assessment of the airship capability for logistics heavy lift is discussed.

4. Airship capability assessment

This section provides a qualitative assessment of the airship lift capability for Northern operations. Different evaluation criteria are considered in the assessment including the environmental impact, survivability to military threats, vulnerability to weather conditions, operational effectiveness as well as other considerations (e.g., infrastructure requirements).

4.1 Environmental impact

Using the buoyant lift mode, airships would provide an opportunity to reduce the environmental impact associated with carbon footprints and would have the potential of becoming a cleaner form of transport for both commercial and military logistics distributions. Indeed, airships have inherently low greenhouse gas emissions because of the static lift provided by the buoyancy of the helium gas. When less fuel is burned, fewer emissions result. In addition, due to the large surface area inherent in airships, the potential to utilize photovoltaic solar energy systems to augment vehicle power can further reduce emission, enhance safety, and lower operating costs. Figure 5 presents the fuel consumption and the greenhouse effect index of different airship and aircraft types for different productivity options (productivity is defined as the payload capacity (tonne) times speed (km/h)) and for current and future technology levels[6]. The greenhouse effect index is a weighting scheme developed to assess the relative environmental pollution associated with various greenhouse gases [19]. The index can be used to make rational comparisons between competing technologies, energy policies, and other choices affecting greenhouse emissions. Figure 5 indicates that airships could potentially have low greenhouse gas emissions and fuel consumption rates compared to current transportation assets (e.g., CC-130).

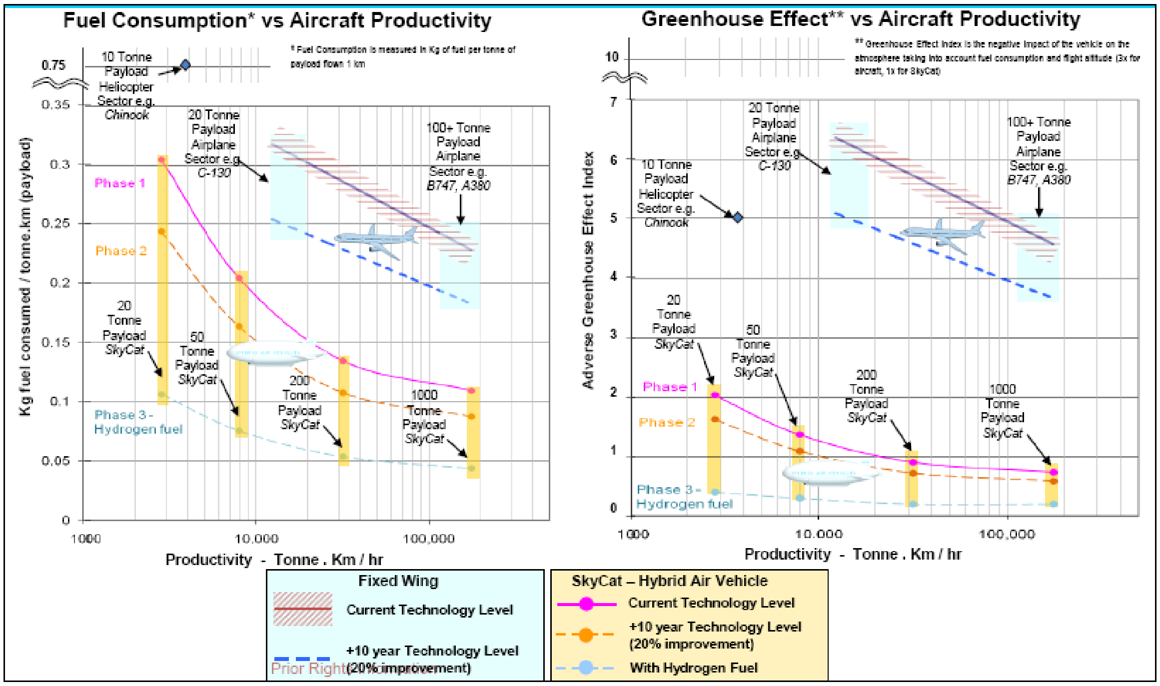

Figure 5: Fuel consumption and greenhouse effect of various aircraft and airship types

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[6] http://www.airshipstothearctic.com/docs/pr/5_Gordon_Taylor.pdf

4.2 Survivability to military threats

Although this study focuses on using airships for domestic operations (i.e. low probability of military threats), the survivability of airships to military threats is discussed here to provide a complete assessment of the airship capability and safety requirements. To support Northern operations and exercises, force deployment and sustainment could be conducted by airship, airlift, sealift or any combination of the three methods, depending on the location of the mission. Compared to a waterborne ship, an airship would be less vulnerable to military threats because over the ocean it is almost always safer to be several thousand feet in the air than on the surface of the water. Threats from mines, torpedoes from submarines or surface vessels, surface-to-surface or air-to-surface anti-ship missile, suicide speedboats, or boarding by pirates simply do not apply to airships. Typical targets that could threaten an airship, such as fighter aircraft or surface vessels armed with surface-to-air missiles or artillery would be just as threatening to surface vessels. So even from a brief qualitative analysis it is readily apparent that only a small subset of the possible threats to surface ships could threaten an airship.

The vulnerability of an airship to a hit would be higher than an aircraft as airships would normally fly at a relatively low speed and at an altitude that is within reach of many surface-to-air weapons, except for small arms. However, because of its extreme size and its lower speed, the airship might be able to land under some control after a hit where an airplane would simply come apart. In summary, the vulnerable areas of an airship may be divided into three categories:

- *Envelope*: Should the envelope be hit by anti-aircraft artillery projectiles that do not detonate but simply make holes, the effect would hardly be noticeable. Because of the low pressure of the lifting gas, the rate of exchange between the helium and the ambient air would not prevent the airship from completing its mission and flying to a safe location to be repaired. Even if a projectile were to detonate against the envelope instead of punching a hole in it, while the resulting hole would be much more significant, it would still take hours, not minutes, to bring the airship down. Also it would land, not crash.
- *Fuselage*: If the fuselage were struck by an anti-aircraft artillery projectile, it would certainly detonate. Airship design should consider armour protection for the fuselage to improve the airship survivability.
- *Propulsion units*. If a projectile were to strike one of the propulsion units of a hybrid airship, it would probably destroy the unit. As with a four-engine airplane, however, the hybrid airship is capable of maintaining flight with one less propulsion unit. In fact, only two are necessary in most circumstances as long as they are on opposite sides.

Finally, it is important to note that unlike a large aircraft, which has to land on a runway near which threats could be pre-positioned, the airship can land anywhere there is sufficient unobstructed ground, significantly complicating the enemy's targeting problem.

4.3 Vulnerability to weather effects

As with the other modes of transport, the weather affects both the survivability and the operational effectiveness of airships. Historic losses of large airships were generally due to extremes of weather such as thunderstorms. Weather prediction methods such as satellites and radars did not exist in the past and airships were flown in hazardous conditions, often by sight alone. Upon encountering severe weather, an airship could not move quickly enough to avoid it if need be, nor were the crew aware in most cases that weather conditions were too severe for the structural integrity of the airship. Modern weather prediction and monitoring capabilities would allow airships to avoid potentially hazardous storms. Indeed, with their higher speed and ability to move over both land and water, they would be much better able than marine transport to avoid severe weather conditions.

The operational performance of airships could also be affected by the increase in ambient temperature. Dexter [20] indicated that temperatures above standard temperature (e.g., -16 ^{o}C at 4.8 km altitude) would have an adverse effect on buoyancy, since at higher temperatures, the expansion of the surrounding air is more pronounced than for helium. Typically, buoyancy is lowered by 1% for every 2.7°C rise above standard temperature due to expansion of air and helium [20]. On the other hand, while colder temperatures generally impose greater stresses on all transportation equipment, airships do benefit from greater lift as the density of air increases. However, some details of cold weather operations, like de-icing systems, have yet to be demonstrated.

For Northern operations, the greater concern is the impact of weather on airship utilization. Strong headwinds and routings to avoid severe weather will require more fuel and reduce the airship effectiveness. Like all forms of transport, severe weather will also limit the operating window for airships and affect ground handling. Like a ship standing off the coast, or an airplane holding at an alternative airport until weather clears, in some instances airships may have to remain aloft until conditions permit docking and the on/off loading of cargo.

A study conducted by SkyHook Inc. for the Boeing Company [21] indicated that airships could generally operate under Arctic weather conditions for up to 310 days (excluding January and February). The analysis used historical environmental data (e.g., temperature, snow, wind speed, storms, etc.) at various Northern locations, and technical characteristics (e.g., fabrics, engine, payload, etc.) of a typical airship model being developed by SkyHook. It indicated that on average the airship under development would operate in the Arctic for 26 days per month.

4.4 Operational effectiveness

Each mode of transport has unique operational strengths and weaknesses in performing logistics lift. While the strengths and weaknesses of airships in meeting the CF logistics heavy lift requirements for Northern operations can be itemized, the levels of those strengths and weaknesses cannot be determined with a high degree of certitude. Indeed, modern heavy lift airships are currently in the scale model prototype phase and consequently real operating data simply do not exist. The operational parameters (lift cost, range, speed, fuel consumption, etc.) of large airships are currently estimated using computer simulations.

Despite the lack of reliable lift data for the large scale heavy lift airships, various studies [5-9] tend to indicate that modern airships could have significant economies of scale due to their potential payload capacities and their fuel consumption efficiency. The economies of scale have been pushed furthest through the design of hybrid airships with lift capacity up to ten times any rigid airship ever built. While there is efficiency of scale, the efficiencies due to technological development may be greater. Indeed, modern airships could contribute almost 30 percent of their gas dead-lift to cargo (lighter structures require less lift) [8]. For comparison purposes, the lift cost ratios (cost per tonne per kilometer) of different fixed-wing aircraft and airships are presented in Table 2. The lift cost ratio can be defined as the ratio of the lift cost rate ($/hour) to the speed (km/h) times the payload (tonne) of the asset. Historical lift rates for the Antonov 124 (AN-124) and the Ilyusin 76 (IL-76) aircraft and operating costs (from the cost factors manual) for CC-177, and CC-130, are used in the calculations.

Table 2: Lift cost ratios of different transport assets

Transport Asset	Payload (tonne)	Speed (km/h)	Lift Cost Rate ($/h)	Lift Cost Ratio ($/tonne × km)
CC-177	76	700	20000	**0.38**
CC-130	18	500	8000	**0.89**
AN-124	90	700	30000	**0.48**
IL-76	40	600	14000	**0.67**
SkyCat-50	50	180	5000	**0.56**
SkyCat-200	200	180	8000	**0.22**

Table 2 indicates that a SkyCat-like airship (with a 50 tonne payload) would be more cost-effective for logistics heavy lift than the CC-130 and the IL-76 aircraft but less cost-effective than the CC-177 and the AN-124. The 200 tonne SkyCat model would, however, be more cost-effective than all other transport assets. While the lift cost ratio is a key parameter for comparing different lift capability options, other operational factors (e.g., speed of delivery) should also be examined for a complete assessment of the airship lift performance.

4.5 Operational requirements

In addition to the environmental impact, survivability, vulnerability, and operational effectiveness assessment criteria, different operational requirements associated with airship lift should be highlighted, particularly for Northern operation applications, including:

- *Infrastructure requirements*: Unlike an airplane, an airship does not require a runway to take off and land and does not have crosswind limits. A large airship would require a landing zone (with gravel) of approximately 500 - 1500 m radius, depending on the airship payload including the fuel load. In addition, an airship would typically operate from the water if leaving from a seaport of disembarkation or from a drop zone if leaving from an Army base.
- *Intermodal transfer*: Cargo transfers associated with ocean-land boundaries can be overflown by airships (but with a lower cost than airplanes) and intermodal transshipments can be performed with minimal infrastructure. This could reduce the numbers of such transfers in point-to-point movement, as the locations of transfers are not tied to geographical features. Transfers with airships should occur in non-congested areas.
- *Topography*: Relative to other modes of transport, airships would have a comparative advantage when operating across rougher terrains with less developed surface transport infrastructure, and where intermodal transfers occur [6]. However, higher mountain ranges would impose some limitations on airship routes as they fly at low altitudes compared to an aircraft flight ceiling.
- *De-icing*: In-flight icing would be addressed by a number of anti-icing and de-icing measures similar to conventional aircraft. Ice accumulation while the airship is parked on the ground could be challenging as the vast area of the envelope means even a thin coating of ice would have significant weight. Conventional de-icing by truck would not be feasible because of the

large size of the airship. A mechanism could be included in the airship design to disperse anti-icing solution over the envelope but this would have its own set of issues regarding the quantity of fluid required and whether the fluid would have to be recovered because of environmental concerns. Snow accumulation while parked is less of a concern than ice because of its reduced weight. The airship could actually take off supporting a thin layer of snow and buildup in excess of that could be prevented by high-speed taxiing.

- *Ground handling requirements*: Large airships would require the development of ground handling procedures for the safe exchange of cargo and ballast. Modern robotic technologies have reached a technological maturity to permit the design of extendable, articulated mooring mast systems with fully automated launch and recovery capability. Such a system could safely capture and launch an airship in all but the worst weather conditions, and would minimize ground personnel requirements [8].
- *Others*: Other requirements for the airship lift need to be discussed, including: hanger infrastructure, helium infrastructure, pilot skill set, conditions for loading, etc. However, as the CF is not necessarily looking for buying an airship fleet (i.e., the CF is rather looking for contracting an airship service), these requirements are not examined in the analysis.

4.6 Tactical airship

While the analysis focused mainly on long-range heavy lift airships, short-range airships could also be considered by the CF for tactical logistics lift requirements of Northern operations. One of the potential capabilities to address these requirements would be the Jess Heavy Lifter (JHL) airship being developed by the Boeing Company and SkyHook International Inc. The JHL model is a hybrid aircraft that combines helicopter rotor systems with a neutrally buoyant airship designed to lift a 40 tonne slung payload over a 320 km range. The rotors lift the payload only which can be jettisoned during emergencies restoring LTA flight characteristics. The aircraft range could be increased with a combination of reduced payload and additional fuel tanks. The airship would be capable of transporting loads at half the current helicopter price per tonne and could operate at -30°C, in zero visibility and 25 knots wind conditions [21].

The SkyHook airship concept of operations in the North would include the development of Forward Operating Bases (FOBs) by leveraging existing airports or dedicated staging bases. A FOB would have a refuelling capability and a ground power and jet fuel storage facility. Typically, a 300×300 m outdoor masting area with a gravel surface would be required for airship docking. To move from its main operating base to the different FOBs, the airship can ferry itself with organic fuel stores up to 650 km with no payload, and this could be extended to 1500 km with an external fuel tank. The airship could also be transported by barge over longer distances.

For the CF Northern operations, the SkyHook airship could potentially be used for tactical airlift from an APOD (instead of the CC-138 aircraft) or a seaport (e.g., Nanisivik deep water port) to destinations. Figure 6 shows the tactical lift coverage from the APODs suitable for CC-177 (blue points) and CC-130 (red squares and blue points) for an airship range of 370 km (200 nm) without refuelling stops. It indicates that most of the Northern regions could be reached with airship tactical lift.

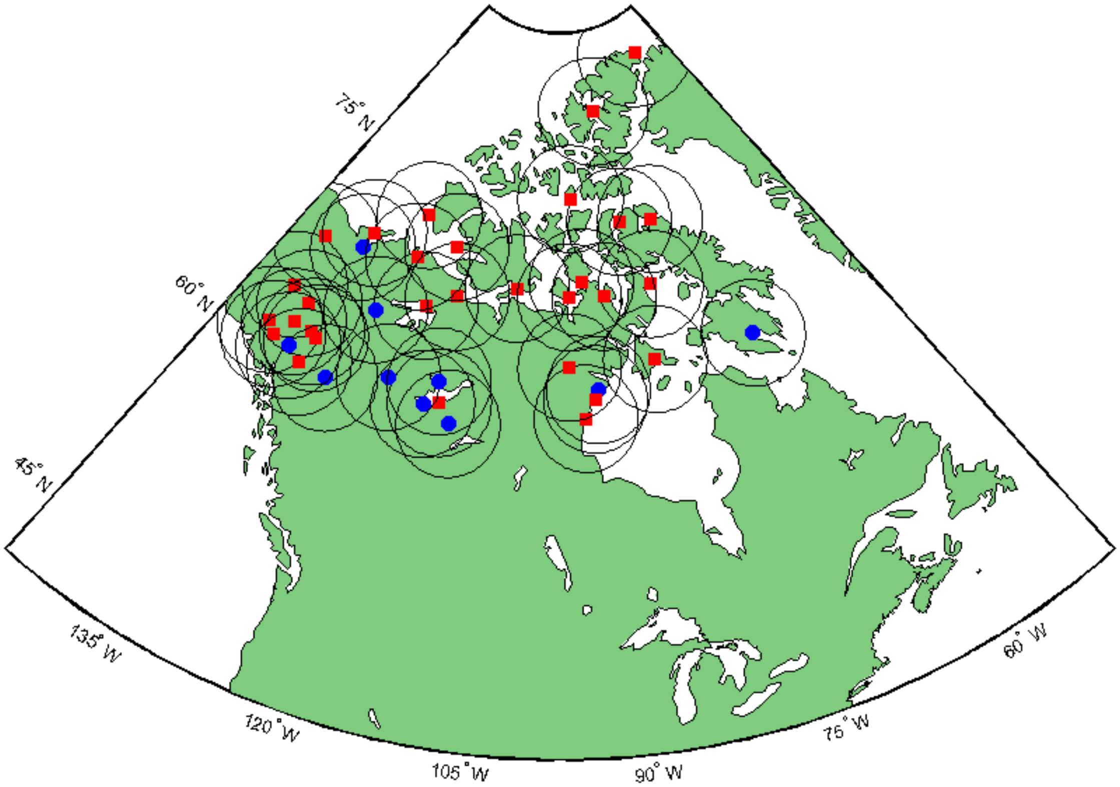

Figure 6: Tactical lift coverage from the APODs for a SkyHook airship with 370-km range

5. Airship lift performance analysis

In this Section, the airship logistics lift performance is assessed for various deployment locations in Northern Canada. The airship lift performance was compared with the current transportation approach that uses a combination of strategic and tactical fixed and rotary wing aircraft. Sensitivity analysis was conducted to address the impact of various operational parameters on the airship lift effectiveness.

5.1 Methodology

To analyse the airship lift performance, a deployment scenario to a given location in Northern Canada (latitude ≥ 60°) was considered. Various deployment locations were examined by dividing the Northern region into different potential deployment areas. The deployment would be sustained by airlift from a number of support hubs in Canada (e.g., Trenton, Edmonton). The logistics requirements of the scenario were determined from previous historical military exercises and operations (e.g., Operation Boxtop). Sustainment lift operations were simulated with airships and with the current transportation approach, for comparison purposes.

Using the current transportation approach, the sustainment lift for Northern operations would be conducted using a strategic lift aircraft (e.g., CC-177) from an airport of embarkation (APOE) to an airport of disembarkation (APOD), followed by a tactical lift to the final destination using a utility transport aircraft (e.g., CC-138). It is assumed that utility aircraft will be deployed from their main base to the APOD in order to conduct the sustainment lift and will return to the main base at the end of the lift. With airships, the sustainment lift would be conducted directly from an APOE to the final destination in theatre. Great circle distances were used to estimate the airlift time for the airship and the aircraft, neglecting issues such as weather conditions, etc. Depending on the travel distance and the asset range, at most one refuelling stop may be required to service some areas of the North. As the cost and time for a single refuelling stop are small compared to the overall cost and time of the sustainment lift, refuelling costs and times are not considered in this study.

A Monte Carlo simulation framework was developed to simulate the scenario sustainment lift using both the current transportation approach and the airship lift. Within the framework, individual parameters such as locations of deployments, assets' cruising speeds, loading times, unloading times, and operating costs are generated stochastically. To allow for meaningful statistical evaluation, measures of effectiveness of logistics lift are collected for a large number of simulation runs.

5.2 Measures of effectiveness

The main measures of effectiveness for a logistics transportation system are the cost effectiveness and the time responsiveness. The cost effectiveness refers to the optimal use of transportation assets whereas the time responsiveness is related to the speed of logistics distribution. In this paper, a *Cost Avoidance* metric is developed to assess the effectiveness of airships for military logistics heavy lift. The cost avoidance is defined as the transportation cost that could potentially be avoided if airships are used for sustainment lift instead of the current transportation approach. On the other hand, the responsiveness of the airship logistics lift is assessed by evaluating the sustainment *Response Time*. Response time is defined as the total time required for the movement of supplies from their origins to their destinations. As airships are inherently fuel efficient and have low greenhouse gas emissions, a third measure of effectiveness called *Carbon Emission*

Avoidance was developed to assess the airship lift capability. The carbon emission avoidance is defined as the quantity of greenhouse gas emissions that could potentially be avoided if airships are used for the sustainment lift instead of the current transportation approach. The carbon emission avoidance measure could be used to assess the environmental impact (based on greenhouse gas emissions) of the airship lift and compare it with the current military logistics transportation assets.

5.2.1 Cost avoidance

Given a list of APOEs and a list of APODs, consider the movement of a quantity of supplies q (in pallets) to a given destination in Northern Canada using a lift asset x ($x = s$ for strategic lift aircraft, $x = t$ for tactical utility aircraft, and $x = a$ for airship). Let p_x be the payload capacity (tonne) of asset x, c_x its volume capacity (number of pallets), v_x its cruise speed (km/h), and r_x its flying rate ($/h). Let d_{ij} be the great circle distance between APOE i and destination j, d'_{ik} the great circle distance between APOE i and APOD k, and d''_{kj} the great circle distance between APOD k and destination j.

The minimum number of sorties (n_x) required for asset x to lift a quantity of supplies (q) can be determined using the asset payload and volume capacities as follows [15]:

$$n_x = \left\lceil \max\left\{ \frac{q}{c_x}, \frac{wq}{p_x} \right\} \right\rceil \tag{1}$$

where w represents the average pallet weight and the symbol $\lceil . \rceil$ indicates the ceiling operator. It is important to note that equation (1) does not determine the exact number of required sorties, rather it provides a lower bound of the total number of sorties (it is an approximation).

Using the current transportation approach, the total lift cost for the movement of a quantity of supplies (q) from APOE i to destination j through APOD k is the sum of the strategic lift cost from APOE i to APOD k, the tactical lift cost from APOD k to destination j and the lift cost for the tactical utility aircraft to reach APOD k from its main base (round trip):

$$R_{ijk} = 2 n_s r_s \frac{d'_{ik}}{v_s} + 2 n_t r_t \frac{d''_{kj}}{v_t} + 2 r_t \frac{d_k}{v_t} \tag{2}$$

where d_k is the distance between the utility aircraft main base and APOD k. The minimum lift cost to destination j (R_j^*) is given by:

$$R_j^* = \min_i \left(\min_k \left(R_{ijk} \right) \right) \tag{3}$$

For the airship lift, the total lift cost for the movement of a quantity of supplies (q) from APOE i to destination j (A_{jj}) can be formulated as follows:

$$A_{ij} = 2 n_a r_a \frac{d_{ij}}{v_a} \tag{4}$$

and the minimum airship lift cost to destination j (A_j^*) is given by:

$$A_j^* \quad = \quad \min_i (A_{ij}) \tag{5}$$

The cost avoidance for the airlift to destination j (K_j) is the difference between the lift cost using the current transportation approach and the airship lift cost:

$$K_j \quad = \quad R_j^* \quad - \quad A_j^* \tag{6}$$

and the relative cost avoidance for the airlift to destination j (Z_j) is given by:

$$Z_j\,(\%) \quad = \quad \frac{R_j^* \quad - \quad A_j^*}{R_j^*} \times 100 \tag{7}$$

5.2.2 Response time

To calculate the response time for the current transportation approach, it is assumed that the tactical utility aircraft is already available at the APOD before the strategic lift aircraft arrives to the APOD in the first sortie. The response time is the sum of the total tactical lift time and the strategic lift time for the first sortie. Let ℓ_x be the loading time (hours) of asset x and u_x its unloading time (hours). The response time (T_{ijk}) from APOE i to destination j through APOD k using the current transportation approach can be formulated as follows [16]:

$$T_{ijk} \quad = \quad \ell_s + u_s + \frac{d'_{ik}}{v_s} + n_t\left(\ell_t + u_t + 2\frac{d''_{kj}}{v_t}\right) - \frac{d''_{kj}}{v_t} \tag{8}$$

and the minimum response time (T_j^*) to destination j is:

$$T_j^* \quad = \quad \min_i \left(\min_k \left(T_{ijk} \right) \right) \tag{9}$$

For airships, the response time (t_{ij}) from APOE i to destination j is given by [16].

$$t_{ij} \quad = \quad n_a\left(\ell_a + u_a + 2\frac{d_{ij}}{v_a}\right) - \frac{d_{ij}}{v_a} \tag{10}$$

and the minimum response time (t_j^*) to destination j using an airship is:

$$t_j^* \quad = \quad \min_i \left(t_{ij} \right) \tag{11}$$

As with the relative cost avoidance, the relative response time was also used to compare the airship lift capability with the current transportation approach. The relative response time (τ_j) is the ratio of the airship lift response time and the lift response time with the current transportation approach:

$$\tau_j\,(\%) \quad = \quad \frac{t_j^*}{T_j^*}\times 100 \tag{12}$$

5.2.3 Carbon emission avoidance

Let f_x be the fuel consumption rate (kg/hour) and e_x be the carbon emission rate (kg/hour) of a lift asset *x*. The carbon emission rate is the average weight of greenhouse gas emitted by the asset per flying hour and is related to the fuel consumption rate as follows[7]:

$$e_x \quad = \quad 3.15\times f_x \tag{13}$$

The carbon emission avoidance metric is the difference between the weight of greenhouse gas emitted by the current transportation approach and the weight of greenhouse gas emitted by an airship. It can be formulated similarity to the cost avoidance formulation but using the carbon emission rate (e_x) instead of the airlift rate (r_x) in equations (4.2 – 4.6). A relative carbon emission avoidance factor is also calculated in the same manner as the relative cost avoidance.

5.3 Performance analysis

5.3.1 Scenario

To analyse the airship lift performance in support of CF Northern operations, a deployment scenario to a given Northern location was considered. The scenario operational demand (i.e. quantity of supplies required per sustainment period) was estimated using the historical Operation Boxtop sustainment flights. A nominal operational demand of 100 tonnes per month (or 35 pallets, assuming an average pallet weight of 2850 kg) was assumed for the scenario. For the purpose of the simulation, the Northern Canada region was divided into 96000 grid cells of 15 x 15 minutes with the centre of the grid cell being the deployment location. Two potential APOEs (the main aircraft bases of Trenton and Edmonton) were assumed for the analysis. A baseline case using a generic 50 tonne airship (e.g., SkyCat-50) to simulate the airship lift and a combination of one CC-177 aircraft and one CC-138 aircraft (currently based in Yellowknife) to simulate the current transportation approach was first examined. Further analysis was conducted to address the impact of the airship payload capacity (e.g., SkyCat-200) and the aircraft option (e.g., CC-130) on the performance measures. Table 3 depicts the performance characteristics and the lift rates of the selected lift assets. For the aircraft (CC-177, CC-130, CC-138), planning factors (obtained from the cost factors manual[8]) were used to estimate the lift cost and the fuel consumption rates. The aircraft technical and operational parameters (payload, capacity, speed, loading and unloading times) were determined from the aircraft technical specifications. For the airships, the performance characteristics and the lift rates were obtained from the SkyCat manual. They are based upon computer simulations and not historical experience under real world conditions.

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[7] www.carbonindependent.org

[8] http://admfincs.mil.ca/subjects/fin_docs/cfm_09/cfm09_e.asp

Table 3: Performance characteristics and lift rates of selected lift assets

Asset	Payload (tonne)	Capacity (pallet)	Loading time (h)	Unloading time (h)	Cruise Speed (km/h)	Lift Cost Rate ($/h)	Fuel Consumption Rate (kg/h)
CC-177	76	18	2	2	700	20,000	8000
CC-130	18	6	1.5	1.5	500	8,000	2500
CC-138	3	1	0.5	0.5	265	1,200	260
SkyCat-50	50	-	1	1	180	5,000	1800
SkyCat-200	200	-	1.5	1.5	180	8,000	5000

Examination of the CC-177 and the CC-130 landing requirements indicates that the assets cannot land in every airport in Northern Canada due to the runway characteristics. In the analysis, selected airfields that are suitable for the CC-177 and the CC-130 aircrafts were used as potential APODs for the deployment scenario. Figure 7 plots the airfields that can accommodate the CC-177 aircraft (blue points) and the airfields that can accommodate the CC-130 aircraft (blue points and red squares). Annex *A* presents the complete list of Northern airfields and their characteristics.

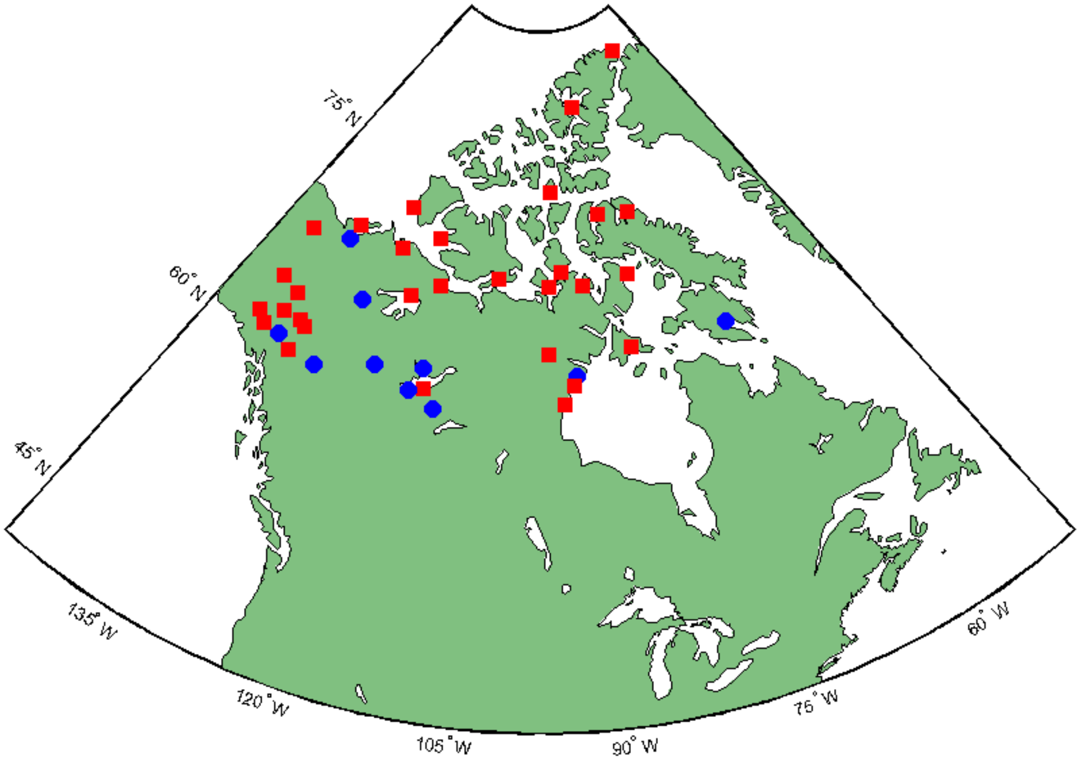

Figure 7: Northern airfields suitable for CC-177 (blue points) and CC-130 (all points)

Monte Carlo simulation was used to generate stochastic lift parameters (e.g., loading time) in the scenario. Monte Carlo simulation is a versatile method that uses random numbers and probability distributions to analyze the behaviour of a process involving uncertainty. The most commonly used distributions are the random uniform, normal and triangular distributions. In this paper, the lift parameters of cruise speed, loading and unloading times, airlift cost rate, and fuel consumption rate are represented by a random uniform distribution (with 20% variation).

5.3.2 Cost avoidance analysis

The number of sorties required for the transport assets to lift 100 tonnes of supplies or 35 pallets would be (using equation 1): 2 for CC-177, 6 for CC-130, 35 for CC-138, 2 for SkyCat-50, and 1 for SkyCat-200. Sustainment lift was simulated for the baseline case (CC-177, CC-138, SkyCat-50) and performance measures were collected for a large number of simulation runs (e.g. 10000). Figures 8 and 9 depict the average cost avoidance distribution and the relative cost avoidance distribution, respectively. They indicate that potential savings (up to $550,000 or 60%) on the sustainment lift cost for Northern operations could be realized using airships for this scenario. The minimum cost avoidance (less than 10%) is observed at locations around the APODs (airfields that can accommodate CC-177). The cost avoidance increases as the distance from the APODs increases due to the tactical airlift costs. Indeed, due to the large number of sorties of CC-138, the tactical airlift cost would be the most expensive portion of the lift, particularly for locations distant from the APODs.

The rationale for using both the cost avoidance and the relative cost avoidance to assess the airship lift performance is that the cost avoidance indicates the total amount of savings for a particular deployment location whereas the relative cost avoidance indicates the fractional savings relative to the current transportation approach. Depending on the deployment location, the cost avoidance could be significant but the relative cost avoidance is low and vice-versa. Using a combination of the cost avoidance and the relative cost avoidance measures, three potential regions are observed in Figures 8 and 9:

- *Low–Low*: Regions where the cost avoidance and the relative cost avoidance are both low. They generally represent locations that require tactical airlift for relatively short distances (e.g., < 300 km) from the APODs. The airship lift cost for these regions is comparable to the current transportation approach.
- *High–High*: Regions where the cost avoidance and the relative cost avoidance are both high. These regions generally represent locations that require tactical airlift for relatively long distances (e.g., > 1000 km) from the APODs. The airship lift for these regions is more cost-effective than the current transportation approach.
- *Low–High*: Regions where the cost avoidance is low but the relative cost avoidance is high. These regions generally represent locations within a medium range (e.g., 300 - 1000 km) from the APODs. The airship lift for these regions is more is cost-effective but the total amount of savings is not significant.

It is important to note that the lift cost is sensitive to the airship payload capacity. If the payload of the airship has to be reduced to 40 tonnes for operational reasons (e.g., extended range, for example), three sorties would be required to lift 100 tonnes of supplies and the total lift cost would be increased by 33.33%.

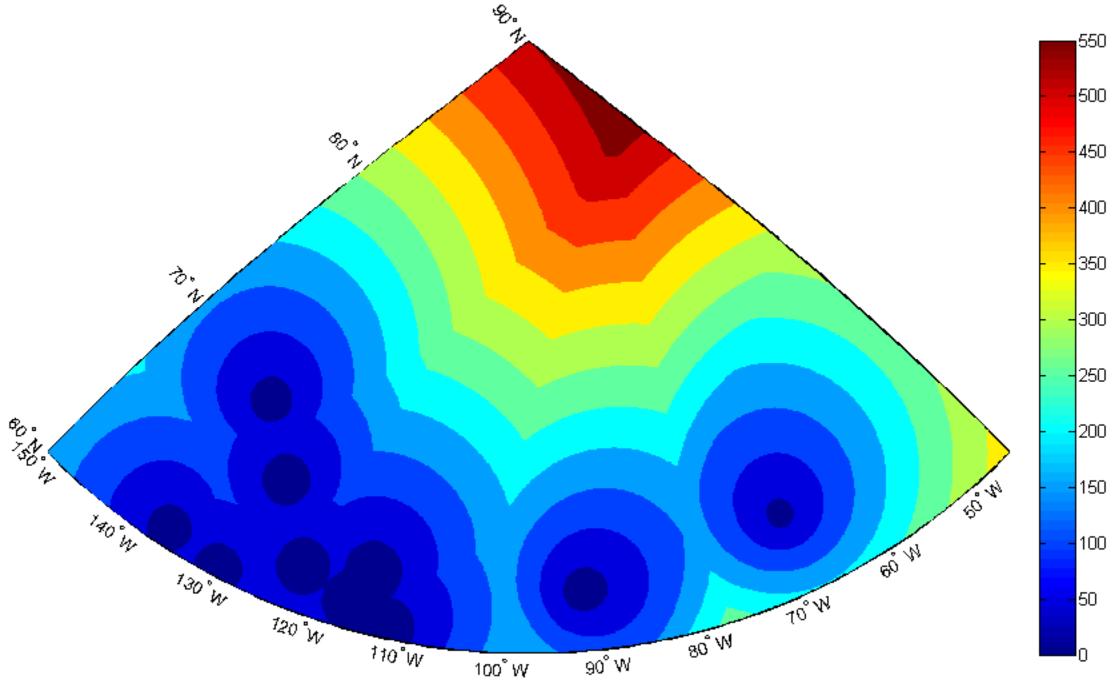

Figure 8: Cost avoidance distribution for the baseline case (in thousands of dollars)

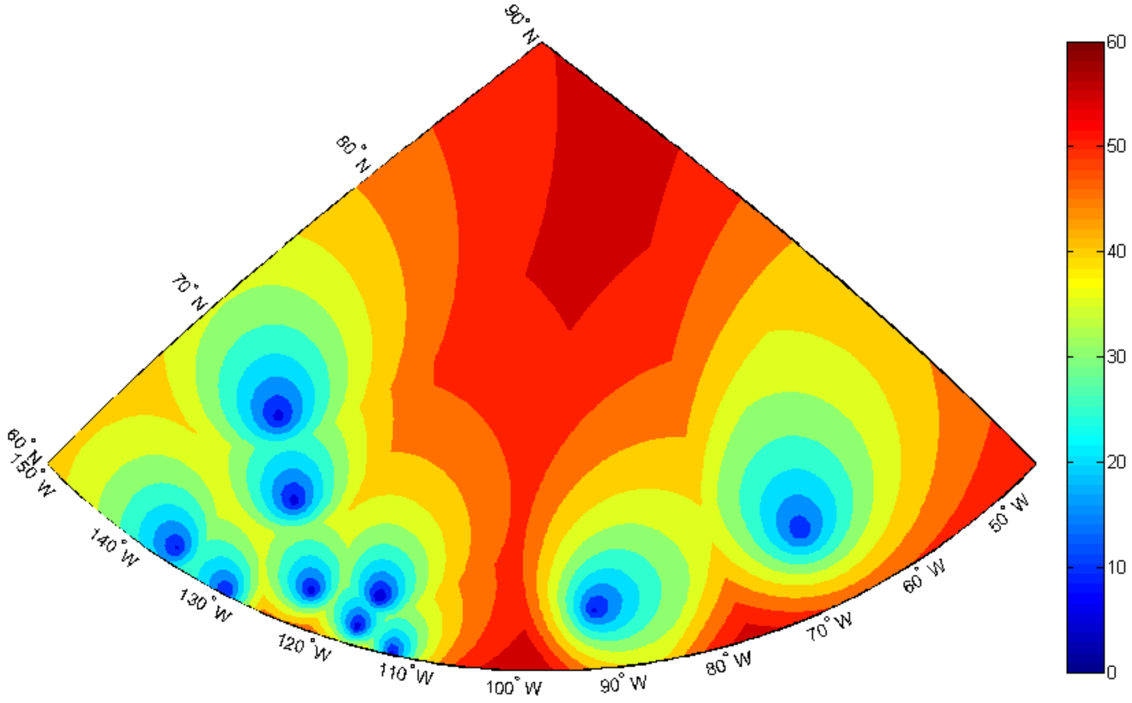

Figure 9: Relative cost avoidance distribution for the baseline scenario (%)

5.3.3 Response time analysis

Figure 10 depicts the iso-response minimum time (hours) distribution for the airship lift of 100 tonnes of supplies from either Trenton or Edmonton to various locations in the North for the baseline case. It indicates that between 20 and 70 hours would be required to move 100 tonnes of supplies using the SkyCat-50 airship. The response time increases as the distance from the APOEs increases. The response time calculation does not include refuelling service times and the time required for the airship to reach a refuelling stop. As the range of the SkyCat-50 is about 2000 km at full load, at most one refuelling stop would be required for some deployment locations (return flights would not require refuelling as airships could carry additional fuel to extend their range). The time for a single refuelling stop would be small compared to the overall time of the sustainment lift. For example, for a distance of 4000 km, the airship lift would be for about 22 hours and would require one hour refuelling time (less than 5%).

Figure 11 shows the relative response time (%) distribution for the baseline case. As the case for the cost avoidance, the maximum relative response time is observed at the APOD locations. In this case, the tactical airlift time is null and the response time using the airship lift would be greater than the response time of the current transportation approach (i.e. relative response time greater than 50%). As the distance from the APODs increases, the relative response time decreases because of the increased tactical airlift time and the airship lift becomes more time-effective than the current transportation approach. In particular, for some remote locations in the North the airship response time would be 80% less than the response time with the current transportation approach. If two tactical lift assets were used instead of one, this ratio (80%) would be much less.

As for the cost avoidance analysis, it is important to note that the response time is also sensitive to the airship payload. In the analysis, a minimum of two sorties, calculated using the asset payload and volume capacity, was considered. If the payload of the airship has to be reduced to 40 tonnes (for example) for different operational considerations (e.g., weather), three sorties would be required to lift 100 tonnes of supplies. In this case, the response time with the airship lift would be increased by 33.3% and the relative response time would be increased by the same ratio. The same rationale applies to the aircraft lift (CC-177 and CC-138).

Finally, while variation in loading and unloading times would not have significant impact on the airship and the CC-177 lift times as only two sorties are required for each case, the tactical lift time would be sensitive to the loading and unloading times. In the analysis, an average of 0.5 hour of loading time and an average of 0.5 hour of unloading time were used for each CC-138 sortie. This represents a total of 35 hours of lift time and corresponds to 50 – 70% of the airship response time, depending on the deployment location.

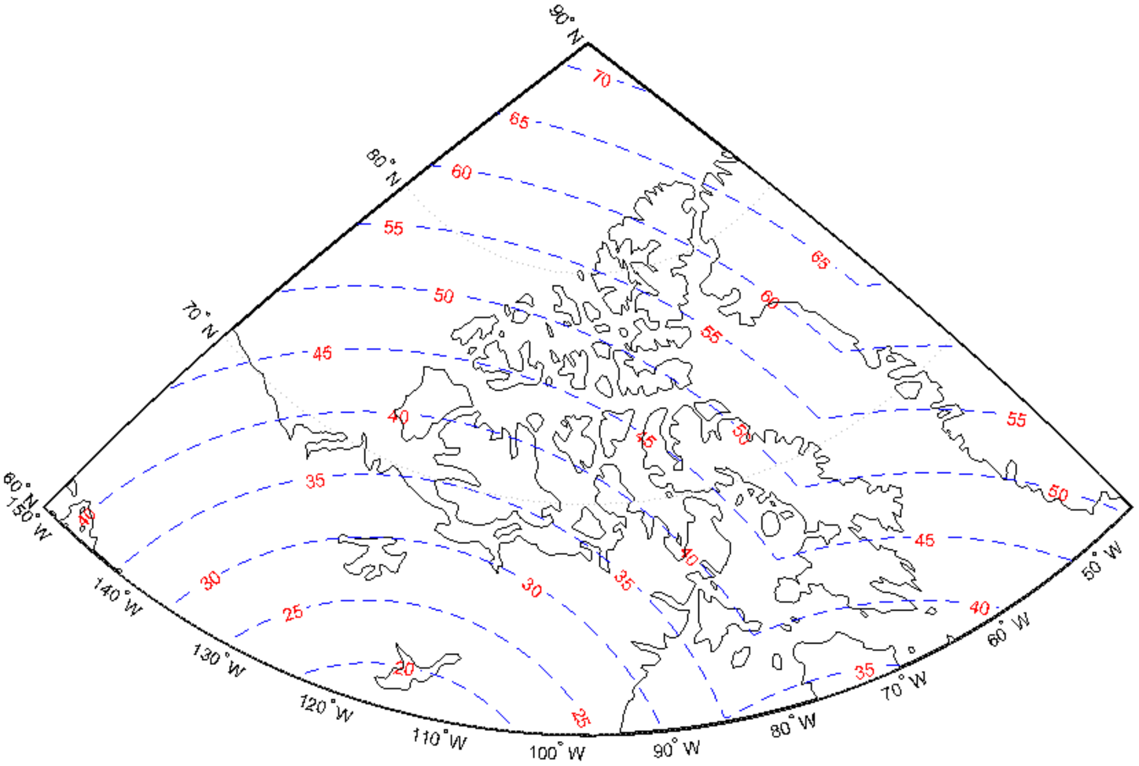

Figure 10: Airship iso-response time distribution for the baseline case (hours)

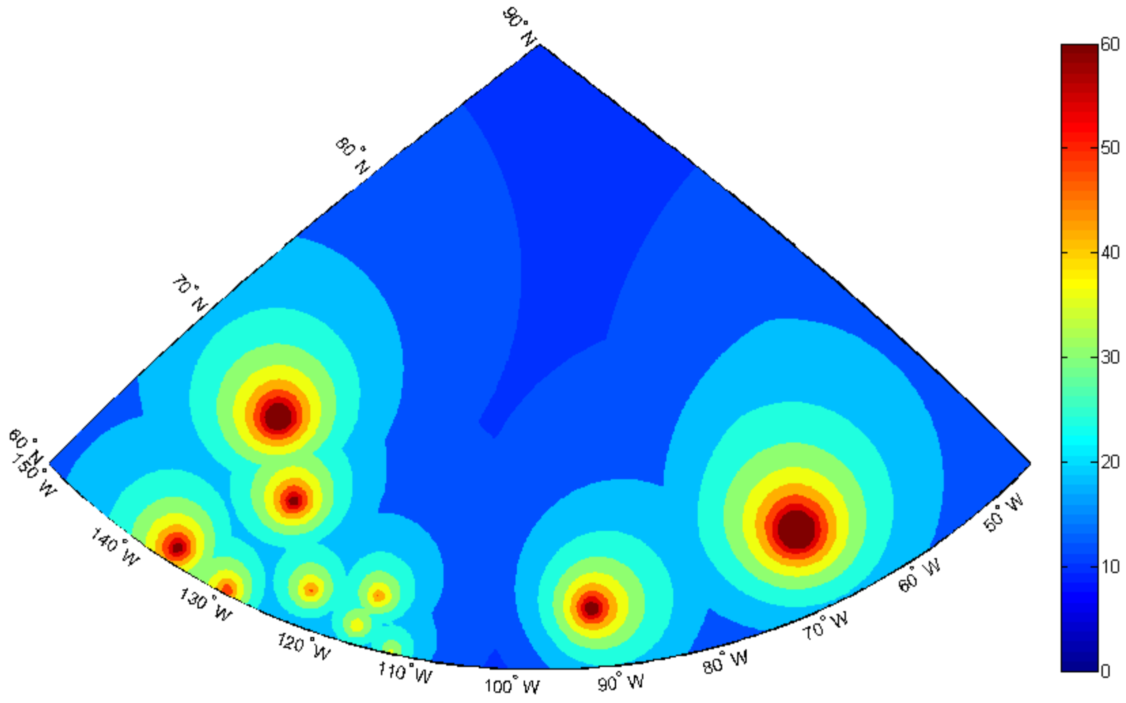

Figure 11: Relative response time distribution for the baseline case (%)

5.3.4 Carbon emission avoidance analysis

Using buoyant lift mode, airships would provide a potential solution for reducing the environmental impact associated with carbon footprint. The carbon emission avoidance measure was not developed to assess the airship lift performance but rather to determine the quantity of greenhouse gas emissions that could potentially be avoided when using airships for military logistics heavy transport. To simulate the quantity of greenhouse gas emitted by the different transport assets, the carbon emission rate (equation 13) was used in the simulation framework instead of the airlift cost rate. Figures 12 and 13 depict the carbon emission avoidance (kg) and the relative carbon emission avoidance (%) distributions for the baseline case, respectively. They indicate similar distribution patterns as the cost avoidance and the relative cost avoidance (both the airlift cost rate and the carbon emission rate are proportional to the fuel consumption rate). Figure 13 indicates that s significant quantity of greenhouse gas emissions (up to 50%) could be avoided by using the airship lift (SkyCat-50) instead of the current transportation approach in support of Northern operations.

Using a combination of the carbon emission avoidance and the relative carbon emission avoidance measures, three potential regions are observed in 10 and 11:

- *Low–Low*: Regions where the carbon emission avoidance and the relative carbon emission avoidance are both low. They generally represent locations that require tactical airlift for relatively short distances (e.g., < 300 km) from the APODs. The airship carbon emission for these regions is comparable to the current transportation approach.
- *High–High*: Regions where the carbon emission avoidance and the relative carbon emission avoidance are both high. These regions are generally located in the South-eastern area of the North. In these regions, the distance traveled by the current transportation assets (including the tactical aircraft flight to and from Yellowknife) is much greater than the distance traveled by the airship.
- *High−Medium*: Regions where the carbon emission avoidance is high but the relative carbon emission avoidance is medium. These regions generally represent locations that require tactical airlift for relatively long distances (e.g., > 1000 km) from the APODs. As the carbon emission rate of the CC-138 is much smaller than the carbon emission rates of the airship and the CC-177 aircraft, the carbon emission of airship lift for these locations is not significantly different from the carbon emission of the current transportation approach.

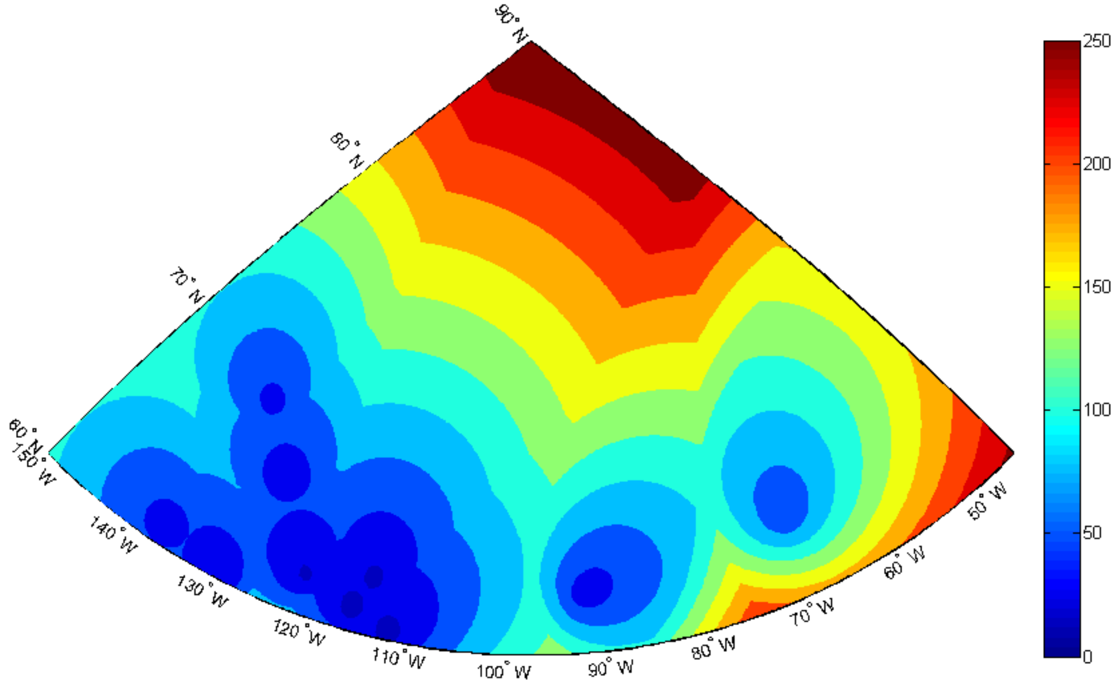

Figure 12: Carbon emission avoidance distribution for the baseline case (kg)

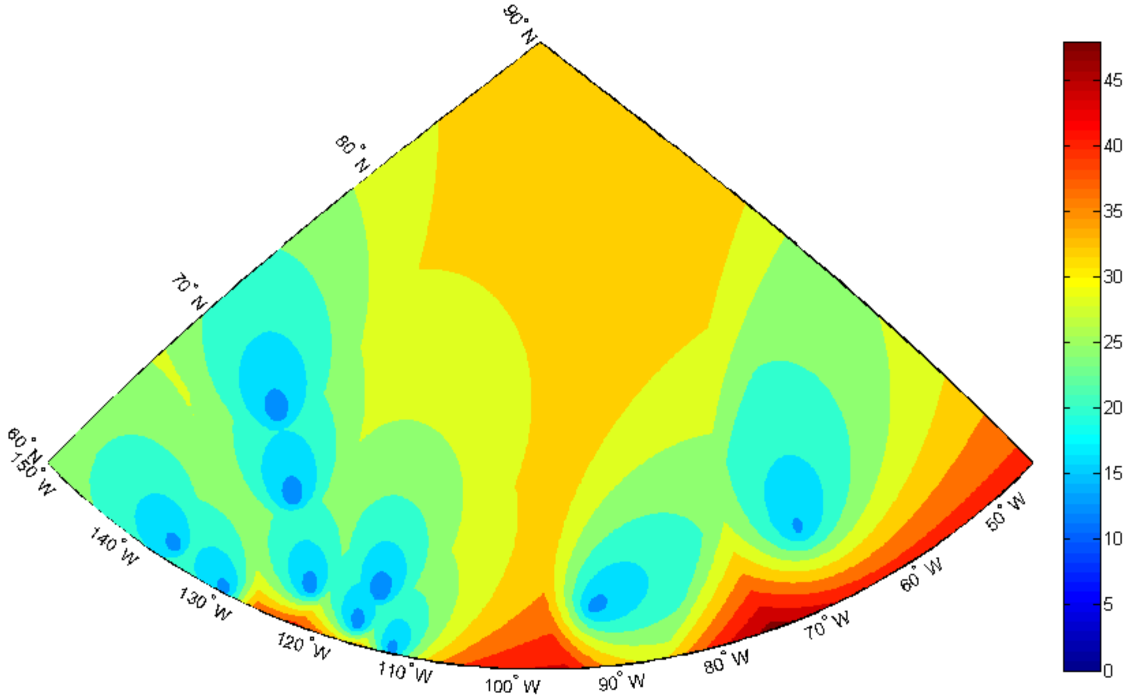

Figure 13: Relative carbon emission avoidance distribution for the baseline case (%)

5.4 Sensitivity analysis

A sensitivity analysis was conducted to address the impacts of key operational parameters on the cost avoidance and the response time distributions. The analysis included the impact of the airship payload, airlift option using CC-130, sealift option and operational demand.

5.4.1 Impact of the airship payload

The impact of the airship payload on the cost avoidance and the response time was examined by exchanging the SkyCat-50 for the SkyCat-200 (i.e. 200 tonne payload) in the baseline case. The performance characteristics and lift rate of the SkyCat-200 airship are indicated in Table 3. Using a 200 tonne airship, one sortie would be required for the lift of 100 tonnes of supplies. Figure 14 depicts the relative cost avoidance (%) distribution for the airship lift using SkyCat-200 (i.e. relative to the cost of the current transportation approach). It indicates that an additional 10 to 20% of lift cost could be avoided with a 200 tonne payload airship. While only one SkyCat-200 sortie is required for the lift (compared with two sorties for the SkyCat-50), the relative cost avoidance with a 200 tonne airship is not significantly higher than the relative cost avoidance with a 50 tonne airship because of the lift rates.

Figure 15 shows the relative response time (%) distribution for the airship lift using SkyCat-200 (i.e. relative to the response time of the current transportation approach). In contrast with the relative cost avoidance, the relative response time is significantly reduced with a 200 tonne airship (about 1/3 of the response time of a 50 tonne airship). While the speed of both airships is the same, a 50 tonne airship would have to travel three times the same distance (including the return flight) than the 200 tonne airship to complete the movement of 100 tonnes of supplies. The analysis indicates that the lift response time could be significantly reduced with airships (in comparison with the current transportation approach), particularly for locations far from the APODs.

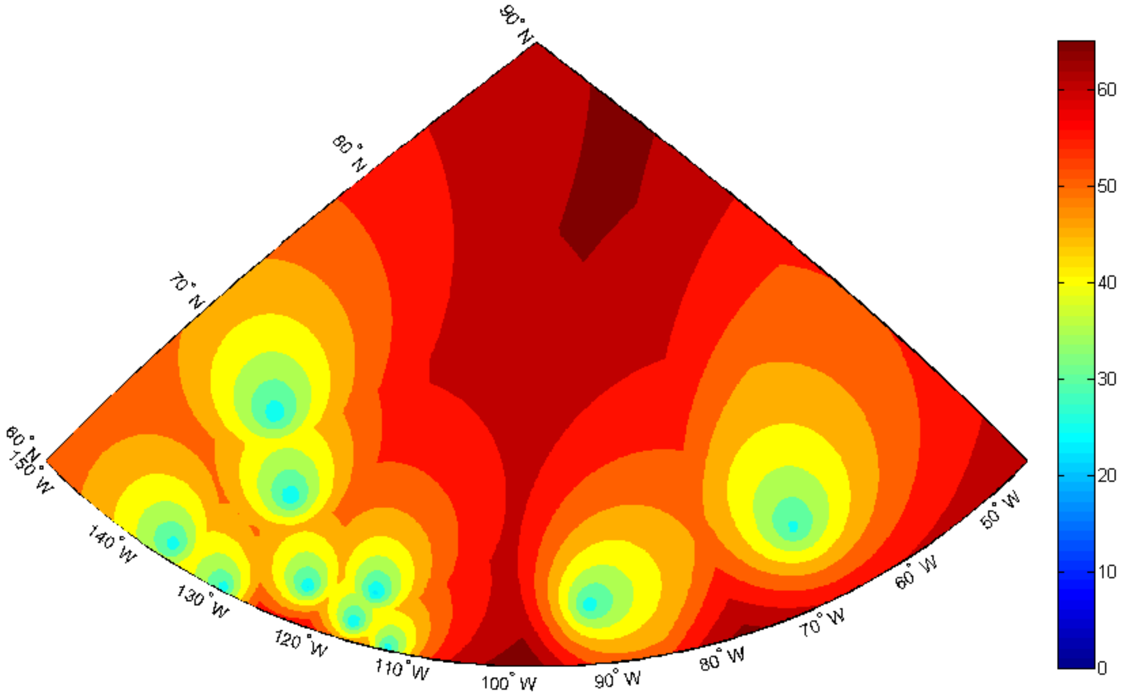

Figure 14: Relative cost avoidance distribution using the SkyCat-200 option (%)

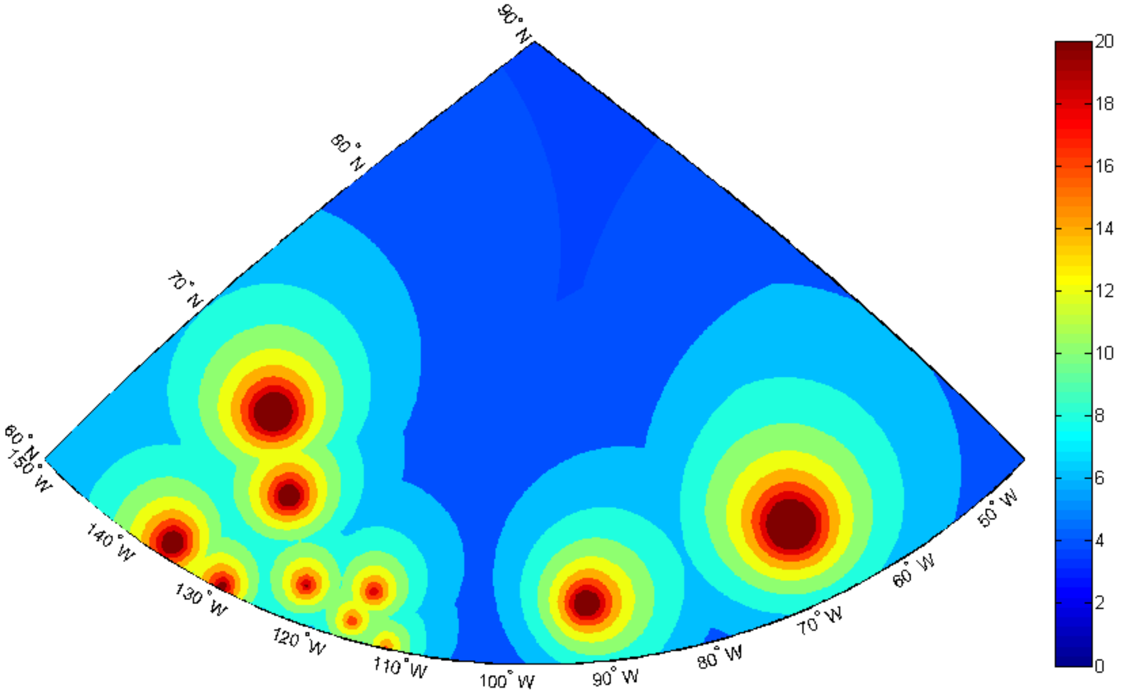

Figure 15: Relative response time distribution using the SkyCat-200 option (%)

5.4.2 Airlift option using CC-130

The impact of the aircraft payload on the cost avoidance and the response time was examined by changing the CC-177 aircraft to the CC-130 aircraft in the baseline case. The performance characteristics and the lift rate of the CC-130 aircraft are indicated in Table 3. As shown in Figure 7, an additional 30 Northern APODs could be used for the CC-130 aircraft. Using the aircraft payload and volume capacity, a minimum of six sorties would be required for the CC-130 to move 100 tonnes of supplies. Figure 16 depicts the relative cost avoidance (%) distribution for the CC-130 airlift option. Compared with the CC-177 airlift option in the baseline case, the relative cost avoidance with the CC-130 airlift option is lower for locations at latitude above 80° because of the availability of APODs suitable for the CC-130 aircraft. Indeed, using the APODs, the tactical lift cost would be reduced for some locations in the North, which reduces the overall lift cost of the current transportation approach.

Figure 17 presents the relative response time (%) distribution for the CC-130 airlift option. As for the baseline case, the airship response time relative to the CC-130 airlift response time is also maximal at the APODs and decreases as the distance from the APOD increases. However, as more APODs are considered for the CC-130 lift option, the relative response time with the CC-130 airlift is higher than the relative response time with the CC-177 airlift, particularly for locations at latitude greater than 80°. As with the cost avoidance, using the additional APODs in the North would reduce the tactical lift time and consequently the overall response time of the current transportation approach.

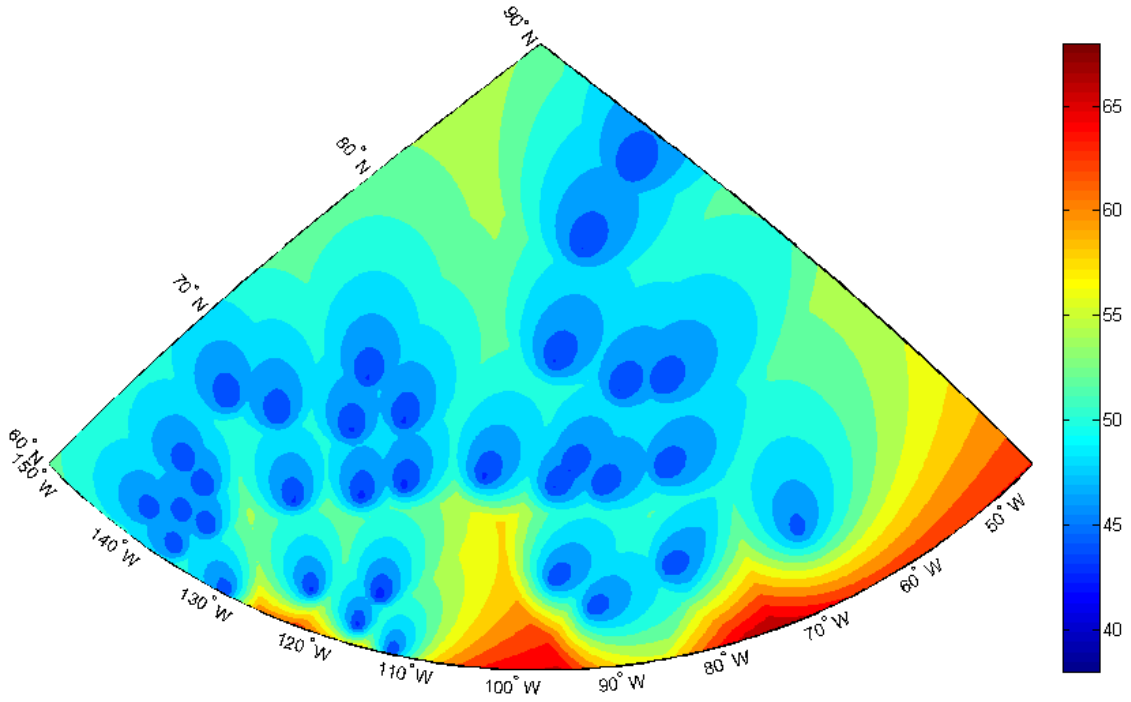

Figure 16: Relative cost avoidance distribution for the CC-130 option (%)

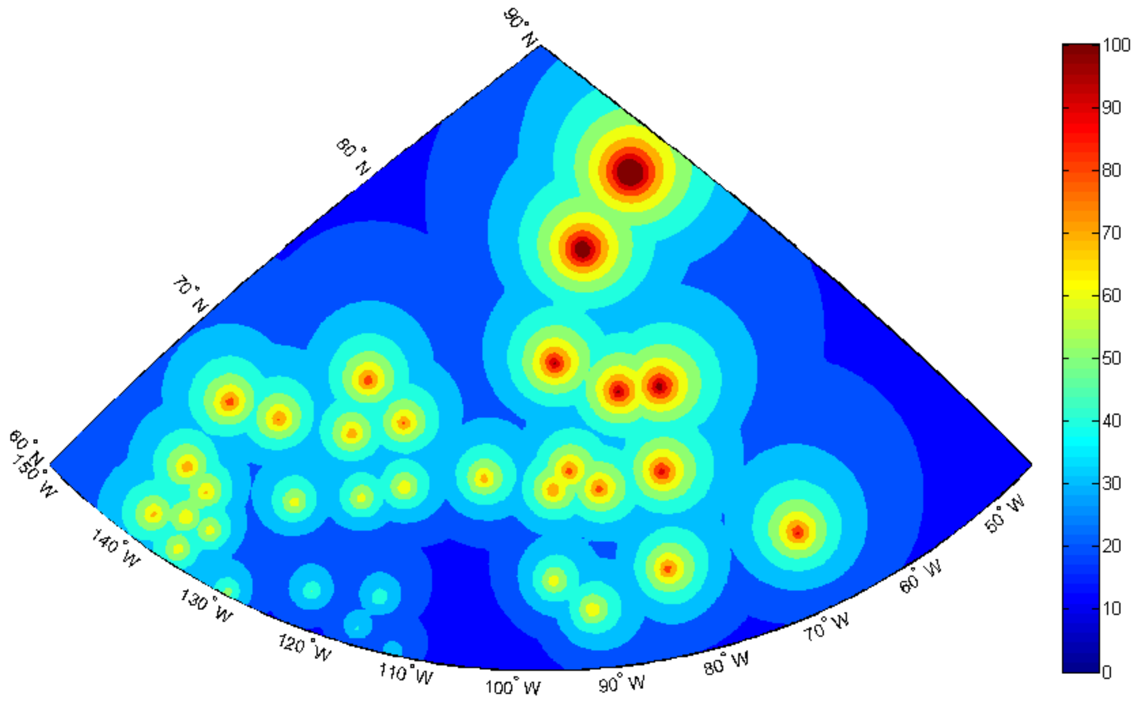

Figure 17: Relative response time distribution for the CC-130 option (%)

5.4.3 Sealift option

In order to boost Canada's sovereign claim over the Northwest Passage, the Canadian Forces is developing two military facilities at strategic locations in the North; a deepwater port at Nanisivik and an army training centre in Resolute Bay. The deepwater port will be used as a docking and refuelling facility for ships deployed to arctic waters. In the future, it could be used as a staging point for Boxtop operations.

To examine the impact of sealift on the cost avoidance and the response time distribution, an analysis was conducted by assuming that supplies could be moved by sealift from the Montreal seaport to the naval facility at Nanisivik and then lifted by airship to various Northern locations. The sealift cost for moving 100 tonnes (approximately 12 sea containers) from Montreal to Nanisivik is estimated, based on historical sealift operations, at $30,000. For the response time, it is assumed that supplies could be shipped in advance to the Nanisivik port and the airship would travel from Trenton to Nanisivik to perform the lift.

Figure 18 presents the relative cost avoidance (%) distribution for the sealift option (i.e. comparison between the current transportation approach and the sealift option). For a given location, the airship lift cost includes the cost for positioning the airship at the Nanisivik port (round trip) and the supply lift cost. Figure 18 indicates that significant savings could be realized on the lift costs by using a combination of sealift and airship movement options. In particular for locations at latitude greater than 70°, the relative cost avoidance would be greater than 70%. Figure 19 presents the relative response time (%) distribution for the sealift option. For a given location, the airship lift response time includes the time required for the airship to reach the Nanisivik port and the supply airlift time. Figure 19 indicates that the response time would be reduced significantly with the sealift option, particularly for locations at latitude greater than 70°.

5.4.4 Operational demand

The impact of the operational demand of the cost avoidance and the response time was assessed using a demand of 150, 200, 250 tonnes. As the demand increases, the number of sorties of each asset (airship, CC-177) increases. For example, with a demand of 150 tonnes, 9 sorties would be required for the CC-177 aircraft and 3 sorties would be required for the SkyCat-50 airship to complete the movement. The analysis indicated that the relative cost avoidance and the relative response time become more significant (compared with the baseline scenario using 100 tonnes) as the demand increases. This is due to the fact that airships are cost effective for heavy loads.

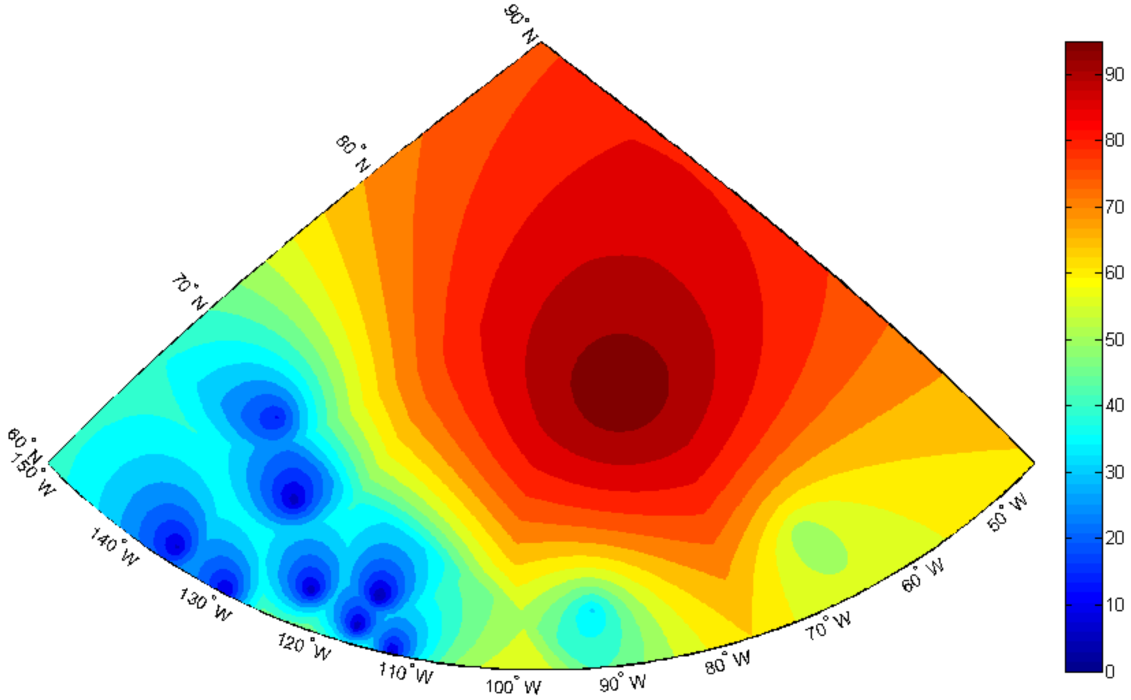

Figure 18: relative cost avoidance distribution for the sealift option (%)

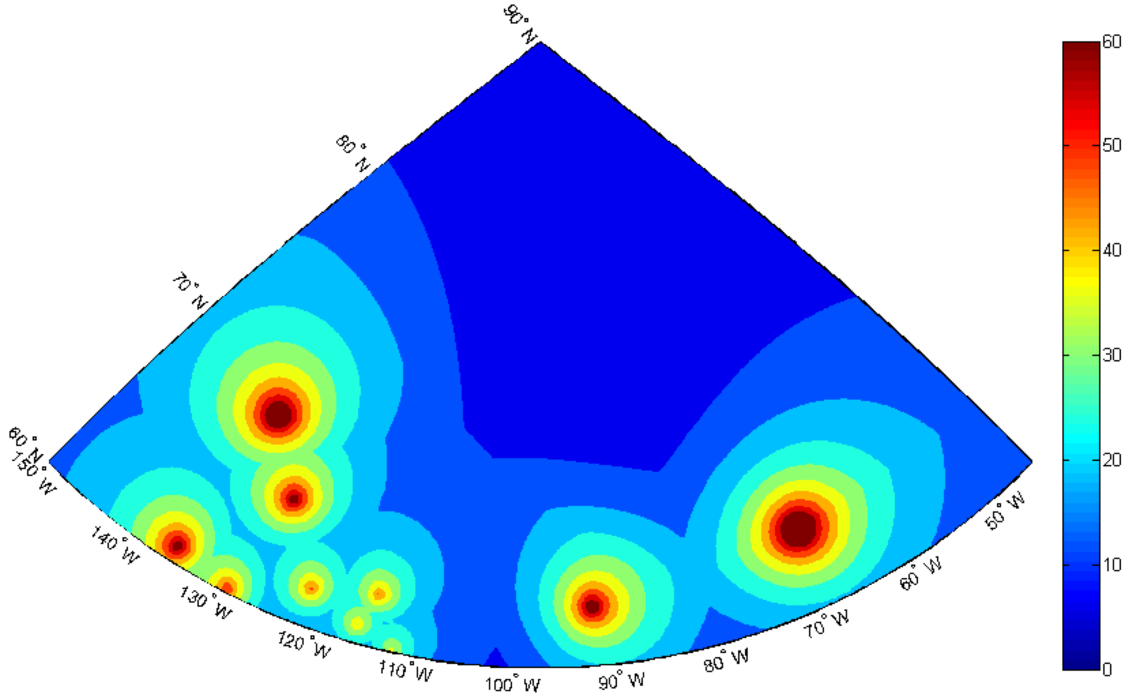

Figure 19: Relative response time distribution for the sealift option (%)

6. Conclusions and recommendations

6.1 Conclusions

This paper presents an assessment of the airship capability for logistics heavy lift in support of CF Northern operations. Performance measures were developed to assess the effectiveness and the responsiveness of the airship lift. A Monte Carlo simulation framework was also developed to simulate various logistics lift scenarios. Historical movement data was used to analyse the airship lift and to compare its performance with the current transportation approach. A baseline case using SkyCat-50 for the airship lift and a combination of CC-177 and CC-138 for the current transportation approach were used in the simulation. A sensitivity analysis was conducted to address the impact of different operational parameters on the airship lift effectiveness. A qualitative assessment of the airship capability was also provided to highlight the limitations and the operational requirements of the airship lift for Northern operations.

The study indicates that airships could potentially improve the sustainability of CF Northern operations. For these operations, the tactical airlift is the challenging component of the sustainment lift and airships could be a potential capability to address this challenge. Depending on the deployment location, potential cost avoidances of up to 60% would be realized on the sustainment lift by using airships instead of the current transportation approach. The lift response time would also be reduced by up to 80%, particularly for areas located far from the APODs. However, as theoretical data for a particular airship were used for the analysis (airships are still in the scale model prototype phase and operating data based on computer simulations are provided by the designer), these operational performances might be different in reality.

The sensitivity analysis of the airship lift performance indicated that the airship cost avoidance and response time would be lower if the CC-130 aircraft was used for the comparison rather than the CC-177 aircraft, particular for regions at latitude above 80°. Indeed, there are more APODs suitable for CC-130 in these regions, which would reduce the cost and the time of the tactical lift. The sensitivity analysis also indicated that the movement option using a sealift to Nanisivik followed by an airship lift would reduce significantly the sustainment lift cost and time (up to 90%) with respect to the current transportation approach, particularly for regions at latitude greater than 70°.

In addition to cost avoidance and response time, airships would have the potential to significantly reduce fuel consumption and greenhouse gas emissions, which would confer substantial environmental benefits. Indeed, airships rely primarily on buoyant gas to keep their mass aloft and consequently require little direct energy to create lift. While the main focus of the analysis has been on the airship lift cost effectiveness and time responsiveness for military logistics heavy lift, an examination of the airship fuel consumption data indicated that up to 50% of carbon emission could potentially be avoided with airships, depending on the deployment location.

6.2 Recommendations

Following this study, it is recommended that:

1. The CF should consider airship technologies to address deficiencies in logistics transportation to support Northern operations. Airships could provide a cost-effective point-to-point delivery capability, mitigate several limitations (e.g., infrastructure requirements) associated with other modes of transport, and potentially improve the sustainability of

Northern operations. Airships could operate in Northern environmental conditions for most of the year (e.g., 10 months) and could be used in most geographical locations in the North.

2. The CF should also consider airships for tactical logistics lift. Freight could be moved by airlift to an APOD using CC-177 or CC-130 or by sealift to a Northern seaport (e.g., Nanisivik) and then lifted by tactical airship to the final destination. The resupply operation of CFS Alert would be a potential application for airship tactical lift that should be considered by CANOSCOM.

3. CANOSCOM should examine the operational requirements for using airships in Northern operations. In particular, the requirements for infrastructure, de-icing, ground handling, refuelling, FOB locations and intermodal transfer need to be investigated.

4. CANOSCOM should examine the different options for contracting airship services, including long term lease and time charter options and determine the appropriate option for domestic operations. This requires a better understanding and analysis of future logistics lift requirements.

5. Further analysis should be undertaken to address other aspects of the airship logistics heavy lift (infrastructure requirements, survivability, etc.), particularly for expeditionary operations. In addition, studies should be initiated into other uses for airships such as surveillance, communication, power generation, and security applications.

References

[01] Federal Government of Canada, the. Speech from the Throne. 17 October 2007 <http://www.sft-ddt.gc.ca/eng/media.asp?id=1364>.

[2] ACIA (2005). *Arctic Climate Impact Assessment*. Cambridge University Press, New York, 1042p.

[3] Carnaghan, M. and Goody, A. (2006). *Canadian Arctic Sovereignty*. Parliament of Canada PRB 05-61E.

[4] Boomer, F.M. (2009). *Northern Lines of Communication (NORLOC): A CANOSCOM Perspective*. Discussion paper, Canada Operational Support Command.

[5] Gazder, R.P. and Rajkumar, S.P. (2002). A Comparative Evaluation of Operation of Airships and Helicopters in Uttaranchal. *Proceeding of the Indian Conference on Lighter Than Air Technologies*, Agra, India.

[6] Prentice, B.E., Phillips, A., Beilock, R.P., and Thomson, J. (2005). The Rebirth of Airships. Journal of the Transportation Research Forum, 44 (1), 173-190.

[7] Newbegin, C.E. (2003). *Modern Airships: A Possible Solution for Rapid Force Projection of Army Forces*, PhD thesis, School of Advanced Military Studies, US Army Command and General Staff College, Fort Leavenworth, Kansas.

[8] Gordon, W.O. and Holland, C. (2005). “Back to the Future: Airships and the Revolution in Strategic Airlift”, Air Force Journal of Logistics, XXIX, 47–58.

[9] Prentice, B.E. and Thomson, J. (2004). Economics of Airships for Northern Re-supply. Proceedings of the 5th International Airship Convention and Exhibition, Oxford (England).

[10] Comeau, P. (1998). *STRATL – A Strategic Mobility Optimization Model for Lift Capability Analysis*, DRDC CORA (Software).

[11] Dickson, R. (2003). *An Examination of the Strategic Lift Capability of Aircraft Fleets with the Potential for Acquisition*, ORD Project Report PR 2003/08.

[12] Scales, C. (2007). *Major Air Disaster Response in Northern Canada: Heavy Transport*. Technical Memorandum, DRDC-CORA TR 2007-16.

[13] Ghanmi, A. and Shaw, R.H.A.D. (2008). Modeling and Analysis of Canadian Forces Strategic Lift and Pre-positioning Options. *Journal of the Operational Research Society*, 59, 1591–1602.

[14] Beomjoon, K., Ghanmi, A., Kaluzny, B. and Shaw, D. (2009). An Optimization Model for Airlift Load Planning: GALAHAD and the Quest for the Holy Grail, *Proceedings of the IEEE Symposium on Computational Intelligence for Security and Defence Applications*, Ottawa, Canada.

[15] Ghanmi, A. (2008). *Modeling and Analysis of Canadian Forces Operational Support Hubs*. Technical Memorandum, DRDC-CORA TM 2008–020.

[16] Ghanmi, A. (2009). *An Operational Support Aircraft Routing Model.* Technical Memorandum, DRDC-CORA TM 2009–044.

[17] Lesser, H. (2009). Height of Surveillance. *MilsatMagazine,* January Edition, 3-5.

[18] Ventry L. and Kolesnik E.M. (1982). *Airship Saga: The history of airships seen through the eyes of the men who designed, built and flew them*. Blandford Press.

[19] Smith, K.R. and Ahuja, D.R. (1990). Toward a Greenhouse Equivalence Index: The Total Exposure Analogy. Climate Change, 17, 1–7.

[20] Dexter J. (2001). *Airship Operations in Uttranchal – Feasibility Study*, Director of Flight Operations, The Lightship Group, USA.

[21] Sklar. M. (2009). SkyHook offers heavy-lift, short-range transportation in remote areas. Boeing Frontiers, August.

Annex A: Northern airfields

This Annex 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).

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
Igloolik	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

List of abbreviations/acronyms

IL-76	Ilyusin 76
AN-124	Antonov 124
APOD	Airport of Disembarkation
APOE	Airport of Embarkation
ATG	Advanced Technology Group
CANOSCOM	Canadian Operational Support Command
CF	Canadian Forces
CFS	Canadian Forces Station
HA	Hybrid Aircraft
ISA	International Standard Atmosphere
JHL	Jess Heavy Lifter
LTA	Lighter-Than-Air
MAJAID	Major Air Disaster
SAR	Search and Rescue
STRATL	Strategic Mobility Optimization Model for Lift Capability Analysis

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