CIRRELT

Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport

Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation

Designing Global Supply Networks for Conflict or Disaster Support: The Case of the Canadian Armed Forces

Alain Martel
Abdelhamid Benmoussa
Marc Chouinard
Walid Klibi
Ossama Kettani

March 2011

CIRRELT-2011-15

Designing Global Supply Networks for Conflict or Disaster Support: The Case of the Canadian Armed Forces

Alain Martel[1,2,*], Abdelhamid Benmoussa[1,3], Marc Chouinard[1], Walid Klibi[1,4], Ossama Kettani[1,2,3]

[1] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT)

[2] Operations and Decision Systems Department, Université Laval, Pavillon Palasis-Prince, 2325, rue de la Terrasse, Université Laval, Québec, Canada G1V 0A6

[3] Modellium Inc., 400 boulevard Jean-Lesage, bureau 260, Québec, Canada G1K 8W1

[4] BEM-Bordeaux Management School, 680 cours de la Libération, 33405 Talence Cedex, France

Abstract. In order to fulfill Canada's international disaster relief, humanitarian assistance, peacekeeping and peace enforcement roles, the Canadian Forces (CF) rely on a supply network to deploy and sustain its overseas missions. Warehousing, maintenance, transhipment and transportation activities are required to support missions. Currently, the CF supply network does not incorporate any permanent overseas depots. Since international needs and Canada's roles have significantly evolved during the last decade, and given that supply network efficiency and robustness are critical for missions' success, reengineering the CF supply network to consider the incorporation of permanent international prepositioning depots has become an important issue. This paper proposes an activity-based stochastic programming model to optimise the CF overseas supply network. It also shows how the model proposed can be used to improve the global reach of the CF.

Keywords. Supply chain, network design, stochastic programming, disaster relief, military operations support.

Acknowledgements. This research was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC) grant no DNDPJ 335078-05, by Defence R&D Canada and by Modellium Inc. The project would not have been possible without the support of the Canadian Armed Forces. We would like to acknowledge, in particular, the contribution of J. Berger, A. Boukhtouta, A. Ghanmi and LCol T. Gibbons. The contribution of S. Girard to the analysis phase of the project is also acknowledged.

---

* Corresponding author: Alain.Martel@cirrelt.ca

Dépôt légal – Bibliothèque et Archives nationales du Québec
Bibliothèque et Archives Canada, 2011

1. Introduction

Canada's current foreign policy includes an effective and timely response to emergency relief, humanitarian assistance, peacekeeping and peacemaking needs around the world, and this policy is not expected to change in the near future. Foreseeable trends also indicate that the frequency of demands for international aid is likely to increase, and the Canadian Forces (CF) will continue to be a major contributor to these efforts. The deployment and sustainment of overseas missions are complex operations requiring a high level of logistics support. Currently, these missions are supported from Canada, mainly via airlifts, and often using third party facilities and transportation assets. This *status quo* solution does not provide the best possible trade-off between costs and support levels, and Canada is examining various capability options to improve the global reach of its Forces. One of these options is the implementation of an offshore network of *operational support depots* (OSDs). These depots would be located in stable regional logistic hubs with good communication infrastructures; they would hold insurance inventories for selected materiel, act as an intermodal transfer point, incorporate a repair shop, and maintain a local network of service/supply partners. This gives rise to a complex global *supply chain network* (SCN) design problem under uncertainty.

There is a large literature on the design of global SCNs. It deals with strategic decisions such as the number, location and capacity of facilities, the selection of suppliers and 3PLs, and the offers to make to product-markets (Meixell and Gargeya, 2005; Martel, 2005). These long-term decisions shape the structure of the SCN used on a daily basis to respond to operational events. However, at design time, the future environment under which the SCN will evolve is unknown. Moreover, in addition to the random variables associated to business-as-usual factors, several catastrophic events can disrupt the SCN, which complicate the elaboration and evaluation of potential designs. Traditional SCN design approaches assume that the environment is deterministic, which give rise to classical location-allocation models (Klose and Drexl, 2005). Typical extensions of these models take into account random factors using stochastic programming, or facility failures using robust optimisation. Recent reviews of location models and SCN design models under uncertainty are found, respectively, in Snyder (2006) and Klibi *et al.*, (2010).

In a humanitarian (Altay and Green, 2006) or military logistics context, catastrophic events such as natural disasters or armed conflicts are not viewed as exceptional disruptions, but rather they are its *raison d'être*. Modeling extreme events in this context is therefore not optional: it is an integral part of the SCN design process. Also, one would like to design these SCNs to provide short deployment times and high sustainment support levels but this can be extremely expensive and usually the budgets available are limited. This means that a compromise must be reached. More specifically, adequate trade-offs must be made between readiness investments, operational mission costs, and support policies specifying maximum deployment times and minimum theater replenishment frequencies. Taking these considerations into account, the SCN design model used must help answering the following questions: How many offshore OSDs should be implemented? Where should they be located and what should their warehousing and repair capacity be? How much insurance inventory should they keep? What are the best support policies to enforce, given available budgets? Some of these issues were examined in the literature. In a military context, Ghanmi and Shaw (2008) and Ghanmi (2010) used location and simulation models to investigate some of the SCN design trade-offs faced by the Canadian Forces. In a humanitarian logistics context, Lodree and Taskin (2008) and Campbell and Jones (2011) combine location and news-vendor inventory analysis to determine where and how much supplies to preposition in preparation for a disaster. However, to the best of our knowledge, no comprehensive modeling approach has been proposed to address the issues raised previously. The objective of this paper is to propose such an approach, and to show how it can be used to design a robust and efficient offshore SCN for the Canadian Forces. The stochastic programming model proposed is relatively generic and it could be exploited to design various types of conflict or disaster support networks.

The modeling approach adopted in the paper is based on the generic design methodology proposed by Klibi and Martel (2009) to obtain effective and robust SCNs. The approach is essentially composed of the three phases illustrated in **Figure 1**: scenario generation, design generation and design evaluation. The first phase is a Monte Carlo scenario generation procedure. A scenario covers all the missions of different type supported in the world during a planning horizon: it details the extreme events occurring at the mission theater locations, as well as the weekly demand and repair profiles of predefined product families for each mission. The scenarios produced are used in the design generation and the design evaluation phases. The design model is a large-scale stochastic program with recourse solved for relatively small samples of scenarios. It finds the design providing the best investment-operational expenses trade-offs for the scenarios considered. It includes a crude anticipation of the recourses necessary to cope with all the scenarios considered. In order to obtain different candidate designs, this model is run several times with different samples of scenarios. The design evaluation phase then compares the candidate designs thus obtained with the status-quo design. This comparison is based on the optimal supply decisions made by the network users under a given design, for a large sample of scenarios. This operational response model corresponds in our case to the second-stage of the stochastic program formulated. Since this model is a linear program, and since it is solved for a single design and scenario at the time, the evaluation can be based on a relatively large sample of scenarios. Comparisons are made using expected values, but also selected dispersion measures to evaluate robustness. With these multi-criteria evaluations, the candidate designs can be ranked, and a *best* design can be selected.

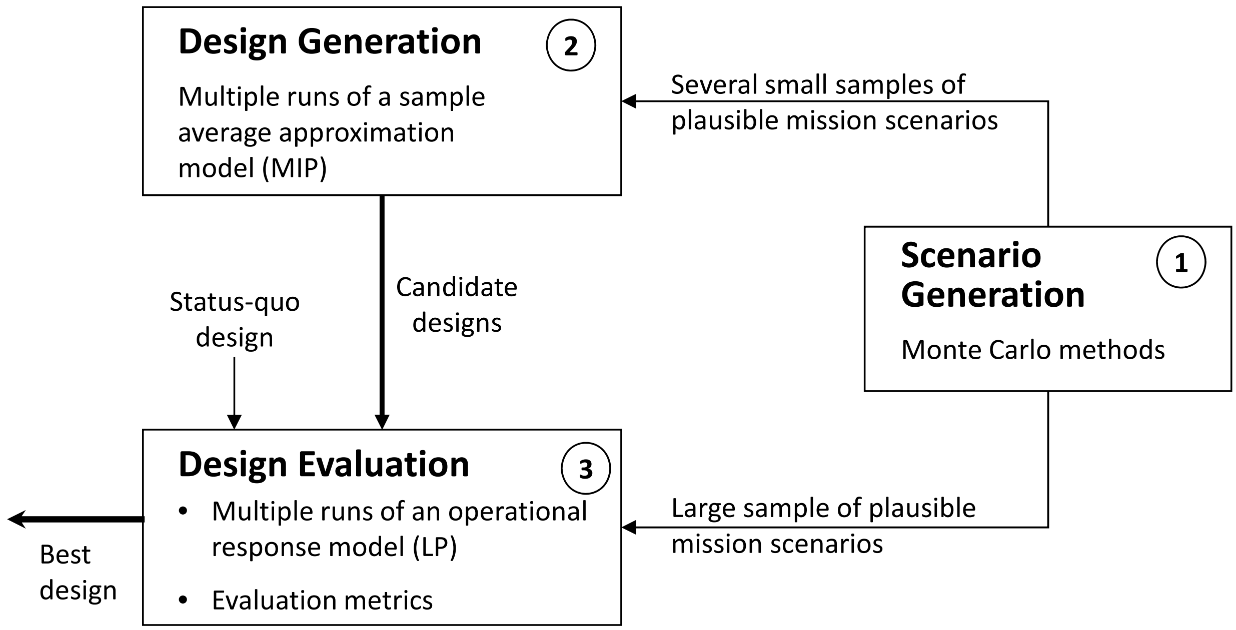

Figure 1 - Network Design Optimization Approach

The rest of the paper is organized as follows. Section 2 presents the CF context. Section 3 proposes an approach to model conflicts and disasters in order to generate overseas missions for the CF. Section 4 describes the activity-based approach used to model the SCN and it formulates the stochastic programming model used to generate SCN designs. Section 5 proposes some performance measures to evaluate candidate designs and select the design to implement. Section 6 discusses the application of the approach to the CF case. Finally, section 7 concludes the paper.

2. Canadian Armed Forces Context

The CF role in today's world has greatly evolved in the last decades. It has stretched both from a geographic and mission spectrum's points of view. The CF are asked to respond to humanitarian assistance (H), peacekeeping (K) and peace making (M) missions around the world. In order to support these international missions, the CF must rely on an efficient and robust SCN. Let $\mathbf{E} = [\mathrm{H,K,M}]$ be the list of the mission types supported by the CF supply network.

The current CF supply network includes only domestic depots and repair facilities, and it is designed to support overseas missions from Canada mainly via airlifts. Since the transportation assets owned by the CF are limited, this imposes the use of costly chartered lifts. *Intermediate staging bases* (ISBs) may also be used during a mission to accommodate intermodal transfers required to reach isolated operational theaters. An alternative to this *status quo* solution is the design of an offshore network of operational support depots with local procurement, warehousing, repair and intermodal transfer activities. These depots would keep an insurance inventory of selected materiel, they would be supplied from Canada or from local vendors using strategic airlift, sealift or ground transportation, and they would supply operational theaters using tactical airlift or ground transportation. They could also serve as an intermodal transfer point for sensitive material (ex: armed systems) shipped directly from Canada (Girard *et al*., 2008).

***Notational Conventions* –** In the following sections:

- Labels are used to refer to *concepts* associated to the modeling framework used (ex: activity types, mission types, product types). Labels are denoted by capital letters and they do not change from an application context to another. They are specified using lists and they are incorporated as *superscripts* in the notation. A summary of the labels found in the paper is provided in *Appendix A*.
- Indexes are used to define application specific instances of a concept (ex: activities, missions, products). They are denoted by italic lowercase letters and defined using sets. They are incorporated as *subscripts* in the notation.
- To distinguish *concept lists* from *index sets*, we use bold capital letters to denote lists and capital italic letters to denote sets. For products, for example, we have: $\mathbf{P}=[\mathrm{C,A,N,U}]$ and $P=\{1,2,\ldots,14\}$. Arbitrary elements of a list are denoted by the corresponding lower case letter (for example: $\mathrm{p}\in\mathbf{P}$), and arbitrary elements of a set by the corresponding italic lower case letter (for example: $p\in P$).
- Sets are partitioned into subsets using concept superscripts. For example: $P^{\mathrm{A}}=\{4,5\}$, $P^{\mathrm{U}}=\{12,13\}\subset P$. The union of type subsets is denoted using sub-list superscripts. For activities, for example, $A^{\mathbf{S}}$, with $\mathbf{S}=[\mathrm{C,F,W}]$, denotes $A^{\mathrm{C}}\cup A^{\mathrm{F}}\cup A^{W}$.
- The arrow $\rightarrow$ is used as a superscript to represent outbound flows or successors and the arrow $\leftarrow$ to represent inbound flows or predecessors.
- Decision variables are denoted by capital italic letters, and parameters by lower-case italic or Greek letters.

The resulting SCN would include four location types: domestic CF supply sources (C), local vendors (V), depot or ISB sites (S), and theater demand zones (D). Let $\mathbf{L}=[\mathrm{C,V,S,D}]$ be the list of these location types, L the set of all potential SCN locations, $L^{\mathrm{C}}\subset L$ the domestic CF bases used to support overseas missions, $L^{\mathrm{V}}\subset L$ the potential local vendors, $L^{\mathrm{S}}\subset L$ the potential sites, and $L^{\mathrm{D}}\subset L$ the potential operational theaters. The latter are geographically associated to the in-theater point of debarkation. The set of potential sites to consider in the study is predetermined based on their logistics and communication infrastructures, and on the capacity of the CF to negotiate long term agreements with the countries involved. Although some products may be purchased from vendors at the operational theaters, these vendors are not considered explicitly in the study: their supplies are subtracted a priori from the operational theater demand.

The geographical dispersion of military operations and the large variety of situations encountered generate a wide spectrum of mission *intensity*. The intensity of a mission depends on its *severity* and on its *magnitude* (size). Magnitude is measured in terms of the number of personnel deployed. A convenient measure of magnitude, in a land operations context, is the number of companies deployed plus the personnel required for services such as command, logistics, maintenance and medical support. The number of companies deployed depends on the engagements taken by Canada in the context of a specific mission. Severity is related more to the nature of the mission itself. It can be characterized in terms of *hostility* and *hardship*. Hostility reflects the level of aggressiveness of enemy forces. Hardship is related to the physical nature of the theater terrain. The logistic support required is clearly directly proportional to the intensity of a mission.

Each mission incorporates several phases. From a logistic support point of view, three mission phases must be distinguished: deployment (D), sustainment (S) and redeployment (R). Let $\mathbf{X}=\left[\mathrm{D,S,R}\right]$ be the list of these mission phases. These phases are congruent with the classical phases of a disaster's lifecycle (Banks, 2006; Tomasini and van Wassenhove, 2009). During the *deployment*, activation activities are first performed to ensure that the incoming troops will find proper shelter and basic commodities when they arrive. Some heavy equipment may also be transported in advance. The units and their equipment are then moved from their base for a tour of duty. The *sustainment* is the main phase of the mission. The supply's job during this phase is to provide the goods consumed during the mission. Some equipment may also be repaired in theater maintenance facilities, or shipped back for repair or overhauling, and new equipment may be brought in. The *redeployment* phase occurs when the mission is over. The actual timing of these phases can vary depending on the mission type. For example, *humanitarian* missions arise virtually without warning, and there may be only a few days before the sustainment starts. For recent humanitarian missions, deployed CF units were operational after 6 to 19 days (Mason and Dickson, 2007). On the other hand, more than a month can be required for the deployment of a mission engaging a full battle group in a land-locked theater. Several factors may complicate and prolong the deployment phases of a mission. In particular, deployment constraints (the landing time-slots available per day, for example) often result from the fact that several countries and support organizations may be deploying simultaneously to the theater of operation.

During the phases of a mission, the CF must move thousands of products. Product families are used to characterize products having similar demand and return patterns, and using the same transportation/handling and storage technology. Products can be classified into three main types:

- *Consumables* (C): Products that have a single use through their lifecycle (e.g.: food, ammunition).
- *Durables* (A): Assets that can be used several times during their lifecycle and for which functionality is generally preserved through maintenance during normal condition of use.

These products would therefore be maintained at the operational theater and either disposed locally at the end of a mission or returned.

- *Reparables*: Components that can be used several times during their lifecycle and for which functionality is generally preserved through preventive and corrective maintenance during normal condition of use. These products can be returned to an OSD for repair during a mission. After repair they are considered as new and they are added to the depot inventory. Repairable products can thus be subdivided in two distinct types according to their state:
  - ✓ *New or as-new (serviceable) reparables* (N): Products that can be (re)used as is.
  - ✓ *Unserviceable reparables* (U): Products that required repair before reuse.

Let $\mathbf{P}$=[C,A,N,U] be the list of possible product types.

From a transportation and storage needs point of view, products can be partitioned into five basic categories: *ammunition, major items, hazardous material (hazmat), refrigerated cargo,* and *non-refrigerated cargo*. These products are moved in units (i.e. as is), in pallets, in refrigerated containers, or in non-refrigerated containers. However, for our purposes, for most products it is sufficient to assume that they are shipped in *pallet-equivalent* units. For major items such as combat vehicles, however, this is not adequate and it is more appropriate to use *lane meters* as a shipping unit. Also, some armed systems are required only for peace enforcement missions. This leads to the definition of a set P of product families, each associated to a collection of NATO Supply Classes. In what follows, the generic term "*product*" is used to designate a product family. To be able to distinguish different product subsets, the following notation is introduced:

$P^{\mathrm{p}} \subset P$: Subset of products of type $\mathrm{p} \in \mathbf{P}$.
$P^{\mathrm{pe}} \subseteq P^{\mathrm{p}}$: Set of products of type $\mathrm{p} \in \mathbf{P}$ required in missions of type $\mathrm{e} \in \mathbf{E}$ ($P^{\mathrm{e}} = \cup_{\mathrm{p}\in\mathbf{P}} P^{\mathrm{pe}}$).
$p^{\mathrm{N}}(p)$: Repairable in P^{N} yielding unserviceable product $p \in P^{\mathrm{U}}$ after a breakdown.
$p^{\mathrm{U}}(p)$: Unserviceable product in P^{U} yielding serviceable product $p \in P^{\mathrm{N}}$ after a repair.
P_p^{A}: Set of durable products requiring repairable product $p \in P^{\mathrm{N}}$ for maintenance purposes ($P_p^{\mathrm{A}} \subseteq P^{\mathrm{A}}$).
$g_{pp'}$: Average quantity of repairable product $p \in P^{\mathrm{N}}$, in shipping units, required to maintain one shipping unit of durable product $p' \in P_p^{\mathrm{A}}$.
w_p: Weight of a shipping unit of product *p*.

The countries where conflicts and disasters occur do not all have the same level of importance for Canada. This leads to the definition of *mission-regions* based on mission types and geopolitical regions. Geopolitical regions are geographical areas where a specific service level is required for a given mission type. A geopolitical region may cover several, possibly non-adjacent, countries but a country belongs to a single region. These regions are defined to reflect

Canadian foreign policies. A mission-region k covers a set of potential operational theaters $L_k^{\mathrm{D}} \subset L^{\mathrm{D}}$, in which a set of products $P_k \subset P$ would be required. Given the three mission types defined, the set K of mission-regions can be partitioned into three subsets K^{e}, $\mathrm{e} \in \mathbf{E}$=[H,K,M]. We assume that a potential theater is associated to a *single* mission type, i.e. if a country can be the theater of several mission types, a theater location l is defined for each of them. The set $L^{\mathrm{De}} \subset L^{\mathrm{D}}$ denotes the potential operational theaters for missions of type $\mathrm{e} \in \mathbf{E}$, e($l$) the mission type of location l, and $k(l)$ the mission-region of operational theater l. The service level to provide for a mission-region $k \in K$ is predetermined for each product in terms of deployment lead times, theater replenishment lead-times and fill-rates. These have an impact on the timing of deployment and sustainment shipments and on the level of safety stocks kept at the operational theater during a mission. The CF manage consumable and repairable theater inventories using a continuous-review ordering system, i.e. an order is placed when a *reorder level* based on replenishment lead-times and required fill-rates is reached, and we assume that reorder level inventories must be shipped to the theater during the deployment phase.

3. Modeling Operational Support Requirements

This section relates to the first step of the design methodology summarized in **Figure 1**. Its aim is first to model the arrival, location and duration of conflicts and disasters in the world, as well as the CF response to these conflicts and disasters. Based on the descriptive models formulated, a Monte Carlo approach is proposed to generate realistic CF mission scenarios. A scenario is a set of plausible future missions deployed in time and in space over the planning horizon considered.

3.1. Planning Horizon and Scenarios

Strategic SCN design decisions generally consider a long planning horizon and, once a design has been implemented, several years may elapse before the network is reengineered. On the other end, missions may last a few weeks up to several years, but the deployment phase of a mission must not exceed a few weeks. Also, during a mission, supply decisions are made on a daily basis and it is these decisions that determine the operational costs and service levels of a given SCN design. For these reasons, the planning horizon considered must be divided in periods of different lengths depending on the aspect of the problem modeled. We assume that design decisions are made only at the beginning of multi-year reengineering cycles $h \in H$. At the other end, when generating mission scenarios the planning horizon is divided into weekly response periods $\tau \in \mathrm{T}$. The granularity of these periods is adequate to model operational SCN user decisions, however using them to anticipate operational costs at the design level would yield intractable design models. Consequently, in the design model, an approximate anticipation of operational costs based on yearly planning periods $t \in T$ is used. The relationship between these time periods is illustrated in **Figure 2**. The design decisions of the first reengineering cycle are implemented but, since these design problems are solved on a rolling horizon basis, subsequent cycles are included in the design model to provide an adequate anticipation of possible future network adaptations.

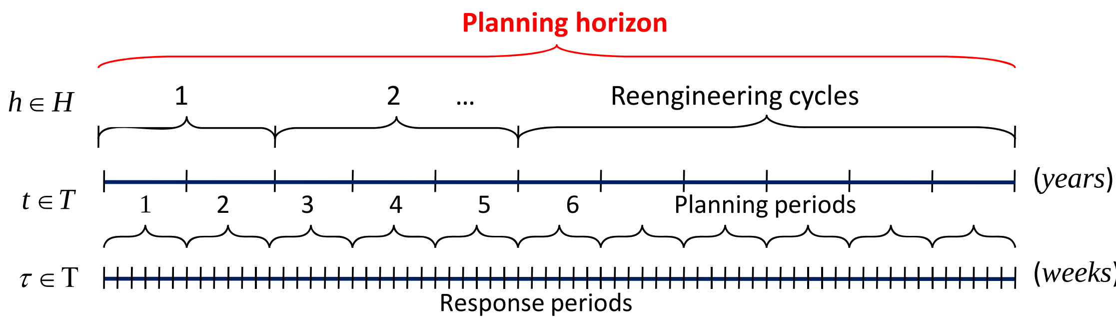

Figure 2 - Planning Horizon, Cycles and Periods

To be able to navigate between these time periods, we introduce the following notation:

T_h : Set of planning periods within reengineering cycle $h \in H$.

T_t : Set of response periods within planning period $t \in T$.

$h(t)$: Reengineering cycle associated to period $t \in T$.

$t(h)$: First period of reengineering cycle *h*.

Scenarios are initially defined over the response periods of the planning horizon, and they are subsequently aggregated into planning periods to provide product demand and return quantities to the design model. Let Ω denote the set of all plausible mission scenarios associated to conflict and disaster occurrence processes and to CF response processes. **Figure 3** represents a typical mission scenario $\omega \in \Omega$ for the CF case. Each bar in the diagram provides the time span and country (in a geographical region) of a type of mission (represented by the color of the bar). In addition, for each mission (bar) in the scenario, weekly demand and return quantities during the three mission phases (deployment, sustainment and redeployment) are provided for each product. The next subsections propose an approach to generate such scenarios.

3.2. Disasters/Conflicts Modeling

The approach proposed to model conflicts and disasters is based on Klibi and Martel (2009). The hazards which may lead to CF missions can take several forms and a practical way of taking them into account, without getting lost in a maze of possible incident types, is to consider meta-events, called multihazards (Scawthorn et al., 2006), with generic impacts in terms of mission requirements. In our context, we concentrate on three multihazards, namely disasters (D), quarrels (Q) and wars (W), embedded in the multihazard list $\mathbf{H} = [\mathrm{D,Q,W}]$. In order to map threats, we define a set of multihazard zones *Z* having similar exposure characteristics. For the CF case, we assume that each country in the world corresponds to a zone. Using geographical coordinates, the set L of potential locations can be partitioned into subsets L_z, $z \in Z$, and the zone $z(l)$ of location $l \in L_z$ can be identified. Also, the theater $l(\mathrm{e},z) \in L^{\mathrm{D}}$ corresponding to the occurrence of a mission of type $\mathrm{e} \in \mathbf{E}$ in country z can be identified. Note that extreme events can also occur at the depots site locations. In this study these extreme events are neglected and we consider only the events giving rise to CF missions. The approach proposed can however be extended to consider the vulnerability of potential network sites (Klibi and Martel, 2009).

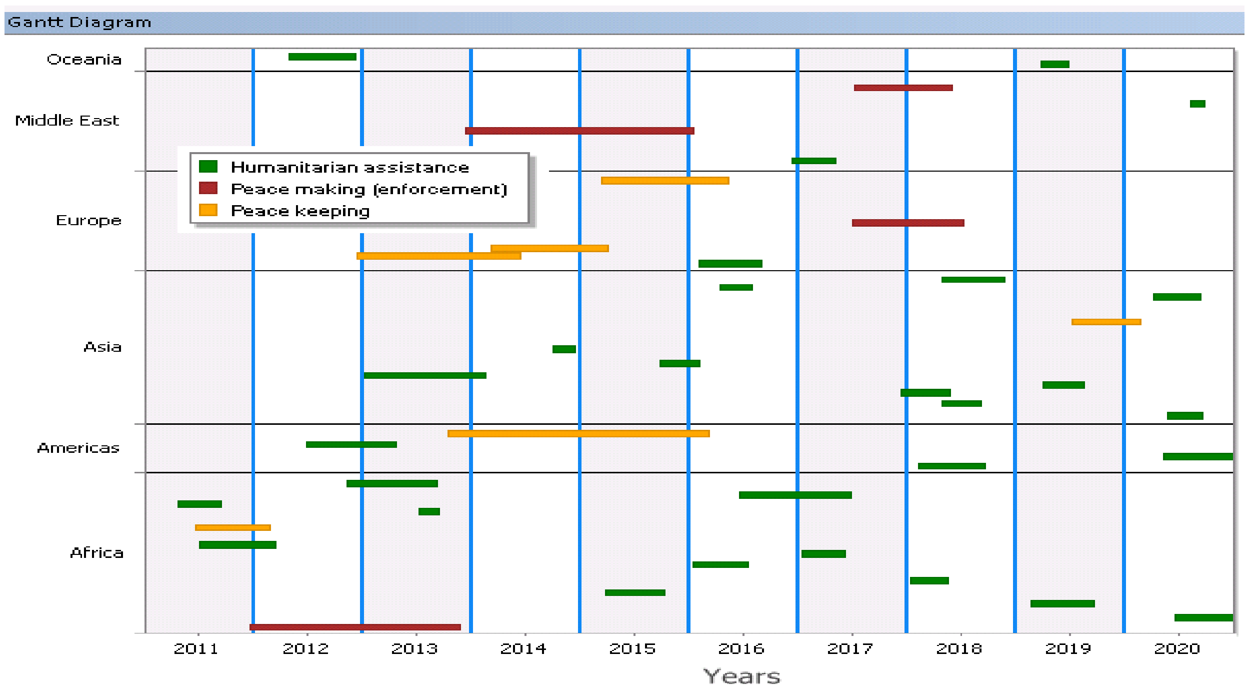

Figure 3 – Spatiotemporal Representation of CF Missions for a Given Scenario

To facilitate the modeling of conflicts/disasters, for each multihazard $\mathrm{h} \in \mathbf{H}$ we introduce a set G^{h} of zone aggregates called *exposure levels*. The notation $g^{\mathrm{h}}(z)$ is used to denote the exposure level $g \in G^{\mathrm{h}}$ including hazard zone $z \in Z$, and $Z_g^{\mathrm{h}} \subset Z$ the set of zones in exposure level $g \in G^{\mathrm{h}}$. In our context, exposure levels can be specified using cluster analysis with exposure indexes provided by public or private data sources. Relevant public sources include the Centre for Research on the Epidemiology of Disasters (CRED, www.cred.be), the Heidelberg Institute for International Conflict (HIIK, www.hiik.de), Foreign Policy (www.ForeignPolicy.com) and the World Economic Forum (WEF). Based on this, the exposure level $g^{\mathrm{h}}(l) = g^{\mathrm{h}}(z(l))$ of a location $l \in L$ can be uniquely determined for each multihazard $\mathrm{h} \in \mathbf{H}$.

This data can also be used to characterize the *arrival* and *intensity* of conflicts/disasters by exposure level. For a given multihazard $\mathrm{h} \in \mathbf{H}$, the time between the arrival of successive hazards for exposure level $g \in G^{\mathrm{h}}$ is a random variable λ_g^{h} with cumulative distribution function $F_{\lambda_g^{\mathrm{h}}}(.)$. In catastrophe models, inter-arrival times are often assumed to be exponentially distributed with mean $\overline{\lambda}_g^{\mathrm{h}}$ (Banks, 2006). The impact intensity is measured in a relevant metric (loss level, casualty level…) and it is a random variable β_g^{h} with cumulative distribution function $F_{\beta_g^{\mathrm{h}}}(.)$. For example, when using CRED data, the intensity of disasters can be considered as a log-Normal loss level (in \$), with mean $\overline{\beta}_g^{\mathrm{D}}$ and standard deviation σ_g^{D}. In order to determine the multihazard zone within the exposure level where incidents occur, conditional probabilities $\mathrm{P}_{z|g}^{\mathrm{h}}, z \in Z_g^{\mathrm{h}}, g \in G^{\mathrm{h}}, \mathrm{h} \in \mathbf{H}$, are used. The latter can be estimated using hazard frequencies $I_{z|g}^{\mathrm{h}}, z \in Z_g^{\mathrm{h}}, g \in G^{\mathrm{h}}, \mathrm{h} \in \mathbf{H}$, compiled for example from CRED and HIIK data. For a given multi-hazard type $\mathrm{h} \in \mathbf{H}$, the following conditional probability mass functions can be calculated:

$$\mathrm{P}_{z|g}^{\mathrm{h}} = I_{z|g}^{\mathrm{h}} \Big/ \sum_{z \in Z_g} I_{z|g}^{\mathrm{h}}, \; z \in Z_g^{\mathrm{h}}, g \in G^{\mathrm{h}}$$

Since we are considering long planning horizons, we also need to take a set of plausible evolutionary paths into account (Shell, 2005). We assume that a set K of evolutionary paths with probability $\pi_\kappa, \kappa \in \mathrm{K}$, is defined, and that they influence the multihazards arrival process but not their severity. Three such paths are illustrated in **Figure 4** for data on annual disaster frequency provided by CRED. Under path $\kappa \in \mathrm{K}$, if an incident occurs in period $\tau \in \mathrm{T}$, then the time before the arrival of the next multihazard of type $\mathrm{h} \in \mathbf{H}$ is an exponentially distributed random variable $\lambda_{g\kappa\tau}^{\mathrm{h}}$ with distribution function $F_{\lambda_{g\kappa\tau}^{\mathrm{h}}}(.)$ and mean $\overline{\lambda}_{g\kappa\tau}^{\mathrm{h}}$. Let $\phi_\kappa^{\mathrm{h}}(\overline{\lambda}_g^{\mathrm{h}}, \tau)$ be a function elaborated by experts to superimpose a time pattern, for path κ, on the historical mean time between hazards $\overline{\lambda}_g^{\mathrm{h}}$ estimated at the beginning of the planning horizon for exposure level g. Then, the required mean inter-arrival times are obtained simply by calculating $\overline{\lambda}_{g\kappa\tau}^{\mathrm{h}} = \phi_\kappa^{\mathrm{h}}(\overline{\lambda}_g^{\mathrm{h}}, \tau)$ for all g, κ and τ. In **Figure 4**, these functions are provided by the three linear regression lines defined for pessimistic, as-is and optimistic futures.

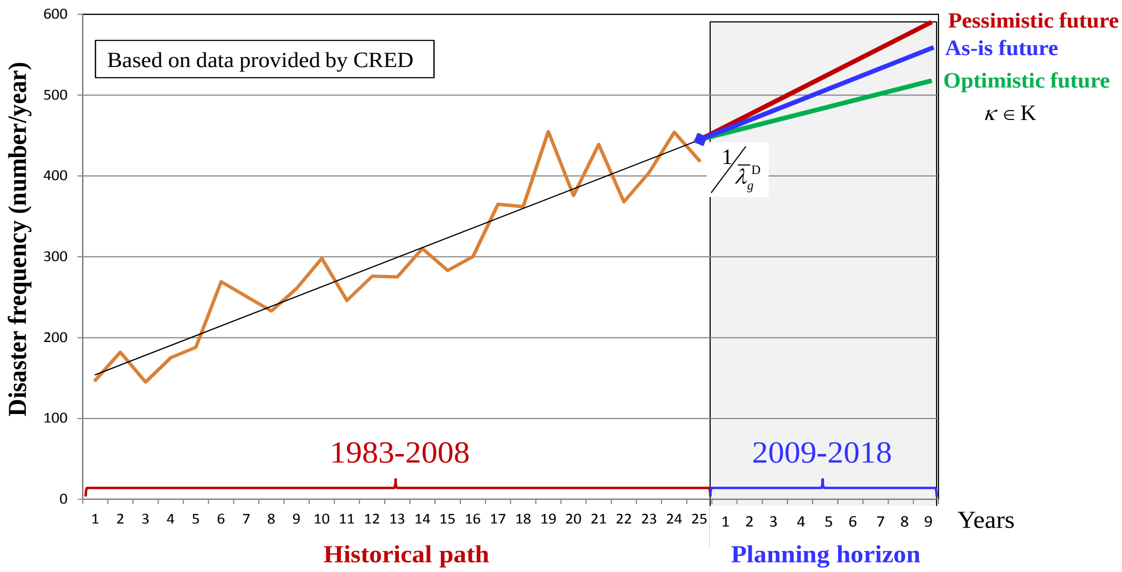

Figure 4 – Evolutionary Paths Based on Disaster Frequency Trend

3.3. CF Response Modeling

The occurrence of a multihazard does not necessarily give rise to a CF mission. Additional conditions must be satisfied for a mission to occur. We assume here that disasters (D) can lead to humanitarian assistance missions (H), quarrels (Q) to peacekeeping (K) missions and wars (W) to peace making (M) missions, and we denote these associations by h(e) (for example, h(K)= Q), or conversely by e(h) (for example, e(Q)= K). Also, when an incident occurs, Canada's response depends on its foreign policies, on the solicitations made by the country and by the UN, on the CF deployment policies, and on the forces available for deployment (Ghanmi and Shaw, 2008). These conditions are modelled through the use of conditional response probabilities and resource constraints. Let α_l^{h} be the probability that a CF mission is initiated when an extreme event of type $\mathrm{h} \in \mathbf{H}$ occurs in zone $l \in L^{\mathrm{De(h)}}$. These response probabilities are estimated subjectively by experts, based on experience and data available. Furthermore, humanitarian mission deployments are limited by the CF personal available, denoted $\eta_{\max}^{\mathrm{H}}$, and peacekeeping/making missions by regular troops available, denoted $\eta_{\max}^{\mathrm{KM}}$, with $\eta_{\max}^{\mathrm{H}} > \eta_{\max}^{\mathrm{KM}}$. We assume that the CF will not deploy in a given country more than once per year.

The intensity of a multihazard determines the duration of the *sustainment* phase of CF missions. This duration is obtained through *intensity-duration functions*, estimated by regression from data on the duration of past CF missions in response to historical hazards. More specifically, we assume that the duration ψ_l^{e} of missions of type $\mathrm{e} \in \mathbf{E}$ in potential theater $l \in L^{\mathrm{De}}$ is a random variable defined by the following relation:

$$\psi_l^{\mathrm{e}} = \underline{\psi}^{\mathrm{e}}(\beta_{g^{\mathrm{h(e)}}(l)}^{\mathrm{h(e)}}) + \varepsilon_l^{\mathrm{e}}(\beta), \quad \varepsilon_l^{\mathrm{e}}(\beta) \sim F_{\varepsilon_l^{\mathrm{e}}(\beta)}(.) = \mathrm{Exp}\left(\overline{\varepsilon}^{\mathrm{e}}(\beta_{g^{\mathrm{h(e)}}(l)}^{\mathrm{h(e)}})\right) \tag{1}$$

where $\underline{\psi}^{\mathrm{e}}(\beta)$ is a known minimum duration function depending on the multihazard intensity β, and $\varepsilon_l^{\mathrm{e}}(\beta)$ is an exponentially distributed random variable with a mean duration function $\overline{\varepsilon}^{\mathrm{e}}(\beta)$ also depending on the multihazard intensity.

Consider a multihazard of type $\mathrm{h} \in \mathbf{H}$ occurring in theater $l \in L^{\mathrm{De(h)}}$ at the beginning of response period $\tau \in \mathrm{T}$, and let $[\tau_l^{\mathrm{first}}, \tau_l^{\mathrm{end}}]$ be respectively, the first and the end period of the last mission (for any mission type) of the CF in theater $l \in L^{\mathrm{D}}$. A CF mission can result from this event with probability α_l^{h}, but only if $\tau \geq \max[t(\tau_l^{\mathrm{first}}), \tau_l^{\mathrm{end}} + 1]$, where $t(\tau)$ denotes the first period of the year following period τ. This condition guarantees that there is no parallel mission and not more than one deployment per year in a given theater. When a mission occurs, the length of its deployment phase depends on the service policy specified. As explained previously, service policies are predetermined by mission-region. For a mission-region $k \in K^{\mathrm{e}}$, $\mathrm{e} \in \mathbf{E}$, the number of periods e_k available for deployment is thus specified. Finally, we assume that materiel is available for redeployment in the first period following the sustainment phase.

When the CF intervene, the number of companies deployed depends on the multihazard intensity $\beta^{\mathrm{h}}_{g^{\mathrm{h}}(l)}$, and on the personnel $\hat{\eta}^{H}_{\tau}$ or $\hat{\eta}^{\mathrm{KM}}_{\tau}$ already engaged in other missions during period τ. To take this into account, we assume that the number of companies deployed for missions of type $\mathrm{e} \in \mathbf{E}$ in potential theater $l \in L^{\mathrm{De}}$ is the following discrete random variable:

$$\eta^{\mathrm{H}}_{l} = \begin{cases} \chi^{\mathrm{H}}_{l} & \text{if } \chi^{\mathrm{H}}_{l} + \hat{\eta}^{\mathrm{H}}_{\tau} \le \eta^{\mathrm{H}}_{\boldsymbol{max}} \\ \eta^{\mathrm{H}}_{\boldsymbol{max}} - \hat{\eta}^{\mathrm{H}}_{\tau} & \text{otherwise} \end{cases}, \quad \chi^{\mathrm{H}}_{l} \sim F_{\chi^{\mathrm{H}}_{l}}(.) = \text{Disc-Unif}[\underline{c}^{\mathrm{H}}(\beta^{\mathrm{D}}_{g(l)}), \overline{c}^{\mathrm{H}}(\beta^{\mathrm{D}}_{g(l)})] \tag{2}$$

$$\eta^{\mathrm{e}}_{l} = \begin{cases} \chi^{\mathrm{e}}_{l} & \text{if } \chi^{\mathrm{e}}_{l} + \hat{\eta}^{\mathrm{KM}}_{\tau} \le \eta^{\mathrm{KM}}_{\boldsymbol{max}} \\ \eta^{\mathrm{KM}}_{\boldsymbol{max}} - \hat{\eta}^{\mathrm{KM}}_{\tau} & \text{otherwise} \end{cases}, \quad \chi^{\mathrm{e}}_{l} \sim F_{\chi^{\mathrm{e}}_{l}}(.) = \text{Disc-Unif}[\underline{c}^{\mathrm{e}}(\beta^{\mathrm{h(e)}}_{g(l)}), \overline{c}^{\mathrm{e}}(\beta^{\mathrm{h(e)}}_{g(l)})],\ \mathrm{e} = \mathrm{K,M} \tag{3}$$

where $\underline{c}^{\mathrm{e}}(\beta)$ and $\overline{c}^{\mathrm{e}}(\beta)$, $\mathrm{e} \in \mathbf{E}$, are symmetric step functions converting multihazard intensity ranges (expressed in loss level for disasters, and intensity level for conflicts) into an integer number of companies. These two functions provide the lower and the upper bounds required by the discrete uniform distribution used to characterize the number of companies deployed during the sustainment phase. We assume here that the number of companies provided by these functions reflects the magnitude and hostility dimensions of their mission type.

The quantity of material supplied during the deployment and sustainment phases of a mission, as well as the quantity of material returned during the sustainment and redeployment phases, must be specified for each product $p \in P$. These quantities depend on the mission type, on the number of companies deployed, and on the service policy specified. For consumable (C) and repairable (N) products, the quantities deployed are based on the products reorder levels. For durable products (A) the CF specify mission scales s^{e}_{p}, $p \in P^{\mathrm{A}}$, i.e. standard quantities of assets to deploy per company for missions of type $\mathrm{e} \in \mathbf{E}$ under normal operating conditions. Given the variety of mission phases and product types involved, several stochastic processes must be defined to characterize products demands and returns. These processes are classified in **Table 1** and they are described in detail in Martel *et al*. (2010).

Product type	Mission phase: Deployment	Mission phase: Sustainment	Mission phase: Redeployment
Consumable	Discrete random variable based on scales, or reorder levels, and on the number of companies deployed	Fast mover (log-Normal)	Dependant on the quantity deployed
Durable (Assets)		Slow mover (Poisson)	
Repairable		Poisson based on asset level*	
Unserviceable repairable		Dependent on repair level	

* Using an aggregate bill-of-material

Table 1- Product Demand/Return Processes Classification

3.4. Scenario Generation

Using the stochastic processes defined in the previous sections, mission scenarios can be generated using the Monte Carlo procedure provided in Martel *et al*. (2010). The procedure starts by selecting an evolutionary path. It then generates a chronological hazard list $\mathrm{H}(\omega)$ providing the type, date, location and intensity $(\mathrm{h}, \tau, z, \beta)$ of each of the hazards associated to the scenario $\omega \in \Omega$ being generated. Then it specifies the reaction of the CF to the hazards in $\mathrm{H}(\omega)$. This part of the procedure calculates the product demand and returns for the deployment, sustainment and redeployment phases of each of the missions in the scenario, as well as the safety stocks for the sustainment phase. These quantities are then used to calculate aggregate product demands and returns for planning periods. In particular, the following quantities are calculated:

$d_{plt}^{\mathrm{x}}(\omega)$: Demand of theater $l \in L_t^{\mathrm{D}}(\omega)$, for serviceable product $p \in P \backslash P^{\mathrm{U}}$ associated to mission phase $\mathrm{x} \in [\mathrm{D,S}]$ during planning period $t \in T$, for scenario $\omega \in \Omega$.

$\delta_{plt}^{\mathrm{B}}(\omega)$: Return of unserviceable product $p \in P^{\mathrm{U}}$ during the sustainment phase from theater $l \in L_t^{\mathrm{D}}(\omega)$ in planning period $t \in T$, for scenario $\omega \in \Omega$.

$\delta_{plt}^{\mathrm{R}}(\omega)$: Quantity of product $p \in P \backslash P^{\mathrm{U}}$ redeployed from theater $l \in L_t^{\mathrm{D}}(\omega)$ during planning period $t \in T$, for scenario $\omega \in \Omega$.

$\varepsilon_{lt}(\omega)$: Number of sustainment weeks of a mission occurring in period *t* at theater *l*, under scenario $\omega \in \Omega$ (see **Figure 3**).

Several other model parameters, such as transportation, handling and depots inventory holding costs, can be random variables, and some of those may depend on evolutionary trends. The incorporation of these random variables in the scenario generation process is straightforward and it is not described explicitly here.

4. SCN Network Modeling

This section relates to the second step of the design methodology summarized in **Figure 1**: the formulation of a SCN optimization model. The CF supply network is composed of domestic CF supply sources, local vendors, internal warehousing, repair and intermodal transfer sites (possibly based in third-party facilities), and external demand zones associated to potential mission theaters. Moreover, the network facilities installed can focus on specific logistic activities or support all supply and repair activities and their mission and capacity must be determined. This gives rise to a complex SCN design problem which is best addressed using an activity based SCN modeling approach (Carle et al., 2010; M'Barek et al., 2010). The modeling concepts required to formulate the problem are defined in this section, and associated parameters, variables and constraints are introduced. The model formulated is a large-scale stochastic program with recourse and, since Ω usually contains an infinite number of scenarios, it can only be solved for a sample of equiprobable scenarios generated using the Monte Carlo procedure described in the previous section. Let $\Omega^J \subset \Omega$ denote a sample of J equiprobable scenarios in Ω. All the concepts introduced in this section are supported by the SCN design software, SCN-STUDIO, implemented to solve the CF case.

4.1. Activity Graph and SCN Locations

The supply chain design policies and the supply processes adopted by the CF can be specified conceptually by a directed activity graph $\Gamma = (A, M)$ such as the one in **Figure 5**. This graph incorporates a set A of internal and external *activities*. Two generic external activities are always present, namely a supply activity ($a = 1$) and a demand/return activity ($a = \bar{a} = |A|$). Three types of internal site activities can be defined: repair ($A^{\mathrm{F}} \subset A$), storage ($A^{\mathrm{W}} \subset A$) and consolidation-transhipment ($A^{\mathrm{C}} \subset A$) activities. This yields the following activity type lists: $\mathbf{A}$=[V,$\mathbf{S}$,D], $\mathbf{S}$=[C,F,W], where V stands for supply (vendor) and D for demand/return. Let $P_a^{\leftarrow}$ and $P_a^{\rightarrow}$ be, respectively, the set of input and output products of activity *a*. For repair activities $a \in A^{\mathrm{F}}$, a repaired output product $p \in P_a^{\rightarrow}$ is obtained from a specified quantity[1] $g_{ap'p}$ of each input products $p' \in P_a^{\leftarrow}$. The arrows between activities define possible product *movements*. Using movement types $\mathrm{m} \in \mathbf{M} = [\mathrm{I,T,D,S,B,R,H}]$, inter-location moves (transportation) are distinguished from intra-location material handling (H). Six types of transportation moves are possible. One of them corresponds to insurance inventory (I) initial provisioning or adjustment shipments to depots at the beginning or the end of a planning cycle. The others occur during missions: deployment (D), sustainment (S) or redeployment (R) shipments, back-transportation (B) of unserviceable repairables (returns) during sustainment, and depots resupply transportation (T) from supply sources. Colors are used on the arcs of the activity graph to represent movement types. Each movement $(a, a', \mathrm{m}) \in M$ in the graph is associated to the set of products $P_{(a,a',\mathrm{m})} \subset P$ which can move on the arc. The numbers on the arcs in **Figure 5** specify these products. We assume that consolidation-transhipment activities can be used only to facilitate theater replenishment during the sustainment phase of missions. The following activity graph notation is required to formulate the SCN design optimization model:

$M^{\mathrm{m}} \subset M$: Subset of movements of type $\mathrm{m} \in \mathbf{M}$.

$\mathbf{M}_a^{\rightarrow}$: Operational outbound movement types associated to activity *a* ($\mathbf{M}_a^{\rightarrow} \subseteq \mathbf{M} \backslash [\mathrm{I}]$).

$\mathbf{M}_a^{\leftarrow}$: Operational inbound movement types associated to activity *a* ($\mathbf{M}_a^{\leftarrow} \subseteq \mathbf{M} \backslash [\mathrm{I}]$).

$P_a^{\mathrm{m}\leftarrow}$: Set of input products of activity $a \in A \backslash \{1\}$ for inbound movements of type m ($P_a^{\mathrm{m}\leftarrow} = \cup_{a' \in A_a^{\leftarrow}} P_{(a',a,\mathrm{m})}$).

---

[1] This quantity can be zero for some input products, and it is necessarily 1 for the unserviceable product $p' = p^{\mathrm{U}}(p)$ being repaired. For the CF case considered, since there is a single repair activity, the goes-into factors $g_{ap'p}$ are provided by the repair quantities $g_{p'p}$ previously defined.

$P_a^{\mathrm{m}\rightarrow}$: Set of output products of activity $a \in A \backslash \{\bar{a}\}$ for outbound movements of type m ($P_a^{\mathrm{m}\rightarrow} = \cup_{a' \in A_a^{\rightarrow}} P_{(a,a',\mathrm{m})}$).

s_{pa}: Space required per unit of product $p \in P_a^{\rightarrow}$ stored in activity $a \in A^{\mathrm{W}}$.

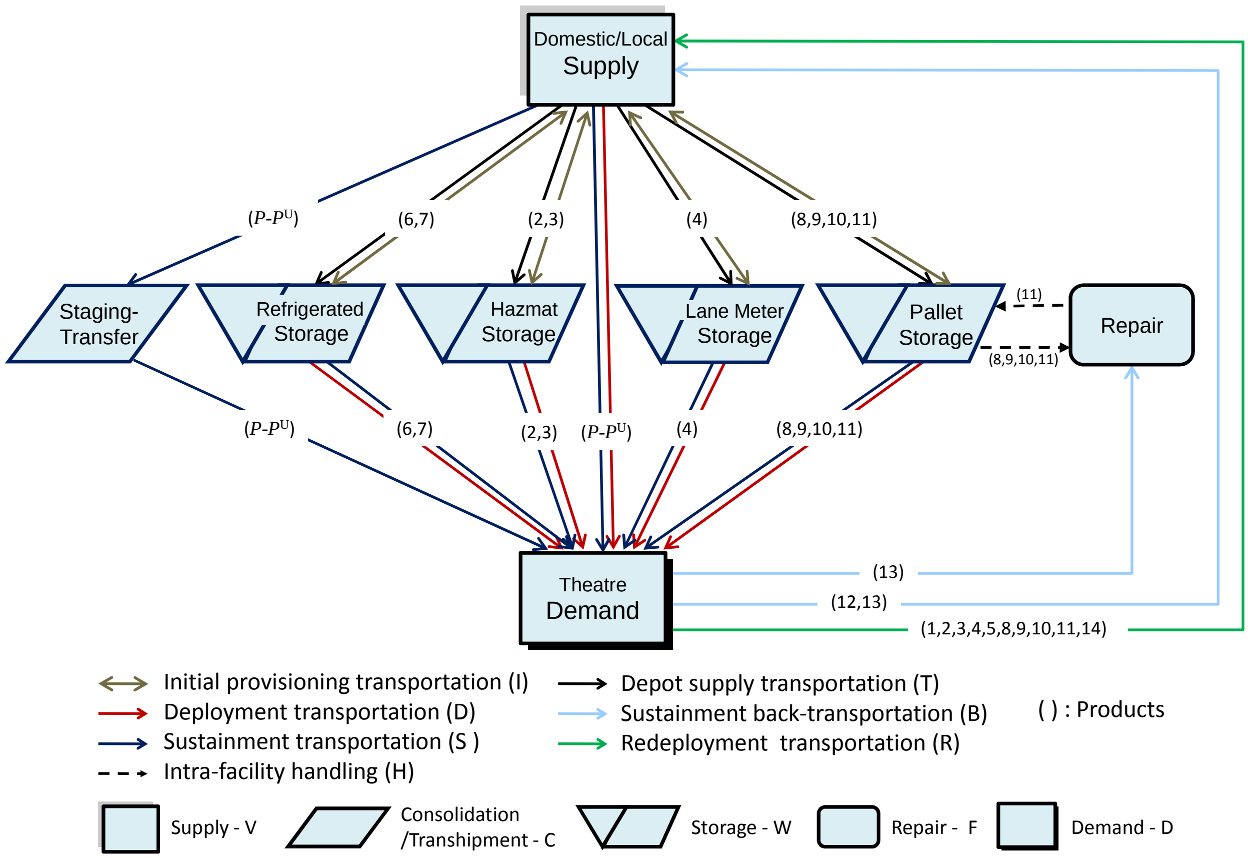

Figure 5- Activity Digraph for the CF Case

Supply activities occur at vendor locations ($L^{[\mathrm{C,V}]}$), storage, repair and consolidation-transhipment activities at potential depot or ISB sites (L^{S}), and demand activities in operational theaters (L^{D}). Distances between locations are calculated using geographical coordinates and they are used to specify transit times and transportation costs. The quantity of product $p \in P_l \subseteq P$ which can be supplied by local vendor l during a planning period $t \in T$ are bounded, but we assume that the supply from domestic CF locations is unbounded. The products purchased from local vendors must always go through an OSD, i.e. there are no direct shipments from local vendors to theaters. Also, since mission locations depend on the scenario considered (see **Figure 3**), for a given scenario $\omega \in \Omega$, in planning period $t \in T$ only a subset $L_t^{\mathrm{D}}(\omega) \subset L^{\mathrm{D}}$ of operational theaters must be supported. To model activities and locations, the following additional parameters are required:

$\bar{b}_{plt}$: Upper bound on the quantity of product $p \in P$ which can be supplied by local vendor $l \in L^{\mathrm{V}}$ during period $t \in T$.

$v_{lt}(\omega)$: Fixed cost of using vendor $l \in L^{[C,V]}$ during period $t \in T$ under scenario $\omega \in \Omega$.

Vendor selection also requires the definition of the following decision variable:

V_{lh}: Binary variable equal to 1 if vendor $l \in L^{[C,V]}$ is selected for reengineering cycle $h \in H$.

4.2. Transportation and Handling

Transportation between locations can be performed using different shipping means $s \in S^{\mathbf{T}}$, subdivided according to their transportation mode: air (S^{A}), ocean (S^{O}), railway (S^{R}), driveway (S^{D}) or intermodal (S^{I}). The network capacity of a shipping mean $s \in S^{\mathbf{T}}$ during a time period is provided by a set O of transportation options. These options may be associated to an internal fleet, a long term 3PL contract or short term for-hire transportation. The capacity provided by some options may be unbounded. It is assumed that a transportation mean is not based at a particular facility site and that it can be used anywhere provided that the required infrastructures are available. There is a variable cost associated to the use of a transportation mean $s \in S^{\mathbf{T}}$ and a fixed cost associated to the use of an option $o \in O$. This fixed cost covers fleet terminal, replacement and repair costs, or external contract costs. Some options may already be in place at the beginning of the planning horizon. Intra-location moves can be performed using different handling means $s \in S^{H}$ with distinct variable costs. Collectively, transportation and handling means define a set of *transfer* means $S = S^{\mathbf{T}} \cup S^{H}$.

For the CF case, we assume that the following transportation means are available: strategic airlift, tactical airlift, container ships, and ground transportation (rail and road). Airlift can be associated to internal or external assets. We assume that when a mission occurs, a predetermined number of CF aircrafts is assigned to the mission, thus providing a known number of flying hours per week to deploy and sustain the mission (calculated by multiplying the number of aircrafts by the maximum number of flying hours per week). Any additional strategic/tactical airlift capacity is provided by external assets. ISBs are used mainly to enable supply from Canada with strategic airlift when strategic aircrafts cannot land at the theater location. Consequently, we assume that Canada-ISB lanes are always associated to airlift and ISB-theater lanes to tactical airlift or ground transportation. Reverse flows of unserviceable products during sustainment are enabled using backhaul transportation. At the end of a mission, the redeployment is made using tailor-made intermodal transportation and products not disposed of locally are shipped back to Canada. Finally, a single generic handling mean is considered.

The following sets, variables and parameters are required to consider transportation options:

$S^{\mathbf{T}\mathrm{m}}$: Transportation means which can be used for movements of type $\mathrm{m} \in \mathbf{M}$.

S_{pm}: Transfer means which can be used for product *p* on movement *m*.

$S_{ll'}^{\mathbf{T}}$: Transportation means that are feasible between locations $l, l' \in L$, which also implies that locations $l, l' \in L$ have the required transportation infrastructures.

O_{sh}: Transportation capacity options available for shipping mean $s \in S$ during reengineering cycle $h \in H$.

$s(o)$: Shipping mean associated to capacity option $o \in O$.

Z_{oh}: Binary decision variable equal to 1 if transportation capacity option $o \in O$ is selected at the beginning of reengineering cycle $h \in H$ (binary parameter for options already in place).

$\tau_{ll's}$: Traveling time consumed per trip (one way if it is a one-time for-hire mean and round-trip otherwise) when shipping mean $s \in S^{\mathbf{T}}$ is used on lane $(l, l') \in L \times L$.

u_{ps}: Transportation capacity consumed (number of Unit Load Device (ULD) required) to move one shipping unit of product $p \in P$ with shipping mean $s \in S$.

ϑ_{ot}: Total traveling time units of shipping mean $s(o)$ available per week for a mission in period t when option $o \in O$ is selected under scenario $\omega \in \Omega$.

$z_{ot}(\omega)$: Fixed cost of using transportation capacity option $o \in O$ during time period $t \in T$ under scenario $\omega \in \Omega$.

4.3. Platforms

Potential repair and storage facilities are implemented using *platforms* specifying their capacity for each of the activities they can accommodate, as well as their fixed and variable costs. A set of alternative platforms C_l (facility configurations) can be considered for each site $l \in L^{\mathrm{S}}$. These alternative platforms may correspond to the current layout of an existing private or third-party facility (3PL, allied country), to a reorganisation of current layouts, to alternative for-hire facilities in a depot location, or to alternative contracts with a public facility. For each potential facility site, a set of possible platforms could thus be considered. For site $l \in L^{\mathrm{S}}$ and planning period $t \in T$, a platform $c \in C_l$ is characterized by:

- A set of activities $A_{lc} \subset A^{\mathbf{S}}$ supported by the platform.
- A capacity $\overline{b}_{(l,a)ct}(\omega)$ for each activity $a \in A_{lc}$ under scenario $\omega \in \Omega$, expressed in terms of an upper bound on a standard capacity measure (repair time, storage space, throughput). It is assumed that all the output products $p \in P_a^{\rightarrow}$ of an activity $a \in A_{lc}$ share the capacity provided by the platform for this activity. A capacity demand rate q_{pac} is used to convert the throughput of product $p \in P_a^{\rightarrow}$ in the standard capacity measure.
- A minimum expected throughput, $\underline{b}_{(l,a)ch}$, for each activity $a \in A_{lc}$, required to implement the platform during reengineering cycle $h \in H$.
- An alternative platform $c'(c)$ which could be used as an upgrade. Upgrade-platform $c'(c)$ can be implemented only when platform c is in place. Some platforms cannot be upgraded.

- A fixed period exploitation cost $y_{clt}(\omega)$ under scenario $\omega \in \Omega$. This cost includes fixed operating costs, as well as market value depreciation and opportunity costs in the case of ownership, or fixed contract costs when a third-party facility is used.
- An implementation cost $y^{+}_{clt}(\omega)$, under scenario $\omega \in \Omega$, if platform c is installed at the beginning of reengineering cycle $h(t)$. This cost is an opening or upgrade project cost paid during the period and it does not include any capital expenditure. It may include personnel hiring costs, support activity set-up costs, etc.
- A disposal cost (return) $y^{-}_{clt}(\omega)$, under scenario $\omega \in \Omega$, when platform c is closed at the beginning of cycle $h(t)$. This would cover any cash flows incurred in period t following a shutdown in the first period of cycle $h(t)$. Closing platform $c \in C_l$ results in the permanent closing of site l, i.e. when a platform is closed on a site, the site cannot be reopened during the horizon.
- A variable throughput cost $x_{p(l,a)ct}(\omega)$, under scenario $\omega \in \Omega$, for each output product $p \in P^{\rightarrow}_{a}$ of activity $a \in A_{lc}$, covering relevant reception, repair, handling and shipping expenses.

The set of activities A_l that could be performed on a potential site $l \in L^{S}$ depends on the platforms considered for that site, i.e. $A_l = \cup_{c \in C_l} A_{lc}$. The following platform related sets and decision variables are also required to formulate the model:

C_{lh} : Platforms that can be used for site *l* during cycle *h*.

C^{o}_{lh} : Original platforms considered in reengineering cycle *h* for site *l*, i.e. platforms that are not an upgrade of another platform ($C^{o}_{lh} \subset C_{lh}$).

$C_{(l,a)h}$: Platforms that can be used to perform activity *a* in site *l* during cycle *h*.

$Y^{+}_{clh}, Y_{clh}, Y^{-}_{clh}$: Binary variable equal to 1 if, respectively, opening, using or closing platform $c \in C_l$ at site $l \in L^{S}$ at the beginning of reengineering cycle $h \in H$. $Y_{cl0}, c \in C_l$, are binary parameters providing the state of site $l \in L^{S}$ at the beginning of the horizon.

Depot and ISB configurations are specified by the platform selection variables Y^{+}_{clh}, Y_{clh} and Y^{-}_{clh}, which must respect the following conditions. One cannot use more than one platform on a site during a reengineering cycle:

$$\sum_{c \in C_{lh}} Y_{clh} \leq 1 \qquad l \in L^{S}, h \in H \tag{4}$$

Also, a site cannot be opened or closed more than once during the planning horizon:

$$\sum_{h \in H} \sum_{c \in C^{o}_{lh}} Y^{+}_{clh} \leq 1 - Y_{cl0} \qquad l \in L^{S} \tag{5}$$

$$\sum_{h\in H}\sum_{c\in C_{lh}} Y^{-}_{clh} \leq 1 \qquad l \in L^{\mathrm{S}} \qquad (6)$$

Precedence relations for the upgrade of platforms must also be followed. An upgrade platform cannot be installed in a cycle unless its preceding platform is installed and not closed at the beginning of the cycle:

$$Y^{+}_{c'(c)lh} \leq Y_{clh-1} - Y^{-}_{clh} \qquad l \in L^{\mathrm{S}}, h \in H, c \in C_{lh} \qquad (7)$$

Finally, a platform can be closed only if it was used during the previous cycle, and it cannot be closed and opened in the same period, which is enforced by the following state accounting constraints:

$$Y_{clh} + Y^{+}_{c'(c)lh} + Y^{-}_{clh} - Y^{+}_{clh} - Y_{clh-1} = 0 \qquad l \in L^{\mathrm{S}}, h \in H, c \in C_{lh} \qquad (8)$$

4.4. Supply Network

When the activity graph $\Gamma = (A, M)$ is mapped onto the potential locations $l \in L$, a supply network is obtained. In this network, the nodes correspond to feasible location-activity pairs $n = (l, a) \in N$, and the arcs (*p*,*n*,*n'*,*s*) to feasible flows of product *p* between nodes *n* and *n'*, using transfer mean *s*, for a given time period and scenario. A location-activity (l, a) pair is feasible if $a \in A_l$. A flow between nodes $n = (l, a)$ and $n' = (l', a')$ is not feasible if $[l = l'] \wedge [\exists (a, a', \mathrm{m}) \in M, \mathrm{m} \in M \backslash M^{\mathrm{H}}]$ or if $[l \neq l'] \wedge [\exists (a, a', \mathrm{H}) \in M]$. For a given node *n*, the set of destinations of feasible outbound arcs is denoted by $N^{\rightarrow}_{n}$, and the set of origins of feasible inbound arcs by $N^{\leftarrow}_{n}$. The transportation means which can be used to ship product *p* from node *n* to node *n'* for movements of type $\mathrm{m} \in M \backslash M^{\mathrm{H}}$ are denoted by $S^{\mathrm{m}}_{pnn'}$. The CF service policies are enforced by defining the set of feasible (origin node, transportation mean) pairs $NS^{\leftarrow}_{pl}$ which can provide the service level required for product $p \in P_{\mathrm{e}(l)}$ in theater $l \in L^{\mathrm{D}}$.

In the network, flow variables are associated to all arcs, activity levels (throughputs or repair quantities) to all nodes and inventory levels to storage nodes. Two types of inventories are considered: strategic insurance inventories kept at the depots, and cycle and safety stocks resulting from procurement lot sizing and demand randomness consideration. The former are considered explicitly and the later implicitly. Insurance inventory levels are strategic design decisions. They provide stock level targets for OSDs to ensure quick responses during the deployment stage of anticipated missions. It is assumed that the initial provisioning of OSD strategic inventories is unbounded. The strategic inventory available in depots limits the quantities that can be deployed from the depots, but the strategic inventory is not consumed. All flows from the depots to the theater during the deployment and sustainment phase must be resupplied, i.e. we must have flow equilibrium. We assume that strategic inventories kept in depots do not have to be purchased: they are simply a part of the Canadian inventory that is relocated. Also, we assume that the cost of holding strategic inventories in the overseas depots is the same as it is in Canada. Under these assumptions, the cost of the strategic inventory is independent of the network design and it does not have to be considered explicitly. Cycle and safety stocks result from decisions on incoming flows at OSDs. All flow, activity and inventory variables are considered as recourses used by the network users to respond to a specific mission scenario $\omega \in \Omega^J$. All flows, inventories and demands are expressed in the shipping unit (pallet or lane meters) of the product considered.

To model activity levels, flows and inventories, the following sets, variables and parameters are required:

$l(n)$: Location of node *n*.

$a(n)$: Activity of node *n*.

N^{C} : Feasible consolidation-transhipment nodes ($N^{\mathrm{C}} \subset L^{\mathrm{S}} \times A^{\mathrm{C}}$).

N^{F} : Feasible repair nodes ($N^{\mathrm{F}} \subset L^{\mathrm{S}} \times A^{\mathrm{F}}$).

N^{W} : Feasible storage nodes ($N^{\mathrm{W}} \subset L^{\mathrm{S}} \times A^{\mathrm{W}}$).

N^{V} : Feasible supply nodes ($N^{\mathrm{V}} \subset L^{[\mathrm{C,V}]} \times \{1\}$).

$N^{\mathbf{S}}$: Feasible site-activity nodes ($N^{\mathbf{S}} = N^{\mathrm{C}} \cup N^{\mathrm{F}} \cup N^{\mathrm{W}}$).

N^{D} : Feasible demand nodes ($N^{\mathrm{D}} \subset L^{\mathrm{D}} \times \{\overline{a}\}$).

N_l^{S}: Subset of nodes in N^{S} associated to location $l \in L^{\mathrm{S}}$.

$N_{pn}^{\mathrm{m}\rightarrow}$: Destinations of feasible outbound arcs from node *n* for product $p \in P_{a(n)}^{\mathrm{m}\rightarrow}$ and movements of type $\mathrm{m} \in \mathbf{M}$, i.e. such that $p \in P_{(a(n),a(n'),\mathrm{m})}$.

$N_{pn}^{\mathrm{m}\leftarrow}$: Origins of feasible inbound arcs to node *n* for product $p \in P_{a(n)}^{\mathrm{m}\leftarrow}$ and movements of type $\mathrm{m} \in \mathbf{M}$, i.e. such that $p \in P_{(a(n'),a(n),\mathrm{m})}$.

$\rho_{pn'ns}$: Average number of period of product $p \in P \backslash P^{\mathrm{U}}$ cycle and safety stock kept at node $n \in N^{\mathrm{W}}$, when supplied from node $n' \in N_{pn}^{\mathrm{m}\leftarrow}$ using transfer mean $s \in S_{pnn'}^{\mathrm{T}}$.

η_{pa}: Order cycle and safety stocks (maximum level)/(average level) ratio of product $p \in P$ for activity $a \in A^{\mathrm{W}}$.

$f_{pnn'st}(\omega)$: Unit cost of the flow of product *p* between node *n* and node n' when using transportation mean *s* during period *t* under scenario $\omega \in \Omega$ (this cost includes the relevant transaction costs, reception-shipping costs, variable transportation costs and inventory-in-transit holding costs).

$f_{pn'nst}^{\mathrm{m}}(\omega)$: Unit cost of reverse type $\mathrm{m} \in [\mathrm{B,R}]$ flows of product *p* between nodes $n' \in N^{\mathrm{D}}$ and $n \in N_{pn'}^{\mathrm{m}\leftarrow}$ when using shipping mean *s* during period *t*, under scenario $\omega \in \Omega$ (includes relevant transaction, reception-shipping and variable transportation costs, as well as unit repair costs for returns of unserviceable products to Canada).

$f_{pnn't}^{\mathrm{H}}(\omega)$: Unit material handling cost of product $p \in P_{(a(n),a(n'),\mathrm{H})}$ between node n and node n' during period *t*, under scenario $\omega \in \Omega$.

$r_{pnct}(\omega)$: Unit inventory holding cost for product $p \in P$ on platform $c \in C_{nh(t)}$ in node $n \in N^{\mathrm{W}}$ during period $t \in T$, under scenario $\omega \in \Omega$.

$F^{\mathrm{m}}_{pnn'st}(\omega)$: Flow of product $p \in P_{(a(n),a(n'),\mathrm{m})}$ from node n to node $n' \in N^{\mathrm{m}\rightarrow}_{pn}$ during period $t \in T$, for movements of type $\mathrm{m} \in \mathbf{M}\backslash[\mathrm{I}]$, using transfer mean $s \in S^{\mathrm{m}}_{pnn'}$, under scenario $\omega \in \Omega$ (forward/reverse flows from/to the supply nodes, handling flows in OSDs, deployment and sustainment flows to the theaters, and back-flows of unserviceable products from the theater).

$F^{\mathrm{I}}_{pnn'sh}$: Strategic inventory provisioning for product $p \in P_{(a(n),a(n'),\mathrm{I})}$ from node n to node n' at the beginning of reengineering cycle $h \in H$, using shipping mean $s \in S^{\mathrm{I}}_{pnn'}$ ($n = (l,1)$ and $n' \in N^{\mathrm{I}\rightarrow}_{p(l,1)}$ for initial provisioning flows, and $n \in N^{W}$ and $n' = (l,1)$ for return flows).

$X^{\mathrm{m}}_{pnct}(\omega)$: Activity level in node n related to movement $\mathrm{m} \in [\mathrm{D,S,H}]$ for product $p \in P^{\rightarrow}_{a(n)}$ when platform $c \in C_{nh(t)}$ is used in period t (quantity repaired when $a(n) \in A^{\mathrm{F}}$ and throughput when $a(n) \in A^{\mathrm{W}} \cup A^{\mathrm{C}}$).

I_{pnch}: Level of strategic inventory for product $p \in P^{\leftarrow}_{a(n)}$ held at node $n \in N^{\mathrm{W}}$ in platform $c \in C_{nh}$ during planning cycle $h \in H$. I_{pnc0} is the insurance inventory for platform c at the beginning of the horizon (equal to 0 for all c if the depot is not already in place).

$\overline{I}_{pnct}(\omega)$: Average level of cycle and safety stocks of product $p \in P^{\leftarrow}_{a(n)}$ held in storage node $n \in N^{W}$ with platform c during period $t \in T$, under scenario $\omega \in \Omega$.

The design problem is formulated as a two-stage stochastic program with complete recourse (Shapiro, 2007), which assumes that design decisions for all reengineering cycles must be made at the beginning of the planning horizon. This is reasonable because, as indicated previously, these design problems are solved on a rolling horizon basis. In these models, first stage design variables and constraints do not depend on scenarios, but second stage recourse variables and constraints depend on the scenarios $\omega \in \Omega^{J}$ in the sample used. The platform selection constraints (4)-(8) previously defined are first stage constraints. Also, the following first stage accounting constraints related to the initial provisioning and subsequent adjustments of strategic inventories are required:

$$\sum_{c \in C_{lh}} I_{pnch} = \sum_{c \in C_{lh}} I_{pnch-1} + \sum_{(l,1) \in N^{\mathrm{I}\leftarrow}_{pn}} \sum_{s \in S^{\mathrm{I}}_{p(l,1)n}} F^{\mathrm{I}}_{p(l,1)nsh} - \sum_{(l,1) \in N^{\mathrm{I}\rightarrow}_{pn}} \sum_{s \in S^{\mathrm{I}}_{pn(l,1)}} F^{\mathrm{I}}_{pn(l,1)sh} \quad n \in N^{\mathrm{W}}, p \in P^{\mathrm{I}\leftarrow}_{a(n)}, h \in H \tag{9}$$

All other constraints in the model are second stage constraints. Under scenario $\omega \in \Omega^{J}$, the aggregate demands for serviceable products during deployment and sustainment are satisfied if:

$$\sum_{(n,s) \in NS^{\leftarrow}_{pl}} F^{\mathrm{m}}_{pn(l,\overline{a})st}(\omega) = d^{\mathrm{m}}_{plt}(\omega) \qquad \mathrm{m} \in [\mathrm{D,S}], l \in L^{\mathrm{D}}_{t}(\omega), p \in P_{l}, t \in T, \omega \in \Omega^{J} \tag{10}$$

Also, product returns from the operational theater require that:

$$\sum_{n \in N^{\mathrm{B}\rightarrow}_{p(l,\overline{a})}} \sum_{s \in S^{\mathrm{B}}_{p(l,\overline{a})n}} F^{\mathrm{B}}_{p(l,\overline{a})nst}(\omega) = \delta^{\mathrm{B}}_{plt}(\omega) \qquad l \in L^{\mathrm{D}}_{t}(\omega), p \in P^{\mathrm{U}} \cap P_{l}, t \in T, \omega \in \Omega^{J} \tag{11}$$

$$\sum_{n\in N^{\mathrm{R}\rightarrow}_{p(l,\bar{a})}} \sum_{s\in S^{\mathrm{R}}_{p(l,\bar{a})n}} F^{\mathrm{R}}_{p(l,\bar{a})nst}(\omega) = \delta^{\mathrm{R}}_{plt}(\omega) \qquad l\in L^{\mathrm{D}}_t(\omega),\, p\in P^{[C,A,N]}\cap P_l, t\in T, \omega\in\Omega^J \tag{12}$$

At the other end of the SCN, supply constraints imposed by limited local vendor capacity must be respected:

$$\sum_{n\in N^{\mathrm{T}\rightarrow}_{p(l,1)}} \sum_{s\in S^{\mathrm{T}}_{p(l,1)n}} F^{\mathrm{T}}_{p(l,1)nst}(\omega) \le V_{lh(t)}\bar{b}_{plt} \qquad l\in L^{\mathrm{V}},\, p\in (P\backslash P^{\mathrm{U}})\cap P_l, t\in T, \omega\in\Omega^J \tag{13}$$

For intermediate SCN nodes, flow equilibrium must be respected for each mission scenario. To specify these constraints, we first define activity-site throughputs by movement types in terms of outflows to other nodes:

$$\sum_{c\in C_{nh(t)}} X^{\mathrm{m}}_{pnct}(\omega) = \sum_{n'\in N^{\mathrm{m}\rightarrow}_{pn}\cap N^{\mathbf{S}}} \sum_{s\in S^{\mathrm{m}}_{pnn'}} F^{\mathrm{m}}_{pnn'st}(\omega) + \sum_{(l,\bar{a})\in N^{\mathrm{m}\rightarrow}_{pn}\cap N^{\mathrm{D}}_t} \sum_{(n,s)\in NS^{\leftarrow}_{pl}} F^{\mathrm{m}}_{pn(l,\bar{a})st}(\omega)$$
$$n\in N^{\mathbf{S}}, \mathrm{m}\in \mathbf{M}^{\rightarrow}_{a(n)}, p\in P^{\mathrm{m}\rightarrow}_{a(n)}, t\in T, \omega\in\Omega^J \tag{14}$$

Note that throughputs must be associated to the platform implemented on a site. This is required because variable throughput costs are not the same for different platforms. Throughputs must also be related to inflows. For repair nodes, this yields the following equations:

$$\sum_{n'\in N^{\mathrm{m}\leftarrow}_{pn}} \sum_{s\in S^{\mathrm{m}}_{pn'n}} F^{\mathrm{m}}_{pn'nst}(\omega) = \sum_{c\in C_{nh(t)}} \sum_{p'\in P^{\mathrm{H}\rightarrow}_{a(n)}} g_{pp'} X^{\mathrm{H}}_{p'nct}(\omega) \qquad n\in N^{\mathrm{F}}, \mathrm{m}\in \mathbf{M}^{\leftarrow}_{a(n)}, p\in P^{\mathrm{m}\leftarrow}_{a(n)}, t\in T, \omega\in\Omega^J \tag{15}$$

For storage nodes the following relations apply:

$$\sum_{\mathrm{m}\in \mathbf{M}^{\leftarrow}_{a(n)}} \sum_{n'\in N^{\mathrm{m}\leftarrow}_{pn}} \sum_{s\in S^{\mathrm{m}}_{pn'n}} F^{\mathrm{m}}_{pn'nst}(\omega) = \sum_{\mathrm{m}\in \mathbf{M}^{\rightarrow}_{a(n)}} \sum_{c\in C_{nh(t)}} X^{\mathrm{m}}_{pnct}(\omega) \qquad n\in N^{\mathrm{W}}, p\in P^{\leftarrow}_{a(n)}, t\in T, \omega\in\Omega^J \tag{16}$$

For consolidation-transhipment nodes, no explicit relations to inflows are required for the following reason. For the CF case, all the products sustained through an ISB originate from a predetermined domestic CF supply location $l\in L^{\mathrm{C}}$, and they are shipped to the ISB using a predetermined transportation mean. That is, the supply source $l_n\in L^{\mathrm{C}}$ and the inbound transportation mean $s_n\in S^{\mathbf{T}}$ of an ISB $n\in N^{\mathrm{C}}$ are predetermined, and thus the inbound lane traveling time $\tau_{l_n l(n) s_n}$ depends only on *n*. Consequently, under scenario ω, the flows of product $p\in P_l$ shipped to theater $l\in L^{\mathrm{D}}_t(\omega)$ in period *t* through lane $((l_n,1),n)$, using transportation mean s_n, are completely determined by the flows between the ISB and the theater. More precisely, these flows are given by:

$$F^{\mathrm{S}}_{p(l_n,1)ns_nt}(\omega) = \sum_{(n,s)\in NS^{\leftarrow}_{pl}} F^{\mathrm{S}}_{pn(l,\bar{a})st}(\omega), \quad n\in N^{\mathrm{C}}, l\in L^{\mathrm{D}}_t(\omega), p\in P_l, t\in T, \omega\in\Omega^J$$

For this reason, the flow variables $F^{\mathrm{S}}_{p(l_n,1)ns_nt}(\omega)$ and the ISB inbound-throughput relationships do not have to be defined explicitly in the model. In what follows, this simplifies the calculation of transportation capacity requirements and costs.

Intermediate SCN nodes are also subjected to some capacity constraints. First, the quantity of product deployed from a depot cannot exceed the strategic inventory kept in that depot:

$$X^{\mathrm{D}}_{pnct}(\omega) \le I_{pnch(t)} \qquad n \in N^{\mathrm{W}}, c \in C_{nh(t)}, p \in P^{\mathrm{D}\rightarrow}_{a(n)}, t \in T, \omega \in \Omega^{J} \qquad (17)$$

Second, a depot can be implemented only if its average throughput exceeds a minimum acceptable level for all activities involved:

$$\underline{b}_{nch} Y_{cl(n)h} \le \frac{1}{J} \sum_{\omega \in \Omega^{J}} \sum_{\mathrm{m} \in \mathbf{M}^{\rightarrow}_{a(n)}} \sum_{t \in T_h} \sum_{p \in P^{\rightarrow}_{a(n)}} X^{\mathrm{m}}_{pnct}(\omega) \qquad n \in N^{\mathrm{S}}, h \in H, c \in C_{nh} \qquad (18)$$

On the other end, the node activity level cannot exceed the capacity provided by the selected platform[2]:

$$\sum_{\mathrm{m} \in \mathbf{M}^{\rightarrow}_{a(n)}} \sum_{p \in P^{\mathrm{m}\rightarrow}_{a(n)}} q_{pa(n)c} X^{\mathrm{m}}_{pnct}(\omega) \le \bar{b}_{nct}(\omega) Y_{cl(n)h(t)} \qquad n \in N^{\mathrm{S}}, t \in T, c \in C_{nh(t)}, \omega \in \Omega^{J} \qquad (19)$$

To facilitate the formulation of inventory level constraints, it is convenient to define the following, platform dependent, average cycle and safety stock variables:

$$\sum_{c \in C_{nh(t)}} \bar{I}_{pnct}(\omega) = \sum_{\mathrm{m} \in \mathbf{M}^{\leftarrow}_{a(n)}} \sum_{n' \in N^{\mathrm{m}\leftarrow}_{pn}} \sum_{s \in S^{\mathrm{m}}_{pn'n}} \rho_{pn'ns} F^{\mathrm{m}}_{pn'nst}(\omega) \qquad n \in N^{\mathrm{W}}, p \in P^{\leftarrow}_{a(n)}, t \in T, \omega \in \Omega^{J} \qquad (20)$$

The following platform storage space constraints can then be specified:

$$\sum_{p \in P^{\rightarrow}_{a(n)}} s_{pa(n)} (\eta_{pa(n)} \bar{I}_{pnct}(\omega) + I_{pnch(t)}) \le \bar{b}_{nct}(\omega) Y_{cl(n)h(t)} \qquad n \in N^{\mathrm{W}}, c \in C_{nh(t)}, t \in T, \omega \in \Omega^{J} \qquad (21)$$

The flows in the network are also constrained by the transportation options selected. Since missions do not necessarily cover a full year, transportation capacity constraints are based on average weekly flows during deployment or sustainment, taking into account the fact that for a given theater, these two mission phases never occur simultaneously. This leads to the following weekly deployment and sustainment transportation capacity constraints:

$$\sum_{p \in P_l} \sum_{(n,s) \in NS^{\leftarrow}_{pl}} \tau_{l(n)ls} u_{ps} \frac{F^{\mathrm{D}}_{pn(l,\bar{a})st}(\omega)}{e_{k(l)}} \le \sum_{o \in O_{sh(t)}} \vartheta_{ot} Z_{oh(t)} \qquad l \in L^{\mathrm{D}}_{t}(\omega), s \in S^{\mathbf{TD}}, t \in T, \omega \in \Omega^{J} \qquad (22)$$

$$\sum_{p \in P_l} \sum_{(n,s) \in NS^{\leftarrow}_{pl}} \tau_{l(n)ls} u_{ps} \frac{F^{\mathrm{S}}_{pn(l,\bar{a})st}(\omega)}{\varepsilon_{lt}(\omega)} + \sum_{p \in P_l} \sum_{(n,s') \in NS^{\leftarrow}_{pl} | n \in N^{\mathrm{C}}_{s}} \tau_{l_n l(n)s} u_{ps} \frac{F^{\mathrm{S}}_{pn(l,\bar{a})s't}(\omega)}{\varepsilon_{lt}(\omega)} \le \sum_{o \in O_{sh(t)}} \vartheta_{ot} Z_{oh(t)} \qquad l \in L^{\mathrm{D}}_{t}(\omega), s \in S^{\mathbf{TS}}, t \in T, \omega \in \Omega^{J} \qquad (23)$$

The second term in (23) gives the total transportation mean *s* traveling time required between domestic CF supply sources and ISBs to sustain theater *l*, and N^{C}_{s} denotes the set of ISBs which can be reached from Canada using transportation mean *s*.

[2] Capacity for storage nodes is often bounded by the space available (see (21)) rather than directly by the platform's throughput. When this is the case, the capacity $\bar{b}_{nct}(\omega)$ in (19) is replaced by an arbitrary large number but the constraints are still required to ensure that the relationship between throughput variables and platform selection variables is properly defined.

Returns from the operational theaters are made using backhaul shipments, but we need to ensure that the weight of the backhauling flows from a theater to a depot (returns to Canada are assumed to be unconstrained) does not exceed the weight of the material shipped from that depot to the theater:

$$\sum_{p \in P^{\mathrm{U}}} w_p F^{\mathrm{B}}_{p(l,\bar{a})(l',a^{\mathrm{F}})s^{\mathrm{B}}t}(\omega) \le \sum_{a \in A^{\mathrm{W}}_{l'}} \sum_{p \in P_a^{(a,\bar{a},\mathrm{S})\rightarrow}} \sum_{s \in S_{p(a,\bar{a},\mathrm{S})}} w_p F^{\mathrm{S}}_{p(l',a)(l,\bar{a})st}(\omega) \quad l \in L^{\mathrm{D}}_t(\omega), l' \in L^{\mathrm{SF}}, t \in T, \omega \in \Omega^J \quad (24)$$

where $s^{\mathrm{B}} \in S^{\mathbf{T}}$ is the index of the backhaul (B) transportation mean, and $a^{\mathrm{F}} \in A^{\mathbf{S}}$ is the index of the repair (F) activity.

4.5. Readiness Investments and Operational Support Costs

Two types of expenses must be distinguished: *readiness* investments and expenditures, and *operational support* costs. The former are usually made beforehand, to ensure that adequate service levels will be provided when the need arises. They include investments in additional strategic inventory (if the inventory kept in depots is not simply relocated from domestic depots, as assumed for the CF case), the costs of setting up and operating depots to stock these inventories, the cost of establishing local vendor agreements, and the investments, maintenance and operating costs required to operate transportation fleets. They are related to SCN design variables: platform and location decisions ($Y^{+}_{clh}, Y_{clh}, Y^{-}_{clh}$), strategic inventory levels (I_{pnct}), initial provisioning flows ($F^{\mathrm{I}}_{pnn'sh}$), local vendor selections (V_{lh}), and transportation options (Z_{oh}). Strategic inventory holding costs are assumed to be the same in all locations and, consequently, they are a constant and they do not have to be taken into account explicitly in the model. The operational support costs are related to the support of individual missions. They depend on mission scenarios, and they are associated to flow ($F^{\mathrm{m}}_{pnn'st}(\omega)$), throughput ($X^{\mathrm{m}}_{pnct}(\omega)$) and cycle and safety stock variables ($\bar{I}_{pnct}(\omega)$). Product prices are assumed to be the same for all supply sources and, consequently, they do not have to be taken into account explicitly. The model could however be modified to accommodate differentiated strategic inventory holding costs and product prices.

In practice investment and operational support expenses are regulated by different control mechanisms. For this reason, for a given service policy, two different SCN optimisation approaches may be pursued. We may want to minimize expected total readiness and operational support costs over the planning horizon (or expected total discounted costs), or minimize expected operational support costs subject to readiness budget constraints. Let:

- B_h: Expected readiness investment and expenditure budget available in reengineering cycle $h \in H$
- $\mathrm{E(OC)}$: Expected supply network operational costs over the planning horizon
- $\mathrm{E(RI}_h)$: Expected supply network readiness investments and expenditures for reengineering cycle $h \in H$

To take readiness budgets into account explicitly, the following constraints must be added to the model:

$$\mathrm{E}(\mathrm{RI}_h) \le \mathrm{B}_h \qquad h \in H \tag{25}$$

$$\mathrm{E}(\mathrm{RI}_h) = \sum_{\omega\in\Omega^J} \frac{1}{J}\left\{ \sum_{t\in T_h}[\sum_{l\in L^{\mathrm{S}}}\sum_{c\in C_{lh}}(y^+_{clt}(\omega)Y^+_{clh} + y_{clt}(\omega)Y_{clh} + y^-_{clt}(\omega)Y^-_{clh}) + \sum_{o\in O} z_{ot}(\omega)Z_{oh} + \sum_{l\in L^{\mathrm{V}}} v_{lt}(\omega)V_{lh(t)}] + \sum_{n\in N^{\mathrm{W}}}\sum_{(p,l,s)}[f_{p(l,1)nst(h)}(\omega)F^{\mathrm{I}}_{p(l,1)nsh} + f_{pn(l,1)st(h)}(\omega)F^{\mathrm{I}}_{pn(l,1)sh}] \right\}$$

The objective then would be to minimize expected SCN operational costs:

$$\min \mathrm{E}(\mathrm{OC}) \tag{26}$$

with

$$\begin{aligned}
\mathrm{E}(\mathrm{OC}) = \sum_{\omega\in\Omega^J}\frac{1}{J}\Bigg\{\sum_{t\in T}\Bigg[& \sum_{n\in N^{\mathrm{S}}}\sum_{c\in C_{nh(t)}}\sum_{p\in P_{\vec{a}(n)}} x_{pnct}(\omega)\sum_{\mathrm{m}\in \mathbf{M}_{\vec{a}(n)}} X^{\mathrm{m}}_{pnct}(\omega) && \text{Activity processing}\\
& + \sum_{l\in L^{\mathrm{S}}}\sum_{a\in A_l}\sum_{a'\in A_l\setminus\{a\}}\sum_{p\in P_{(a,a')}}\sum_{s\in S^{\mathrm{H}}} f^{\mathrm{H}}_{p(l,a)(l,a')t}(\omega)F^{\mathrm{H}}_{p(l,a)(l,a')st}(\omega) && \text{Material handling}\\
& + \sum_{n\in N^{\mathrm{W}}}\sum_{l\in L^{[\mathrm{C,V}]}}\sum_{(p,s)} f_{p(l,1)nst}(\omega)F^{\mathrm{T}}_{p(l,1)nst}(\omega) && \text{Provisioning flows}\\
& + \sum_{\mathrm{m}\in[\mathrm{D,S}]}\sum_{l\in L^{\mathrm{D}}_t(\omega)}\sum_{n\in N^{[\mathrm{W,V}]}}\sum_{(p,s)} f_{pn(l,\bar{a})st}(\omega)F^{\mathrm{m}}_{pn(l,\bar{a})st}(\omega) && \text{Mission flows}\\
& + \sum_{l\in L^{\mathrm{D}}_t(\omega)}\sum_{n\in N^{\mathrm{C}}}\sum_{(p,s)}(f_{pn(l,\bar{a})st}(\omega) + f_{p(l_n,1)ns_nt}(\omega))F^{\mathrm{S}}_{pn(l,\bar{a})st}(\omega) && \\
& + \sum_{\mathrm{m}\in[\mathrm{B,R}]}\sum_{l\in L^{\mathrm{D}}_t(\omega)}\sum_{n\in N_{\overrightarrow{(l,\bar{a})}}}\sum_{(p,s)} f^{m}_{p(l,\bar{a})nst}(\omega)F^{\mathrm{m}}_{p(l,\bar{a})nst}(\omega) && \text{Reverse flows}\\
& + \sum_{n\in N^{\mathrm{W}}}\sum_{c\in C_{nh(t)}}\sum_{p\in P_{\vec{a}(n)}} r_{pnct}(\omega)\bar{I}_{pnct}(\omega)\Bigg]\Bigg\} && \text{Inventory holding costs}
\end{aligned}$$

If instead we want to minimize total expenses over the planning horizon, then the objective function to use is:

$$\min \sum_{h\in H}\mathrm{E}(\mathrm{RI}_h) + \mathrm{E}(\mathrm{OC}) \tag{27}$$

With either approaches, constraint (4)-(24) formulated previously must be included in the model, as well as all decision variables non-negativity or binary value range. As indicated at the beginning of the paper, in order to obtain different candidate designs, this model is run several times with different scenario samples. Let I be the number of model replications solved with different samples of *J* scenarios. The mixed integer programs (MIPs) thus obtained can be solved for each sample replication using a commercial solver such as CPLEX-12. The sample size *J* used should be as large as possible but, given the complexity of the model, when *J* is very large it becomes intractable. Results are available in the stochastic programming literature to determine the sample size to use to provide a desired statistical optimality gap (Shapiro, 2003), but in practice J is also limited by the size of the models that can be solved. Let C_i and $\mathbf{x}_i$, $i = 1,...,\mathrm{I}$, be the optimal value and the vector of the optimal design variables of the MIPs solved for the I samples used.

5. SCN Designs Evaluation and Selection

This section relates to the third step of the design methodology summarized in **Figure 1**. Since the design model incorporates only an aggregated anticipation of response decisions, and since it is solved for relatively small samples of scenarios, there is no guarantee that a given design $\mathbf{x}_i$ will be robust when considering all plausible scenarios. The models solved should however provide some high performance designs to compare with the status-quo design denoted $\mathbf{x}_0$. Let $\mathbf{x}_i$, $i = 0,1,...,\bar{\mathrm{I}}$ ($\bar{\mathrm{I}} \leq \mathrm{I}$), be the list of distinct designs to compare. In order to evaluate these designs, one should use an independently generated sample of scenarios $\Omega^{J^+} \subset \Omega$ with $J^+ >> J$, and base the evaluation on a response model that is as close as possible to the decision processes used in practice at the operational level. In the CF context, this model could be a mathematical program formulated to minimize weekly network flow and inventory holding costs over the planning horizon for a given scenario. In two-stage stochastic programming with recourse, it is customary to use the second stage program to make this evaluation, which is the approach adopted here. For a given scenario $\omega \in \Omega^{J^+}$ and a given design $\mathbf{x}_i$, this program is obtained simply by fixing the value of the design variables in the previous model and by considering a single scenario. The first stage constraints then drop and $\mathrm{E(RI)} = \Sigma_{h \in H} \mathrm{E(RI}_h)$ becomes a constant. This yields a linear program (LP) solved easily with CPLEX-12. Let $C(\mathbf{x}_i, \omega)$, $i = 0,1,...,\bar{\mathrm{I}}$, $\omega \in \Omega^{J^+}$, be the objective function values (including $\mathrm{E(RI)}$) obtained when solving this LP for all the designs and scenarios considered.

An adequate SCN design evaluation cannot be based only on expected values; it must also include some robustness measures. The expected cost $\bar{C}(\mathbf{x}_i)$ of a design $\mathbf{x}_i$ is provided by:

$$\bar{C}(\mathbf{x}_i) = \frac{1}{J^+} \sum_{\omega \in \Omega^{J^+}} C(\mathbf{x}_i, \omega) \tag{28}$$

Robustness is related to the variability of the costs obtained under different scenarios. Since downside deviations from mean costs are undesirable, an adequate variability measure to assess a design $\mathbf{x}_i$ is the mean-semideviation $MSD(\mathbf{x}_i)$ given by:

$$MSD(\mathbf{x}_i) = \frac{1}{J^+} \sum_{\omega \in \Omega^{J^+}} \max\left[\left(C(\mathbf{x}_i, \omega) - \bar{C}(\mathbf{x}_i)\right); 0\right] \tag{29}$$

Decision-makers are also interested by the behaviour of the designs under extreme conditions. Using worst-case scenarios, this is often evaluated with the absolute robustness criteria proposed by Kouvelis and Yu (1997). For design $\mathbf{x}_i$ this gives the largest cost $AR(\mathbf{x}_i)$ under all scenarios, calculated as follows:

$$AR(\mathbf{x}_i) = \max_{\omega \in \Omega^{J^+}} \{C(\mathbf{x}_i, \omega)\} \qquad (30)$$

Measures (28)-(30) provide the basis for a multi-criteria evaluation of the designs considered, and for the selection of a design to implement. These measures can also be used to construct a compound utility function reflecting the decision-makers aversion to variability and to extreme events. Finally, the values C_i and $C(\mathbf{x}_i, \omega)$, $\omega \in \Omega^{J^+}$, can be used to estimate a statistical optimality gap for the selected design (Shapiro, 2003).

6. CF Case Analysis

The SCN design methodology proposed was validated by applying it to a version to the CF case with realistic but fictitious data to preserve the confidentiality of some sensitive information. In addition to the case elements already introduced in the text, the following features were considered:

- A planning horizon involving a single reengineering cycle subdivided in 10 yearly planning periods, each comprising 52 weekly response periods, was specified. Three evolutionary trends were examined as illustrated in **Figure 4**.
- Products were classified into 14 product families and possible product movements are specified in the **Figure 5** activity graph. Eight potential overseas sites in the following locations were preselected: Dakar, Ramstein, Mombasa, Panama, Singapour, Taranto, Derince and Dubai. For each site, an OSD with 2 potential platforms (small and large) is considered, as well as a nearby ISB for intermodal transfers and a potential local vendor with specified capacity for locally sourced products. The following domestic CF supply sources are used: Trenton for airlift and Montreal for sealift. All the countries in the world are considered as potential operational theaters.
- A maximum of 3 CC-130 (Hercules) and one CC-177 (Globemaster) aircrafts from the CF fleet can be assigned to a given overseas mission. All additional transportation requirements are satisfied using for-hire air, sea or ground transportation. The fixed cost of transportation options is negligible and for-hire transportation capacity is unbounded. Material handling costs are assumed to be negligible.
- The objective pursued in the design generation phase was the minimisation of expected total readiness and operational support costs over the planning horizon. Five SAA model replications (I = 5) were run, each including 10 Monte Carlo scenarios (J = 10). For the evaluation

and selection phase, 50 mission scenarios ($J^+ = 50$) were used. Sensitivity analyses were also performed for several model parameters.

The experiments reported in this section were performed on a 64 bits server with a 2.5 GHz Intel XEON processor and 16 GB of RAM. SCN-STUDIO, the tool developed to support the methodology, was programmed in the Microsoft Visual Studio environment and it incorporates a SQL Server database. The design models generated include about 350 000 variables (with 120 binary variables) and 120 000 constraints, and they are solved in 30 minutes or so with CPLEX-12. Each mission scenario generated includes about 2000 yearly product-location demand points over the ten year horizon considered.

Among the five design model replications solved, two distinct depot sets were obtained. Both include OSD’s with small platforms in Mombasa and Derince, and one also comprises a small-platform depot in Singapore. These set are denoted MD-designs and MDS-designs, respectively. Three MDS-designs and two MD-designs were obtained. Within each set, the designs are slightly different because they do not involve the same strategic inventory levels in the depots, but their expected total cost is very close. These five designs were compared with the status-quo (supporting all missions from Trenton and Montreal in Canada). The sustainment flows of consumable cargo during a 10-year mission scenario are illustrated in **Figure 6** for a Mombasa-Derince design. The evaluation of each design in terms of the performance measures defined previously is provided in **Table 2**, which lists only the most expensive design in each set. The results show that although the MDS-designs require the largest initial investment, they are the best for all the performance criteria specified, i.e. they are the cheapest and the most robust. They provide a decrease in expected costs of about 5% over the status-quo, their downside risk is lower and their worst-case behaviour is better.

Several sensitivity analyses were made with SCN-STUDIO. They showed first that the mission scenarios obtained are influenced significantly by the CF response probabilities used. These probabilities are subjective and it is important to base them on in-depth analyses of Canadian foreign relations and policies. The test made also showed that the optimal solution is sensitive to transportation and platform costs. The difference between sealift and airlift costs is certainly a strong motivation to open some OSDs but it is not sufficient in itself to cover depot investment costs. If fuel costs continue to increase, however, this may not be true anymore. Also, if depots fixed costs can be lowered (for example, by transforming part of the fixed costs into variable costs), more or larger depots would be opened. This stresses the requirement for an accurate estimation of all the costs involved and for the consideration of evolutionary trends. Our results also show that local sourcing is a significant economy opportunity. In the CF case solved, only about 15% of the missions demand can be sourced at the depot locations. Increasing this percentage would lead to more substantial savings.

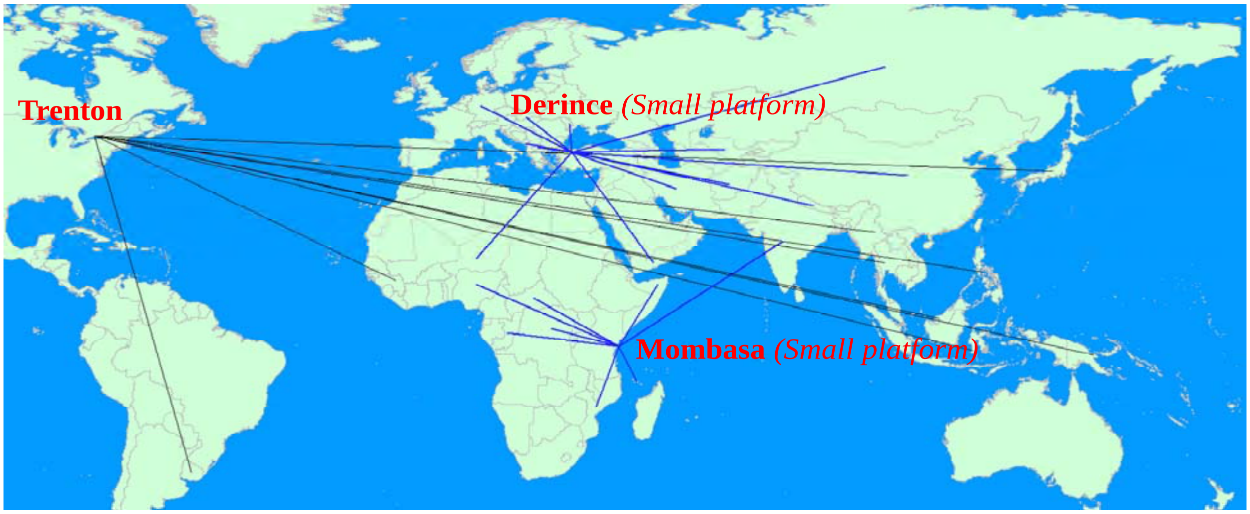

Figure 6 – Sustainment Flows of Consumable Cargo for a Mombasa-Derince Design

Design	Readiness investments	Expected ops support costs	Expected total expenses	MSD (% of expenses)	AR
MD-design	\$6 612 126	\$189 974 334	\$196 586 460	10,8%	\$300 246 809
MDS-design	\$10 330 019	\$185 935 701	\$196 265 720	10,6%	\$298 950 042
Status-quo	\$400	\$205 756 521	\$205 756 921	11,0%	\$316 653 829

Table 2 – Comparison of Candidate Designs

Another important issue is the investigation of different service-expense trade-offs. In the model, the service policy of the CF is considered by defining sets of feasible (origin node, transportation mean) pairs $NS_{pl}^{\leftarrow}, p \in P_{e(l)}, l \in L^{D}$, and by specifying theater replenishment lead times and fill rates by mission-regions. An (origin node, transportation mean) pair implicitly specifies the maximum time that can be taken to deploy a product *p* to a theater *l*, which clearly depends on the distance between the origin node and the theater and the speed of the transportation mean used. By specifying different maximum deployment time targets, redefining the sets $NS_{pl}^{\leftarrow}, p \in P_{e(l)}, l \in L^{D}$, accordingly and solving the model for each target, a service-expense efficiency frontier can be constructed. This trade-off curve can then be used to select adequate service targets. Similar analysis can be made by examining different theater replenishment lead times and fill rates.

Some of the assumptions made in our proof-of-concept tests are critical. We assumed that the insurance inventory kept in overseas OSDs was redeployed from existing domestic depots, and that product purchase and repair costs were the same in Canada and abroad. If this is not the case, the optimal solution obtained would certainly be different. To take differentiated product purchase and repair costs into accounts, the activity graph in **Figure 7** would have to be slightly modified to capture the storage and repair activities made in Canada, and purchasing costs would have to be added in the objective function of the model. We also assumed that the OSDs are not vulnerable, i.e. that they cannot be affected by disasters or political unrests. In real life, this is certainly not the case. The methodology proposed can deal which such events and the model could be modified to take them into account (Klibi and Martel, 2009).

7. Conclusions

This paper presents a methodology for the design of global supply networks to support humanitarian, peacekeeping and peace enforcement missions around the world, and it applies it to the case of the Canadian Armed Forces. The approach proposed involves three phases: scenario generation, design generation and design evaluation. The first phase is a Monte Carlo procedure to generate worldwide disasters and conflicts over a planning horizon, to determine if these give rise to a mission and, if so, to specify product demands and returns at the theaters during the mission deployment, sustainment and redeployment phases. The second phase uses a stochastic programming model to generate candidate SCN designs. The third phase evaluates and compares candidate designs, including the status quo, using expected value, downside risk and absolute robustness measures based on the performance of the designs for a large sample of scenarios. The validity and the value of the approach are demonstrated using the CF case.

Currently, the CF support all overseas missions directly from Canada using mainly strategic airlift. The objective pursued was to examine the possibility of improving the global reach of the Forces by designing an offshore network of operational support depots and by comparing this capability option to the status quo. The results obtained show clearly that this option is viable and that the CF would profit by adopting it. However, the CF case solved included some fictitious but realistic data to preserve the confidentiality of sensitive information. Before a final conclusion is reached, the reengineering approach proposed needs to be reapplied with more precise data. Some variants of the model considering differentiated product and repair costs and depots vulnerabilities should also be examined.

8. References

[1] Altay N, Green III W G (2006). OR/MS Research in Disaster Operations Management. *European Journal of Operational Research* 175: 475–493.

[2] Banks, E (2006). *Catastrophic risk: Analysis and Management*. Wiley Finance.

[3] Campbell A M and P C Jones (2011). Prepositioning supplies in preparation for disasters. *European Journal of Operational Research* 209: 156-165.

[4] Carle M A, A Martel and N Zufferey (2010). *The CAT Metaheuristic for the Solution of Multi-Period Activity-Based Supply Chain Network Design Problems*. Research Document CIRRELT-2010-52, Université Laval, Canada.

[5] Ghanmi A and R Shaw (2008). Modeling and analysis of Canadian Forces strategic lift and pre-positioning options. *Journal of the Operational Research Society* 59: 1591–1602.

[6] Ghanmi A, (2010). Canadian forces global reach support hubs: facility location and aircraft routing models. *Journal of the Operational Research Society*, doi:10.1057/jors.2010.22.

[7] Girard S, Martel A, Boukhtouta A, Chouinard M, Ghanmi A, Guitouni A (2008). *Canadian Forces Overseas Supply Network: Strategic Need and Design Methodology*, Research Document CIRRELT-2008-34, Université Laval, Canada.

[8] Klibi W and A Martel (2009). *The Design of Effective and Robust Supply Chain Networks*, Research Document CIRRELT-2009-28, Université Laval, Canada.

[9] Klibi W, A Martel and A Guitouni (2010). The Design of Robust Value-creating Supply Chain Networks: A Critical Review, *European Journal of Operational Research* 203-2: 283-293.

[10] Klose A and Drexl A (2005). Facility location models for distribution system design, *European Journal of Operational Research* 162: 4-29.

[11] Kouvelis P and G Yu (1997). *Robust discrete optimization and its applications*. Kluwer Academic Publishers.

[12] Lodree E J and S Taskin (2008). An insurance risk management framework for disaster relief and supply chain disruption inventory planning. *Journal of the Operational Research Society* 59: 674-684.

[13] Martel A (2005). The Design of Production-distribution Networks: A Mathematical Programming Approach. In Geunes and Pardalos (eds.), *Supply Chain Optimization*, Kluwer Academic Publishers.

[14] Martel A., A. Benmoussa, I. Ezzedine, W. Klibi, J. Berger, A. Boukhtouta, M. Chouinard, S. Girard and O. Kettani (2010). Military Missions Scenario Generation for the Design of Logistics Support Networks, Proceedings of ILS 2010, Casablanca, Morocco.

[15] M'Barek W, A Martel and S D'Amours, *Designing Multinational Value-Creating Supply Chain Networks for the Process Industry*, Research Paper CIRRELT-2010-51, Université Laval, Canada.

[16] Meixell M J and Gargeya V B (2005). Global Supply Chain Design: A Literature Review and Critique. *Transportation Research Part E* 41: 531-550.

[17] Scawthorn C, P J Shneider and B A Shauer (2006). Natural Hazards - The Multihazard Approach. *Natural Hazards Review* 7-2: 39.

[18] Shapiro A (2003). Monte Carlo Sampling Methods, in *Handbooks in OR. & MS Vol.10*, A Ruszczynski and A Shapiro Editors, Elsevier.

[19] Shell Global Scenarios to 2025 (2005). The future business environment: trends, trade-offs and choices. Shell International Limited.

[20] Silver E, D Pyke and R Peterson (1998). *Inventory Management and Production Planning and Scheduling*. 3rd ed., Wiley.

[21] Snyder L V (2006). Facility location under uncertainty: A review. *IIE Transactions* 38-7: 537-554.

[22] Tomasini, R and L van Wassenhove (2009). *Humanitarian Logistics*. Palgrave Macmillan.

Appendix A: Concept Lists Notation Summary

$\mathbf{L}=[C,V,S,D]$: Location types

- C: Domestic CF supply source
- V: Local vendor
- S: Site locations
- D: Operational theater

$\mathbf{E}=[H,K,M]$: Possible mission types

- H: Humanitarian assistance (DART)
- K: Peacekeeping
- M: Peace making (enforcement)

$\mathbf{X}=[D,S,R]$: Mission phases

- D: Deployment
- S: Sustainment
- R: Redeployment

$\mathbf{P}=[C,A,N,U]$: Possible product types

- C: Consumable products
- A: Durable products (assets)
- N: New or as-new repairable products
- U: Unserviceable repairable products

$\mathbf{H}=[D,Q,W]$: Possible multihazards

- D: Natural disasters
- Q: Quarrel (tense situations with sporadic incidents)
- W: War (armed conflicts)

$\mathbf{A}=[V,\mathbf{S},D]=[V,C,F,W,D]$: Activity types

- V: Supply (vendors)
- $\mathbf{S}=[C,F,W]$: Internal site activity types
  - C: Consolidation and transhipment
  - F: Repair (fabrication)
  - W: Warehousing (storage)
- D: Demand and return

$\mathbf{M}=[I,T,D,S,B,R,H]$: Movement types

- I: Initial provisioning transportation
- T: Depot supply transportation
- D: Deployment transportation
- S: Sustainment transportation
- B: Sustainment back-transportation
- R: Redeployment transportation
- H: Intra-facility handling

$\mathbf{T}=[A,O,\mathbf{G},I]=[A,O,R,D,I]$: Possible transportation modes

- A: Air
- O: Ocean
- $\mathbf{G}=[R,D]$: Ground transportation
  - R: Railway
  - D: Driveway (trucking)
- I: Intermodal