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Optimizing non-combatant evacuation operation transportation logistics

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Abstract. A non-combatant evacuation operation (NEO) is designed to deploy forces in a short notice situation as a result of a deteriorating situation in an affected nation that is threatening the safety of citizens or eligible persons living abroad. An optimization model was developed to study the feasibility and logistical complexities of transportation asset usage of a NEO, enabling decision makers to better plan and prepare NEO execution.

Keywords: optimization, mixed-integer linear programming, non-combatant evacuation operations, military planning, logistics.

Introduction

A non-combatant evacuation operation (NEO) is designed to deploy forces in a short or no-notice situation as a result of a deteriorating situation in an affected nation that is threatening the safety of citizens living abroad. Large scale NEOs are extremely complex; often being conducted in a hostile environment, dealing with multiple uncertainties, and requiring whole of government expertise and coordination across multiple areas. The NEO process considered in this paper is illustrated in Figure 1.

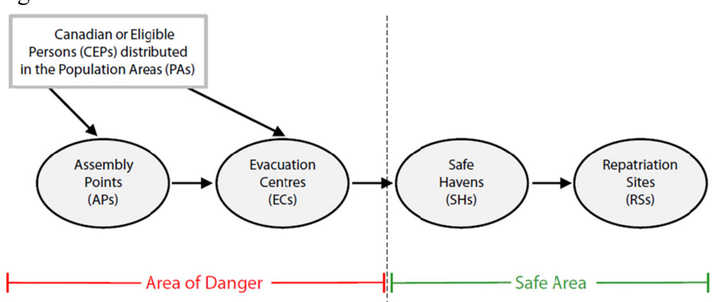

Figure 1: Non-combatant evacuation process.

The generic elements of the evacuation include:

- Assembly Points (APs): APs, which are often schools, churches or hotels, are normally first in the evacuation chain. Typically, the Canadian or eligible persons (CEPs) make their own way to an AP - the one allocated to them through the warden system. The APs serve as meeting points while the CEPs await transport, organized by the embassy, to an EC. CEPs may also proceed directly to an EC from their place of residence;
- Evacuation Centres (ECs): an EC is the main processing facility, where basic screenings are conducted and detailed processing takes place. ECs are secure sites and are likely to be located at, or in proximity to, an airport, a sea port or a beach site. The screening confirms the identities and eligibility of the persons seeking evacuation, and security and medical checks are performed. The transport of CEPs from ECs to SHs is arranged by the Government of Canada, typically using commercial or military sealift or airlift assets;
- Safe Havens (SHs): an SH is defined as an area beyond the effects of the disturbance from which evacuees are removed. It may be elsewhere in the host nation, in another country, on a ship, or in the country of origin itself. At the SH, CEPs are safe from threat and await onward movement to an RS or back to the affected nation once the disturbances have ceased; and,
- Repatriation Site (RS): a RS refers to a place of safety where the CEPs exit the evacuation chain and are no longer dependent on diplomatic or military assistance. In most NEO instances, the RS is the country of origin itself.

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Embassies are typically responsible for developing and maintaining contingency plans to provide guidance to local missions in their response in safeguarding CEPs during the on-set, peak, and aftermath of a crisis. Plans provide information and instructions, including:

- total number of CEPs and break down by local area and by category;
- evacuation chain data, with the locations of evacuation facilities (APs and ECs), routes, and points of contact for facilities, contracts, etc.; and,
- evacuation supporting data, particularly the locations and technical data for terminals (e.g. airports, sea ports, beach sites), existing transportation infrastructure and commercial links (air, land and sea) in the affected nation.

In support of the Canadian Department of National Defence, and by extension, the Department of Foreign Affairs, Trade and Development, the Defence Research and Development Canada (DRDC) Centre for Operational Research and Analysis initiated the development of a NEO modelling and simulation toolset for optimizing non-combatant evacuation (STONE). STONE comprises of a visualization component (automated map generation and graphical reports), optimization component (modeling resource utilization and evacuation timeline), and a discrete event simulation component (for "what-if" analysis and to model uncertainty). This paper presents the optimization component of STONE, henceforth referred to as STONE(Opt). Certain elements presented in this paper have been previously published in an internal DRDC scientific report (Caron & Kaluzny, 2015).

NEO, from the Canadian perspective, has been studied in the recent past mainly through reviews of policy, departmental doctrine, and case studies (Chaloux, 2007; Eyre, 2011). Elsewhere, the United States Naval Postgraduate School developed an optimization model to plan non-combatant evacuation (Dell & Sparling, 2008), an effort sponsored by the Center for Army Analysis. The model was leveraged by planners in the Africa, Europe and Pacific regions in support of operational plan development, exercises and crisis planning (Murphy, 2012). The Air Force Institute of Technology (Gregg, 2010; Olsen, 2007) and the Center for Army Analysis (Kuchel, 2013) also proposed NEO models and analysis based on discrete event simulation. Within the Ministère de la Défence (France), the Centre de doctrine d'emploi des forces division simulation et recherche opérationelle planned the development of successive modeling and analysis to optimize the deployment and operation of NEO. Initial modelling efforts were to focus on the flow of CEPs through evacuation centres (Bougeret, 2009).

STONE(Opt) was developed to optimize the Canadian evacuation process, focusing on the movement of CEPs between sites. STONE(Opt) takes as configurable input:

- a relative time period length and appropriate level of time granularity;
- the list of APs, ECs, and SHs, and respective site capacities;
- the total number of CEPs to be evacuated and the anticipated arrival rate of CEPs to respective APs and ECs;
- the network specifying the possible movement of CEPs between sites (APs, ECs, SHs), specified by directed edges (routes) and distances between sites; and,
- the list of transporter types, specifying the quantity, speed, capacity, and which network routes each can be employed on.

Optional inputs include specifying transporter departure times along specific network routes, minimum or maximum utilization rates of transporters, time periods when transportation is not permitted or times when sites are not capable of accepting further CEPs, and specifying processing time of CEPs at ECs. It is acknowledged that the model may share analogies with the aforementioned United States Center for Army Analysis model which was not fully disclosed.

Mixed Integer Linear Programming Model

Define P be the total number of time periods to be considered. A single time period can be interpreted as an hour, a few hours, a half-day, day, etc. Let $T = \{1,...,P\}$ be the set of time periods. *lastP* is an input parameter indicating the desired last time period by which all CEPs should be evacuated to safe havens. Let AP be the set of assembly points, EC the set of evacuation centres, SH the set of safe havens, and define $Sites = AP \cup EC \cup SH$ to be the set of all sites being considered. Define a set $ST = Sites \times T$ with indices $\{i,t\}$. Define SCi to be the capacity (number of people) of site $i \in Sites$. Let $Arr_{i,t}$ be the input parameter indicating the number of CEPs from population areas expected to arrive at site $i \in AP \cup EC$ at time period $t \in T$. Define $totalCEP$ as the sum of all $Arr_{i,t}$:

$$totalCEP = \sum_{\{i,t\} \in AP \cup EC \times T} Arr_{i,t}. \tag{1}$$

Let M be the set of transporter types and define TC_m to be the capacity (number of CEPs) of transporter type $m \in M$, and TQ_m to be the total number of transporters of type $m \in M$ available. Define TA to be the set of triples $\{i,j,m\}$ of feasible network arcs indicating which transport types $m \in M$ can travel from site i to j with $i,j \in Sites$. Let $TAT_{i,j,m}$ with $\{i,j,m\} \in TA$ be the maximum number of trips that a single transporter of type m can accomplish in a single time period between sites i and j. A fractional value of $TAT_{i,j,m}$ is permitted and indicates that a single trip spans more than one time period (i.e. it spans $\frac{1}{TATi,j,m}$ time periods).

Constraints are primarily driven by site capacities and requirements, network routes, transporter availability and capacity:

- all CEPs are to be evacuated to SHs by *lastP*;
- the number of CEPs arriving at a site is equal to the number of CEPs departing that site at a later time (excluding SHs);
- the number of CEPs arriving a site at a particular time corresponds to the number of CEPs arriving on their own to that site plus any CEPs that have departed from other sites via transporters destined for that site - taking into account transportation time;
- the number of CEPs departing a site is constrained by the number of transporters available and their capacities and utilization rates; and,
- the number of transporters of a specific type being used at a given time must respect the limit on the total number of such transporters available;

Optional constraints include fixing the number of trips of a transporter on a particular route and time, specifying time periods were specific sites can neither accept new CEP arrivals nor let CEPs depart, specifying time periods of transporter availability, and ensuring that the number of CEPs processed or accommodated at a site at a particular time period is constrained by the site's capacity;

Define $x_{i,j,m,t}$ to be a nonnegative variable indicating the number of people that departed from site i to site j during time period t on transporter type m with $\{i,j,m\} \in TA$. By design, $x_{i,j,m,t}$'s are allowed to take fractional values as the output of interest of the optimization model is not how many CEPs travel on any particular transporter, but rather the assignment and usage of transporters and feasibility of sites (with respect to capacity). Let $z_{i,j,m,t}$ be an integer variable specifying the number of transporters of type m departing site i to site j during time period t with $\{i,j,m\} \in TA$. Variable $u_{i,j,m,t}$ is defined as an integer variable specifying the number of transporters of type m being used on arc $\{i,j\}$ during time period t. When transporters can complete a trip within a time period, then corresponding variables $u_{i,j,m,t}$ are equal to their counterparts $z_{i,j,m,t}$. Let $w_{i,j,m,t}$ be an integer variable specifying the number of trips that transporters of type m commence on arc $\{i,j\}$ during time period t with $\{i,j,m\} \in TA$. Define $CEP_{i,t}$ be the number of people located at site $i \in Sites$ and time $t \in T$. Define $D_{i,t}$ with $\{i,t\} \in ST$ to be the number of people departing site i during time period t. Define $A_{i,t}$ with $\{i,t\} \in ST$ to be the number of people arriving at site i during time period t. Define Y_t for each $t \in T$ to be a binary variable indicating whether the evacuation of affected individuals from the danger area is complete ($Y_t = 0$) or not ($Y_t = 1$).

Constraint (2) forces Y_{lastP} to be set to zero (indicating the evacuation is complete) at the specified time period. Constraints (3) are needed to ensure that if Y_t is set to zero, then all subsequent time periods, $t+1$, $t+2,...,P$ are also set to zero. Constraints (4) relate the arrival of all CEPs at an SH to the evacuation completion variables:

$$Y_{lastP} == 0, \tag{2}$$

$$\text{for all } t \geq 2: \quad Y_{t-1} \geq Y_t, \tag{3}$$

$$\text{for all } t \in T: \quad totalCEP \sum_{s \in SH} IP_{s,t} \leq Y_t \cdot totalCEP. \tag{4}$$

Constraints (5) and (6) ensure proper accounting of CEPs arriving and departing sites at each time period.

$$\text{for all } \{i,t\} \in ST:$$
$$\text{if } t \geq 2: CEP_{i,t} == CEP_{i,t-1} + A_{i,t} - D_{i,t} + Arr_{i,t}, \tag{5}$$
$$\text{else}: \text{CEP}_{i,1} == A_{i,1} - D_{i,1} + Arr_{i,1}. \tag{6}$$

Constraints (7) and (8) ensure proper accounting of the arrival and departure by linking the variable representing the number of CEPs arriving/departing to the number of CEPs travelling via transporters from site to site at a particular time period:

$$\text{for all } \{i,t\} \in ST:$$
$$\text{D}_{i,t} == \sum_{\{i,j,m\} \in TA} x_{i,j,m,t}, \tag{7}$$
$$\text{A}_{i,t} == \sum_{\substack{\{j,i,m\} \in TA \\ \text{with } t > \left\lfloor \max(1, \frac{1}{TAT_{j,i,m}}) \right\rfloor}} x_{j,i,m,t-\left\lfloor \max(1, \frac{1}{TAT_{j,i,m}}) \right\rfloor}. \tag{8}$$

Constraints (8) sum the number of CEPs that are arriving over all arcs leading to site *i*. When the transport time for a transport arc exceeds one time period, the equation looks back sufficient time period steps to properly account for arrivals.

Constraints (9) to (13) are defined to link variables $x_{i,j,m,t}$, indicating the number of CEPs departing from site *i* to site *j* on transporter type *m* and time *t*, to variables $z_{i,j,m,t}$ and $w_{i,j,m,t}$ representing the number of transporters initiating travel along that arc and the number of trips commencing during time period *t*, respectively:

$$\text{for all } \{i,j,m,t\} \in TA \times T:$$
$$\text{w}_{i,j,m,t} \leq \max(1, \lfloor TAT_{i,j,m} \rfloor) \cdot z_{i,j,m,t}, \tag{9}$$
$$\text{x}_{i,j,m,t} \leq TAT_{i,j,m}^{max} \cdot TC_m \cdot w_{i,j,m,t}, \tag{10}$$
$$\text{x}_{i,j,m,t} \geq TAT_{i,j,m}^{min} \cdot TC_m \cdot w_{i,j,m,t}, \tag{11}$$
$$\text{x}_{i,j,m,t} \geq z_{i,j,m,t}, \tag{12}$$
$$\text{w}_{i,j,m,t} \geq z_{i,j,m,t}. \tag{13}$$

Together, constraints (9) and (10) ensure that the number of trips and transporters conforms to transporter capacity and usage upper bounds while being sufficient to transport the number of CEPs represented by $x_{i,j,m,t}$. Constraints (11) ensure that the number of trips takes into consideration the transporter's minimum utilization factor. Constraints (12) and (13) constrain the number of transport assets departing on an arc at a particular time to be less than or equal to both the number of CEPs departing and also the number of trips of that commence.

Further to the constraints above, variables $u_{i,j,m,t}$, representing the number of transportation assets of type *m* in use on arc $\{i, j\}$, are linked to the number of transporters initiating travel along that arc, represented by variables $z_{i,j,m,t}$, taking into account the length of such trips:

$$\text{for all } \{i,j,m,t\} \in TA \times T:$$
$$\text{if } \text{TAT}_{i,j,m} < 1$$
$$\text{then } \text{u}_{i,j,m,t} == \sum_{\substack{s \in \{1,\ldots,t\} \\ \text{with } s \geq t+1-\left\lceil \frac{1}{TAT_{i,j,m}} \right\rceil}} z_{i,j,m,s} \tag{14}$$
$$\text{else } \text{u}_{i,j,m,t} == z_{i,j,m,t}. \tag{15}$$

The number of transportation assets of a specific type being used anywhere in the network at any given time period must respect the upper bound on the total number of transportation assets available:

$$\text{for all } \{m,t\} \in M \times T: \sum_{\{i,j,m\} \in TA} u_{i,j,m,t} \leq TQ_m. \tag{16}$$

Given the required inputs and constraints, the mathematical model formulated is solved to determine a schedule for transporters to evacuate CEPs in an optimal fashion; the objective function may be to complete the NEO as quickly as possible (17), or to minimize the average time CEPs spend in the area of danger (18), or minimize the use of transportation resources (19):

$$\text{minimize} \sum_{t \in T} Y_t; \tag{17}$$

$$\text{minimize} \sum_{\{i,t\} \in SH \times T} -1 \cdot t \cdot CEP_{i,t}; or, \tag{18}$$

$$\text{minimize} \sum_{\{i,j,m\} \in TA} u_{i,j,m,t}. \tag{19}$$

The formulation presented herein has $|T|\cdot(4\cdot|TA| + 3\cdot|Sites| + 1)$ variables, $|T|\cdot(3\cdot|TA| + 3\cdot|Sites| + 1)$ of which are integer/binary, and $|T|\cdot(3\cdot|Sites| + 6\cdot|TA| + |M| + 1)$ constraints. The formulation was converted to standard Mathematical Programming System using Zimpl (Koch, 2004).

Example Application

Consider an island country divided into 17 districts or population areas (PAs). Figure 2 depicts the distribution of 7,400 CEPs across the PAs, where black represents the areas with the most CEPs and white represents the converse. The scenario assumes that CEPs leave their homes by their own means to get to an AP (white squares in Figure 2) or EC (white triangles). For the purpose of the example, the percentage of CEPs going directly from a PA to an EC is estimated at 20%. From an AP they are transported by ground to one of the two ECs, and are moved by sealift from the ECs to the SH (white circle). The network of connections between the locations is also represented in Figure 2. Thirteen buses with a capacity of 40, speed of 75km/h, are available for use between APs and ECs. Five ferries are available between ECs and the SH, with a capacity of 200 and speed of 20km/h.

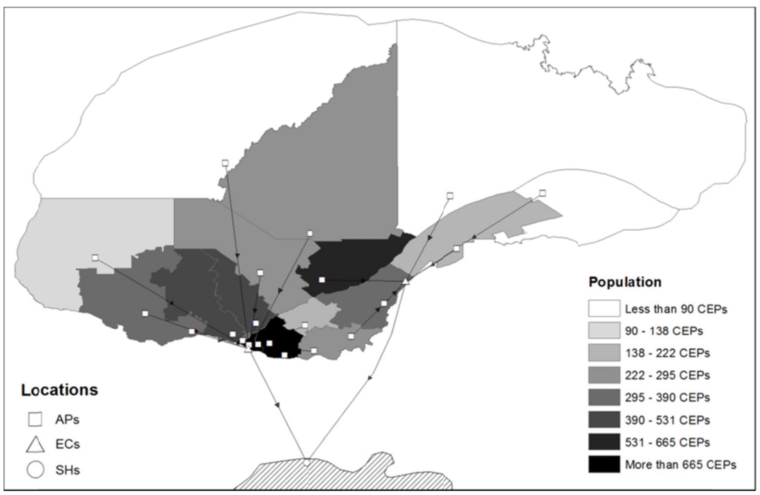

Figure 2: PAs in affected nation, APs, ECs, SH, and transportation routes.

NEO planners are interested in estimating how many resources would be required to evacuate all CEPs as a function of a desired evacuation time. Intuitively, if the objective is to move 7,400 CEPs like in this example, more resources would be needed if one wants to achieve the evacuation in 5 days versus 10 days. "How many resources?" STONE(Opt) was used to minimize transportation resources subject to a constrained evacuation deadline (varying the *lastP* parameter). Solutions were found using the SCIP-SoPLEX integer program solver (Achterberg, 2009; Wunderling, 1996), yielding solutions in under a minute. Figure 3 shows the number of resources of each type (i.e. buses and ferries) required as a function of the desired evacuation time. The lines show how many resources on average are required per day. As expected, the average number of resources required per day decreases as the desired evacuation time increases. Such results can be used by planners to determine whether or not a plan may be feasible. For example, it would be unrealistic to think that all CEPs can be evacuated in 8 days if 10 buses and 4 ferries were available to execute a plan. On the other hand, the figure indicates that such number of resources may be enough to evacuate all CEPs in 14 days or more.

Another important aspect to consider is the site capacities, in particular, "do the sites reach maximum capacity during the evacuation process and for how long?" In practice, the key sites, mainly the ECs and the SHs, are surveyed to determine the maximum number of CEPs that can be held and serviced at one time. From a planning perspective, the objective is to develop an evacuation plan that would satisfy the capacity of the sites used during the evacuation. Furthermore, once the plan is set on the number of resources available and on the desired evacuation time, more in-depth analysis on the expected resource utilization can be performed. More details and additional examples of the types of analyses that can be performed with STONE(Opt) are presented in Caron & Kaluzny (2015).

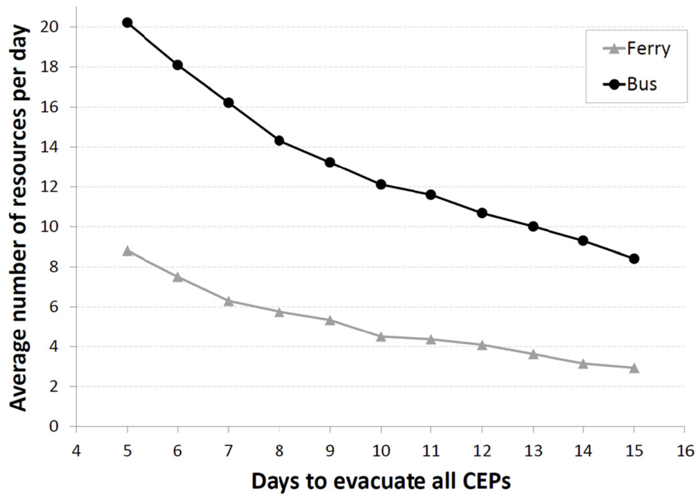

Figure 3: Number of resources required versus number of days to evacuate.

Conclusion

The mathematical model described herein is generic, capturing the general structure and elements of a NEO while maintaining the flexibility to represent the uniqueness of a specific NEO case. STONE(Opt) is deterministic and doesn't explicitly take into account variability of uncertain elements. As the arrival rates of CEPs to APs or ECs are a source of variability, the development of a discrete event simulation model to simulate NEO is a natural extension to optimization modelling.

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