Simulating the Repatriation of Canadian Forces Materiel from Afghanistan

Bohdan L. Kaluzny
CJOC OR&A

Raman Pall
CJOC OS OR&A

DRDC CORA TM 2013–032
March 2013

Defence R&D Canada
Centre for Operational Research and Analysis

CJOC Operational Research and Analysis
Canadian Joint Operations Command

National Defence Défense nationale

Canada

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Technical Memorandum
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March 2013

Principal Author

Original signed by Bohdan L. Kaluzny and Raman Pall

Bohdan L. Kaluzny and Raman Pall

Approved by

Original signed by Isabelle Julien

Isabelle Julien
Section Head (Land, Commands and Readiness)

Approved for release by

Original signed by Paul Comeau

Paul Comeau
Chief Scientist

Abstract

The Canadian Forces completed its combat mission in the Kandahar province of Afghanistan in 2011 and were instructed by the Government of Canada to complete its redeployment out of Kandahar by the end of December 2011. Materiel and equipment were transported back to Canada over several lines of communications. Nearly 1500 sea containers full of materiel, 800 vehicles, and 200 air pallets of material were returned to Canada by combinations of air, sea, and ground transport. This paper describes a discrete-event simulation model developed to analyze the repatriation of Canadian equipment from Afghanistan to Canada via the applicable lines of communication. The objective was to develop a model that could be used to analyze the repatriation in order to enable and improve future mission planning. The discrete-event simulation model is shown to be representative of the actual repatriation effort and is subsequently used to determine the impacts of different potential courses of action, measured mainly through results on the total cost and duration of the repatriation.

Résumé

En 2011, les Forces canadiennes ont mis fin aux opérations de combat dans la province de Kandahar en Afghanistan. Le gouvernement du Canada leur a ensuite demandé de veiller à ce que tous les militaires canadiens aient quitté Kandahar avant la fin de décembre 2011. Le matériel et l'équipement ont été retournés au Canada le long de plusieurs lignes de communication. Près de 1 500 conteneurs maritimes remplis de matériel, 800 véhicules et 200 palettes de matériel pour transport aérien ont été retournés au Canada par des moyens de transport aériens, maritimes et terrestres. Le présent document décrit un modèle de simulation d'événements discrets conçu pour analyser le rapatriement de l'équipement canadien de l'Afghanistan au Canada par l'entremise de lignes de communication applicables. L'objectif visé était d'élaborer un modèle qui pourrait être utilisé pour analyser le rapatriement afin d'améliorer la planification de missions futures. Le modèle de simulation d'événements discrets est représentatif de l'activité réelle de rapatriement et est ensuite utilisé pour déterminer les répercussions des différentes mesures d'action suivre possibles, mesurées principalement par les résultats liés aux coûts totaux et à la durée du rapatriement.

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Executive summary

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Bohdan L. Kaluzny, Raman Pall; DRDC CORA TM 2013–032; Defence R&D Canada – CORA; March 2013.

Background: In 2008, the Government of Canada directed the Canadian Forces (CF) to cease Operation ATHENA in 2011, ending Canada's 10 year contribution to NATO's International Security Assistance Force combat operations in Afghanistan. The CF was instructed to complete its redeployment out of Kandahar by the end of December 2011 and a Mission Transition Task Force (MTTF) was set up to conduct the closure.

Materiel and equipment were transported back to Canada over several lines of communications (LOCs). Approximately 1500 sea containers, 800 vehicles, and 200 air pallets of material were transported via LOCs destined for Canada. The main LOCs were: air lines of communication (ALOC) from Kandahar direct to Canada or to Intermediate Staging Terminals (ISTs) using CC-177s or contracted AN-124s, ground lines of communication (GLOC) from Kandahar to Karachi, Pakistan using contracted trucks, and sea lines of communication (SLOC) from Karachi or from the ISTs back to Canada using leased ships or merchant sea liner service. Time, the sensitivity of material being shipped, threat, and costs were the main factors used to determine the mode of transportation and the LOC used.

The MTTF recorded and managed the retrograde operations with a spreadsheet-based tool that provided a common operating picture (COP). This was used as the primary planning tool and was updated daily—it provided a comprehensive listing of all vehicles, sea containers, ammunition, and general freight identified for retrograde, prioritized for movement along the applicable LOC. The MTTF COP was limited with respect to assisting in options or predictive analyses. In September 2011 Commander Canadian Expeditionary Force Command (CEFCOM) expressed the need to further analyze the efficiency of the Op ATHENA MTTF materiel and equipment repatriation.

Objective: This paper describes a discrete-event simulation model developed to analyze the repatriation of Canadian equipment from Afghanistan to Canada via the LOCs. With a goal of enabling and improving future mission planning, the objective is to accurately model the movement of equipment via the applicable LOCs at the level of granularity recorded in MTTF COP data.

Summary of principal results: The (baseline) discrete-event simulation model was shown to be representative of the actual repatriation of items from Afghanistan. The model was then used to determine the impacts of different potential courses action, measured mainly through results on the total cost and duration of the repatriation. Results indicate that increases to the number of items using the ALOC direct-to-Canada method of shipment would have both increased total cost and decreased the time to complete the repatriation. Decreasing the number of items returning by GLOC would have increased cost to a moderate extent while dramatically decreasing the time to complete the repatriation. Delaying the departure of the flights to the cooler months would have decreased the

total costs as well as the number of flights required of the aircraft while having no effect on the time to complete the repatriation. Finally, increasing the availability of the aircraft would have increased the cost and the number of flights while having no effect on the time to complete the repatriation due to GLOC and SLOC timings.

The results pertaining to the total cost incurred in the returns and the time to complete 95% of the returns are plotted in Figure ES1. The results for the scenarios are specified as relative increases or decreases over the results found for the baseline scenario. A total of 16 scenarios were considered. Each scenario is associated to an integer, which is referenced in the legend of the figure. The results for the baseline scenario are encircled in the figure.

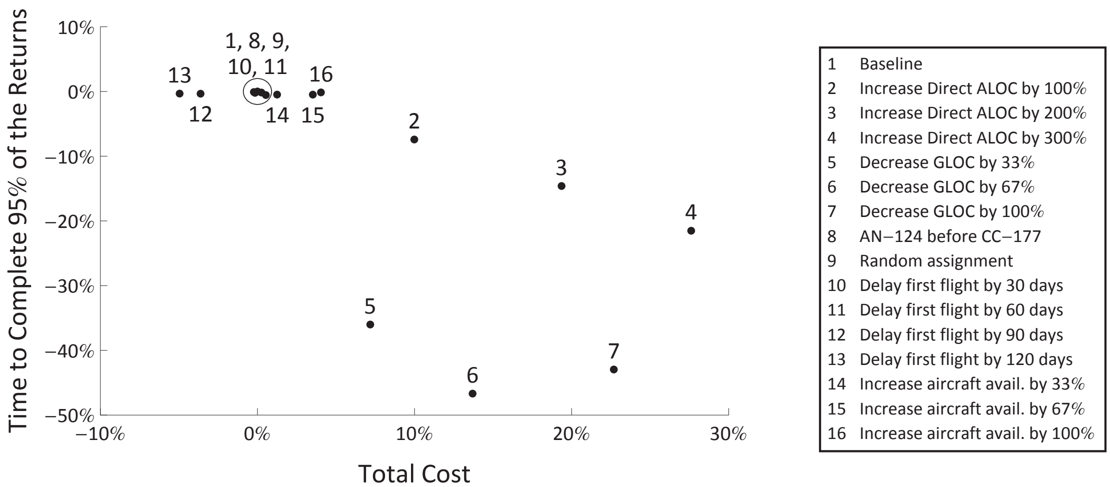

Figure ES1: *The results obtained in the scenarios, plotted on axes specifying the 95% time to completion vs. the total costs incurred.*

Of note is the fact that delaying the flight schedule by four months can reduce costs (by 5%) while not significantly altering the time to complete 95% of the returns. Moreover, changing the method of shipment of some (but not all) of the items moving by GLOC to ALOC through the IST can increase costs slightly, but can dramatically reduce the time required to complete 95% of the returns. For example, in scenario 6 the costs were increased by 14%, but the completion time was reduced by 47%.

Recommendations: It is recommended that in future operations a model similar to one detailed here be constructed to investigate how the repatriation could be optimized prior to the initial departures and during mission execution. More specifically, this model can be used in the repatriation of the materiel from Operation ATTENTION, which is expected to conclude in 2014.

Sommaire

Simulating the Repatriation of Canadian Forces Materiel from Afghanistan

Bohdan L. Kaluzny, Raman Pall ; DRDC CORA TM 2013–032 ; R & D pour la défense Canada – CARO ; mars 2013.

Contexte : En 2008, le gouvernement du Canada demandait aux Forces canadiennes (FC) de mettre fin à l'opération Athena en 2011, terminant ainsi la contribution de dix ans du Canada aux opérations de combat de la Force internationale d'assistance à la sécurité de l'OTAN en Afghanistan. Les FC recevaient alors comme directive de veiller à ce que tous les militaires aient quitté la région de Kandahar avant la fin du mois de décembre 2011 et une Force opérationnelle de transition de la mission (FOTM) avait été établie pour mener l'exercice de clôture.

Le matériel et l'équipement ont été retournés au Canada par le biais de plusieurs lignes de communication (LOC). Environ 1 500 conteneurs maritimes remplis de matériel, 800 véhicules et 200 palettes de matériel pour transport aérien ont été transportés le long de LOC en destination du Canada. Les LOC principales étaient les suivantes : les LOC aériennes directes du Kandahar au Canada ou aux terminaux d'étape intermédiaire (TÉI) au moyen de CC177 ou de AN124 sous contrat ; les LOC terrestres de Kandahar à Karachi, au Pakistan, au moyen de camions sous contrat, et les LOC maritimes, de Karachi ou des TÉI jusqu'au Canada au moyen de navires loués ou d'un service de ligne maritime. Les facteurs clés qui servaient à déterminer le mode de transport et les LOC utilisées étaient le temps, la nature délicate du matériel expédié, la menace et les coûts.

La FOTM a effectué le suivi et la gestion des opérations de retrait au moyen d'un outil fondé sur des feuilles de calcul permettant de fournir une image commune de la situation opérationnelle (ICSP). Cet outil, mis à jour quotidiennement, était l'instrument principal de planification et fournissait une liste exhaustive de tous les véhicules et conteneurs maritimes, de toutes les munitions et des marchandises générales à rapatrier, classés par ordre de priorité pour transport le long des LOC applicables. L'ICSP de la FOTM était limitée en ce qui a trait à l'aide à l'analyse des options ou des options prévisionnelles. En septembre 2011, le commandant du Commandement de la Force expéditionnaire du Canada (COMFEC) a exprimé le besoin d'analyser plus en profondeur l'efficacité du rapatriement du matériel et de l'équipement de la FOTM de l'opération Athena.

Objectif : Le présent document décrit un modèle de simulation d'événements discrets conçu pour analyser le rapatriement de l'équipement canadien de l'Afghanistan au Canada par l'entremise des LOC. Le but principal étant l'amélioration de la planification des missions futures, l'objectif est de reproduire de façon précise le déplacement de l'équipement par le biais de LOC applicables, au niveau de précision des données de l'ICSP de la FOTM.

Résumé des résultats principaux : Le modèle (de référence) de simulation d'événements discrets est représentatif du véritable rapatriement du matériel en provenance de l'Afghanistan. Le modèle a ensuite été utilisé pour déterminer les répercussions des différentes mesures d'action possibles,

mesurées principalement par les résultats liés aux coûts totaux et à la durée du rapatriement. Les résultats indiquent qu'une augmentation du nombre d'articles expédiés au moyen des LOC aériennes directement vers le Canada aurait augmenté le coût total et réduit le temps requis pour compléter le rapatriement. Le fait de réduire le nombre d'articles expédiés par les LOC terrestres aurait augmenté le coût dans une certaine mesure tout en réduisant de façon dramatique le temps requis pour compléter le rapatriement. Retarder le départ des vols aux mois plus froids aurait eu comme résultat de réduire les coûts totaux, de même que le nombre de vols requis, tout en n'ayant aucun effet sur la durée du rapatriement. Enfin, le fait d'accroître la disponibilité de l'avion aurait accru le coût et le nombre de vols, tout en n'ayant aucune incidence sur la durée requise pour compléter le rapatriement en raison du temps des LOC terrestres et maritimes.

Les résultats découlant des coûts totaux liés aux articles expédiés et au temps qu'il faut pour compléter 95 % des expéditions sont représentés à la Figure ES2. Les résultats pour les scénarios sont précisés comme augmentations ou réductions par rapport aux résultats du scénario de référence. En tout, 16 scénarios ont été étudiés. Chaque scénario est associé à un nombre entier, auquel l'on fait référence dans la légende des activités. Les résultats du scénario de référence sont encerclés dans la figure.

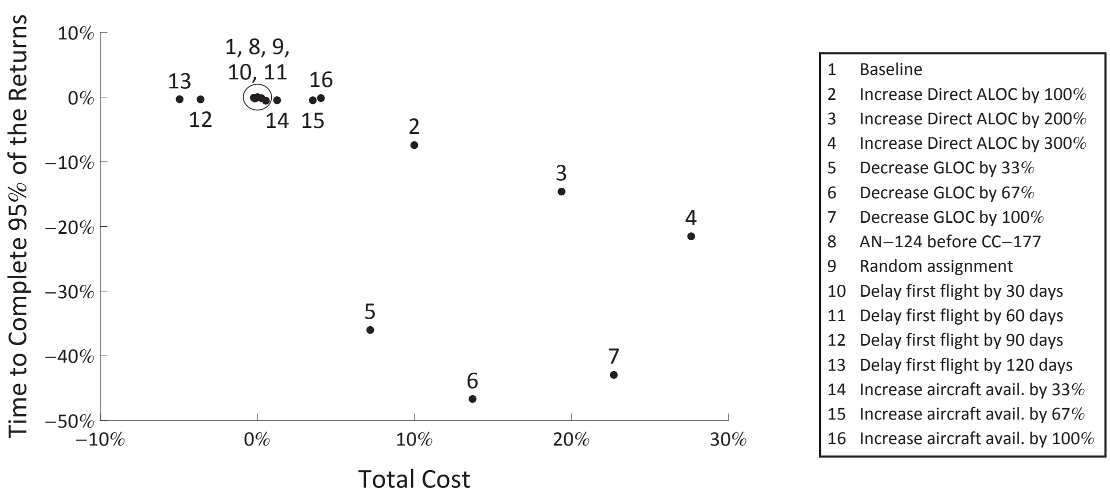

Figure ES2 : *Les résultats obtenus dans les scénarios sont représentés sur des axes, précisant 95 % du temps requis pour la clôture comparativement aux coûts totaux.*

Notez que le fait de retarder l'horaire de vol de 4 mois peut réduire les coûts (de 5 %), tout en ne changeant pas de façon importante le temps requis pour compléter 95 % du transport. De plus, le fait de changer la méthode d'expédition de certains articles (mais pas de tous les articles), en passant de LOC terrestres aux LOC aériennes par le biais des terminaux d'étape intermédiaire peut légèrement augmenter les coûts, mais peut réduire de façon importante le temps requis pour compléter 95 % du transport. Par exemple, dans le scénario 6, les coûts ont augmenté de 14 %, mais le temps requis pour compléter la tâche est réduit de 47 %.

Recommandations : Il est recommandé que, dans les opérations futures, un modèle semblable à celui décrit en détail ici soit conçu pour évaluer comment optimiser le processus de rapatriement avant les départs initiaux et durant l'exécution de la mission. Plus précisément, ce modèle peut être utilisé dans le cadre du rapatriement de matériel de l’opération Attention, qui doit se terminer en 2014.

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Acknowledgements

The authors wish to acknowledge the contributions of Capt. Greg Campbell, of CANOSCOM Chief of Operational Support Transformation, who provided information regarding the historical context of the problem during the early phases of the project. The authors are also indebted to the reviewer for helpful suggestions that improved the presentation of the paper.

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1 Introduction

In March 2008, the Government of Canada directed the Canadian Forces (CF) to cease combat operations in the Kandahar province of Afghanistan by July 2011, ending Operation (Op) ATHENA, Canada's 10 year contribution to NATO's International Security Assistance Force. The CF was instructed to complete its redeployment out of Kandahar by the end of December 2011 and a Mission Transition Task Force (MTTF) was set up to conduct the closure. MTTF planning commenced in early 2010. The Canadian Expeditionary Force Command (CEFCOM) and the Canadian Operational Support Command (CANOSCOM) established a Material Management Infrastructure Board which liaised with stakeholders to produce the Materiel and Infrastructure Disposal Directive, the authoritative document for how all material and infrastructure was handled, packed, preserved, returned, and disposed of over the course of mission transition. Materiel and equipment were transported back to Canada over several lines of communications (LOCs). Time, the sensitivity of material being shipped, threat, and costs were the main factors used to determine the mode of transportation and the LOC that would be used for shipments from Afghanistan back to Canada. Sensitive materiel consisted of most vehicles, communications equipment, weapons systems, spare parts, munitions, and high value items. Approximately 1500 sea containers, 800 vehicles, and 200 air pallets of material were transported by LOCs destined for Canada.

The main LOCs were:

1. Air lines of communication (ALOC) from Kandahar direct to Canada or to Intermediate Staging Terminals (ISTs), referred to hereafter as *ALOC Direct* and *ALOC IST*, respectively. The IST was initially located in Cyprus and transitioned to Kuwait in September 2011. ALOCs were used to retrograde material and vehicles that were deemed time or security sensitive[1], with highly sensitive equipment transported exclusively via ALOC Direct. The 1 Canadian Air Division devoted daily CC-177 Globemaster III airlift assets to support mission closure. Contracted Antonov AN-124 airlift was also employed and necessary to move large and heavy vehicles such as main battle tanks and RT-240 sea container handlers. Restrictions were imposed on use of the AN-124 for the move of weapons systems, ammunition and classified materiel due to security considerations. Escorts were utilized on a number of flights to mitigate risk.

2. Ground lines of communication (GLOC) from Kandahar to Karachi, Pakistan. Contracted trucks were used to transport containers from Kandahar Airfield to the port of Karachi for onward movement by scheduled maritime liner service to Canada. Only non-sensitive materiel was transported through GLOC. During mission planning, this route represented the least costly LOC, but was potentially risky due to the possibility of criminal activity along the route.

3. Sea lines of communication (SLOC) from Karachi or the IST back to Canada. Regularly scheduled liner service was used from Karachi to the Port of Montreal. Sea travel from Cyprus and Kuwait was done by four specially contracted ships. The International Port of Kuwait was used for the loading of materiel and vehicles while the Kuwait Naval Base provided a safe and secure area for the loading of ammunition.

[1] Abiding by the request of the Cypriot Government, there would be no movement of Main Battles Tanks or ammunition and explosives through the island. The Kuwait IST relaxed these restrictions.

The MTTF recorded and managed the retrograde operations with a spreadsheet-based tool that provided a common operating picture (COP). This was used as the primary planning tool and was updated daily—it provided a comprehensive listing of all vehicles, sea containers, ammunition, and general freight identified for retrograde, prioritized for movement along the applicable LOC. The MTTF COP was an information management tool, not an analysis tool. It provided a wealth of detailed data such as vehicle/container weights, and aircraft departure times and loads, however lacked ability for options or predictive analyses. In September 2011 Commander CEFCOM expressed the need to further analyze the efficiency of the Op ATHENA MTTF repatriation [1, 2].

1.1 Previous Work

Research into modelling military logistics has received much attention, benefiting from both simulation and optimization approaches.

Schank *et al.* [3], and more recently Powell *et al.* [4] provide a review of military logistic modelling efforts. They group the modelling approaches into deterministic linear programming, simulation, and stochastic programming categories (and furthermore propose a method to combine simulation and optimization). Primary focus has been on airlift modelling. Dantzig and Ferguson [5] developed one of the earliest mathematical models for optimizing air-based transportation. Research at the United States (U.S.) Naval Postgraduate School (NPS) and the RAND Corporation were combined to create NRMO (NPS/RAND Mobility Optimizer) described by Baker *et al.* [6]. The heart of NRMO is a linear programming model that minimizes the amount of cargo delivered late or not at all. Burke *et al.* [7] developed the Transportation System Capability discrete-event simulation model to simulate the deployment of forces from U.S. Army bases. The U.S. Air Mobility Command employs a rules-based simulation model called the Air Mobility Operations Simulator (AMOS) for strategic and theatre operations to deploy military and commercial airlift assets. Most of the mentioned models are proprietary and unavailable for distribution. It is also unclear how customizable they would be if made available.

Defence Research and Development Canada studies include an aircraft load allocation optimization model [8] which uses a hybrid of simulated annealing and genetic algorithm methods to solve a multi-objective optimization problem associated with allocating a set of cargo items across a heterogeneous fleet of available airlift assets. The model was used to conduct analysis of some of the strategic lift options for the Canadian Forces and to develop a simulation framework to study the effectiveness of a variety of pre-positioning options [9]. Taylor [10] examined Airlift Operations Planning Guide [11] and developed a model to determine airlift requirement based on physical dimensions and weight of items to be moved. Comeau [12] developed the Strategic Mobility Optimization Model for Lift Capability Analysis for strategic lift capability options analysis of fleet mix problems involving sealift and airlift assets. Campbell and Moorhead [13, 14] developed a movement estimator tool (MET) with an easy-to-use spreadsheet interface useful for military move planners to determine time and cost estimates of strategic movement of materiel.

Of the models listed, MET enjoyed recent success as it was adopted by CANOSCOM Operation Support Movement (OS Mov) planners. It proved to be a valuable tool during planning of Op HESTIA (Canada's humanitarian assistance mission to Haiti in 2010) and for early planning of Op ATHENA redeployment. Given a list of items to be moved, specification for possible lift assets, and LOCs (airlift, sealift). A simulation module generates a series of movement scenarios considering variability in item ordering for load planning and aircraft payload capacities. Strengths of MET include detailed modelling of items (length, width, height, weight), linkage to a CF database of materiel, modelling of aircraft payload and approximate bulk constraints, and a graphical summary of the cost/tradeoff region facilitating comparison of different courses of action. MET also incorporates item movement priority. Higher priority items are moved first (the simulation re-orders items within the priority set). This priority is very useful for deployments, but not necessarily applicable for redeployment: During Op ATHENA MTTF items were turned in by CF units over the course of many months. While items of the same priority level were indeed grouped together and lifted along appropriate LOCs, items (whether high or low priority) could only be shipped once available. The available version of MET models airlift and sealift, but not ground transportation (GLOC) as was used in Op ATHENA MTTF. Similarly, the cross loading between airlift, sealift, ground transportation is not supported.[2] Cross loading between airlift, sealift, ground was the norm during Op ATHENA MTTF repatriation. During Op ATHENA MTTF the scheduling of lift assets was intricate and dependent on lift asset availability and item availability. The schedule included a shift in IST location from Larnaca to Kuwait. In MET the schedule for airlift and sealift departures need to be specified by the user as a constant number per week or per month, and the actual number of lift assets used is not modelled (availability of trucks for GLOC proved to be an issue during Op ATHENA MTTF). In early planning the exact weight of loaded sea containers, and even individual vehicles, is not known. Similarly, the exact ratio of container types (quadcons, tricons, and TEU (twenty foot equivalent)) cannot be specified with certainty.

1.2 Objective

This paper describes a discrete-event simulation model developed to analyze the repatriation of Canadian equipment from Afghanistan to Canada via LOCs. With a goal of enabling and improving future mission planning, for example the repatriation of Op ATTENTION materiel, the objective is to accurately model the movement of equipment via applicable LOCs at the level of granularity recorded in MTTF COP data. The intent is to complement existing movement tools, including the MET briefly summarized in the previous section, addressing some of the model gaps identified when comparing to reality. The main modelling gaps addressed by the discrete-event simulation model are:

- Ability to model the actual number of lift assets (*e.g.*, number of trucks available) or by strictly by schedule (*e.g.*, number of flights per week);
- Ability to model complicated schedules and uncertainties in lift asset availability;
- Ability to model any combination of ALOC, GLOC, SLOC and cross loading between LOCs;
- Ability to model specific events (*e.g.*, transition of IST or closure of GLOC); and,
- Ability to model uncertainty in input items (cardinality, weights, shipment method).

[2] The authors of MET indicate these features will be available in a subsequent software release that was not available to OS Mov planners when this study was initiated.

Complementing models allow for more intricate modelling, what-if analyses, and result verification. Additionally, the discrete-event simulation approach taken provides the ability to generate independent cost and time estimates, better positioning Canadian Joint Operational Command (CJOC) OS Mov planners and senior CJOC decision makers when considering courses of action for Op ATTENTION redeployment.

1.3 Scope

Operation ATHENA MTTF was a large undertaking encapsulating several efforts. For example, more than 2700 shipping containers and 1000 vehicles were processed, more than 250 structures/buildings were transferred, over 10000 contracts were reviewed or closed, over 7000 cubic meters of soil was remediated, 150 terabytes of electronic data was processed, and 120 thousand pounds of paper was repatriated [15]. The scope of discussion in this paper is focused on the equipment repatriated and the LOCs used for the repatriation. It is assumed that materiel has been packed into containers or onto air pallets—grouped and tagged for a particular shipping method. The simulation model developed queues of containers/pallets/vehicles that shared the same shipment method and sent them along the appropriate LOCs taking into account possible variation in resource availability, scheduling, etc. The shipping order of containers/vehicles/pallets within a set sharing the same shipment method differs for each simulation iteration. The disposal or transfer of items within Afghanistan, holding costs at the Kandahar airfield, materiel and vehicle processing (*e.g.*, for inspection, or repair), and the distribution of the items upon arrival to Canada were not considered. These and other model assumptions are further discussed in Section 2.7.

1.4 Outline

The paper is structured as follows: Section 2 describes the discrete-event simulation model of the repatriation of Canadian equipment along the different LOCs as well as the relevant data recorded in the MTTF COP. Section 3 compares the results of the baseline simulation model to reality (as captured in the MTTF COP), and subsequently Section 4 reports on results obtained from select scenarios deviating from the baseline. Actual cost and time figures are purposely omitted. Instead, results are reported as relative differences.

2 Methodology

2.1 Overview

A discrete-event simulation model was built in the *Arena* simulation environment [16] in order to recreate the repatriation of materiel from Afghanistan to Canada via the LOCs. An *Arena* model is a computer program containing components called modules that represent processes or logic. Connector lines are used to join these modules together and specify the flow of entities. While modules have specific actions relative to entities, flow, and timing, the precise representation of each module and of each entity relative to real-life objects is subject to the modeller. In this case, entities within the model represent the various items that are to be returned to Canada from Afghanistan. The lowest level of granularity of the items in the simulation are containers, vehicles, and air pallets – the specific contents in the containers or pallets are not specified. Resources in the model representing the various modes of shipment govern the availability of the AN-124 and CC-177 aircraft used for the ALOCs, the contracted trucks used for the GLOC, and the ships used for the SLOC.

Data used in this study was extracted from the MTTF COP spreadsheets (containing entries up to 28 November 2011) and consisted of item weights (containers, vehicles, and air pallets), flight times, aircraft loads (weight and number of items), aircraft availability (schedule), and the LOC chosen for each item shipped.

The simulation model is explained in four parts (detailed in Sections 2.2 to 2.5):

1. Vehicles, containers, and air pallets;
2. Aircraft availability and loading;
3. GLOC; and,
4. Sea lift.

Cost data incorporated into the simulation model is discussed in Section 2.6; Section 2.7 details the notable model assumptions; and Section 2.8 details the simulation model outputs.

2.2 Modelling Vehicles, Containers, and Air Pallets

The MTTF COP records report on 757 vehicles, 1408 containers, and 170 air pallets shipped out of Afghanistan. The MTTF COP was maintained up until 28 November 2011 and is known to exclude up to two weeks of data (during which the Op ATHENA MTTF itself was being repatriated). The ideal data set would have contained complete information on item dimensions (length, width, height) and weight. Unfortunately the MTTF COP data is incomplete: no weight is specified for 10% of vehicles and 5% of the containers, no volume dimensions (bulk) are specified for 15% of the vehicles. No container dimensions are specified and the first instinct to assume containers are twenty-foot equivalents (TEUs) is rebuked given that 3% of CC-177 flights carried more than 3 containers (some up to 6), 11% of CC-177 flights carried more than 3 items (vehicles or containers), and 7% of AN-124s carried more than 11 containers (some up to 16)—CJOC OS J4 Mov planners affirmed that CC-177s can carry a maximum of 3 TEUs, and AN-124s a maximum of 11 TEUs. In addition to incomplete data, it is unknown what percentage of the MTTF COP records are erroneous (due to user input). Given the disparate nature of the data set, the decision was made to not model the size and dimensions of items. Only the weight of items is considered in the simulation model.

At the start of the simulation, all items (vehicles, containers, and air pallets) are created. Given the incompleteness and potential inconsistencies of the source data, probability distribution functions (pdf) were fitted to the container and vehicle weights found in the MTTF COP data set to generate realistic weights for the simulation model. The log-normal distribution, a probability distribution of a random variable whose logarithm is normally distributed, is commonly used for positive data; *e.g.*, the log-normal distribution domain of zero to infinity is more suitable for item weights than a normal distribution which includes the negative domain. The weight of a container/vehicle was sampled from the respective pdf. Figure 1 illustrates the histogram of the container weights and the fitted pdf. The mean container weight was 15,125 pounds (lbs) and the pdf's standard deviation was 7,604 lbs.

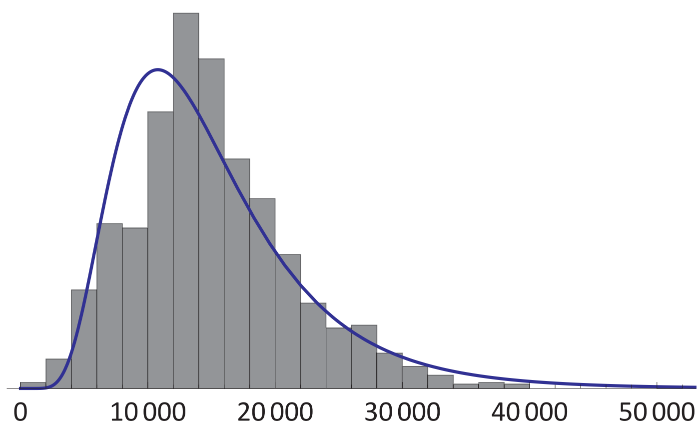


Figure 1: *Histogram of container weights (lbs) and fitted pdf.*

Vehicles were categorized into light (under 20,000 lbs), medium (20,000 to 100,000 lbs), and heavy (over 100,000 lbs) groups. To model vehicle weights in the simulation model, three pdfs for the light, medium, and heavy vehicle weights were fitted with means of 7,443 lbs, 39,648 lbs, and 126,531 lbs respectively; and standard deviations of 7,078 lbs, 13,123 lbs, and 5,460 lbs respectively. Figure 2 illustrates the pdfs overlaid on the histogram of the vehicle weights (observed weights). According to this weight classification, 36% of the vehicles moved were considered light weight, 61% were considered medium weight, and 3% were considered heavy weight. This proportion of vehicles was maintained in the simulation model. Vehicles over 100,000 lbs were airlifted exclusively by AN-124s.

Air pallets were shipped exclusively via ALOC Direct to Canada. Figure 3 illustrates the histogram of the weights of air pallets. Over 70% of all air pallets weighed between 3,000 and 6,000 lbs. The figure also illustrates the best-fit log-normal distribution with a mean of 4,563 lbs and standard deviation of 2,153 lbs, and a uniform distribution with a minimum of 3,000, a mean of 4,500 and a maximum of 6,000. The results discussed in Sections 3 and 4 were generated assuming the uniform distribution of aircraft pallet weights.[3]

[3]While the log-normal distribution accounts for more variation in the tails of the distribution (at the expense of the

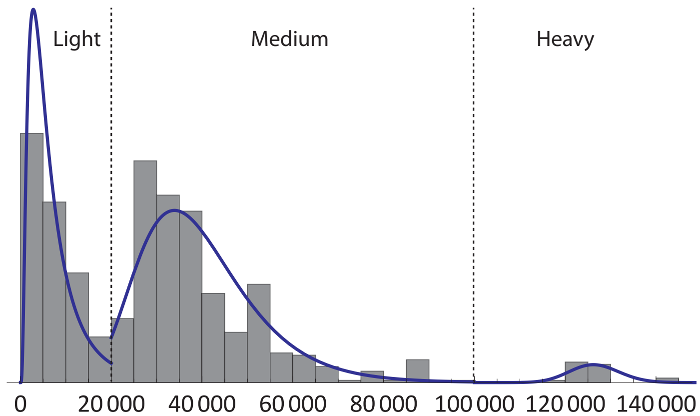


Figure 2: *Histogram of vehicle weights (lbs) and the fitted probability density functions for light, medium, and heavy vehicles respectively.*

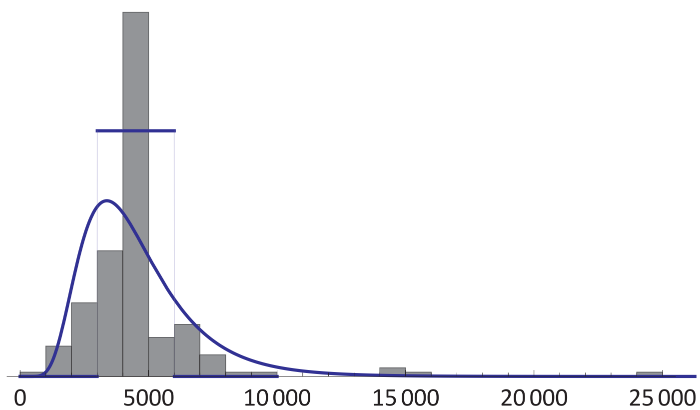


Figure 3: *Histogram of air pallet weights (lbs) and the fitted probability density functions.*

Containers, vehicles, and air pallets are assigned a shipment method. Based on MTTF COP data, Table 1 indicates the observed percentage of containers, vehicles, and air pallets that were sent by ALOC Direct, ALOC IST, and GLOC. Each item in the simulation model is assigned a shipment method based on these observed percentages. Items are then binned by shipment method (randomly sorted and placed in LOC-specific queues) and assumed to be available for loading onto trucks or aircraft.

dense number of weight around the mean), the Kolmogorov-Smirnov test [17] found, with 99% confidence, that the null hypothesis—that the distribution of the number of ALOC Direct flights with air pallets modelled by the uniform pdf has the same distribution as the number of flights with air pallets modelled by the log-normal pdf—could not be rejected.

Table 1: *Percentage of containers, vehicles, and air pallets sent via respective LOCs.*

LOC	Containers	Vehicles	Air Pallets
ALOC Direct	6%	6%	100%
ALOC IST	52%	88%	0%
GLOC	42%	7%	0%

2.3 Modelling Aircraft Availability and Loading

MTTF flights out of Afghanistan started in the first week of May 2011. The MTTF COP reports on completed CC-177 flights out of Afghanistan as follows: 33 were routed to Canada, 90 to Cyprus, and 93 to Kuwait. It is useful to note that Cyprus was also used by the Canadian Forces for troop rotation referred to as "relief-in-place." CC-177 assets were used to transport over 1000 passengers out of Afghanistan. Nearly a quarter of CC-177 flights from Kandahar to Larnaca carried a significant number of passengers (over 40) and containers/vehicles. The MTTF COP reports on 127 completed AN-124 flights from Kandahar to Kuwait or Cyprus, and 14 routed to Canada. Combined, this represents a total of 357 flights. Figure 4 illustrates the frequency of CC-177 and AN-124 flights between May and December 2011. This schedule of flights was incorporated into the simulation model.

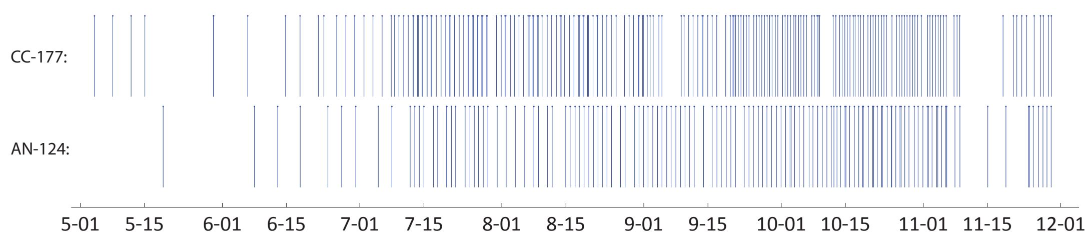


Figure 4: *CC-177 and AN-124 flights between May and December 2011.*

There are numerous factors that determine what items and how many items can fit into a given aircraft. Weight and volume (of items and cargo bay) are just two of these factors. Other, equally important factors, include centre-of-gravity constraints, floor tie-down locations, floor shear constraints (amount of pressure that can be applied at certain locations), ordering and orientation of items (*e.g.*, it would be unnatural to load a vehicle "sideways"), etc. The general feasibility problem of determining whether a certain set of items can be placed in an aircraft bay is an NP-complete (computationally hard) problem (see [8] for a discussion and further references). It relates to the classic bin-packing and set-partition problems. Existing aircraft loading tools often approximate volume constraints but cannot guarantee load feasiblity. The discrete-event simulation model described herein does not generate load plans. Rather, at a high level, each simulation iteration estimates the number of flights (of different lift assets) that may be required. Taking into consideration the challenge in accurately modelling bulk and other complicated factors, exasperated by the disparate nature of the data set, only the weight of items is considered in the simulation model—as is the lift asset payload.

In the simulation model, the assigned shipment method of the next item to be moved drives how an available aircraft is used (whether for ALOC Direct or IST). Certain items even drive the selection of aircraft type (*e.g.*, heavy vehicles were moved by AN-124s only). If both types of lift assets are available then CC-177s are given preference for ALOC IST and AN-124s are given preference for ALOC Direct.[4] Once an item is loaded onto a particular aircraft, only items with similar shipment methods are subsequently considered for loading onto this aircraft. Items are added as long as the aircraft's maximum payload (MPL) is not exceeded. A consequence of the decision not to model item bulk is that the simulation model does not consider bulk-out. If an item cannot be loaded (because it would violate the MPL constraint) then it is randomly placed back into the LOC-specific queue. If none of the subsequent four[5] items can be loaded, then the aircraft loading is ceased. This mitigates against an aircraft being loaded by a very light item followed by an attempt to load a very heavy item (*e.g.*, a tank) that would exceed the MPL. Rather than ceasing the loading (and having the aircraft departed with a very light payload) the simulation model is programmed to examine the next few items to determine if further item loading is possible. By placing "surplus" items randomly back into the queue (as opposed to the back of the queue) prevents a clustering of heavy items in the final aircraft loads.

Again, aircraft bulk constraints are not considered as item sizes/dimensions are not modelled. Similarly, the specific placement of items within the aircraft (affecting the load balancing, tie-down locations, and shear constraints) is not modelled. While the impact of not modelling item bulk cannot be measured, Section 3 shows that resulting distribution of aircraft bulk loads does not stray too far from the actual when modelling Op ATHENA MTTF repatriation. The decision not to model bulk reinforces the complementary nature of the approach to existing tools such as the MET or more sophisticated bin-packing/load optimization algorithms.

2.3.1 Modelling the Impact of External Temperature on MPL

Average daily highs in Afghanistan reached above 40 ^{o}C in the period from June to October 2011 during which the bulk of the CC-177 and AN-124 flights were scheduled. The average monthly temperatures for Kandahar (based on 9 years of collected data) are presented in Table 2 [18].

Table 2: *Average monthly temperatures (in ^{o}C) for Kandahar, Afghanistan.*

Period	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Average Temperature	6	9	14	19	24	29	31	29	24	17	10	6
Average High Temperature	13	17	22	27	33	38	40	38	34	28	19	14
Average Low Temperature	0	2	7	12	16	20	23	20	15	7	2	-1
Highest Recorded Temperature	22	28	31	39	41	43	43	43	40	35	28	25
Lowest Recorded Temperature	-12	-7	-2	2	8	12	16	12	6	-1	-10	-12

As high external temperatures can adversely affect the MPL of an aircraft, movement was preferred at night when temperatures were at their lowest. Moreover, OS J4 Mov staff suggested that temperature

[4] Sensitivity analysis presented in Section 4 indicates that the selection of lift asset, when both are available, doesn't affect the total number of flights and total time for repatriation.

[5] Subjectively chosen.

restrictions on takeoff had at times reduced the maximum observed payload of an AN-124 flight from 80 tons to values as low as 28 to 35 metric tons, a remarkable decrease in efficacy [19]. As such, it was necessary to consider the impact of the external temperature on the MPL of the aircraft in the simulation model.[6]

The external air temperature for any given day in the simulation was specified using the data in Table 2. Using the current month of the simulation, two triangular distributions were created from which the daily high (and low) could be sampled; ensuring that the means of the distributions matched the average highs and lows in the month, and the maximum and minimum of the distributions were the average daily temperature in the month and the highest (or lowest) recorded values in the month. Given that the triangular distribution is generally specified in terms of its minimum, maximum, and mode (most likely value), specifying it in terms of its minimum, maximum, and mean (values which are provided in Table 2) required specification of the mode in terms of these other three values (minimum, maximum, and mean).

A random integer value (uniformly chosen on an integer scale) between the sampled high and low temperature was then determined, which was then assumed to be the temperature at the time of the flight, and subsequently used for payload considerations.

In the simulation model the MPL of the AN-124s was computed as a function of the external air temperature which was known (details to follow). However, data concerning the external air temperature at take-off for the CC-177 was not available—hence, the MPL of the CC-177 aircraft assets was determined by sampling from the historical dataset of all observed payloads of CC-177 flights departing Afghanistan in a given month. In effect, two proxy measures were related to one another in the case of the CC-177 flights: the month was used as a proxy for the temperature, which was itself a proxy for the combined factors affecting an aircraft's MPL.

These calculations result in a distribution of possible MPL values for a given aircraft on a specified day in the simulation. The uncertainty in the MPL value is due to the fact that the maximum safe payload for a given aircraft is a function of a multitude of factors—temperature, air pressure, altitude, flight path, fuel consumption rate, and cruising speed, amongst others. As we only specify the partial function for the MPL (by focusing on external air temperature, or a proxy for the temperature in the case of the CC-177), there are a distribution of possible MPL values for the aircraft. One of these values is randomly selected (in a uniform fashion) for the aircraft's simulated MPL.

Additional mathematical details on the fashion in which the payloads were calculated for the AN-124s can be found in the Annex A.

[6] Although methods exist for estimating the maximum safe payload for a given aircraft operating under a given set of conditions (temperature, air pressure, altitude, flight path, fuel consumption rate, and cruising speed, among others), these methods require significant data regarding atmospheric conditions at the time of flight [20]. Such information concerning the conditions at Kandahar Airfield was not readily available to the authors. As a result, the authors constructed a method to estimate the MPL of an aircraft as a function of one parameter which was thought to have the biggest impact on MPL values—external temperature.

2.4 Modelling GLOC and Sea Liner Service

An estimated 40 to 45 trucks were available to the contractor responsible for GLOC [21]. A number of constraints at the base in Kandahar led to delays in trucks picking up containers before embarking on a circuit from Kandahar to the Spin-Buldak/Chaman, Pakistan border crossing to Quetta (for customs inspection) to Sibbi to Jacobabad to Sukkur to Hyderbad and finally to Karachi. Figure 5 shows NATO supply trucks near the Pakistani border and the GLOC route. Trucks did not depart Kandahar in convoys (but drivers may have subsequently formed them *ad hoc*). It took approximately 30 days to complete the entire Kandahar-Karachi-Kandahar trip (roughly 2, 000 kilometers). In the simulation model, the time to complete the round trip is sampled from a triangular distribution with a minimum value of 25 days, most likely value of 30 days, and a maximum of 35 days.

Figure 5: *GLOC trucks near Pakistani border (©AFP/File A Majeed) and a map of the route from Kandahar, Afghanistan to Karachi, Pakistan.*

Items arriving in Karachi were placed onto merchant ships (sea liner service) and shipped to Canada. No significant waiting times occurred at the port. The time required to ship to Canada by sea was randomly selected from a triangular probability distribution with minimum 25 days, most likely value of 32 days, and maximum value of 40 days.

2.5 Modelling Sea Lift

Vehicles and containers sent by ALOC to ISTs were subsequently shipped to Canada via contracted sealift on specified dates. Items arriving at the IST for transport to Canada waited until the next scheduled ship departure date, incurring holding costs each day until they departed. The first ship departed Larnaca, Cyprus on 11 September 2011, and ships departed Kuwait on 23 October 2011, 10 December 2011, and 7 February 2012. The simulation codes these dates explicitly. Due to the potential for variation in arrival times of aircraft from Kandahar, a fictional fifth ship is introduced in the simulation model set at a date that ensures no items can arrive at the IST by ALOC awaiting shipment after the final ship departs.

2.6 Costs

Each type of resource has its own specified distribution for the time required to reach its next destination (Canada, one of the ISTs, Karachi, etc.). As items travel along each of the LOCs, costs of each segment are determined stochastically, as are the durations for which the resources are travelling along the LOCs. At the end of the simulation, all costs are aggregated into a final figure.

CEFCOM and CANOSCOM Move Planners provided cost information for contracts (AN-124 flights, GLOC trucks, chartered or merchant sealift) [22]. The Canadian Department of National Defence Cost Factors Manual [23] was used to estimate the costs of using CC-177 assets native to the CF. Flight duration times for the CC-177 were provided by CANOSCOM OS J3 [24]. Costs are not disclosed herein, however Figure 6 provides insight into the relative costs of using each of the different LOCs:

- ALOC Direct using an AN-124;
- ALOC Direct using a CC-177;
- ALOC IST using an AN-124;
- ALOC IST using a CC-177;
- Sealift from an IST;
- GLOC using a truck followed by sea liner service from Karachi.

The cost of ALOC to Cyprus and Kuwait is assumed to be equal. All numbers in the figure are mean costs associated with each of the LOCs, and are expressed as fractions of the cost associated with the ALOC Direct method using a CC-177 aircraft.

Since each method of shipment can carry a different number of items, the costs of transporting an individual container back to Canada are illustrated in Figure 7, calculated by taking the cost per lift asset per LOC times the number of times the lift asset type used that LOC divided by the total number of items moved by the lift asset type along that LOC. In this figure the costs of the ALOC IST and the subsequent sealift portion of the return are combined into one expression. All numbers in the figures are expressed as fractions of the ALOC Direct cost using a CC-177 aircraft, which is given a cost of 1.

In simple terms, the different LOCs have widely varying costs per container. The costs of travelling directly to Canada via airlift are slightly more than double the costs of travelling to an IST via airlift and using sealift to return to Canada; and the costs of forgoing airlift at all and using the GLOC and subsequent sea liner service is approximately fifteen times cheaper than the IST option. Moreover, the costs of using contracted AN-124 airlift is slightly higher than using CC-177 airlift native to the CF.

2.7 Notable Assumptions and Limitations

In this section, the assumptions inherent in the data and the methodology are described in detail.

Lift resources. The actual number of lift resources (as oppose to number of flights, truck/ship departures) can be modelled with the discrete-event simulation model. Section 3 models the Op

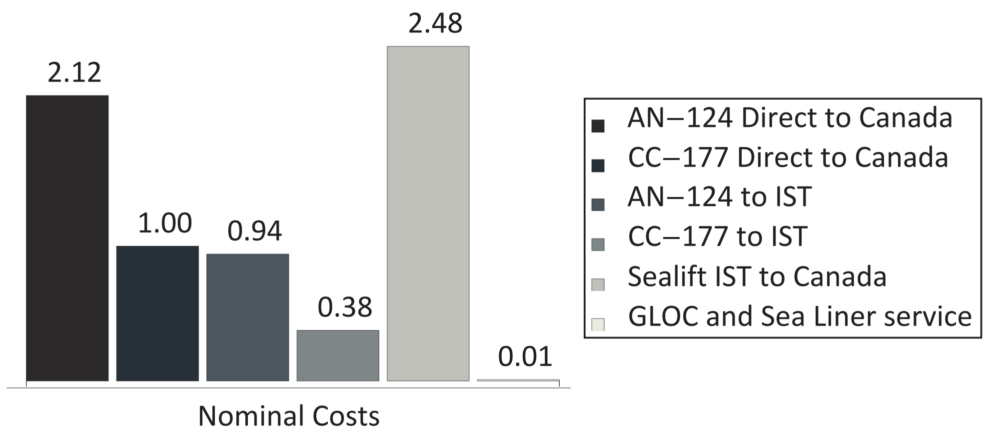


Figure 6: *The relative costs of the different LOCs.*

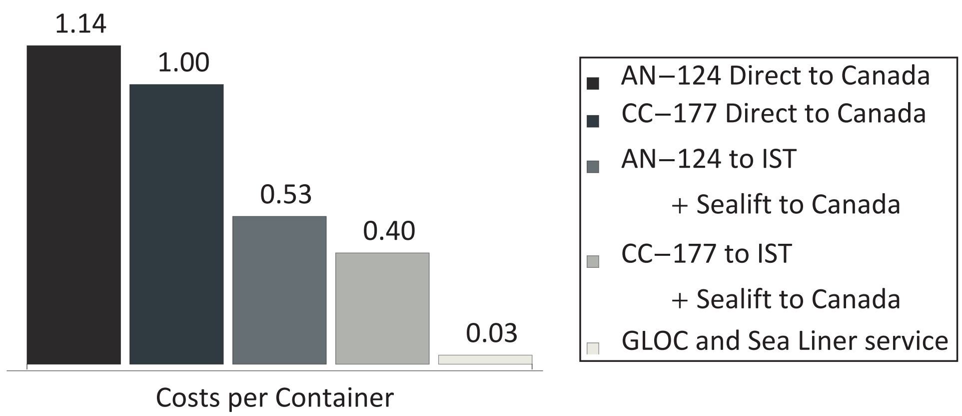


Figure 7: *The relative costs per container of the different LOCs.*

ATHENA MTTF repatriation. In this case the actual number of trucks used for GLOC are modelled. In this case flight schedules are modelled, but not the actual number of lift resources.

Materiel and vehicle processing in Kandahar. CF units handed over their equipment and vehicles to the MTTF over several months. Vehicle and materiel production lines were established to process and prepare the returns. Vehicles and containers were inspected, sent for maintenance/repair, and fumigated. All materiel was tagged and grouped by shipping destination and placed into containers. Vehicles and containers then were moved to the airfield or put aside for pick-up (by truck). These MTTF efforts within Kandahar were outside the scope of the analysis.

Modelling of distribution within Canada. After arriving in Canada (either in Trenton if arriving by ALOC Direct, or in Montreal if arriving by sealift) the items were distributed amongst the various CF supply depots, facilities, and bases. However, no efforts were made to model the distribution of the items in Canada, as it was not within the scope of the analysis.

Disposal, transfers, and sales. A significant portion of non-essential items in Afghanistan used by the CF were disposed of (*i.e.*, destroyed), transferred, or sold to external organizations (*e.g.*, foreign militaries, non-governmental organizations, etc.). These items were not modelled – the simulation only included those items which were to be returned to Canada.

Other aircraft used in the airlift. The model incorporates airlift handled by the CC-177 aircraft and the contracted AN-124 aircraft. However, there were other types of aircraft involved in the airlift to a much lesser extent—these included the CC-130 aircraft, which was primarily used to transport materiel from one location in Afghanistan to another; and the CC-150 aircraft, which was primarily used to transport personnel from Kandahar to the ISTs. As the model was focused on the return of materiel from Afghanistan these aircraft were not included in the model.

Equipment used by Op ATTENTION. Operation ATTENTION is Canada's participation in the NATO Training Mission-Afghanistan (NTM-A), which delivers training and professional development support to the national security forces of Afghanistan. The MTTF was directed to move a small portion of the materiel used by Operation ATHENA to another region of Afghanistan for use by Operation ATTENTION. As this materiel were not repatriated by the MTTF, they were not included in the model; nor was the airlift that was used for their movements (which included AN-124 and CC-130 aircraft).

Aircraft payload: average vs. max. When determining the maximum payload able to be carried by the aircraft under the different temperature conditions, the *actual* payloads of the aircraft were used instead of their *maximum* payloads, which was unavailable to the authors. As the items loaded on the aircraft were discrete in number, the modelled payloads were necessarily smaller than they were in reality. Furthermore, there was a deliberate assumption in the model that items (containers, vehicles, and pallets) would always be available for loading on an aircraft—hence, an aircraft would never depart without a full load (either in terms of bulk, or payload). The impacts of this assumption will be discussed further in Section 3.1.

Warehousing costs. Items arriving at the IST incur holding costs each day until they depart on a ship for transport to Canada. Due to the unavailability of information on the the warehousing costs at the IST, the holding costs in the model were specified to be equal to those of comparable military warehouses in Canada. Holding costs at the Kandahar airfield were not considered.

2.8 Key Outputs

As the model involves various stochastic elements, there was a need to perform multiple runs of the model in order to obtain a representative sample of the various outputs of the model. The results in this paper are based on 800 runs of the model (50 runs for each scenario discussed).

After the simulation has run to completion, several outputs are collected. These outputs include the route taken by each item to return to Canada, along with costs incurred, and timestamps along each section of the route. However, the main outputs of the model consist of the following four quantities:

Total cost. This quantity consists of all costs incurred, and includes contracted costs of the AN-124 airlift, costs of the CC-177 airlift (operating costs, crew costs, and amortization costs of the equipment).[7], costs of the contracted sealift from the IST, sea liner service costs from Karachi, holding costs for items at the IST, and costs of the contracted trucks used for transport of items for the GLOC.

Number of flights required. The total number of flights (AN-124 and CC-177) required to repatriate the items using the ALOC Direct and ALOC IST methods.

Completion of 50% of the returns. The simulated time at which 50% of all items have been repatriated from Afghanistan using any of the various LOCs.

Completion of 95% of the returns. The simulated time at which 95% of all items have been repatriated from Afghanistan using any of the various LOCs. *N.B.* the return date of the final item was not used as there were instances when the vast majority (in the order of 99%) of all items were repatriated by a given date, but a few items were delayed in their arrival to the IST and so had to wait for several months for another ship to depart for Canada. Considering the end date in such an instance would have unfairly skewed the results.

[7] The cost of use of CC-177s is typically not accounted for against mission termination budgets if the aircraft are used within their yearly flying hour constraints. These costs are paid for by the Royal Canadian Air Force.

3 Validation of the Model

In this section, the outputs of the simulation of the baseline scenario are compared to corresponding actual quantities in order to validate the model.

3.1 Aircraft Bulk and Payloads

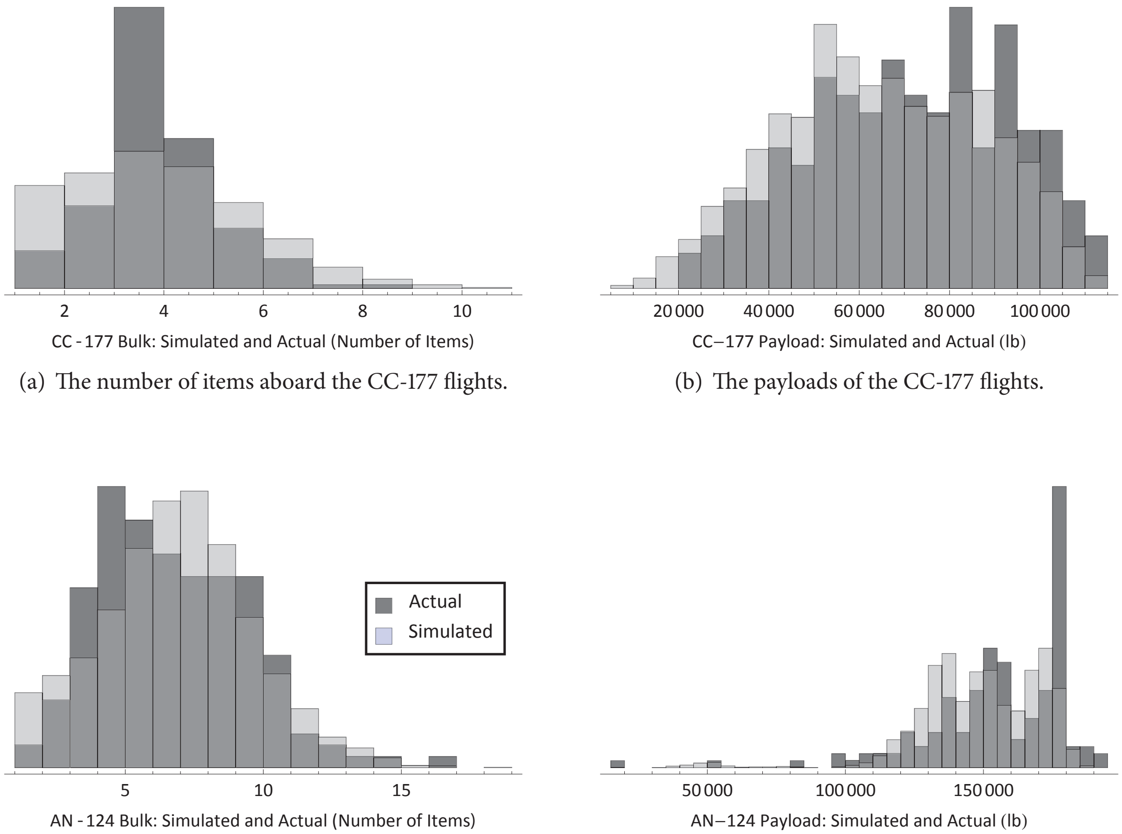
Since the actual MPLs are unknown (only the actual final load weights), one cannot examine how the estimated MPLs used in the simulation compare to the actual MPLs. The first set of quantities that are compared are the number of items on-board the aircraft flights (also referred to as the flight's *bulk*), and the payloads of these flights. All figures concerning the actual historical quantities were taken from the COP. The figures concerning the simulated quantities were taken over all simulated iterations.

When comparing the payload and bulk quantities for the CC-177 aircraft, it was found that the mean simulated bulk (3.44 items) was comparable to the mean actual bulk (3.36 items). However, a Kolmogorov-Smirnov test [17] found that the null hypothesis that the datasets have the same distribution was rejected at the 95% confidence level. A similar result was found when the mean simulated payload (64,700 lbs) was compared to the mean actual payload (71,500 lbs). These distributions are presented graphically in Figure 8. The legend describes the two histograms—light and dark shades of gray. The middle shade indicates where the histograms overlap.

The difference in these distributions may be explained by the simulation using an unrefined method when selecting items to load on to the aircraft (in the order in which the items were received at the loading area), whereas in actuality experienced load masters carefully select items in order to maximize the load of the aircraft. Evidence for this conjecture comes from the fact that the average unused payload of the CC-177 aircraft was 4,100 lbs in the simulation; and when this quantity was added to the simulated payloads, the null hypothesis was not rejected at the 95% level (with a p-value of 0.42). Another potential contributor to the discrepancy is that the simulation model queues items that share the same shipment method and sends them along the appropriate LOCs. In this process the order of items within a set sharing the same shipment method differs for each simulation iteration. The specific order of items loaded represent a single instance (and corresponding payload and bulk loads) that may very well differ from the average of all simulated instances.

The simulated and actual bulk and payload quantities were also compared for the AN-124 aircraft. The mean simulated bulk of the AN-124 (6.38 items) was comparable to its mean actual bulk (6.25 items), and in this case the Kolmogorov-Smirnov test did not reject the null hypothesis at the 95% confidence level (with a p-value of 0.27). Moreover, the Kolmogorov-Smirnov test did reject the null hypothesis at the 95% confidence level when comparing the payloads of the AN-124 aircraft (the mean simulated payload was 149,600 lbs and the mean actual payload was 157,600 lbs). These distributions are presented graphically in Figure 8.

The average unused payload of the AN-124 aircraft was 6,900 lbs in the simulation. When this quantity was added to the simulated payloads, the null hypothesis that the simulated plus unused payload of the AN-124 and the actual payload datasets have the same distribution was not rejected at the 95%



(a) The number of items aboard the CC-177 flights.

(b) The payloads of the CC-177 flights.

(c) The number of items aboard the AN-124 flights.

(d) The payloads of the AN-124 flights.

Figure 8: *Subfigures 8(a) to 8(d) illustrate the bulk and payloads of the CC-177 and AN-124 flights departing Afghanistan in support of the MTTF.*

level (with a p-value of 0.12). Hence the difference in the payloads may be explained by the aircraft loading method, which can reduce the sizes of the unused payloads on the aircraft.

No correction for the observed systematic bias (with respect to aircraft payloads) was implemented in the simulation model. While this is an acknowledged shortcoming, mitigation measures considered (*e.g.*, increase MPL by half of the mean weight of a sea container) only added to modelling assumptions and it was unclear whether they offered overall improvement taking into consideration all other modelling assumptions made. Not correcting for the bias mentioned may yield risk-averse flight totals (and cost)—which may be desirable during early planning stages.

3.2 Repatriation as a Function of Time

One of the key measures used by the MTTF to estimate the progress made in the repatriation was the number of items (containers and vehicles) that had been returned to Canada as a function of time.

The MTTF COP provides the weekly (cumulative) number of items that had left the main Canadian base in Afghanistan (Kandahar Airfield). The actual number of items repatriated was compared to their corresponding simulated quantities. Both series can be found in Figure 9 (actual values are dotted in black and simulation values shown by gray lines). The multiple series shown in the figure for the simulated quantities are due to the variance in the runs of the simulation.

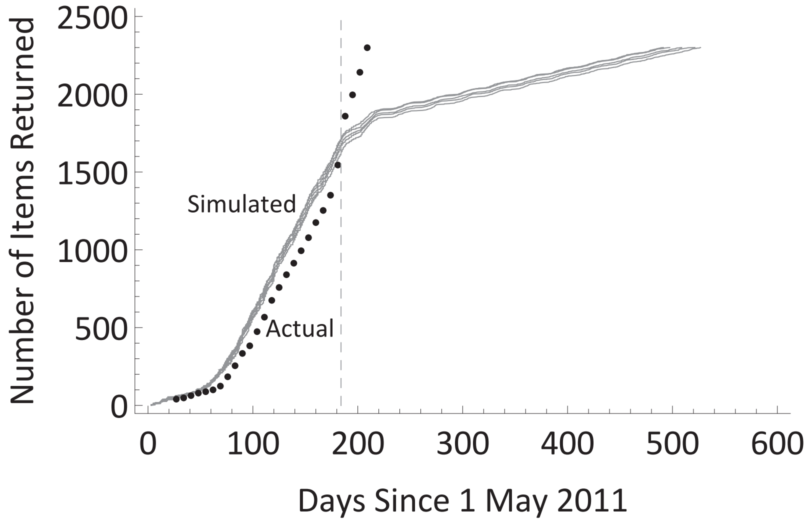


Figure 9: *The number of items returned to Canada as a function of time (in days). Note that Day 1 corresponds to May 1, 2011.*

Note that the simulation matches up with the actual quantities (off by at most 12%) until day 184 (1 November 2011), when the series diverge substantially. This is highlighted by the vertical dashed line in Figure 9. In late October 2011 the Op ATHENA MTTF realized that, at the observed pace, containers and vehicles destined for GLOC would not be entirely moved out of Kandahar base by the end-of-December deadline. To mitigate this risk, the Canadian Forces arranged for a holding yard off-base where containers could be stored for eventual onward movement to Karachi via the GLOC [25]. Between 23 October and 26 November, nearly 500 containers were transported by truck to the holding yard and were then considered off-base (and counted as such in the MTTF COP). On 28 November 2011 Pakistan closed its borders to NATO supply trucks [26]. Due to the border closure 446 CF containers remained in the holding yard.[8]

In summation, the simulation model reasonably portrays the return of items from Afghanistan as a function of time, until the creation of the holding yard.

3.3 Number of Flights Required

Finally, the last point of validation concerned the number of flights needed to complete the ALOC portion of the repatriation. In modelling the baseline scenario, the number of aircraft was not modelled,

[8] Pakistan reopened the border in July 2012, however as of November 2012 most of the CF containers were yet to be moved.

rather just the schedule of possible flight departures. The number of flights (CC-177 and AN-124) needed in the simulation ranged from 333 to 370, with a median of 351. The actual number of flights needed was 357, which corresponds to the 75% percentile in the range found in the simulation. This information is presented graphically in Figure 10.

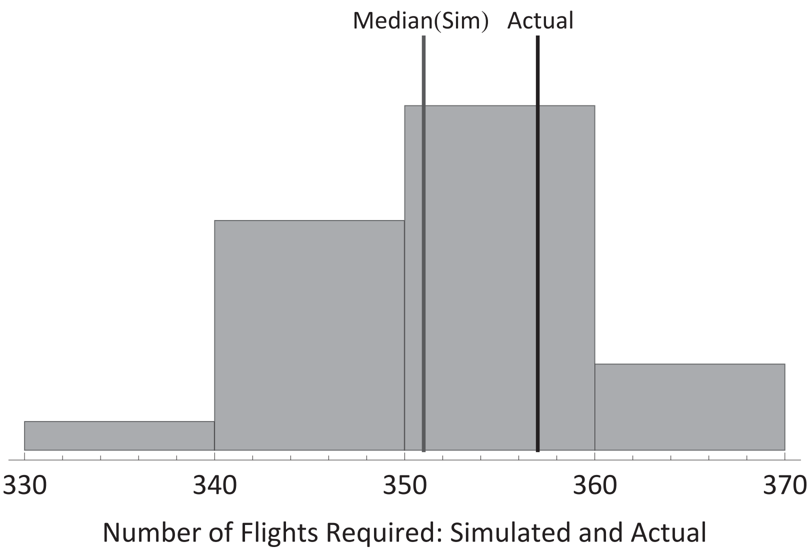


Figure 10: *The total number of CC-177 and AN-124 flights required.*

Table 3 shows the breakdown of the number of simulated flights by lift asset. The median number of AN-124 flights is 24 flights more in the simulation than actual (resulting in 31 fewer CC-177 flights in the simulation compared to actual).

Table 3: *The median number of flights per lift asset for simulation of baseline scenario.*

	Simulation		Actual	
Destination	CC-177	AN-124	CC-177	AN-124
Trenton	17	18	33	14
IST	169	147	183	127
Totals	186	165	216	141

3.4 Validation Summary

The simulation models reality to the extent that it can approximately replicate the number of flights needed to return items from Afghanistan to Canada, at the correct rate, and subject to similar constraints on the load placed on each aircraft. As such, despite limiting model assumptions, the simulation model can be used as an illustrative model for sensitivity analyses.

Up to this point in the paper the model has been used as a descriptive model of reality. In the next sections, the model is used to evaluate the impact of changes to physical or procedural aspects of the MTTF repatriation efforts.

4 Results and Discussion

Several versions of the model were run with changes made to its various parameters to determine the impact of these changes on the four measures of performance of the MTTF (specified in Section 2.8: total cost, number of flights, 50% completion time, and 95% completion time). The unaltered version of the model is referred to below as the *baseline* model. The relative increases or decreases of the outputs over the baseline are specified in this section. In each case the median value found in the corresponding simulation is presented.

The analyses performed were fourfold—wherein one (and only one) of the following things were varied, with all else remaining constant:

1. Increases to the number of items returning by ALOC Direct, with proportional removal from one of the other two methods;

2. Decreases to the number of items returning from GLOC, with increases going to the number returning by ALOC IST;

3. Delaying the first scheduled departure of all flights (ALOC Direct, and ALOC IST) by several months (30, 60, 90, or 120 days) to take advantage of the lower temperatures in the later months; or

4. Increases to the availability of the different aircraft (AN-124s and CC-177s), *i.e.*, the number of aircraft of each type available for use in the ALOCs each day. Note that availability is modelled by schedule, not by actual aircraft numbers.

The results of each of these changes is discussed in sequence in the following subsections.

4.1 Increases to ALOC Direct

It was hypothesized that increasing the number of items transported via ALOC Direct would decrease the total time to complete the total return but would increase the total costs (due to increases in the number of flights required). The analysis found that this hypothesis was correct: increasing the number of items returning by ALOC Direct, and correspondingly decreasing the number of items returning via one of the other two methods (ALOC IST or GLOC), would have had the effect of increasing costs while decreasing the total time to complete the total return by approximately equal factors.

Based on the medians of simulation runs, doubling the number of items returning by ALOC Direct would have had the effect of increasing the total cost by 10% while decreasing the time to complete 95% of the repatriation by 7%. If instead the number of items returning by ALOC Direct was increased fourfold, the total cost would have increased by 28% and the time to complete 95% of the repatriation would have decreased by 22%. The results for this modification are presented in Figure 11. In Figures 11-14 the relative changes of each of the key outputs (total cost of the MTTF, the number of flights required, completion of 50% of the materiel returns, and completion of 95% of the materiel returns) are illustrated as relative increases or decreases to the baseline value found in the unchanged version of the model.

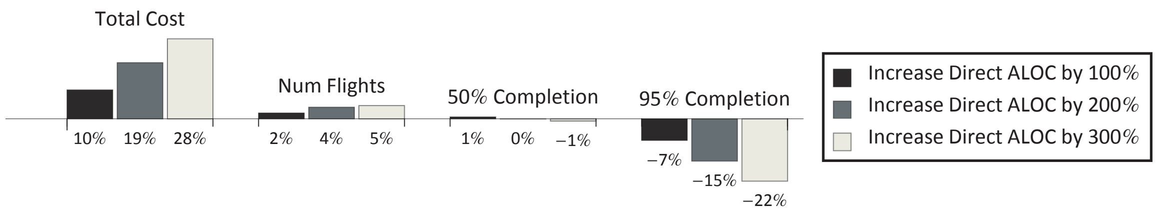


***Figure 11:** Effects of increasing the number of items returning by ALOC Direct, and correspondingly decreasing the number of items returning via one of the other two methods (ALOC IST or GLOC).*

4.2 Decreases to GLOC

Another possibility for speeding up the repatriation was a reduction in the number of items requiring transport by GLOC, which was thought to be the slowest of all options. It was found that decreasing the number of items returning by GLOC (and subsequent movement by SLOC) would have had the effect of increasing costs and the number of flights required, and would have had a marginal effect on the time to complete half the returns. However, it would have had a substantial effect on the time to complete 95% of the return of the items. This result is due to the fact that the the airlift portion of the repatriation is done much earlier than the sealift portion; hence, hastening the sealift portion of the returns has a large impact on the time required for the total return.

Based on the medians of simulation runs, decreasing the number of items returning by GLOC by 67% of its original value would have had the effect of increasing the total cost by 14%, increasing the number of flights by 18%, and decreasing the time to complete 50% of the returns by 3%. However, the time to complete 95% of the repatriation would have decreased by 47%. The results for this modification are presented in Figure 12.

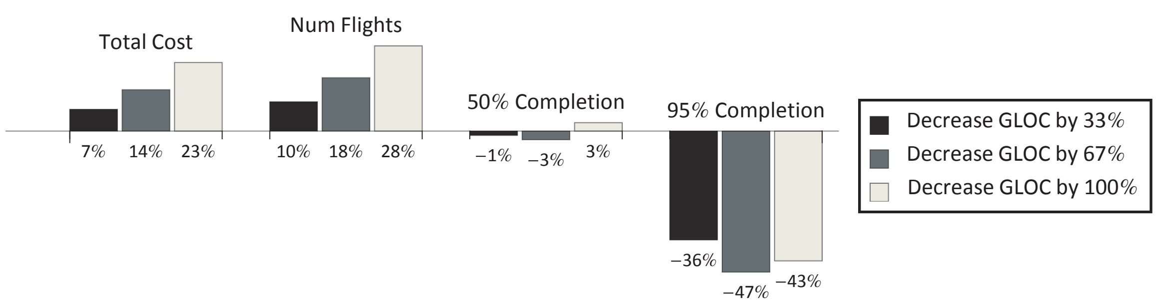


***Figure 12:** Effects of decreasing the number of items returning by GLOC, and correspondingly increasing the number of items returning via ALOC IST.*

4.3 Delaying the Aircraft Departures

Recall that the external air temperature has a large effect on the maximum allowable payload for both the AN-124 and CC-177 aircraft. It was hypothesized that by delaying the first scheduled departure of all flights (for ALOC Direct as well as ALOC IST) by several months (30, 60, 90, or 120 days), one could take advantage of the lower temperatures in the later months, potentially reducing the flights required.

It was found that these delays would have had a small effect on total costs (up to a median of 5% savings for a 120 day delay), but the (absolute) time needed to complete half the returns was increased by substantial amounts (up to a median of 38% for a 120 day delay). The impact of temperature on MPL is clearly evident by a reduction of number of flights required (6% less flights, or roughly twenty flights, for a 120 day delay). The results indicate that the temperature effect on MPL is a factor, but certainly not the sole nor most important factor affecting cost and time.

The time to complete 95% of the returns would have been unchanged due to the final items always awaiting a ship for sealift via the SLOC. The results for this modification are presented in Figure 13.

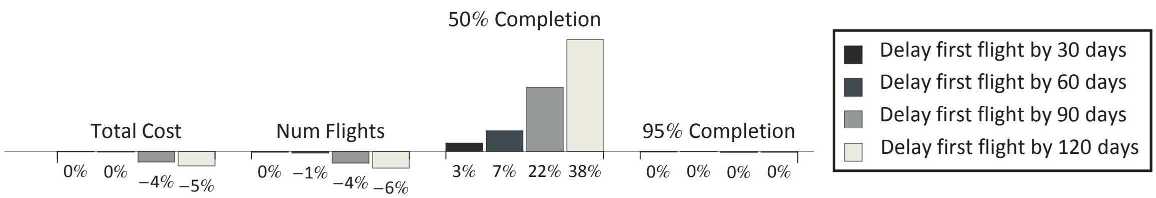


Figure 13: *Effects of delaying the first scheduled departure of all flights (ALOC Direct, and ALOC IST) by several months (30, 60, 90, or 120 days) to potentially take advantage of the lower temperatures in the later months.*

4.4 Increasing Aircraft Availability

It was hypothesized that if there were more aircraft (CC-177s and AN-124s) available to the MTTF, the repatriation of the items may have progressed at a faster rate. This analysis tested that hypothesis, by increasing the number of aircraft available for ALOC purposes by 33%, 66%, or 100%.

It was found that increasing the availability of the aircraft would have increased the cost and total flights by small amounts (up to 4% and 6%, respectively), but the time to complete 50% of the returns would have been dramatically reduced - by up to 35%. Again, the time to complete 95% of the returns would have been unchanged due to the dates of the sealift portion of the returns. The results for this modification are presented in Figure 14.

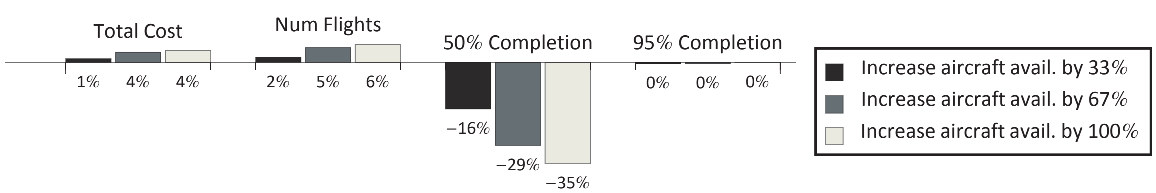


Figure 14: *Effects of increasing the availability of the different aircraft (AN-124s and CC-177s) for use in the ALOC.*

4.5 Uncertainty in the Results

In order to illustrate the uncertainty in the results, the 10% and 90% quantiles for two of the key results – the total cost of the returns and the number of flights required – is provided in Table 4. These uncertainty bounds are presented for each of 14 model scenarios studied, in which each of the model's four main parameters (detailed in Sections 4.1 to 4.4) were altered. As in the previous sections the results are specified as relative increases or decreases over those of the baseline.

In the table, the median value for these two results are proceeded by the range in their associated 10% and 90% quantiles, which signifies the range of values within which 80% of the results lie. For example, the total costs of increasing the Direct ALOC by 200% has a median value of 19%, with an associated 10% to 90% quantile range of 15% to 25%.

Table 4: *Uncertainty in the results concerning the total costs of the returns and the number of flights required for each of the scenarios. Each entry in the table is the median value found in the simulation, followed by its associated 10% and 90% quantiles.*

Scenario	Total Cost		Num Flights	
Baseline	0%	[-4%, 5%]	0%	[-2%, 3%]
Increase Direct ALOC by 100%	10%	[6%, 14%]	0%	[-2%, 3%]
Increase Direct ALOC by 200%	19%	[15%, 25%]	4%	[1%, 8%]
Increase Direct ALOC by 300%	28%	[25%, 33%]	5%	[3%, 9%]
Decrease GLOC by 33%	7%	[5%, 11%]	10%	[6%, 13%]
Decrease GLOC by 67%	14%	[11%, 16%]	18%	[14%, 21%]
Decrease GLOC by 100%	23%	[20%, 26%]	28%	[25%, 31%]
Delay first flight by 30 days	0%	[-4%, 4%]	0%	[-2%, 4%]
Delay first flight by 60 days	0%	[-4%, 2%]	-1%	[-3%, 2%]
Delay first flight by 90 days	-4%	[-7%, -2%]	-4%	[-6%, -2%]
Delay first flight by 120 days	-5%	[-8%, -1%]	-6%	[-8%, -3%]
Increase aircraft avail. by 33%	1%	[-2%, 4%]	2%	[0%, 6%]
Increase aircraft avail. by 67%	4%	[-1%, 6%]	5%	[3%, 9%]
Increase aircraft avail. by 100%	4%	[0%, 8%]	6%	[4%, 10%]

4.6 The Non-Dominated Front of Scenarios

The concept of *dominance* is used to compare objects when there are multiple objectives, or metrics. One object is said to dominate another if the first is at least as good at optimizing each objective as the second, and is better than the second on at least one of the objectives. If neither object dominates the other, we say that the solutions are incomparable. In general, the set of all non-dominated objects is of particular interest to the decision-maker, as it is comprised of the scenarios which scored "best" on the objectives considered.

In this study, two key results that were computed for each scenario were the total cost incurred in the returns and 95% completion time for the scenario. The results for 16 scenarios considered are plotted in Figure 15.[9] The results for the scenarios are specified as relative increases or decreases over the results found for the baseline scenario. Each scenario is associated to an integer, which is referenced in the legend of the figure. The results for the baseline scenario are encircled in the figure.

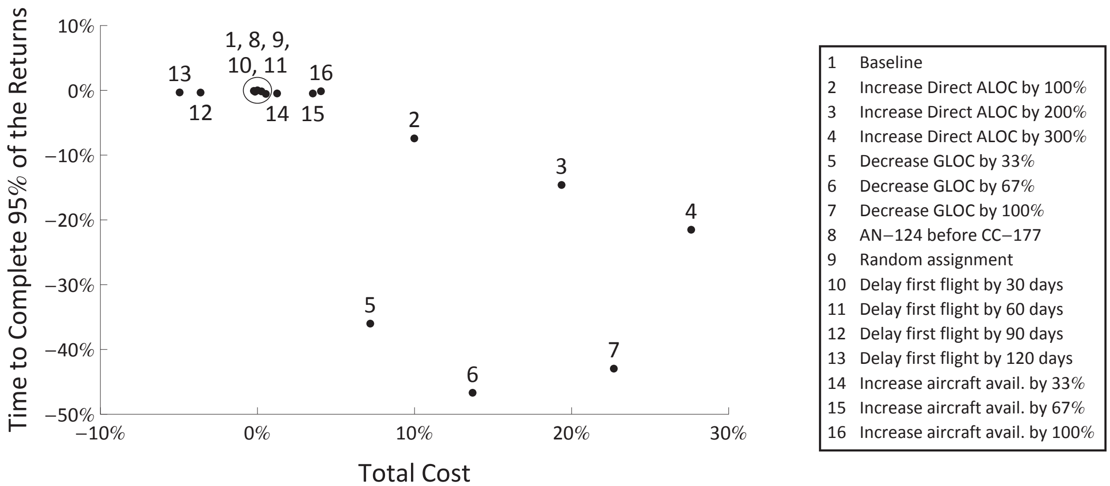


Figure 15: *The results obtained in the scenarios, plotted on axes specifying the 95% time to completion vs. the total costs incurred.*

As is clear from the figure, the non-dominated scenarios are numbered 13 – "Delay first flight by 120 days"; 5 – "Decrease GLOC by 33%"; and 6 – "Decrease GLOC by 67%". Of note is the fact that delaying the flight schedule by four months can reduce costs (by 5%) while not significantly altering the time to complete 95% of the returns. Moreover, changing the method of shipment of some (but not all) of the items moving by GLOC to ALOC IST can increase costs slightly, but can dramatically reduce the time required to complete 95% of the returns. For example, in scenario 6 the costs were increased by 14%, but the completion time was reduced by 47%.

[9] Scenarios 8 and 9 tested the sensitivity of lift asset selection when both types of lift assets are available. The baseline simulation model gives preference to CC-177s for ALOC IST and AN-124s are given preference for ALOC Direct. Changing this to random selection or strict preference for AN-124s did not affect the total number of flight or total time for repatriation.

5 Conclusions and Recommendations

The objective of this study was to develop a model that could be used to analyze the repatriation of Canadian equipment from Afghanistan to Canada via the LOCs, in order to enable and improve future mission planning.

A discrete-event simulation model was developed and shown to be representative of the actual repatriation of items from Afghanistan. The model was then used to determine the impacts of different potential courses of action, measured mainly through results on the total cost and duration of the repatriation.

Results indicate that increases to the number of items using the ALOC Direct method of shipment would have both increased total cost and decreased the time to complete the repatriation. Decreasing the number of items returning by GLOC would have increased cost to a moderate extent while dramatically decreasing the time to complete the repatriation. Delaying the departure of the flights to the cooler months would have decreased the total costs as well as the number of flights required of the aircraft while having no effect on the time to complete the repatriation. Finally, increasing the availability of the aircraft would have increased the cost and the number of flights while having no effect on the time to complete the repatriation.

There is a subtle and complex relationship between the parameters of the model and its main outputs (the total cost incurred and the time to complete the repatriation) that is due to the scheduling of the returns via airlift and sealift, as well as the overall per-container cost for each different method of shipment. It is recommended that in future operations a model similar to one detailed here be constructed to investigate how the repatriation could be optimized prior to the initial departures and during mission execution. More specifically, this model can be used in the repatriation of the materiel from Operation ATTENTION, which is expected to conclude in 2014.

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Annex A: MPL Calculation for the AN-124 Aircraft

Before proceeding to an explanation of how the MPL calculations were performed for the AN-124 aircraft, it is worth noting that observed payloads may differ from the maximum payloads due to a number of factors—either due to insufficient items being available for loading on the aircraft; or the aircraft reaching maximum capacity (in terms of bulk) before they reach their maximum payloads. The impact of the first factor is lessened through a deliberate assumption that items (containers, vehicles, and pallets) would always be available for loading on an aircraft—hence, an aircraft would never depart without a full load (either in terms of bulk, or payload). The impact of the second factor, that the aircraft can reach their maximum capacity (in terms of bulk) before they reach their maximum payloads, is a noted shortcoming of the methodology, and its impact on the results are further discussed in Section 3.1.

Data on the external temperature at the time of the contracted flights (*i.e.*, AN-124 flights) was made available to the authors by OS J4 Mov staff [27]. The remainder of this annex will detail how the MPLs of the AN-124 flights (as opposed to the CC-177 flights) were specified in the model based on the external air temperature and the data on the observed payloads of the AN-124 flights. A simple correlation calculation found that there was a weak negative connection between the external air temperature and the observed MPL of the aircraft, with a correlation coefficient of -0.24. A bootstrap method was then used to determine if the weak negative connection was statistically significant. The bootstrap procedure involves choosing one thousand random samples with replacement from the data set and analyzing each sample the same way. The number of elements in each bootstrap sample equals the number of elements in the original data set. The range of sample estimates obtained can then establish the uncertainty in the correlation coefficient.

Nearly all the estimates were found to lie on the interval [-0.7 0.1], with a 95% confidence interval for the correlation coefficient lying on the interval [-0.51 0.09]. Hence, there was strong quantitative evidence that the external air temperature and the observed MPL of the aircraft are weakly negatively correlated. Moreover, this evidence does not require any strong assumptions about the probability distribution of the correlation coefficient.

A generalized linear regression model [28], a flexible generalization of ordinary linear regression models, was then used to compute a vector of coefficient estimates of the responses (the observed MPL values) as a function of the predictors (the temperature values).[10] The residuals of the model could then be used to add noise to the predicted values, by binning the residuals according to their corresponding predictors (the temperature values). This is done to insert variability into the MPL estimates associated with temperature as temperature is not the only factor influencing MPL. The simulation model samples from the list of residuals associated to the observed payloads occurring at the specified temperature in the simulation (found using the triangular distributions described in the beginning of this annex) as well as those on either side of the specified temperature by at most two degrees. This sampled residual is then added to the regressed value of the generalized linear regression model, and the sum is a simulated payload for the simulated AN-124 flight. As a result, up to 32 data points were generated for the distribution of AN-124 MPL values at each temperature point.

[10] The link function chosen for the GLM was identity, and maximum likelihood estimates were used to perform the fitting.

Figure A.1 specifies the distribution of possible payloads of the AN-124 flights in the model, based on the simulated temperature. The "plus" marks in the figure are the actual historical data obtained from OS J4 Mov; the regressed predicted values using the generalized linear regression are illustrated as a green line; and all the payload values from which the model can sample for a given temperature value are shown as black dots.

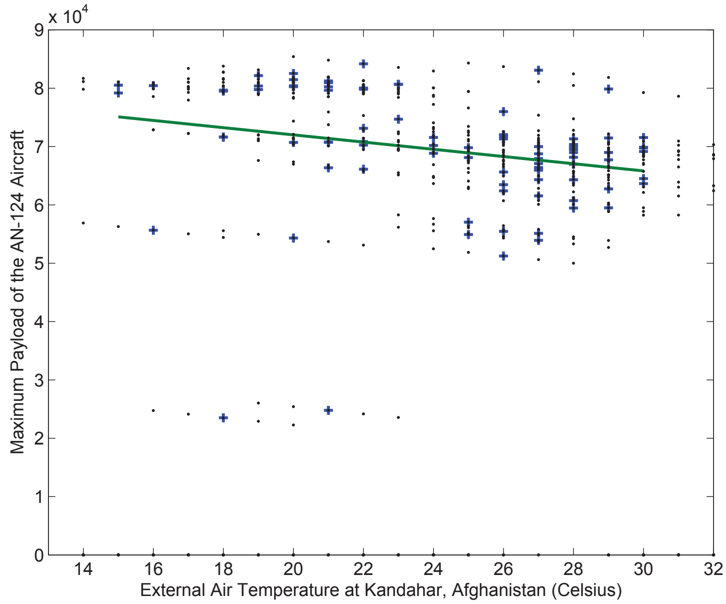

Figure A.1: *An illustration of the distribution of possible AN-124 MPL values based on the simulated temperature. The "plus" marks are the actual historical data obtained from OS J4 Mov; the regressed predicted values using the generalized linear regression are illustrated as a green line; and all the payload values from which the model can sample for a given temperature value are shown as black dots.*

List of Acronyms & Abbreviations

ALOC	Air Lines of Communication
AMOS	Air Mobility Operations Simulator
CANOSCOM	Canadian Operational Support Command
CEFCOM	Canadian Expeditionary Force Command
CJOC	Canadian Joint Operational Command
CF	Canadian Forces
COMFEC	Commandement de la Force expéditionnaire du Canada
COP	Common Operating Picture
CORA	Centre for Operational Research & Analysis
DND	Department of National Defence
DRDC	Defence Research and Development Canada
GLOC	Ground Lines of Communication
FOTM	Force opérationnelle de transition de la mission
FC	Forces canadiennes
ICSP	image commune de la situation opérationnelle
IST	Intermediate Staging Terminal
lbs	pounds
LOC	Line of Communication
MET	Movement Estimator Tool
MPL	Maximum Payload
MTTF	Mission Transition Task Force
NATO	North Atlantic Treaty Organization
NPS	Naval Postgraduate School
NRMO	NPS/RAND Mobility Optimizer
NTM-A	NATO Training Mission—Afghanistan
Op	Operation
OS Mov	Operational Support Movements
pdf	probability distribution function
SLOC	Sea Lines of Communications
TEI	terminaux d’étape intermédiaire
TEU	Twenty foot equivalent (container)
U.S.	United States (of America)

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3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

Simulating the Repatriation of Canadian Forces Materiel from Afghanistan

4. AUTHORS (Last name, followed by initials – ranks, titles, etc. not to be used.)

Kaluzny, B. L.; Pall, R.

5. DATE OF PUBLICATION (Month and year of publication of document.)

March 2013

6a. NO. OF PAGES (Total containing information. Include Annexes, Appendices, etc.)

50

6b. NO. OF REFS (Total cited in document.)

28

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Technical Memorandum

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

Defence R&D Canada – CORA
Dept. of National Defence, MGen G. R. Pearkes Bldg., 101 Colonel By Drive, Ottawa ON K1A 0K2, Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)

N/A

9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)

10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)

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The Canadian Forces completed its combat mission in the Kandahar province of Afghanistan in 2011 and were instructed by the Government of Canada to complete its redeployment out of Kandahar by the end of December 2011. Materiel and equipment were transported back to Canada over several lines of communications. Nearly 1500 sea containers full of materiel, 800 vehicles, and 200 air pallets of material were returned to Canada by combinations of air, sea, and ground transport. This paper describes a discrete-event simulation model developed to analyze the repatriation of Canadian equipment from Afghanistan to Canada via the applicable lines of communication. The objective was to develop a model that could be used to analyze the repatriation in order to enable and improve future mission planning. The discrete-event simulation model is shown to be representative of the actual repatriation effort and is subsequently used to determine the impacts of different potential courses of action, measured mainly through results on the total cost and duration of the repatriation.

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