Defence Research and Development Canada | Recherche et développement pour la défense Canada

DRDC | RDDC

Simulation Tool for Optimizing Non-Combatant Evacuation (STONE)

Optimization of evacuation time and transportation resource utilization

Jean-Denis Caron
Bohdan L. Kaluzny
Canadian Joint Operations Command OR&A Team
DRDC – Centre for Operational Research and Analysis

Defence Research and Development Canada

Scientific Report
DRDC-RDDC-2015-R074
May 2015

Canada

Simulation Tool for Optimizing Non-Combatant Evacuation (STONE)

Optimization of evacuation time and transportation resource utilization

Jean-Denis Caron
Bohdan L. Kaluzny
Canadian Joint Operations Command OR&A Team
DRDC – Centre for Operational Research and Analysis

Defence Research and Development Canada
Scientific Report
DRDC-RDDC-2015-R074
May 2015

Abstract

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 foreign nation where the safety of Canadians abroad is adversely affected. In the event of a rapidly deteriorating civil situation that may overwhelming local authorities, the Department of Foreign Affairs, Trade and Development (DFATD) may seek assistance from the Canadian Armed Forces (CAF) in order to conduct an evacuation of the Canadians from the affected nation.

In support of Canadian Joint Operational Command (CJOC) (and by extension DFATD and 1st Canadian Division Headquarters planners), the CJOC Operational Research and Analysis (OR&A) Team initiated the development of the Simulation Tool for Optimizing Non-Combatant Evacuation (STONE) analysis toolset to support NEO planning. This Scientific Report documents the STONE optimization component, STONE(Opt). STONE(Opt) can help to determine the best allocation and utilization of transportation resources and estimate evacuation time.

Significance for defence and security

The Government of Canada bears a fundamental responsibility for the safety and well-being of all Canadians. The DFATD assumes this responsibility for Canadians living abroad. Following the evacuation of approximately 13,000 Canadian or Eligible Persons (CEPs) from Lebanon in 2006, a Standing Senate Committee on Foreign Affairs and International Trade recommended that more frequent assessments of NEO plans be conducted, particularly for those areas with large Canadian resident populations and areas where the potential for destabilization is high, to ensure thorough contingency planning and logistical preparation for large-scale emergencies, and assessments of resources required for that mission.

This Scientific Report presents a mathematical optimization model that has the potential to enable better understanding of the feasibility and efficiency of logistic operations of a NEO, helping senior decision makers to better plan and execute a NEO. In particular, STONE(Opt) can be used to:

- determine the number of resources required versus desired evacuation time;
- estimate the number of evacuees at particular locations and time;
- assess the feasibility of evacuation timeline given sites' capacities;
- estimate resource utilization rates;
- determine the optimal allocation of transportation resources and their schedules; and
- estimate the evacuation rate of evacuees to safe havens.

Résumé

Une opération d'évacuation de non-combattants (OEN) consiste à déployer des forces sans ou avec très peu de préavis dans une région où la situation se détériore et où il existe une menace pour la sécurité ou la santé de Canadiens à l'étranger. Dans le cas où la situation se dégrade trop rapidement ne permettant pas aux autorités locales de répondre adéquatement aux besoins requis pour affronter la situation, le Ministère des affaires étrangères, du commerce et du développement (MAECD) peut demander l'aide des Forces armées canadiennes (FAC) pour mener une évacuation.

En soutien aux planificateurs du Commandement des opérations interarmées du Canada (COIC) et par le fait même à ceux du MAECD et du Quartier général de la 1re Division du Canada, l'équipe d'analyse et de recherche opérationnelle du COIC a développé des outils d'analyse pour aider à la préparation des OEN. Le présent rapport décrit un module d'optimisation faisant parti d'un outil nommé STONE (*Simulation Tool for Optimizing Non-Combatant Evacuation*). Ce module permet de déterminer la meilleure manière d'allouer et d'utiliser les ressources de transports lors d'une OEN et d'estimer le temps nécessaire pour compléter l'évacuation.

Importance pour la défense et la sécurité

Le gouvernement du Canada est responsable de la sécurité et du bien-être de tous les Canadiens. Le MAECD assume cette responsabilité pour les Canadiens qui se trouvent à l'étranger. À la suite de l'évacuation de quelque 13 000 Canadiens du Liban en 2006, un comité sénatorial permanent des Affaires étrangères et du commerce international a recommandé que des évaluations dans ses missions à l'étranger soient faites plus fréquemment, particulièrement celles qui sont situées dans une région à forte proportion de résidents Canadiens et celles où le risque de déstabilisation est élevé. Il pourrait ainsi actualiser l'évaluation des risques de la région et des risques pour les Canadiens, planifier minutieusement les mesures d'urgence et la logistique d'une situation d'urgence à grande échelle, ainsi qu'évaluer les ressources nécessaires à une telle mission.

Le travail décrit dans ce rapport permet en partie d'adresser cette recommandation. Plus spécifiquement, ce rapport présente un modèle d'optimisation mathématique qui permettra une meilleure compréhension de la faisabilité et de l'efficacité des opérations logistiques lors d'une évacuation de non-combattants, aidant ainsi les hauts fonctionnaires à mieux planifier et mettre en œuvre une OEN. Entre autre, le modèle peut répondre à des questions telles que :

- déterminer le nombre de ressources nécessaires pour une évacuation en un temps désiré ;
- estimer le nombre d'évacués à des endroits spécifiques en fonction du temps ;
- évaluer la faisabilité d'un plan d'évacuation en considérant le nombre de ressources disponibles ainsi que la capacité maximale des sites ;

- estimer les taux d’utilisation des ressources ;
- déterminer l’affectation optimale des ressources et de leurs horaires ; et
- estimer le taux d’arrivée des évacués à l’endroit de sécurité.

Acknowledgements

The authors would like to thank CJOC J5 NEO planners, particularly LCol Abboud, LCol McKinnon, LCdr Mullen, and LCdr McKay for insightful discussions during the development of STONE. The authors also acknowledge the guidance by DFATD: Carlos Munante (Director Policy, Partnerships and Governance); Stephane Allard (Deputy Director Emergency Planning); Beth Dyson (Policy Advisor and FCO Exchange Officer); Nicole Poulin (Policy Advisor Security and Emergency Management, Policy, Governance and Partnership Division); Brittany Blackstone (Emergency Planning Officer); and Stéphanie Bédard (Emergency Planning Officer).

Finally, the authors acknowledge the suggestions provided by the anonymous reviewer that improved the presentation of the report.

Table of contents

List of figures

List of tables

This page intentionally left blank.

1 Introduction

1.1 Background

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 (AN) that is threatening the safety of Canadians. NEO is defined by North Atlantic Treaty Organization (NATO) as an "operation conducted to relocate designated non-combatants threatened in a foreign country to a place of safety" [1].

Large scale NEO are extremely complex; often being conducted in a hostile environment, dealing with multiple uncertainties, and requiring whole of government expertise and coordination across multiple issues. Cooperation between friendly countries is very important but also adds to the complexity as every nation is evacuating their citizens from the conflict region while competing for the same support and resources (e.g. transporters, assembly points/evacuation centres). For example, the 2006 NEO in Lebanon exhibited the full spectrum of complexities where approximately 50 countries were evacuating their citizens from threatening circumstances to a safe location [2]. The Lebanon crisis is the largest-scale NEO in Canadian history where an estimated 13,000 Canadian or Eligible Persons (CEPs)[1] were evacuated during the operation [4].

The Government of Canada bears a fundamental responsibility for the safety and well being of all Canadians. The Department of Foreign Affairs, Trade and Development (DFATD) assumes this responsibility for Canadians living abroad. The largest Canadian populations abroad by country, rounded to the nearest thousand, are listed in Table 1. The data was compiled from various sources [5].

***Table 1:** The largest Canadian populations abroad by country.*

Country or Territory	Canadian citizens	Country or Territory	Canadian citizens
United States	1,063,000	Egypt	10,000
Hong Kong SAR	300,000	New Zealand	7,800
United Kingdom	73,000	Philippines	7,500
Lebanon	45,000	Haiti	6,000
Australia	27,000	Mexico	5,800
China (mainland)	20,000	Switzerland	5,000
South Korea	14,000	Singapore	5,000
Germany	13,000	Thailand	5,000
United Arab Emirates	12,000	Trinidad and Tobago	5,000
France	12,000	Belgium	4,000
Japan	11,000		

[1] CEPs are "Canadian citizens (civilian but also military personnel classified as non-combatant and non-essential), categories of persons holding legal status in Canada (ranging from landed immigrants to various visa holders) as specified by the Canadian Government, and designated third-country nationals and [host nation] persons as specified by the Canadian Government, deemed to be eligible applicants for evacuation" [3].

The DFATD leads and coordinates any NEO on behalf of the Government of Canada. In the event of rapidly deteriorating civil environment where there is high risk that the DFATD's mission (embassy, consulate, etc.) for the affected nation may be overwhelmed—i.e. when all other options for helping Canadians and eligible persons leave an affected zone have been exhausted—the DFATD may seek assistance from the Department of National Defence (DND) and the Canadian Armed Forces (CAF) to conduct an evacuation. Other departments and organizations including, but not limited to, the Canada Border Services Agency (CBSA), the Canadian Security Intelligence Service (CSIS), the Citizenship and Immigration Canada (CIC) and the Royal Canadian Mounted Police (RCMP) also support the DFATD as required.

Given its complex nature, strategic and comprehensive planning and preparation are key to a successful NEO. This was stressed in the final report produced by a Standing Senate Committee on Foreign Affairs and International Trade following the Lebanon evacuation in 2006 [6]. Recommendations 2 and 4 in the final report were as follows:

> **Recommendation 2:** *The Department of Foreign Affairs and International Trade should conduct more frequent assessments of its missions abroad, particularly those situated in areas with large Canadian resident populations and areas where the potential for destabilization is high, to ensure updated risk assessments of the region and the risks to Canadians, thorough contingency planning and logistical preparation for large-scale emergencies, and assessments of resources required for that mission.*
>
> **Recommendation 4:** *In undertaking large-scale evacuations like the case of Lebanon in 2006, the Department of National Defence and Canadian Forces should coordinate and lead the government's evacuation effort, particularly so that DND personnel can oversee the security and logistics of the operation and the movement of large numbers of Canadians.*

The DND Joint Doctrine Manual on NEO [3] formally defines NEO as a "military operation conducted to assist the DFATD in evacuating Canadians and selected non-Canadians from threatening circumstances in a foreign affected nation and moving them to a safe haven". When DND assistance is solicited, the CAF are typically requested to assist DFATD in the overall evacuation process, including planning and execution, and to provide appropriate security. The Canadian Joint Operational Command (CJOC) develops Contingency Plan (CONPLAN) ANGLE [7] and the 1st Canadian Division Headquarters (1st Cdn Div HQ), a suboordinate command to CJOC, has the task of preparing a country-specific Operational Plan (OPLAN).

In support of CJOC and 1st Cdn Div HQ planners, the CJOC Operational Research and Analysis (OR&A) Team initiated the development of an analysis toolset to support NEO planning within the CAF and by extension DFATD other Canadian organizations. The toolset is named Simulation Tool for Optimizing Non-Combatant Evacuation (STONE). This work is part of an overarching Assistant Deputy Minister Science and Technology (ADM(S&T)) project that delivers operational and strategic research and analysis support to CJOC.

1.2 Previous work

An examination of the literature within DND showed that NEO in Canada has been studied in the recent past mainly through reviews of policy, departmental doctrine and case studies – in particular with papers produced at the Canadian Armed Forces Staff College [8, 9]. It appears however that from an OR&A and Modelling and Simulation (M&S) perspective, this subject has not been studied within a Canadian context.

Scientific research on NEO has been undertaken in the United States. For instance, the Naval Postgraduate School developed an optimization model using integer linear programming to plan non-combatant evacuation [10, 11], an effort sponsored by the Center for Army Analysis (CAA). CAA claimed to provide analysis using the optimization model for planners in the Africa, Europe and Pacific regions in support of operational plan development, exercises and crisis planning [11]. The Naval Postgraduate School models, implementations, and documentation (beyond presentation slides) were not made available to the authors.

The Air Force Institute of Technology (AFIT) [12–14] and the CAA [11, 15] also proposed NEO models and analysis based on Discrete-Event Simulation (DES). DES has also been used by the CAA to evaluate various courses of action and support decision making in real crisis.

Within the Ministère de la Défense (France), the Centre de doctrine d'emploi des forces division simulation et recherche opérationelle (DSRO) planned the development of successive modelling and analysis to optimize the deployment and operation of NEO in support of the commandment de la force logistique terrestre. Initial modelling efforts were to focus on the flow of CEPs through evacuation centres [16]. It was anticipated that the tool developed would benefit planning requirements for lodging, food, and transportation out of the evacuation centres. The authors could not identify any follow-up to the proposed DSRO modelling plans.

In an effort to gain better insight into the modelling and analysis efforts of representative countries (including details of United States CAA and France's DSRO efforts to date), and recognizing the need for international cooperation, a NATO Science and Technology Organization (STO) Systems Analysis and Studies (SAS) technical activity [17] was initiated in 2015 to enable NATO, NATO Partnership for Peace, and NATO Global Partners countries to collaborate in OR&A support to NEO.

1.3 Objective

The objective of this research is to enhance the NEO planning capabilities of DFATD, CJOC, and 1st Cdn Div HQ planners. The report presents an optimization model built into a graphical interface that provides a better understanding of the feasibility and logistical complexities of NEO, with the ultimate goal of enabling senior decision makers to better plan and prepare NEO execution. The NEO modelling toolset, STONE, that is currently being developed by the CJOC OR&A Team comprises of three main components:

1. visualization – to provide situational awareness by quickly and automatically creating maps that show geographic site locations and the connectivity between them in the form of “map layers”;
2. optimization – a mathematical model to help determine best allocation and utilization of resources and estimate evacuation timeline; and
3. simulation – a discrete event simulation to model the operation which enables an analyst to perform “what-if” type analysis, characterize uncertainty, evaluate various courses of action, and estimate queue size and time spent by evacuees in the system and at specific locations.

The herein Scientific Report documents the elements of the mathematical optimization model (item 2). The optimization component of STONE is henceforth referred to as STONE(Opt). STONE(Opt) can be used to:

- determine the number of resources required versus desired evacuation time;
- estimate the number of evacuees at particular locations and time;
- assess the feasibility of evacuation timeline given sites’ capacities;
- estimate resource utilization rates;
- determine the optimal allocation of transportation resources and their schedules; and
- estimate the evacuation rate of evacuees to safe havens.

It is anticipated that STONE(Opt) has analogous concepts to the model developed by the United States CAA as both model the movement of CEPs through NEO sites and the allocation of transportation resources to accomplish the movement.

1.4 Outline of the report

The report is structured so as to provide NEO planners a high level of understanding of the potential capabilities of STONE. Details of the model implementation and development information, valuable to users and analysts, are deferred to appendices.

This Scientific report contains four more sections. Section 2 provides definitions, assumptions and describes the aspects of a NEO operation that are considered in STONE(Opt). The NEO optimization problem was mathematically modelled and is presented at a high level in Section 3. Section 4 presents, using a notional scenario, examples of questions that can be answered and types of analysis that can be conducted with STONE(Opt). Conclusions and proposed areas for future work are summarized in Section 5. Annex A presents the Graphical User Interface (GUI) developed for STONE(Opt). It facilitates input generation, model generation, optimization, and output processing. Annex B documents the mathematical formulation of STONE(Opt) and Annex C documents the software implementation of the mathematical formulation.

2 Evacuation process

This section provides a general overview of the NEO process and definitions considered in STONE(Opt) that will be presented later in Section 3. The process is mainly based on the information found in the Canadian Joint Doctrine Manual on NEO [3]. Doctrinal material from other nations such as the United States [18], the United Kingdom [19] and France [20] were also reviewed. Each nation uses different plans and terminology; however, the general structure and elements of a NEO are very similar.

Other key Canadian documents detailing NEO planning are also briefly discussed in this section. References to the 2006 Lebanon evacuation are used to illustrate the evacuation process and its various elements.

2.1 Typical evacuation chain

The NEO process considered in this Scientific Report is illustrated in Figure 1. The geography of the affected nation, the threat environment (permissive versus hostile) and the political context at the time of the crisis make every NEO unique. Although no two NEOs are the same, the generic elements of the evacuation chain are identical. They include: Assembly Points (APs), Evacuation Centres (ECs), Safe Havens (SHs) and Repatriation Sites (RSs). The four elements of the process are outlined in the paragraphs below.

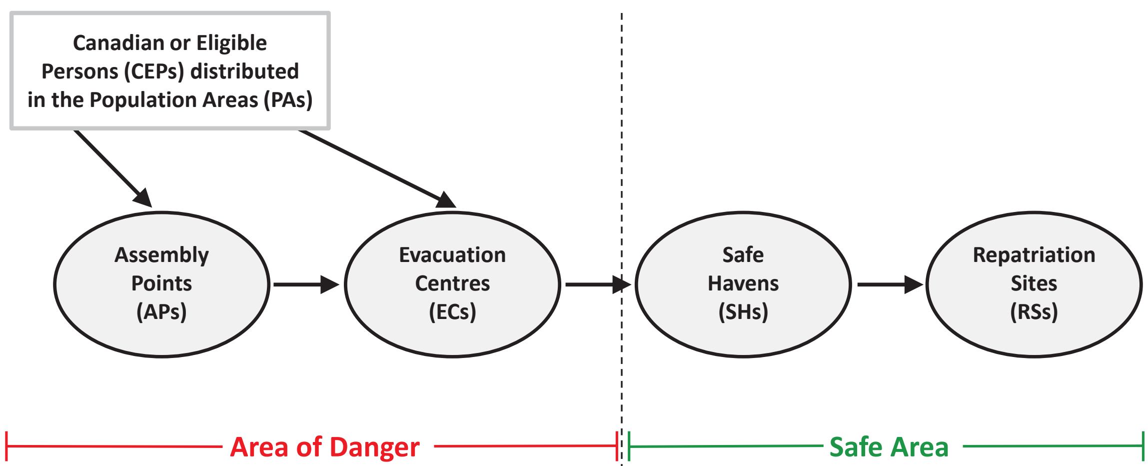


Figure 1: *Non-combatant evacuation process.*

Assembly points (APs): The APs, which are often schools, churches or hotels, are normally first in the evacuation chain. Typically, the CEPs make their own way to an AP—the one communicated to them by the mission. The APs are intended to serve as meeting points while the CEPs await transport to an EC. Typically the transfer of CEPs from an AP to an EC is done through CEPs' own transport and/or transport set up by the embassy. Of note, depending on their personal circumstances, CEPs may not report to an AP and instead proceed directly to an EC from their place of residence.

Evacuation centres (ECs): According to DND doctrine [3], an EC is "the main processing facility, where basic screenings are conducted (or completed) and detailed processing takes place. An EC must also act as an AP for evacuees proceeding directly to it from their place of residence." ECs are secure sites and are likely to be located at, or in the proximity of, an airport, a sea port or a land border. The screening and processing that occur at an EC is intended to admit to or eliminate from the evacuation chain each person wanting to leave the affected nation. Identities are confirmed, and security and medical checks[2] are performed. If eligible, the CEPs are then prioritized for transportation outside the affected nation. Once at an EC, the transport of CEPs is arranged by the Government of Canada, typically using sealift or airlift assets.

Safe havens (SHs): A SH is defined as "an area beyond the effects of the disturbance to which evacuees are removed and in which they are administered pending final disposition. It may be elsewhere in the host nation, in another country, on one of Her Majesty's Canadian Ships, or in Canada itself" [3]. At the SHs, CEPs are safe from threat and await onward movement to the RS or back to the affected nation once the disturbances have ceased.

Repatriation site (RS): For the purpose of this work, 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 Canada itself.

STONE(Opt) focuses on the movement of CEPs from APs to ECs to SHs and the related transporation resources required for that movement. STONE(Opt) does not model the processing of CEPs at a particular site, apart from factoring a fixed processing time.

2.2 Key NEO planning documents

The Joint Doctrine Manual on NEO [3] details CAF procedures and processes to support the evacuation of Canadians abroad. Two other key sets of publications on Canadian NEO planning are the following:

CAF Operational Level Plans: CONPLAN ANGLE [7] is maintained by CJOC and serves as a functional plan for NEO. It uses the Joint Doctrine Manual on NEO as a basis and expands to form a bridge between the strategic level and the tactical level plan [8]. The CONPLAN focusses mainly on command and control, force generation and how the forces would be deployed overseas to assist DFATD during the crisis. CJOC also maintains CONPLAN ANGLE Eastern Mediterranean (EM) which is more focussed, serving as an operational / geographic CONPLAN [21].

Mission Emergency Plan (MEP): The DFATD is responsible for developing and maintaining contingency plans, referred to as MEPs[3], that cover evacuation of non-combatants

[2] Medical checks are not a standard part of the process but it can be conducted when a CEP is visibiliy sick or if there is a known outbreak of a worrisome illness in the area.
[3] The MEPs were formally known as the Consular Emergency Contingency Plan (CECP).

in all nations.[4] These plans are “designed to provide guidance to missions to assist them in their response regarding the safety of Canadians before, during the lead up to, and during crises” [3]. The MEP is the foundation document in the event of an emergency necessitating an evacuation. It provides information and instructions, including, but not limited to:

- total number of CEPs and break down by area;
- evacuation chain data, with the locations (primary and alternate) of evacuation facilities (APs and ECs), routes (primary and alternate), and points of contact for facilities, contracts, etc.;
- 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;
- CEPs’ notification system[5]; and
- warden system.

The CAF, who are expertly trained in logistics, security and crisis planning, assist DFATD in the development of some MEPs—those pertaining to higher risk areas. The method through which they assist DFATD is called a Contingency Planning Assistance Team (CPAT). During a CPAT, a joint DND and DFATD team visits a specific region (usually visiting three missions in the region) in order to enhance existing evacuation plans. The team then reviews the relevance of the plans to determine where CAF support may be required, and to increase DND situational awareness of conditions and challenges in the area. At the onset of a crisis, the CAF may also send a strategic reconnaissance team (mainly 1st Cdn Div HQ personnel) to assist with the preparation of more detailed plan.

Most of the required inputs to STONE(Opt) are presented in the MEP. The results of STONE(Opt) can be used to influence MEP development (e.g. setting capacity requirements for evacuation facilities), or to help validate the contingency plans.

2.3 NEO elements in the 2006 evacuation in Lebanon

Table 2 shows the NEO elements of the 2006 evacuation in Lebanon. At the time, there was an estimated 50,000 Canadians living in or visiting the country. As discussed briefly above, during an evacuation, not all elements are necessarily used or activated. For the 2006 Lebanon operation, the plan had CEPs transit directly from home locations to the EC, eliminating the use of APs.

An EC was established at the Port of Beirut where the CEPs embarked on ships which sailed to one of the two safe havens – Lanarka, Cyprus and Adana, Turkey. According to

[4] These plans *cover* all nations, but there is not necessarily a plan dedicated for each individual nation. The MEPs are done by the missions—each mission is accredited to specific countries.

[5] The notification system is called the Registration of Canadians Abroad (ROCA) system. Through this system, Canadians whom are registered (voluntarily) in the system, are notified when the mission recommends an evacuation.

Table 2: *Sites used in the 2006 NEO in Lebanon.*

NEO elements	Locations
Assembly points	–
Evacuation centre	Port of Beirut, Lebanon
Safe havens	Lanarka, Cyprus Adana, Turkey
Repatriations sites	Montréal, Canada Toronto, Canada

Chaloux [8], ten ships were contracted by the Government of Canada for a total cost of $24.7 million (2006 Canadian dollars). The total capacities of all ships was 20,071 people. The observed occupancy rate was approximately 70%. From the SHs, the CEPs were repatriated to Canada using 13 aircraft contracted by the DFATD, which flew a total of 65 flights to Montréal and Toronto. For this part of the repatriation, the occupancy rate and cost were estimated to 78% and $35 million, respectively [8].

By the end of the operation, approximately 13,000 Canadians were evacuated from Lebanon via the Government of Canada's non-combatant evacuation operation [4] at a cost of approximately $2,700 per person.

STONE(Opt) aims to provide NEO planners a better understanding of the potential costs and timelines of a NEO before it occurs, as well as the ability to assess the cost efficiency of an evacuation after the operation is completed (i.e. assess the evacuation strategy post-mortem). Within the context of the Lebanon 2006 NEO, this may have entailed optimizing the schedule and number of contracted ships, for example.

While STONE(Opt) focuses on the movement of CEPs from APs to ECs to SHs (CEPs in areas of potential danger), it can also be customized to consider movement from SHs to RSs to minimize costs (e.g. minimize number of aircraft contracted)—however, this is outside the scope of the present Scientific Report.

Section 3 describes, at a readable level, how the various NEO elements are mathematically modeled. Followed-up by an example application in Section 4, the material provides insight as to how NEO planners can leverage STONE(Opt) to determine the best allocation and utilization of resources, and estimate an evacuation timeline.

3 Mathematical modelling

STONE(Opt) was developed to analyze the evacuation process described in Section 2. The NEO network is modelled where NEO sites (APs, ECs, SHs) represent nodes and the permissible routes of CEP movement between the sites are represented as directed arcs connecting the nodes. Transporters provide the movement of CEPs between NEO element sites. STONE(Opt) determines which transportation resources to assign to which arcs and at what time in order to move the CEPs from node to node (and finally to a SH node). Figure 6 enables visualization of the NEO network for an example.

STONE(Opt) is time-based: variables keep track of how many CEPs are at what state (at a site, on a transporter, etc.) at any given time. The user specifies a time period (e.g. two weeks) and time step granularity (e.g. six hours) and the NEO process is modelled one time step after another: variables model how many CEPs arrive where and when, how many are transported from site to site (and when), ultimately leading to a time step where all CEPs have been evacuated to a safe haven.

3.1 Optimization

STONE(Opt) is formulated to determine the required number and schedule for transporters in order to evacuate CEPs in an *optimal fashion*. What constitutes an optimal NEO is multi-faceted and often requires NEO planner subject matter expertise, but is simplified as the challenge of either:

- minimizing the duration of the NEO;
- minimizing the average time CEPs spend in the areas of danger;
- minimizing the use of transporters (both the number required and their number of trips); or
- a combination any of the above.

3.2 How the optimization model works

The NEO network model is formulated as an integer linear problem. An integer linear program is a mathematical optimization or feasiblity program in which a subset of the variables are restricted to be integers and the constraints are linear (i.e. no multiplication of variables). It is an extension of linear programming [22], which is the heart of operational research and whose theory was developed initially for military applications. The popularity of the approach is due to the ease of implementation, modelling flexibility, and availability of solvers. The approach caters to the inclusion of custom constraints and problem-specific features.

In STONE(Opt), mathematical decision variables are defined to model:

- the number of CEPs at a particular site at a particular time;
- the number of CEPs moving from one site to another via a transporter at a particular time;
- the number of transporters assigned to move CEPs from a site to another site at a particular time; and
- the number of trips performed by a transporter for a particular assigned route at a particular time.

A "trip" is the movement of a single transporter from one site to another (transporting CEPs). A single transporter can perform multiple trips over a time period (taking into account return travel to point of departure). It also may be that a transporter's trip spans multiple time periods. The time for a transporter to complete a trip from one site to the next is a function of its speed and the route's distance (rest stops, loading/unloading times are not explicitly modelled).

The assignment of transporters to routes represent the main decision variables. How many CEPs travel on any particular transporter is secondary. The relationships between the decision variables are encoded via mathematical formulae (constraints) and secondary variables. Given the required inputs, the mathematical model formulated is solved by an integer linear programming solver. The solver applies algorithms to determine a schedule for transporters to evacuate CEPs in an *optimal fashion*. A solution to a particular instance can either be a statement of infeasibility (e.g. cannot complete the operation in ten days without violating the capacity of a particular site), or the generation of an optimal schedule and estimate of completion time.

3.3 Input and assumptions

The mathematical model developed is generic, capturing the general structure and elements of a NEO while maintaining the flexibility to represent the uniqueness of a specific NEO case. Each NEO, modelled within STONE(Opt), is based on the following inputs, assumptions, and definitions:

- a length of (e.g. two weeks) and appropriate level of time granularity (e.g. one time step equals 12 hours). The time granularity should be selected to be insightful yet not to prescriptive (i.e. modelling down to single minutes). The selection of appropriate time granularity is key for solution fidelity and may affect solver running time;
- the list of the APs, ECs, and SHs, as defined in Section 2 and respective site capacities (number of CEPs);

- the expected CEP processing times[6], in time steps, at each EC (if relevant given the granularity specified);
- the total number of CEPs to be evacuated and the anticipated arrival rate of CEPs (number of CEPs per time period) to each AP and EC;
- the network specifying the possible movement of CEPs between sites (APs, ECs, SHs), specified by directed edges (routes) and distances between sites;
- a list of available transporters, specifying the quantity, speed (e.g. km/hr), capacity (number of CEPs), and which network routes each transporter can be employed on; and
- optional inputs include specifying transporter departure times along specific network routes, minimum or maximum utilization rates of transporters, or time periods when transportation is not permitted or times when sites are not capable of accepting further CEPs.

STONE(Opt) assumes that CEPs remain in the evacuation network once they enter (no attrition). If no further transporters are available from a site at a given time period, then CEPs remain at the site until the next available transporter can depart (potentially overnight).

3.4 Constraints

Constraints are primarily driven by context imposed requirements, site capacities, network routes, and the availability and capacity of transporters. Constraints can be selectively applied by the analyst as per the NEO scenario being modelled. Typically, constraints will include:

- all CEPs are to be evacuated to SHs by a user-specified end time (e.g. used in conjunction with optimizing transportation resource usage);
- the number of CEPs processed or accommodated at a site at a particular time period is constrained by the site's capacity (if specified);
- the number of CEPs departing from 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 be less than or equal to the limit on the total number of such transporters available.

[6] CEP processing time represents a delay between arrival and possible departure of a CEP at a site. If the time granularity is greater than the processing time (e.g. 12 hour time steps compared to a one hour processing time), then processing time is not modelled. However if the time granularity is smaller (e.g. one hour time steps and two hour processing times), then the processing time is modelled.

Optional constraints include fixing the number of trips for a transporter on a particular route and time, specifying time periods were specific sites can neither accept new CEP arrivals nor let CEPs depart, and specifying time periods when resources are unavailable.

Several other intuitive "model" constraints are also implemented to ensure the proper accounting of CEPs within the NEO network. For example, 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.

3.5 Usage and limitations

Section 4 provides and example application of the model which should provide the reader with greater understanding of the applications of STONE(Opt).

The selection of objective function (Section 3.1) represent the different usage modes of STONE(Opt). Furthermore, the analyst can elect to apply only a subset of the constraints, or to fix certain decision variables (e.g. require a specific transporter to make a trip at a particular time).

As CEP arrival rates to APs or ECs are a source of variability, one of the benefits of mathematical modelling is the ability to analyze the impact of changes to the arrival rates (e.g. constant, mad-rush, wait-and-see), both in terms of NEO completion time and resource requirements. This "what-if" type of analysis can indeed be performed using STONE(Opt) by creating separate model runs and analyzing the differing outputs. For example, the analyst can compare transportation asset usage across the separate runs. That being said, comprehensive examination of a particular solution subject to input variability is best accomplished via a discrete event simulation model.

STONE(Opt) is focused on the movement of people from assembly points onward to safe havens. STONE(Opt) does not explicitly model uncertainty estimates or "error bounds" associated with model parameters. STONE(Opt) does not significantly attempt to address or optimize resource usage and related procedural detail inside each NEO location (e.g. processing of CEPs at an EC).

Mathematical details of the formulation are presented in Annex B and are further elaborated in external literature [23]. The formulation was implemented in Zimpl [24]—the implementation of the formulation is available in Annex C. Solutions were found to realistic problem instances (e.g. examples of the magnitude of the 2006 Lebanon NEO, considering approximately 15 days with half-day time granularity) using the open-source SCIP-SoPLEX integer program solver [25, 26], yielding solutions in under a minute. The selection of time period length and time step granularity are the primary drivers of the problem size and by extension solution time.

3.6 Comparison to other models

Section 2 stated that a review of doctrine showed that the general structure and elements of a NEO are very similar among allied nations. It is anticipated that STONE(Opt) presented herein shares analogies with a model developed by the United States CAA [10, 11]. Similarities may include defining variables to keep track of: the location of CEPs; number of transporters; and network-flow constraints. STONE(Opt) enhancements include:

- the definition of trips to model travel time of transporters spanning multiple time periods, or use of a single transporter for multiple trips within a single time period. This enhancement empowers the analyst to select a suitable time granularity as the situation requires;
- enforcement of minimum/maximum use of transporters' capabilities. This enables specifying desired utilization rates;
- different usage modes to facilitate analysis (e.g. feasibility of a plan, optimization of transportation usage, optimization of NEO time, etc.); and
- development using readily available or open-source software (Microsoft Excel, Zimpl, SCIP-SoPLEX) enabling cost-free portability and code-sharing amongst partners.

4 Example application

In this section, we first explain how STONE(Opt) is typically run. We also present potential uses of STONE(Opt) using a notional scenario. The scenario is described in Section 4.2. The types of questions that can be answered and the kinds of analysis that can be conducted with the tool are presented in Section 4.3.

4.1 Using STONE(Opt)

To illustrate how STONE(Opt) is normally run, we consider its four main planning factors as shown in Figure 2: the CEPs' information, the sites, the transporters and the evacuation time.

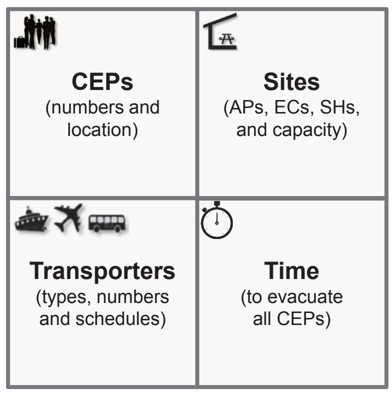


Figure 2: *Four main planning factors considered in the STONE.*

To run STONE(Opt), the following three steps are normally performed:

1. Specify
   - the data related to the sites considered in the evacuation chain, i.e. the list of APs, ECs and SHs, their respective capacities and their connections; and
   - the information about the CEPs, including their numbers and locations within the affected nation, and the sites to which they are expected to make their own way to.
2. Set one of the following
   - a desired total evacuation time (i.e. time to move all CEPs to safe haven) in order to determine how many transporters of each type are required and associated transport schedules; or
   - the types and numbers of transporters available to estimate the expected time required to conduct the evacuation.
3. Use Microsoft Excel macros or Matlab scripts for postprocessing analysis of the results produced by the tool to get a more comprehensive picture. For example, graphs and tables can be generate to answer questions such as:

- How many CEPs at specific locations as a function of time?
- How many trips are required at each site?
- What is the average utilization for each transporter? and
- How much time in the system do the CEPs spend?

The remainder of the section shows how STONE(Opt) and Steps 1 to 3 can be used to analyze a scenario.

4.2 Notional scenario description

4.2.1 Population areas and number of Canadian or eligible persons

We consider the country illustrated in Figure 3. The country is an island divided into 17 districts, referred to as Population Areas (PAs) and noted $PA_{01}, PA_{02}, \ldots, PA_{17}$. The total population of the island is approximately 5,000,000 people of which, 7,400 are CEPs.

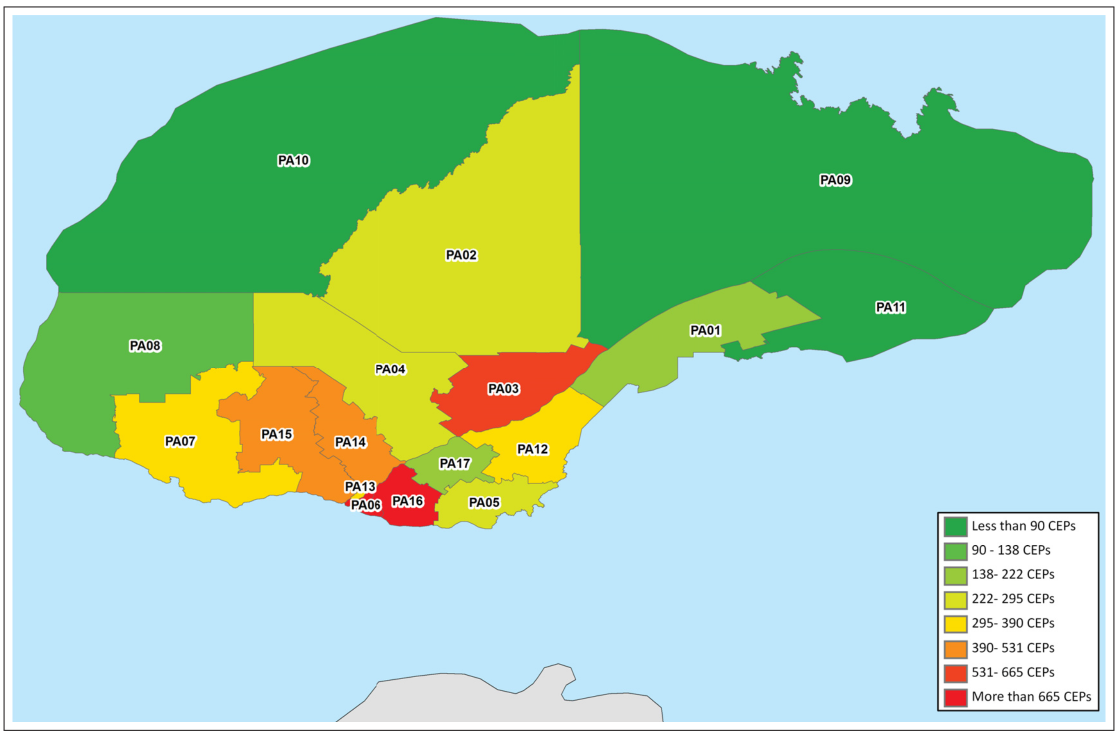


Figure 3: *Distribution of CEPs across the 17 PAs.*

Figure 3 also depicts the distribution of CEPs across the 17 PAs, where red represents the areas with the most CEPs and green represents the converse. The PAs with the most CEPs are PA_{06} and PA_{16} with 1,790 and 1,369 CEPs, respectively, while PA_{10} is the least populated with only 40 CEPs. The exact numbers of CEPs in each PA are included Figure A.3 of Annex A (Column E).

4.2.2 Assembly points, evacuation centres and safe havens

In total, there are 21 assembly points ($AP_{01}, AP_{02}, \ldots, AP_{21}$), two evacuations centres (EC_{01} and EC_{02}) and one safe haven (SH_{01}) considered in the example. The locations of the APs, the ECs and the SH are shown in Figure 4.

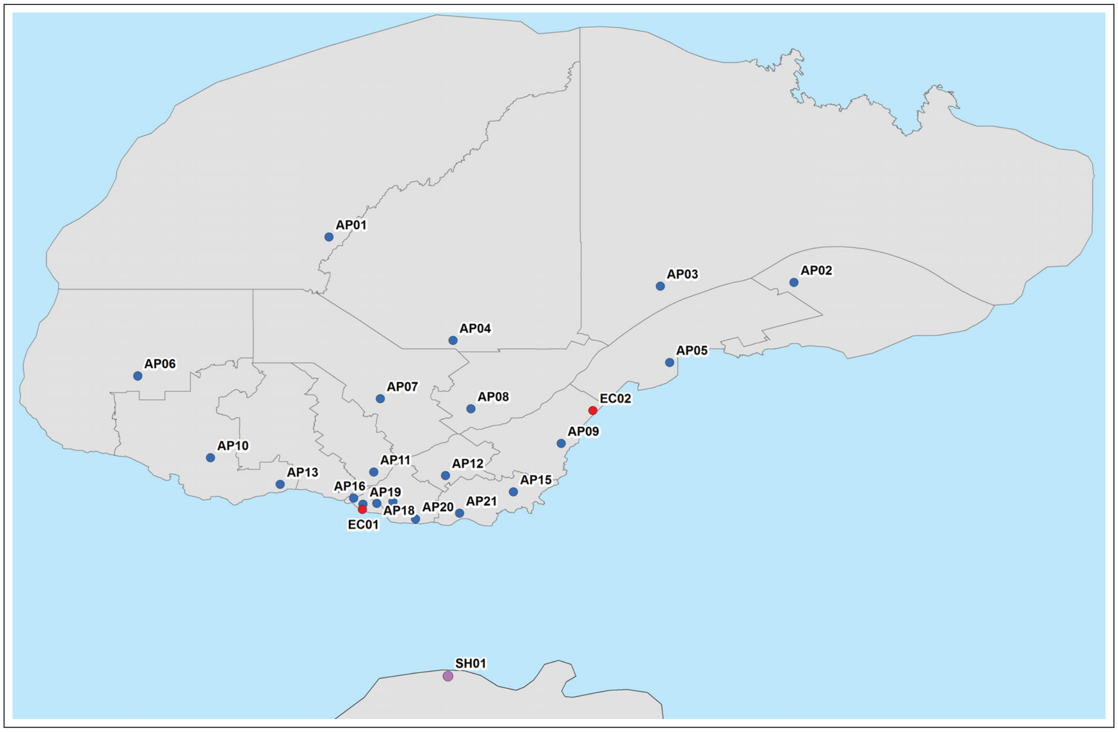


Figure 4: *Assembly points, evacuation centres and safe havens.*

The scenario assumes that CEPs leave their homes (located in the respective PAs) by their own means to get to an AP. Then, they are transported by ground to one of the two ECs. Finally, they are moved by sealift from the EC to SH_{01}.

The network of connections between the locations is represented in Figures 5 and 6. For example, AP_{13} receives CEPs coming from PA_{07} and PA_{15}. EC_{02} is used to process CEPs coming from $AP_{02}, AP_{03}, AP_{05}, AP_{08}, AP_{09}$, and AP_{15} while EC_{01} is used for all other APs.

In addition, the model handles CEPs who go directly to an EC (on their own) without going through an AP. This was not explicitly illustrated in Figure 5 to reduce the clutter (i.e. more connections between PAs and ECs). So, we also assumed that CEPs in $PA_{04}, PA_{06}, PA_{07}, PA_{08}, PA_{10}, PA_{13}, PA_{14}, PA_{15}, PA_{16}$ and PA_{17} will go to EC_{01}, those in $PA_{01}, PA_{03}, PA_{09}, PA_{11}$ and PA_{12} will go EC_{02}, while those in PA_{02} and PA_{05} will go to either one of the two ECs. For the purpose of the example, the percentage of CEPs going directly from a PA to an EC is estimated at 20%. As an example, it is expected that approximately 152 CEPs in PA_{01} (80% of 190 CEPs) would go to AP_{05} while the other 38 CEPs (20% of 190 CEPs) would get to EC_{02} on their own. This is shown in columns E to K in Figure A.3 (Annex A).

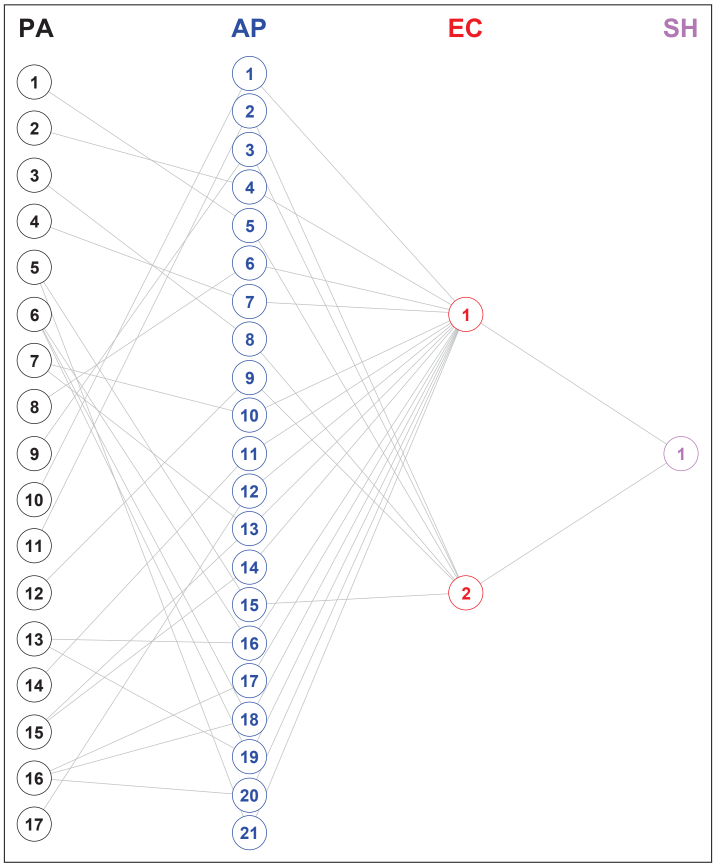


Figure 5: *Connections between PA, AP, EC, and SH sites.*

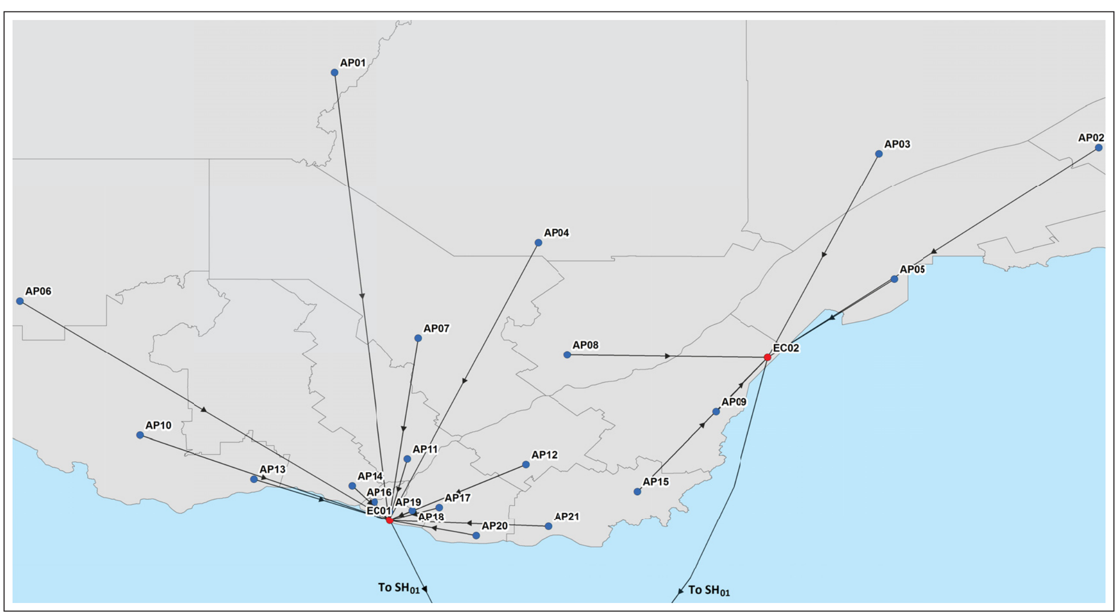


Figure 6: *Connections between AP, EC, and SH sites.*

4.2.3 Transport types

Two transport types, presented in Table 3, are considered in this example. For the ground transportation between the APs and the ECs, the scenario includes the use of buses with a maximum capacity of 40 CEPs. The movement of CEPs between the ECs and SH_{01} is done by ferries with a capacity of 200 CEPs. The minimum utilization is set to 0.66 for both transport types, meaning the all bus and ferry trips are required to fill up to a minimum of 27 and 132 CEPs, respectively, prior to departure[7]. Speeds of 75 km/h for the buses and 20 km/h for the ferries are assumed in the scenario. The speed values are used to calculate the maximum number of trips that the transport resources can accomplish within a time step.

Table 3: *Transport types considered in the example.*

ID	Name	Description	Number Available	Capacity	Speed (km/h)	Min/Max Utilization
TT_1	Bus	Between AP and EC	13	40	75	0.66 / 1.00
TT_2	Ferry	Between EC and SH	5	200	20	0.66 / 1.00

4.3 Potential uses

4.3.1 Number of transport resources required versus desired evacuation time

NEO planners are interested in estimating how many transport 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 transporters would be needed if one wants to achieve the evacuation in 5 days versus 10 days. But how many transport resources? Figure 7 shows the number of each transport type (i.e. bus in blue and ferry in red) required as a function of the desired evacuation time. To arrive at this figure, the number of days to evacuate CEPs was varied between 5 and 15 with an increment of 1, assuming the CEPs evacuate in an *orderly fashion*[8]. The lines show how many transport resources *on average* are required per day (the sum of transportation resources required per day divided by the number of days). For instance, the results indicate that in order to evacuate all CEPs in 8 days, an average of 14.3 buses and 5.8 ferry would be required every day. As expected, the average number of transporters required per day decreases as the desired evacuation time increases.

The numbers in Figure 7 represent averages, which means that using those exact numbers of transport resources would not be sufficient to evacuate all CEPs in the desired time—not providing enough transport capacity to meet the peaks and valleys (the number of CEPs who are moved every day is not necessarily constant as it may vary through time). However, such a figure can be used by planners to determine whether or not a plan is feasible in a best

[7] If the minimum utilization were set to zero, then some buses might go with only one CEP in.

[8] As discussed in Scheer [14], *orderly fashion* refers to a constant CEPs' departure rate (from their home). For instance, if a PA has a total 100 CEPs and the plan consists of an evacuation in ten days, then an average of 10 CEPs will leave their home every day for an AP or an EC. From a planning purpose, this corresponds to the ideal case.

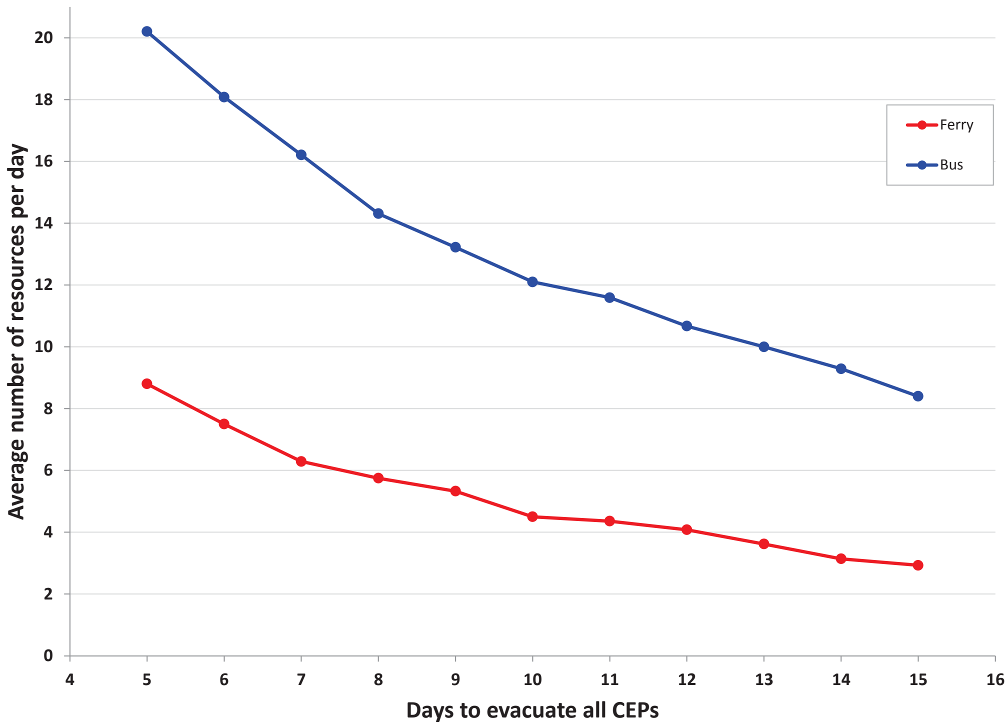


Figure 7: *Number of transport resources as a function of evacuation time.*

case scenario. For example, it would be unrealistic to think that all CEPs can be evacuated in 8 days if only 10 buses and 4 ferries were available to execute a plan. On the other hand, the figure indicates that this quantity of transport resources could provide evacuation of all CEPs, in a best case scenario, over a 14 day period, or longer.

4.3.2 Feasibility of evacuation timeline given specific number of transport resources and sites' capacity

Given an estimate of the number of transporters available, it is possible to use the tool to determine a realistic evacuation timeline. In the current example, we assumed that the plan includes 13 buses and 5 ferries (see Table 3). Figure 7 suggests that with 13 buses and 5 ferries available, the evacuation of all 7,400 CEPs should be possible in 10 days or more. STONE(Opt) was run to confirm that an evacuation is indeed achievable in 10 days.

The second important aspect to consider is the sites' capacity, 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. The capacity here refers to the maximum holding capacity in terms of people (i.e. CEPs) that each site can accommodate.

For illustration purpose, we focus on EC_{01} which is assumed to have a capacity of 375 CEPs. Figures 8a, 8b and 8c show the projected number of CEPs at EC_{01} as a function of time based on a desired evacuation time of 10, 11 and 12 days, respectively. The red lines represent the site capacity of 375 CEPs. The bars denotes the number of CEPs at the location at the end of each time period. In all three cases, we used an orderly (i.e. constant) arrival rate of CEPs over the first $n-2$ days, where n represents the desired evacuation time (10, 11 or 12 days).

Figure 8 suggests that planning to complete the evacuation in 12 days is preferable when accounting for the capacity. The results show that for an evacuation in 10 days, the capacity of EC_{01} would be exceeded approximately 40% of the time (8 time periods out of 20), i.e. on time periods "Day 2 – AM", "Day 3 – AM", "Day 3 – PM", "Day 4 – AM", "Day 5 – AM", "Day 7 – AM", "Day 7 – PM" and "Day 8 – PM". This includes a total of almost 600 CEPs at once on time period "Day 5 – AM", which is 160% of the capacity of the site. For an evacuation in 11 days, the capacity is exceeded approximately 18% of the time (4 time periods out of 22), with a maximum of more than 500 CEPs on time period "Day 9 – AM". On the other hand, Figure 8c indicates that for the evacuation in 12 days, the capacity is exceeded for a single time period (i.e. "Day 9 – PM") and only by 10 CEPs. It is however important to note that because the time step used here is relatively large (i.e. half-day), the estimate of whether the number of CEPs exceed the sites' capacity should be contextualized. The exact number of CEPs are estimated at the beginning and at the end of each time step, but the variation of CEPs in between these points in time remains unknown.

4.3.3 Transport resources utilization

Once the plan is set on the number of transporters available and on the desired evacuation time, more in-depth analysis on the utilization of transport resources can be performed. To illustrate this functionality, we consider an evacuation time of 12 days with 13 buses and 5 ferries. Table 4 shows the total number of trips and the average resource utilization forecasted with the notional scenario.

Table 4: *Projected total number of trips and utilization for both transport types.*

ID	Name	Number of trips	Utilization rate
TT_1	Bus	188	77.57%
TT_2	Ferry	46	79.91%

Table 4 provides overall summary but the data can also be broken down by individual day. The blue bars in Figures 9a and 9b show the projected number (Nbr) of buses and ferries required per day. The red dots in the figures represent the number of trips (or departures) forecasted. For instance, in the morning of Day 3, 11 of the 13 buses are required and the total number of trips is 9 (Figure 9a). For the same period, all 5 ferries are busy and there are only 2 ferry trips (Figure 9b). The number of resources required may exceed the number of trips because the time needed for a trip could be more than a time step. This is the case here where the ferry transit time (roundtrip) is more than a half-day, which is the time step used in this scenario.

4.3.4 Allocate transport resources and building schedule

The number of trips and number of transporters required on any given day can also be broken down by location. For example, Table 5 depicts the number of buses required per day at AP_{09}, AP_{18} and AP_{19} as computed with STONE(Opt). The distribution of ferries and associated trips are also included for both ECs. The numbers in parenthesis represent the number of trips departing the location.

Such information can be used to help planners building preliminary transport schedule. For instance, the table shows that one bus should be allocated to AP_{18} from Day 1 to Day 10. The bus would have to conduct two trips per day—one in the morning and one in the afternoon. On the other hand, AP_{09} would not need a full-time dedicated bus because only two trips are required at that location to move the CEPs to its associated EC.

For the ferries, STONE(Opt) results indicate that for most days, four ferries should be allocated to EC_{01}, i.e. from Day 2 to Day 8. On Day 9, one ferry at EC_{01} should move to EC_{02} to meet the higher demand expected on Days 9 to 11.

This is a relatively simple scenario with only two ECs and one SH. However, it illustrates how the output data from STONE(Opt) can be used to inform NEO planners on number of transport resources and trips, and therefore help building resource schedule that can be later implemented in a real-life scenario.

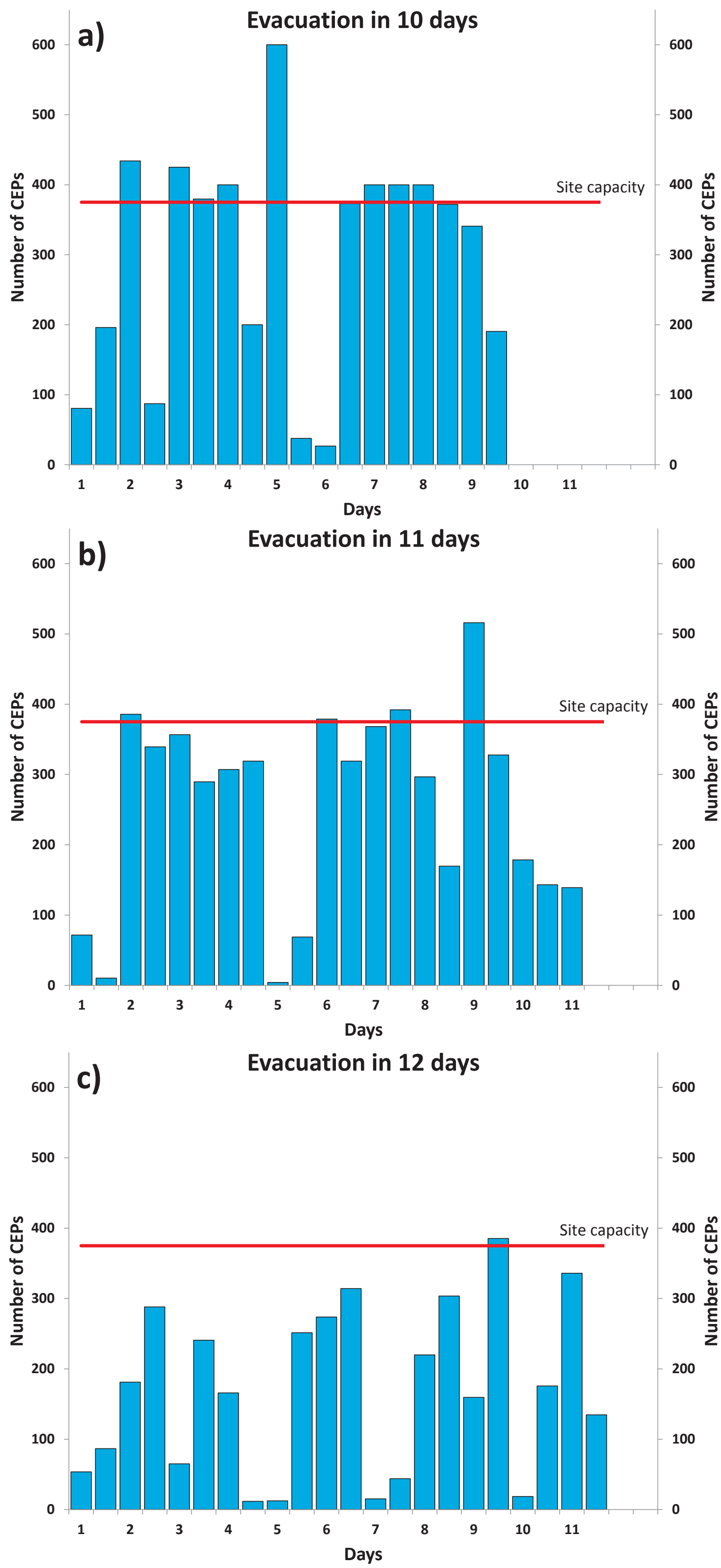
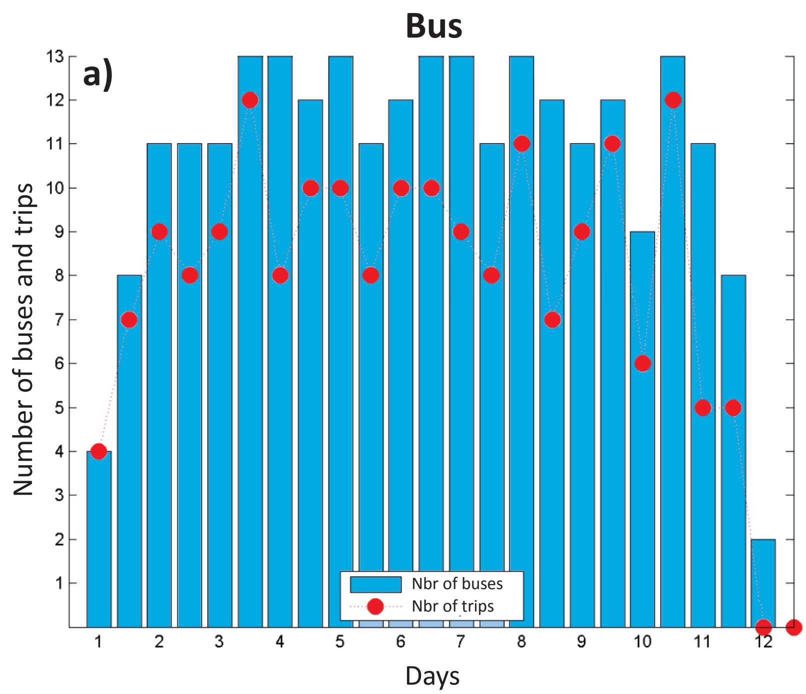


Figure 8: *Number of CEPs as a function of time at* EC_{01} *for: a) an evacuation in 10 days; b), an evacuation in 11 days; and c) an evacuation in 12 days.*



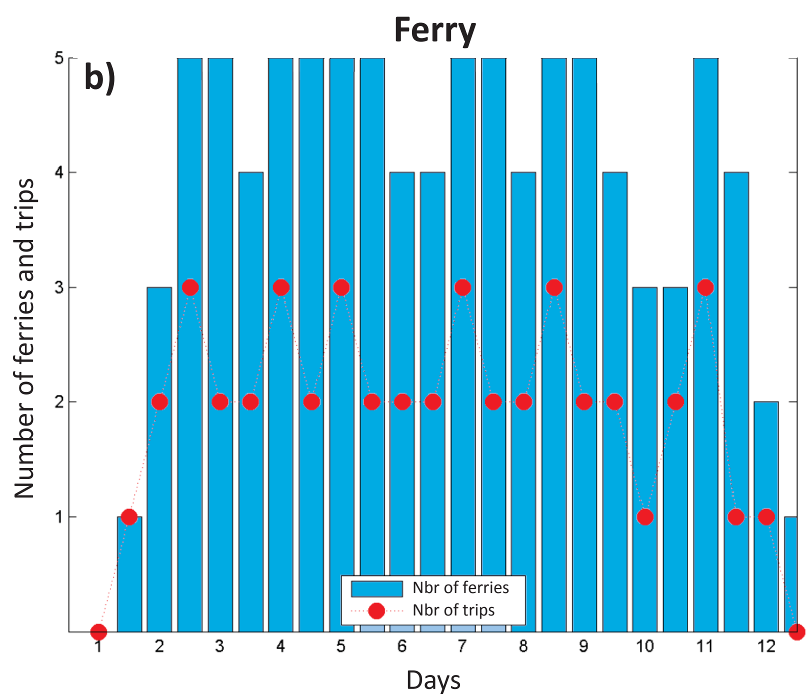


Figure 9: *Number of transport resources and trips projected per day for: a) buses (TT_1); and b) ferries (TT_2).*

Table 5: *Number of transport resources and trips (in parenthesis) required at specific locations.*

Day		Assembly points				Evacuation centres		
		AP_{09}	AP_{18}	AP_{19}	Total**	EC_{01}	EC_{02}	Total
1	AM	–	1 (1)	1 (1)	4 (4)	–	–	–
	PM	–	1 (1)	1 (1)	8 (7)	1 (1)	–	1 (1)
2	AM	–	1 (1)	1 (1)	11 (9)	3 (2)	–	3 (2)
	PM	–	1 (1)	1 (1)	11 (8)	4 (2)	1 (1)	5 (3)
3	AM	–	1 (1)	1 (1)	11 (9)	4 (2)	1 (0)	5 (2)
	PM	–	1 (1)	1 (1)	13 (12)	4 (2)	–	4 (2)
4	AM	–	1 (1)	1 (1)	13 (8)	4 (2)	1 (1)	5 (3)
	PM	–	1 (1)	1 (1)	12 (10)	4 (2)	1 (0)	5 (2)
5	AM	–	1 (1)	1 (1)	13 (10)	4 (2)	1 (1)	5 (3)
	PM	1 (1)	1 (1)	1 (1)	11 (8)	4 (2)	1 (0)	5 (2)
6	AM	–	1 (1)	1 (1)	12 (10)	3 (1)	1 (1)	4 (2)
	PM	–	1 (1)	1 (1)	13 (10)	3 (2)	1 (0)	4 (2)
7	AM	–	1 (1)	1 (1)	13 (9)	4 (2)	1 (1)	5 (3)
	PM	–	1 (1)	1 (1)	11 (8)	4 (2)	1 (0)	5 (2)
8	AM	–	1 (1)	1 (1)	13 (11)	4 (2)	–	4 (2)
	PM	–	1 (1)	–	12 (7)	4 (2)	1 (1)	5 (3)
9	AM	–	1 (1)	1 (2)	11 (9)	3 (1)	2 (1)	5 (2)
	PM	–	1 (1)	–	12 (11)	3 (2)	1 (0)	4 (2)
10	AM	–	1 (1)	1 (2)	9 (6)	3 (1)	–	3 (1)
	PM	1 (1)	1 (1)	–	13 (12)	2 (1)	1 (1)	3 (2)
11	AM	–	–	1 (1)	11 (5)	3 (2)	2 (1)	5 (3)
	PM	–	–	–	8 (5)	3 (1)	1 (0)	4 (1)
12	AM	–	–	–	2 (0)	2 (1)	–	2 (1)
	PM	–	–	–	–	1 (0)	–	1 (0)
				Total:	13 (188)		**Total**:	5 (46)

**Note that this total is calculated across all APs and not just AP_{09}, AP_{18} and AP_{19}.

4.3.5 Movement of CEPs from safe heavens to repatriation sites

The CEP evacuation process modeled in this Scientific Report begins at the population area and ends at the safe havens. In general, the objective of the model is to move all CEPs to the safe havens in the minimum amount of time and within the transport resources available. The movement of the CEPs to the final destination, i.e. a repatriation site, is not explicitly considered. In some scenarios, the safe havens may be the same as the repatriation sites, but this is rarely the case. For instance, in 2006 during Op LION, more than 13,000 CEPs were evacuated from Lebanon by sea to two safe haven locations (in Turkey and Cyprus) before being repatriated to Canada (Montréal and Toronto) by airlift [6].

Even if the repatriation sites are not directly accounted for in this current version model, number of assets required to repatriate the CEPs can be estimated by doing post-analysis of output data generated by the tool. In particular, the model outputs include the number of CEPs arriving at the safe havens as a function of time. Table 6 shows how many CEPs arrive every day at the safe haven for the scenario considering 13 buses and 5 ferries, and an evacuation in 12 days.

Table 6: *Number of CEPs arriving at safe haven as a function of time.*

Day	AM	PM	Total
1	0	0	0
2	200	483	683
3	446	299	745
4	351	482	833
5	274	456	730
6	340	335	675
7	380	407	787
8	319	270	589
9	515	332	847
10	349	200	549
11	348	524	872
12	146	145	291

For illustration purpose, we assume here that the CEPs are moved to the repatriation site by airlift. The numbers in Table 6 can be used to estimate the entire evacuation timeline given a certain flight schedule from SH_{01} to Canada. Consider the notional schedule shown in Table 7, which consists of four flights a day (two in the morning and two in the afternoon), every other day, starting on Day 3 and ending on Day 13.

Figure 10 shows the number of CEPs in the danger zone (red line) and at repatriation site (green line) as a function of time. We assumed that each scheduled flight can carry up to 400 CEPs. CEPs in the danger zone refers to the total CEPs who are either still at their home (but planning to evacuate), at an AP or at an EC. This can be estimated using Table 6. The green line shows that given the schedule provided in Table 7, the last CEPs repatriated to Canada occurs on Day 13. The schedule includes 24 flights, for a total capacity of 9,600

Table 7: *Notional flight schedule from SH_{01} to repatriation site.*

Day	Number of departures AM	PM
3	2	2
5	2	2
7	2	2
...	...	...
13	2	2

CEPs. Considering that all 7,401 CEPs are repatriated, this corresponds to a utilization rate of approximately 77%. This example uses a notional schedule to demonstrate how output from the model can be used to analysis the repatriation process. Many different schedules can be tested. Additionally, similar to the way that the movement of CEPs between PAs and APs, and between APs and ECs is optimized, it would be possible to optimize the CEPs repatriation, i.e. the movement of CEPs from the SHs to the repatriation site.

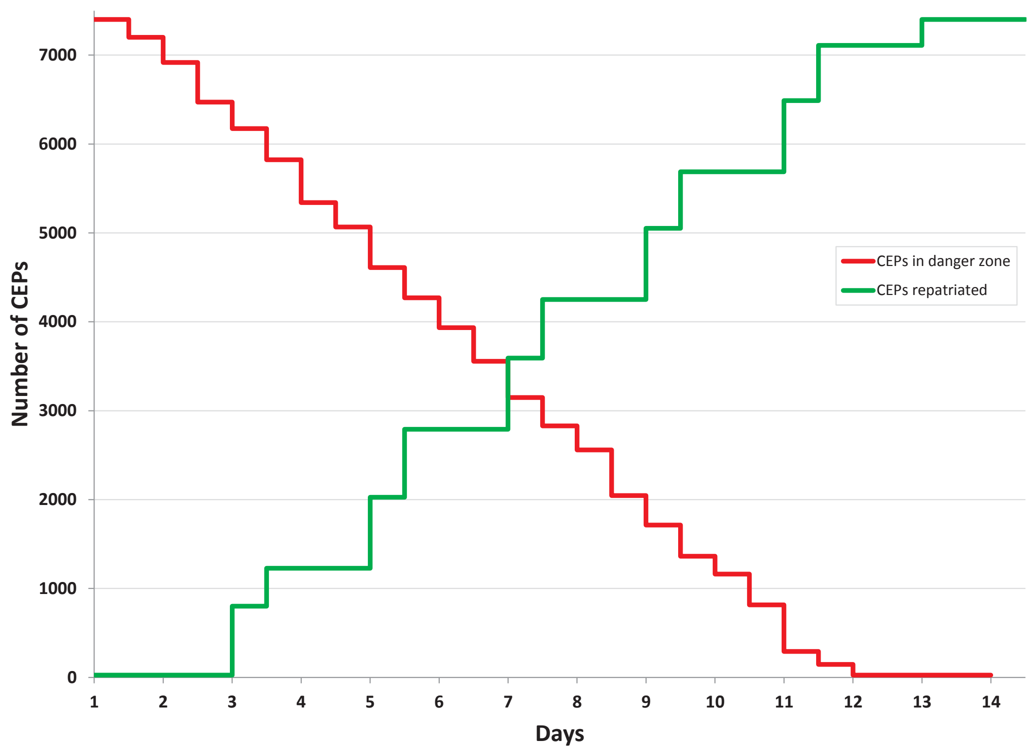


Figure 10: *Number of CEPs in danger area and at repatriation site as a function of time.*

4.4 Discussion

The analyses discussed in this section are not exhaustive but provide a representative sample of the types of questions that can be answered using STONE(Opt) in support of high level NEO planning efforts.

It should be noted that there are many other questions that STONE(Opt) presented herein cannot answer. For example, “what is the queue size a specific location?”, “how much time each CEPs spend in the system?”, or “how long does the CEPs spend in the whole system or a specific location?” These types of questions require modelling at a lower level of granularity.

Hence, the natural extension to optimization modelling is the development of a DES to simulate the operation allowing to perform “what-if” type analysis, model uncertainty, evaluate various courses of action, and estimate queue size and time spent by evacuees in the system and at specific locations. Many of these aspects are incorporated in the other elements of the STONE as explained in Section 1.3.

5 Summary and future work

The NEO modelling toolset called STONE that is being developed by the CJOC OR&A Team comprises of three main components:

1. Visualization – to provide situational awareness by quickly and automatically creating maps showing the sites locations and the connectivity between them in the form of map layers;
2. Optimization – a mathematical model (STONE(Opt)) to help determine best allocation and utilization of resources and estimate evacuation timeline; and
3. Simulation – a discrete event simulation (DES) to simulate the operation allowing to perform "what-if" type analysis, model uncertainty, evaluate various courses of action, and estimate queue size and time spent by evacuees in the system and at specific locations.

This Scientific Report documents the elements of the mathematical optimization model named STONE(Opt) and presents, using a notional scenario, examples of questions that can be answered and types of analysis that can be conducted with the model.

The development of a DES to simulate NEO is a natural extension to the optimization model presented in this document. This work is planned as part of the Operational and Strategic Research and Analysis Support to CJOC project of the ADM(S&T) Force Employment portfolio.

In November 2014 the CJOC OR&A Team, accompanied by CJOC J5 NEO, presented STONE to the Director Policy, Partnerships and Governance, and the Deputy Director of Emergency Planning, DFATD. Action items identified include:

1. application of STONE on high-risk missions identified by DFATD; and
2. development of STONE(DES) to model ECs is greater detail (with sub-processes) in order to facilitate answering questions such as "how many personnel are required to process CEPs in a given time period?"

5.1 International collaboration

Cooperation between friendly countries is very important but also adds to the complexity as each nation attempts to evacuate their citizens but while competing for the same support and resources (e.g. transporters, assembly points/evacuation centres).

In 2014 a NATO STO SAS technical activity was initiated by Defence Research & Development Canada (DRDC) Centre for Operational Research and Analysis (CORA) [17] to enable NATO, NATO Partnership for Peace, and NATO Global Partners countries to collaborate in OR&A support to NEO. The purpose of this activity is to develop and maintain a cohesive OR&A community to support the planning of the NEO Coordination

Group (NCG). The NCG consists of military planners and foreign affairs representatives of nineteen member nations, fourteen of which are NATO or Partnership for Peace (PfP) members (Austria, Belgium, Canada, Denmark, France, Germany, Italy, Norway, Portugal, Spain, Sweden, The Netherlands, United Kingdom, United States of America) and two NATO Global Partners (Australia, New Zealand). Switzerland, Cyprus, and the European Union (European External Action Service) are the other NCG participants not affiliated with NATO. The NCG meets twice annually to coordinate NEO planning efforts and share best practice. The main objective of the scientific collaboration is to support and complement the NCG efforts. Collaboration areas to be explored include:

- tools, models, analyses undertaken by OR&A teams supporting military planners in the planning of NEOs; and
- establishment of a network of operational analysts supporting military planners in planning of NEOs facilitating data sharing, promoting cohesion in analysis and increase situational awareness of resource constraints and problem commonalities.

The efforts of this SAS activity is expected to influence the development and applications of STONE.

This page intentionally left blank.

References

[1] North Atlantic Treaty Organization Standardization Agency (2013), Allied Administrative Publication-06, NATO Glossary of Terms and Definitions.

[2] WorldReach Market Research Series (2007), Lebanon Evacuation Summary (online), http://www.worldreach.com/Resource%20Document/worldreach_market_research_series_lebanon_evacuation_summary3.pdf (Accessed: 15 September 2014).

[3] Department of National Defence (2003), Joint Doctrine Manual on Non-Combatant Evacuation Operations, B-GJ-005-307/FP-050.

[4] CBC News (2006), Evacuation Timeline: The Biggest Rescue in Canadian History (online), www.cbc.ca/news2/background/middleeast-crisis/evac_timeline.html (Accessed: 15 September 2014).

[5] Asia Pacific Foundation of Canada (2011), Canadians Abroad: Canada's Global Asset (online), www.asiapacific.ca/sites/default/files/canadians_abroad_final.pdf (Accessed: 29 September 2014).

[6] The Standing Senate Committee on Foreign Affairs and International Trade (2007), The Evacuation of Canadians from Lebanon in July 2006: Implications for the Government of Canada (online), www.parl.gc.ca/content/sen/committee/391/fore/rep/rep12may07-e.pdf (Accessed: 15 September 2014).

[7] Lessard, LGen J.G.M. (2011), CEFCOM Contingency Plan (CONPLAN) ANGLE – 20852/11 Canadian Forces Assistance to Non-Combatant Evacuation Operations.

[8] Chaloux, LCol R. (2007), Canadian Non-Combatant Evacuation Operations – A Better Way, Canadian Forces College, JCSP 33.

[9] Eyre, Maj R. (2011), Complexities in Non-Combatant Evacuation Operations, Master of Defence Studies, Canadian Forces College, JCSP 37.

[10] Dell, R. and Sparling, S. (2008), Optimal Distribution of Resources for Non-Combatant Evacuation, 76th Military Operations Research Society Symposium, New London, Connecticut.

[11] Murphy, P. (2012), Noncombatant Evacuation Operations: Analysis and Modeling Methods, Center for Army Analysis, 17th US/Canada OR Symposium, Ottawa, Canada.

[12] Gregg, Maj A.N. (USAF) (2010), Optimizing Crisis Action Planning in the Noncombatant Evacuation Operation Setting, Graduate Research Paper, AFIT/IOA/ENS/10-02, Department of Operational Sciences, Air Force Institute of Technology.

[13] Olsen, Maj C.M. (USAF) (2007), Simulation Study of Evacuation Control Center Operations Analysis, Graduate Research Paper, AFIT/IOA/ENS/11-04, Department of Operational Sciences, Air Force Institute of Technology.

[14] Scheer, Maj M.A. (USAF) (2011), Noncombatant Evacuation Operations in USEUCOM, Graduate Research Paper, AFIT/IOA/ENS/11-05, Department of Operational Sciences, Air Force Institute of Technology.

[15] Kuchel, D. (2013), Analyzing Noncombatant Evacuation Operations Using Discrete Event Simulation, Center for Army Analysis, Proceedings of the 2013 Winter Simulation Conference.

[16] Bougeret, LCol P. (2009), La recherche opérationnelle au service de l'évacuation de ressortissants, *Doctrine—Revue détudes générales*, 16, 69–71.

[17] Caron, J. D. and Kaluzny, B. (2014), Exploratory Team on Operational Research and Analysis supporting Non-Combatant Evacuation Operations, NATO STO SAS Technical Activity Proposal, NATO STO SAS Fall 2014 Panel Business Meeting PDT, Czech Republic, 22–24 October 2014.

[18] Department of Defense (2010), Noncombatant Evacuation Operations, Joint Publication 3–68.

[19] Ministry of Defence (2013), Non-combatant Evacuation Operations, Joint Doctrine Publication 3–51 (JDP 3-51) (2^{nd} Edition).

[20] Ministère de la défense, Armée de Terre (2009), Doctrine Revue d'Études Générales – Les Opérations d'Évacuation de Ressortissants (online), `www.cdef.terre.defense.gouv.fr/content/download/3306/51025/file/Doctrine16fr.pdf` (Accessed: 20 October 2014).

[21] Canadian Joint Operations Command (2014), United in Purpose (online), `http://cjoc-coic.mil.ca/sites/intranet-eng.aspx?page=16409` (Accessed: 12 November 2014).

[22] Dantzig, G. (1998), Linear Programming and Extensions, 11th ed, New Jersey, U.S.: Princeton University Press.

[23] Kaluzny, B. and Caron, J. D. (2015), Optimization of Evacuation Time and Resource Utilization for Non-Combatant Evacuation Operations, *submitted to* Lecture Notes in Management Science (2015) vol. 7, Proceedings of the 7th International Conference on Applied Operational Research (ICAOR'15).

[24] Koch, T. (2004), Rapid Mathematical Programming, Ph.D. thesis, Technische Universität Berlin. ZIB-Report 04–58.

[25] Achterberg, T. (2009), SCIP: Solving constraint integer programs, *Mathematical Programming Computation*, 1(1), 1–41. `http://mpc.zib.de/index.php/MPC/article/view/4` (Accessed: 4 April 2014).

[26] Wunderling, R. (1996), Paralleler und objektorientierter Simplex-Algorithmus, Ph.D. thesis, Technische Universität Berlin. `http://www.zib.de/Publications/abstracts/TR-96-09/` (Accessed: 4 April 2014).

Annex A: Instructions and graphical user interface for STONE(Opt)

This annex presents technical data related to STONE optimization component, referred to as the STONE(Opt), including the setup instructions, the directories and files structure, the main requirement needed to run the tool, and an overview of the GUI functionalities.

A.1 Setup instructions and requirements

There are no specific installation instructions required since STONE(Opt) is a self-contained package. All that is required is the use of the directories and files structure presented in Figure A.1. Note that all the files needed to run STONE(Opt) are available from the authors.

```
InputData.xlsm
Templates <DIRECTORY>
     NEO_Opt_Formulation.zpl          ScipCommands.dat
     ProcessScipBatch.bat             scip302.exe
DataFiles <DIRECTORY>
     Arrival.dat                      SafeHavens.dat
     AssemblyPoints.dat               SiteCapacities.dat
     Blackout.dat                     TimeInterval.dat
     EvacuationCentres.dat            TransportArcs.dat
     FixedTimeTransportArcs.dat       TransportersType.dat
```

Figure A.1: *Directories and files structure.*

The file `InputData.xlsm` is the GUI, developed in Microsoft Excel and Visual Basic for Applications. It is detailed in Section A.2.

The directory `Templates` includes the four files required to run the SCIP-SoPLEX integer program solver. The file `NEO_Opt_Formulation.zpl` contains the mathematical formulation and is included for completeness in Annex C. The file `ScipCommands.dat` is a parameter file read by the SCIP-SoPLEX solver. The file specifies which formulation file to read (`NEO_Opt_Formulation.zpl`), the solver time limit in seconds, and where to write the solution output (`ScipOutput.dat`). The formulation file reads in a series of ten ".dat" files specifying instant-specific inputs and optimization parameters. The ".dat" files represent the user-specified problem to be solved. Although the user has the option to create the ".dat" files manually, they are typically auto-generated by the GUI (the Microsoft Excel file) based on input parameters provided by the user (details in Section A.2). Once generated, they are automatically put in the directory `Datafiles`. The format of the ".dat" files is discussed later in the annex.

The file `ProcessScipBatch.bat` is a Windows batch file that invokes SCIP-SoPLEX solver[9] with parameter file `ScipCommands.dat` and then parses the solution file (`ScipOutput.dat`) via the Windows powershell scripting language. Details of the parsing process are provided in Section A.4.

A.2 Graphical user interface

As mentioned previously, the ".dat" files required by the SCIP-SoPLEX integer program solver can be created manually by the user. However, this process is prone to errors due to the number of variables and constraints that a typical problem contains. To ease this process, a GUI has been built in Microsoft Excel to capture the inputs from the user. Input data is then automatically converted in the ".dat" files in the appropriate format. The GUI contains the following eight worksheets:

- `SimulationInformation`;
- `PopulationAreas`;
- `AssemblyPoints`;
- `EvacuationCentres`;
- `SafeHavens`;
- `DistMatrix`;
- `TransportTypes`; and
- `FixedTransport`.

Each of them is described below.

A.2.1 Worksheet `SimulationInformation`

The worksheet `SimulationInformation` is shown in Figure A.2.

The green-shaded cells in the tool (e.g. cells E2, E3, F3, E4, E5, E6 and F6 in Figure A.2) represent parameters that must be specified by the user. The six parameters that must be entered in this worksheet are described in Table A.1.

[9] The executable `scip302.exe` can be obtained from `http://scip.zib.de/`.

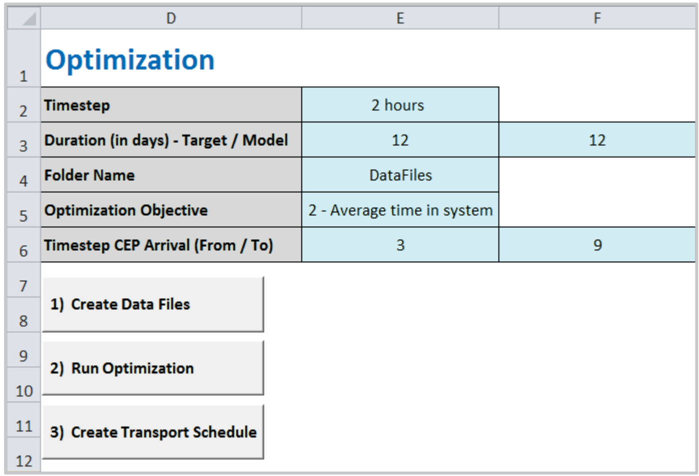


Figure A.2: *Graphical user interface – main worksheet.*

The worksheet also includes the following action buttons:

- **Create Data Files** – as its name suggests, this button is used to auto-generate the ten ".dat" files. If clicked, the application reads the input data entered by the user in the different worksheets, converts the data in the ".dat" files, and saves them in the directory "DataFiles" (or whatever directory name given by the user in cell E4).

- **Run Optimization** – once the ".dat" files have been generated, either automatically using the "Create Data Files" button or manually by the user, the SCIP-SoPLEX integer program solver can be called by clicking the "Run Optimization" button. This process may take some time as the problems to solve can be quite large. The optimization process will terminate if either a) the solver finds the optimal solution, or b) a time limit is reached. In the latter case, the best solution found is returned. The time limit is set by default to 300 seconds, but it can be changed in the file `ScipCommands.dat`. The solver can also be launched manually outside the GUI by clicking on the file `ProcessScipBatch.bat` (in Windows Explorer). However, for this to work, the four files in the directory `Templates` must first be copied in the directory `DataFiles` with the ten ".dat" files.

- **Create Transport Schedule** – it allows the user to view partial results produced by STONE(Opt). Once the button is pressed, a worksheet named `OptTransport` is populated showing the expected number of assets and the number of trips required (by individual resource type, e.g. ferry) at each time step extracted from the solution found. The "Create Transport Schedule" button is typically used as a means for debugging and validation as it provides a quick overview at a glance of the number of transportation resources required. We recommend to develop more sophisticated postprocessing analysis scripts to get a more comprehensive picture of the results calculated by STONE(Opt). This is discussed further in Section A.4.

Table A.1: *Input parameters in worksheet* `SimulationInformation`*.*

	Cell	Description
Time step	E2	The level of time granularity. Possible values from a dropdown list are "24 hours, ", "12 hours", "8 hours", "6 hours", "4 hours", "3 hours" and "2 hours".
Duration – Target	E3	Target length of NEO (in days).
Duration – Model	F3	Total number of days to be modelled.
Folder Name	E4	Name of the directory containing the ".dat" files. The recommended value is "Datafiles".
Optimization Objective	E5	The desired optimization type picked from a dropdown list with the following potential values: 1 - Minimum number of days 2 - Average time in system 3 - Minimize capacity flow 4 - Minimize transport usage 5 - Total number or trips.
Time step CEP Arrival (From)**	E6	First time step in a day when CEPs are expected to arrive.
Time step CEP Arrival (To)**	F6	Last time step in a day when CEPs are expected to arrive.

**For example, if the time step is "2 hours", and the time step CEP arrival from and to values are 3 and 9, respectively, then it means that in the particular scenario, the CEPs are expected to arrive at the APs and ECs between 0600 and 1800 every day (i.e. at time steps 3, 4, 5, 6, 7, 8, 9 (Day 1), at time steps 15, 16, 17, 18, 19, 20, 21 (Day 2), etc.

A.2.2 Worksheet `PopulationAreas`

Figure A.3 shows the worksheet used to specify information about the location and the number of the CEPs. Depending on the affected nation, the Population Areas (PAs) could correspond to provinces, regions, districts, counties or any subdivisions relevant to the area. The blue-shaded cells represent values that are auto-generated by the GUI and should not be modified by the user.

Each row is associated with one PA and must contain the information shown in Table A.2. For the example in Figure A.3, the estimated 261 CEPs located in PA_{02} are expected to go by their own means to either AP_{04}, EC_{01} or EC_{02} in a proportion of 80%, 10% and 10%, respectively. They are expected to leave at a rate of 10% per day, for 10 days (as specified in cells P4:Y4).

nPAs = 17 (max is 50) Version = (change if input data is changed) 3

ID	Name	Lat	Lon	Population	AP Connections	AP Percentage	AP Sum	EC Connections	EC Percentage	EC Sum
1	PA01	48.6	-67.7	190	[5]	[0.80]	80.0%	[2]	[0.20]	20.0%
2	PA02	49.1	-72.2	261	[4]	[0.80]	80.0%	[1,2]	[0.10,0.10]	20.0%
3	PA03	47.6	-71.4	665	[8]	[0.80]	80.0%	[2]	[0.20]	20.0%
4	PA04	47.9	-73.8	250	[7]	[0.80]	80.0%	[1]	[0.20]	20.0%
5	PA05	45.5	-71.5	295	[15,21]	[0.40,0.40]	80.0%	[1,2]	[0.10,0.10]	20.0%
6	PA06	45.5	-73.7	1790	[16,18,19]	[0.25,0.25,0.25]	75.0%	[1]	[0.25]	25.0%
7	PA07	46.9	-76.5	350	[10,13]	[0.40,0.40]	80.0%	[1]	[0.20]	20.0%
8	PA08	47.9	-77.8	350	[6]	[0.80]	80.0%	[1]	[0.20]	20.0%
9	PA09	50.2	-66.2	138	[3]	[0.80]	80.0%	[2]	[0.20]	20.0%
10	PA10	49.7	-75.9	90	[1]	[0.80]	80.0%	[1]	[0.20]	20.0%
11	PA11	48.9	-65.3	40	[2]	[0.80]	80.0%	[2]	[0.20]	20.0%
12	PA12	46.6	-70.6	89	[9]	[0.80]	80.0%	[2]	[0.20]	20.0%
13	PA13	45.6	-73.7	390	[16,19]	[0.40,0.40]	80.0%	[1]	[0.20]	20.0%
14	PA14	46.4	-73.6	381	[11]	[0.80]	80.0%	[1]	[0.20]	20.0%
15	PA15	46.4	-74.7	531	[13,14]	[0.40,0.40]	80.0%	[1]	[0.20]	20.0%
16	PA16	45.6	-72.9	1369	[17,18,20]	[0.25,0.25,0.30]	80.0%	[1]	[0.20]	20.0%
17	PA17	46.0	-72.1	222	[12]	[0.80]	80.0%	[1]	[0.20]	20.0%

ID	Departure Distribution	Overview	Sum	Percentage of People Leaving per Day									
				1	2	3	4	5	6	7	8	9	10
1	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
2	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
3	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
4	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
5	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
6	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
7	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
8	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
9	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
10	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
11	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
12	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
13	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
14	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
15	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
16	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
17	1 - Manual		100.0%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10

Figure A.3: *Graphical user interface – population areas worksheet.*

The information about the PAs is not directly used in the optimization process; it is rather used to approximate new CEPs' arrival at the APs and ECs.[10]

A.2.3 Worksheet `AssemblyPoints`

The input parameters on the APs are captured in the worksheet presented in Figure A.4. In the worksheet, one row is associated with a single AP. Similar information as for the PAs are required. In addition to the identifier (column A), the name of the AP (column B), the latitude and longitude (columns C and D), and the connected EC[11] (column F), the user must enter the capacity of the APs (column E) and the transporter type available to move CEPs from the AP to its connected EC (column I).

The cells in columns M to V are calculated automatically inside the GUI. For example, the estimated number of CEPs arriving on their own on Day 1 at AP_{13} (rounded to the nearest integer) is 35 (cell M15). It corresponds to the sum of the number of CEPs coming from PA_{07} and from PA_{15} on Day 1. As shown in cell H15, PA_{07} and PA_{15} are the only population areas connected to AP_{13}. Numerically, it is calculated as follows:

$$\begin{array}{ccccc} \mathbf{<From\ PA_{07}>} & & \mathbf{<From\ PA_{15}>} & & \\ ((0.40 \times 350) \times 0.10) & + & ((0.40 \times 531) \times 0.10) & & \\ 14.00 & + & 21.24 & = & 35.24 \end{array} \quad (A.1)$$

The values in Equation A.1 were taken from row 9 (for PA_{07}) and row 17 (for PA_{15}) in Figure A.3.

[10] The number of new CEPs' arrival at the ECs is also a function of the CEPs who arrive via transporters (i.e. buses). This is accounted for in the mathematical formulation of the problem.

[11] It is assumed that each AP is connected to at most one EC.

Table A.2: *Input parameters in worksheet* `PopulationAreas`.

	Column	Description
ID	A	Identifier of the PA. It must be a numerical value starting at 1.
Name	B	Name of the PA.
Lat and Lon	C–D	Representative latitude and longitude coordinate of the PA. It could be the geometric centre of the area.
Population	E	Estimated number of CEPs to be evacuated in the PA.
AP Connections	F	Vector containing the APs used by CEPs in the PA.
AP Percentages	G	Vector with fraction of CEPs going to each AP. The dimension of the vector should match the vector **AP Connections**.
EC Connections	F	Vector containing the ECs used by CEPs in the PA
EC Percentages	G	Vector with fraction of CEPs going to each EC. The dimension of the vector should match the vector **EC Connections**.
Departure Distribution	M	The type of distribution departure. The potential values are: “1 - Manual”, “2 - Mad Rush”, “3 - Wait and See” and “4 - Orderly”.
% of CEPs at the PA leaving per day	P–...	Expected percentages of CEPs leaving on any day. If the **Departure Distribution** is set to “1 - Manual”, then the percentages must be entered by the user, otherwise, they are auto-calculated.

nAPs = 21 (max is 30) Version = (change if input data is changed) 3

Estimated Number of People Arriving (on the own) at Assembly Points Centre per Day

ID	Name	Lat	Lon	Capacity	EC Connections (max of 1)	# of PA Connected	List of PAs Connected	Transport Type(s) to EC	Sum	1	2	3	4	5	6	7	8	9	10
1	AP01	49.9	-74.2	100	[1]	1	[10]	[1]	72	7	7	7	7	7	7	7	7	7	7
2	AP02	49.1	-66.4	100	[2]	1	[11]	[1]	32	3	3	3	3	3	3	3	3	3	3
3	AP03	49.1	-68.7	100	[2]	1	[9]	[1]	110	11	11	11	11	11	11	11	11	11	11
4	AP04	48.1	-72.2	100	[1]	1	[2]	[1]	209	21	21	21	21	21	21	21	21	21	21
5	AP05	47.8	-68.5	100	[2]	1	[1]	[1]	152	15	15	15	15	15	15	15	15	15	15
6	AP06	47.5	-77.5	100	[1]	1	[8]	[1]	280	28	28	28	28	28	28	28	28	28	28
7	AP07	47.2	-73.4	100	[1]	1	[4]	[1]	200	20	20	20	20	20	20	20	20	20	20
8	AP08	47.0	-71.9	100	[2]	1	[3]	[1]	532	53	53	53	53	53	53	53	53	53	53
9	AP09	46.4	-70.3	100	[2]	1	[12]	[1]	71	7	7	7	7	7	7	7	7	7	7
10	AP10	46.2	-76.2	100	[1]	1	[7]	[1]	140	14	14	14	14	14	14	14	14	14	14
11	AP11	45.9	-73.5	100	[1]	1	[14]	[1]	305	30	30	30	30	30	30	30	30	30	30
12	AP12	45.9	-72.3	100	[1]	1	[17]	[1]	178	18	18	18	18	18	18	18	18	18	18
13	AP13	45.7	-75.1	100	[1]	2	[7,15]	[1]	352	35	35	35	35	35	35	35	35	35	35
14	AP14	45.7	-74.1	100	[1]	1	[15]	[1]	212	21	21	21	21	21	21	21	21	21	21
15	AP15	45.6	-71.1	100	[2]	1	[5]	[1]	118	12	12	12	12	12	12	12	12	12	12
16	AP16	45.5	-73.8	100	[1]	2	[6,13]	[1]	604	60	60	60	60	60	60	60	60	60	60
17	AP17	45.4	-73.2	100	[1]	1	[16]	[1]	342	34	34	34	34	34	34	34	34	34	34
18	AP18	45.4	-73.4	100	[1]	2	[6,16]	[1]	790	79	79	79	79	79	79	79	79	79	79
19	AP19	45.4	-73.7	100	[1]	2	[6,13]	[1]	604	60	60	60	60	60	60	60	60	60	60
20	AP20	45.1	-72.8	100	[1]	1	[16]	[1]	411	41	41	41	41	41	41	41	41	41	41
21	AP21	45.2	-72.1	100	[1]	1	[5]	[1]	118	12	12	12	12	12	12	12	12	12	12

Figure A.4: *Graphical user interface – assembly points worksheet.*

A.2.4 Worksheet `EvacuationCentres`

A screenshot of the worksheet `EvacuationCentres` is shown in Figure A.5. Each row represents an EC. The information required for each EC includes the site identifier (column A), the name of the EC (column B), the site coordinates (columns C and D), the capacity of the EC (column E), the connected SH (column F) and the transporter type (column I).

The values in Column K represent the expected time to process each CEP at the EC. Specifically, they correspond to the delay between the CEP's arrival at the EC and its possible departure. The time values are fixed for each CEP and are expressed in terms of minutes. In this example, the value for each EC is set to 50 minutes which is less than "2 hours", i.e. the time step considered in the formulation (see cell E2 in Figure A.2), implying that the processing time would not be modelled. On the other hand, if the time step was still "2 hours" but that the processing time was 240 minutes, then a delay of 2 time steps (240 minutes divided by 120 minutes per time step) would be applied to each CEP when they arrived at the EC.

The number of CEPs arriving each day directly at the EC without going through an AP (i.e. the blue-shaded cells on the right in Figure A.5) is calculated in a similar way as shown in Equation A.1.

	A	B	C	D	E	F	G	H	I	K
1	nECs =	2	(max is 30)		Version = (change if input data is changed)	3				
2	ID	Name	Lat	Lon	Capacity	SH Connections (max of 1)	# of AP Connected	List of APs Connected	Transport Type(s) to SH	Process Time (in min)
3	1	EC01	45.3	-73.7	450	[1]	15	[1,4,6,7,10,11,12,13,14, 16,17,18,19,20,21]	[2]	50
4	2	EC02	47.0	-69.8	200	[1]	6	[2,3,5,8,9,15]	[2]	50

	L	M	N	O	P	Q	R	S	T	U	V	V
1			Estimated Number of People Arriving (on their own) at Evacuation Centre per Day									
2		Sum	1	2	3	4	5	6	7	8	9	10
3		1290	129	129	129	129	129	129	129	129	129	129
4		280	28	28	28	28	28	28	28	28	28	28

Figure A.5: *Graphical user interface – evacuation centres worksheet.*

A.2.5 Worksheet `SafeHavens`

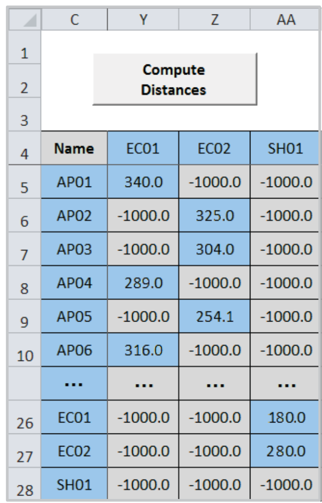
Figure A.6 includes the form with the data on the SHs. For each SH, the required information consists of an identifier (column A), the name (column B), the coordinates (columns C and D) and the site capacity (column E). The content of the blue-shaded cells are auto-populated from the information entered in the Worksheet `EvacuationCentres`.

	A	B	C	D	E	F	G
1	nSHs =	1	(max is 10)		Version = (change if input data is changed)	3	
2	ID	Name	Lat	Lon	Capacity	# of EC Connected	List of ECs Connected
3	1	SH01	45.9	-77.3	10000	2	[1,2]
4							
5							

Figure A.6: *Graphical user interface – safe havens worksheet.*

A.2.6 Worksheet `DistMatrix`

The distances between the various locations in the evacuation chain must also be specified by the user. This is completed using the form in Figure A.7. The distances must be expressed in kilometers (km). A value of -1000 indicates that there is no connection between the two sites. For example, there is no connection between AP_{01} and EC_{02}, and AP_{01} and SH_{01}. The list of locations on the left in the matrix (cells C5:C28) and at the top (cells Y4:AA4) are automatically filled by the GUI based on the data provided in Worksheets `AssemblyPoints`, `EvacuationCentres` and `SafeHavens`. For instance, the distance that the ferry has to sail between EC_{02} and SH_{01} is 280 km. The distances are used to estimate the number of trips that a transporter can complete in a given time period.



	C	Y	Z	AA
4	Name	EC01	EC02	SH01
5	AP01	340.0	-1000.0	-1000.0
6	AP02	-1000.0	325.0	-1000.0
7	AP03	-1000.0	304.0	-1000.0
8	AP04	289.0	-1000.0	-1000.0
9	AP05	-1000.0	254.1	-1000.0
10	AP06	316.0	-1000.0	-1000.0
	...	...	...	...
26	EC01	-1000.0	-1000.0	180.0
27	EC02	-1000.0	-1000.0	280.0
28	SH01	-1000.0	-1000.0	-1000.0

Figure A.7: *Graphical user interface – distance matrix worksheet.*

When there is a large number of sites in the scenario, the button "Compute Distances" at the top of the GUI can be used to automatically calculate the distances between the sites. Once clicked, the distances in the blue-shaded cells are computed by GUI using internal calls to Google Maps. This feature may not be available depending whether or not, Google Maps has required data pertaining to the area where the NEO is conducted.

A.2.7 Worksheet `TransportTypes`

The data on the transporter types considered in the scenario are specified via the form presented in Figure A.8. The list of parameters that must be specified are described in Table A.3.

	A	B	C	D	E	F	G	H	I	J	K
1	nTTs =	2	(max is 20)								
2	ID	Name	Description	Number Available	Capacity	Speed (km/h)	Operates from (timestep)	Operates until (timestep)	Utilization Threshold Min	Max	TT can be used at
3	1	Bus	Mini-van type 1 used between AP and EC	13	40	75	4	10	50%	100%	AP[1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21] - EC[]
4	2	Ferry	Ferry EC to SH	5	200	25	1	24	50%	100%	AP[] - EC[1,2]
5											

Figure A.8: *Graphical user interface – types of transporters worksheet.*

Table A.3: *Input parameters in worksheet* `TransportTypes`.

	Column	Description
ID	A	Identifier of the transporter. It must be a numerical value starting at 1.
Name	B	Name of the transporter.
Description	C	A description of the asset.
Number Available	D	Total number of assets available per time step.
Capacity	E	Maximum number of CEPs for one trip.
Speed	F	Speed of the transporter (expressed in km/h).
Operates from (time step)	G	Time steps between which the transporter
Operates for (time step)	H	is available during each day.
Min/Max Utilization	I-J	Minimum and maximum fill of a transporter's capacity.

The "Speed" (column F) and the "Time Step" (cell E2 in Figure A.2) values are used in conjunction with the distances provided in Figure A.7 to estimate the maximum number of trips that a transport asset can do in one time step. To illustrate how this is calculated, we consider the following example:

- A bus is used to move CEPs between AP_A and EC_B;
- Distance between AP_A and EC_B is 100 km;
- Speed of the bus is 75 km/h; and
- Time period considered in the model is 6 hours.

Based on this information, the maximum number of trips that the bus can complete between AP_A and EC_B in one time period is 2, and is calculated as follows:

$$\left\lfloor \frac{6 \text{ hours}}{2 \times (\frac{100 \text{ km}}{75 \text{ km/h}} + 0.125 \text{ hours})} \right\rfloor = \lfloor 2.057 \rfloor = 2 \text{ trips}. \tag{A.2}$$

In Equation A.2, the denominator corresponds to the total time needed to complete a roundtrip between AP_A and EC_B. The 0.125 hour represents the time delay allotted at each site in between the arrival and the next departure. This value is currently set to 0.125 hour but can be easily changed.

A.2.8 Worksheet `FixedTransport`

There are NEO scenarios where part of the transportation schedule may be set in advance. For example, it is possible that another nation has a bus running a trip every morning between two sites with empty seats made available to Canadians. Such information should be considered in the optimization process. This is done in the Worksheet `FixedTransport` shown in Figure A.9. The user must specify the departure site (column B), the destination site (column C), type of transporter used to move the CEPs (column D), the time period (column E) and the number of trips (column F). For example, the first record in Figure A.9 indicates that the solution produced by the optimization process should include one bus trip between AP_{01} and EC_{01} on the time period 2.

	A	B	C	D	E	F
1	nTripsFixed =	2	(max is 1000)	Used as contraints in the optimization		
2	ID	From (e.g., AP01)	To (e.g., EC01)	TT	TimeStep	Nbr of Trips
3	1	AP01	EC01	Bus	2	1
4	2	AP02	EC02	Bus	2	1
5						
6						

Figure A.9: *Graphical user interface – fixed transport worksheet.*

A.3 Format of the input data files

The format of the ten ".dat" input files are presented in Figure A.10 and consists of semi-colon separated files:

1. `AssemblyPoints.dat`: a list of the assembly points (names);
2. `EvacuationCentres.dat`: a list of the evacuation centres and their processing times;
3. `SafeHaven.dat`: a list of the safe havens;
4. `Arrival.dat`: lists the location, time, and number of CEPs arriving at that time period;
5. `TransporterTypes.dat`: lists the transporter name, quantity, capacity, operates from and operates to;
6. `TransportArcs.dat`: lists the source location, destinations, transporter type, maximum number of trips in the time step, minimum and maximum utilization;
7. `TimeInterval.dat`: lists the number of time periods to be modelled, and also the desired maximum number of time periods to complete the NEO;
8. `SiteCapacities.dat`: lists location names and capacity (number of CEPs) of each location;
9. `FixedTimeTransportArcs.dat`: lists the source and destination locations, transporter type and time for a mandatory trip; and

10. `BlackOut.dat`: lists the set of time periods when no new movement of CEPs via transporters is permissible.

A.4 Processing of output data

There is a large amount of data generated once the optimal (or near optimal) solution has been found by SCIP-SoPLEX integer program solver. The output data is written to a file called `ScipOutput.dat` that is automatically saved in the directory `DataFiles`. To generate and parse solution output, the batch file (`ProcessScipBatch.bat`) parses the raw SCIP-SoPLEX output (`ScipOutput.dat`) and creates four tab-separated files:

1. `OptTransport.dat`: lists the source location (e.g. AP), destination location (e.g. EC), transporter type, time, and number of transporter departures of the respective type departing the source to destination at the specified time;

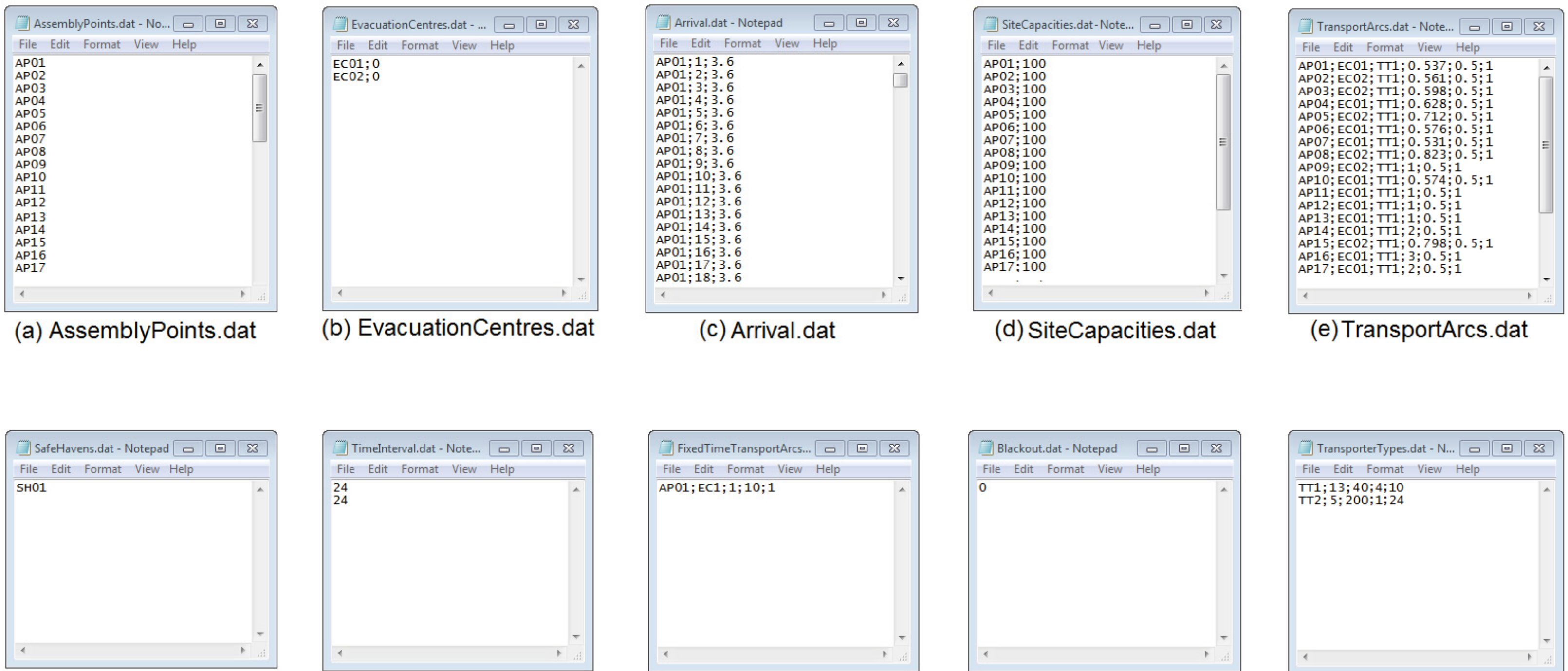
2. `OptTrips.dat`: lists the source location, destination location, transporter type, time, and number of trips taken by the transporters during the time period;

3. `OptUsage.dat`: lists the source location, destination location, transporter type, time, and number of transporters used during specified time period;

4. `OptIP.dat`: lists the location, time, and number of people at the location at that time; and

5. `OptTravelling.dat`: lists the source location, destination location, transporter type, time, and number of people travelling via the transporter type during the specified time period.

The tab-separated files are then read by the Microsoft Excel macros or Matlab scripts to generate meaningful graphs and tables. For example, the authors created Matlab scripts to show the expected number of CEPs as a function of time at specific location (see Figure 8 in Section 4) and the number of assets and trips required per transporter type as a function of time (see Figure 9 in Section 4). The Matlab scripts are not included neither are they explicitly discussed in this annex, but they can be made available to the user.



(a) AssemblyPoints.dat (b) EvacuationCentres.dat (c) Arrival.dat (d) SiteCapacities.dat (e) TransportArcs.dat

(f) SafeHaven.dat (g) TimeInterval.dat (h) FixedTimeTransportArcs.dat (i) Blackout.dat (j) TransporterTypes.dat

Figure A.10: *Required format for the ten input files.*

A.5 ProcessScipBatch

The contents of the batch file (`ProcessScipBatch.bat`) are listed below:

```
scip302   -b ScipCommands.dat
powershell -Command "(gc ScipOutput.dat)  | ? { $_ -match $control -and $_ -match 'z' -and $_ -notmatch 't_z'} | Out-File Temp.txt"
powershell -Command "(gc Temp.txt) -replace 'z\$', '' -replace '\$', ' ' -replace '\#', ' ' -replace '\(obj:0\)', ' ' | Out-File OptTransport.dat"
del Temp.txt
powershell -Command "(gc ScipOutput.dat)  | ? { $_ -match $control -and $_ -match 'w' -and $_ -notmatch 't_w'} | Out-File Temp.txt"
powershell -Command "(gc Temp.txt) -replace 'w\$', '' -replace '\$', ' ' -replace '\#', ' ' -replace '\(obj:0\)', ' ' | Out-File OptTrips.dat"
del Temp.txt
powershell -Command "(gc ScipOutput.dat)  | ? { $_ -match $control -and $_ -match 'IP' -and $_ -notmatch 't_IP'} | Out-File Temp.txt"
powershell -Command "(gc Temp.txt) -replace 'IP\$', '' -replace '\$', ' ' -replace '\#', ' ' -replace '\(obj:0\)', ' ' | Out-File OptIP.dat"
del Temp.txt
powershell -Command "(gc ScipOutput.dat)  | ? { $_ -match $control -and $_ -match 'x' -and $_ -notmatch 't_x'} | Out-File Temp.txt"
powershell -Command "(gc Temp.txt) -replace 'x\$', '' -replace '\$', ' ' -replace '\#', ' ' -replace '\(obj:0\)', ' ' | Out-File OptTravelling.dat"
del Temp.txt
```

This page intentionally left blank.

Annex B: Mixed integer linear program formulation

This section presents mathematical details of the mixed integer linear program formulation for STONE(Opt). The model is further elaborated in external literature [23].

B.1 Sets and input parameters

B.1.1 Time period, sites, and CEP arrival

Define $nPeriods$ 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 $T = \{1, ..., nPeriods\}$ be the set of time periods. Let $lastPeriod$ be an input parameter less than or equal to $nPeriods$ indicating the last time period by which all CEPs have been 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 $SitesTimes = Sites \times T$ with indices {i,t}. Define $SiteCapacity_i$ to be the capacity (number of people) of site $i \in Sites$, and $ProcessTime_i$ to be the processing time of an individual at evacuation centres $i \in EC$.

Let $Arrival_{i,t}$ 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 $totalPopulation$ as the sum of all $Arrival_{i,t}$: $totalPopulation = \sum_{\{i,t\} \in AP \cup EC \times T} Arrival_{i,t}$.

B.1.2 Transporters and transport arcs

Let M be the set of transporter types and define $TransCapacity_m$ to be the capacity (number of CEPs) of transporter type $m \in M$ and $TransQty_m$ to be the total number of transporters of type $m \in M$ available.

Define $TransportArcs$ 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 $TransportArcsTrips_{i,j,m}$ with $\{i, j, m\} \in TransportArcs$ 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 $TransportArcsTrips_{i,j,m}$ is permitted and indicates that a single trip spans more than one time period (i.e. the trip spans $\frac{1}{TransportArcsTrips_{i,j,m}}$ time periods).

B.1.3 Optional inputs

Define $TransportArcsMinUse_{i,j,m}$ with $\{i, j, m\} \in TransportArcs$ to be the minimum percent of transporter type m's capacity to which the transporter needs to be filled to consider a trip between sites i and j.

Similarly, define $TransportArcsMaxUse_{i,j,m}$ with $\{i,j,m\} \in TransportArcs$ to be the maximum percent of transporter type m's capacity to which the transporter may be filled to consider a trip between sites i and j.

Let $FixedTransportTimes_{i,j,m,t}$, with $\{i,j,m\} \in TransportArcs$ and $t \in T$, prescribe the exact number of trips required by transporter type m at time period t from site i to j.

B.2 Decision variables

- 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 ($\{i,j,m\} \in TransportArcs$). 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). The $x_{i,j,m,t}$'s can be constrained to be integers, at the expense of computational time.
- 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 $\{i,j,m\} \in TransportArcs$.
- 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 $\{i,j,m\} \in TransportArcs$.
- Define $IP_{i,t}$ be the number of people located at site $i \in Sites$ and time $t \in T$, and let $ip_{i,t}$ be the number of people located at an evacuation centre ($i \in EC$) at time t who have been processed and are waiting to travel further.
- Let Pr be the number of people located at an evacuation centre ($i \in EC$) who are being processed during time t.
- Define $D_{i,t}$ with $\{i,t\} \in SiteTimes$ to be the number of people departing site i during time period t.
- Define $A_{i,t}$ with $\{i,t\} \in SiteTimes$ 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 ($Y_t = 1$).
- Define $o_{i,t}$ with $\{i,t\} \in SiteTimes$ be a multiplier greater than or equal to one indicating the degree to which site i's capacity is exceeded at time t.

B.3 Constraints

B.3.1 NEO end time and limiting the number of days to evacuate from area of danger

Recall that Y_t for $t \in T$ is a variable that indicates whether the evacuation of CEPs from the danger area is complete (Y_t=0), and input parameter $lastPeriod$ specifies the last time period by which all CEPs have been evacuated to safe havens. The constraint

$$Y_{lastPeriod} == 0 \tag{B.1}$$

forces $Y_{lastPeriod}$ to be set to zero (indicating the evacuation is complete) at the specified time period. Constraints (B.2) relate the arrival of all CEPs at an SH to the evacuation completion variables:

$$\text{for all } t \in T : totalPopulation - \sum_{s \in SH} IP_{s,t} \leq Y_t \cdot totalPopulation \tag{B.2}$$

A constraint is needed to ensure that if Y_t is set to zero, then all subsequent time periods, $t+1, t+2, ..., nPeriods$ are also set to zero:

$$\text{for all } t > 1 : Y_{t-1} \geq Y_t. \tag{B.3}$$

B.3.2 Site accounting constraints

Variables $IP_{i,t}$ indicate the number of CEPs at site i at time t. The constraints

$$\text{for all } \{i,t\} \in (AP \cup SH) \times Times :$$

$$\text{if } t > 1 : IP_{i,t} == IP_{i,t-1} + A_{i,t} - D_{i,t} + Arrival_{i,t}, \tag{B.4}$$

$$\text{else } : IP_{i,1} == A_{i,1} - D_{i,1} + Arrival_{i,1}, \tag{B.5}$$

ensure proper accounting of CEPs arriving and departing sites at each time period.

Equivalent constraints for evacuation centre sites are listed below and include processing periods:

$$\text{for all } \{i,t\} \in EC \times Times :$$

$$IP_{i,t} == ip_{i,t} + \sum_{\substack{s=\min((t-ProcessTime_i+1),t) \\ \text{with } s>0}}^{t} \left(A_{i,s} + Arrival_{i,s}\right), \tag{B.6}$$

$$\text{if } t > 1 : ip_{i,t} == ip_{i,t-1} - D_{i,t} + Pr_{i,t}, \tag{B.7}$$

$$\text{else } : ip_{i,1} == Pr_{i,1} - D_{i,1}. \tag{B.8}$$

Recall that $ip_{i,t}$ represents the number of CEPs at an EC that have been processed and are waiting to travel further. Constraint B.6 determines the total number of CEPs at an EC by summing the CEPs that have arrived and are being processed with the CEPs processed and waiting to travel further.

B.3.3 Site capacity constraints

Sites may have a limit to the number of CEPs that can be processed or accommodated within a particular time period. The constraint

$$\text{for all } \{i,t\} \in SitesTimes: \quad IP_{i,t} \leq SiteCapacity_i \cdot o_{i,t} \tag{B.9}$$

determines to what extent a site's capacity is violated at a particular time period—variable $o_{i,t}$ represents the percentage of over capacity.

B.3.4 Transportation arc flow constraints

The following constraints 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:

$$\text{for all } \{i,t\} \in SitesTimes:$$

$$D_{i,t} == \sum_{\{i,j,m\} \in TransportArcs} x_{i,j,m,t}, \tag{B.10}$$

$$A_{i,t} == \sum_{\substack{\{j,i,m\} \in TransportArcs \\ \text{with } t > \left\lfloor \max(1, \frac{1}{TransportArcsTrips_{j,i,m}}) \right\rfloor}} x_{j,i,m,t - \left\lfloor \max(1, \frac{1}{TransportArcsTrips_{j,i,m}}) \right\rfloor}. \tag{B.11}$$

Equation B.11 sums the number of CEPs that are arriving over all arcs leading to site i. When the transport time for an transport arc exceeds one time period, the equation looks back sufficient time period steps to properly account for arrivals.

B.3.5 Link travel of CEPs to transporter trips

Constraints 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:

$$\text{for all } \{i,j,m,t\} \in TransportArcs \times T:$$

$$w_{i,j,m,t} \leq \max(1, \lfloor TransportArcTrips_{i,j,m} \rfloor) \cdot z_{i,j,m,t}, \tag{B.12}$$

$$x_{i,j,m,t} \leq TransportArcTripsMaxUse_{i,j,m} \cdot TransportCapacity_m \cdot w_{i,j,m,t}, \tag{B.13}$$

$$x_{i,j,m,t} \geq TransportArcTripsMinUse_{i,j,m} \cdot TransportCapacity_m \cdot w_{i,j,m,t}, \tag{B.14}$$

$$x_{i,j,m,t} \geq z_{i,j,m,t}, \tag{B.15}$$

$$w_{i,j,m,t} \geq z_{i,j,m,t}. \tag{B.16}$$

Together, constraints B.12 and B.13 ensures that the the number of trips and transporters conforms to transporter capacity and usage upperbounds while being sufficient to transport the number of CEPs represented by $x_{i,j,m,t}$. Constraint B.14 ensures that the number of trips takes into consideration the transporter's minimum utilization factor.

Constraints B.15 and B.16 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 transporters 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:

$$\text{for all } \{i,j,m,t\} \in TransportArcs \times T :$$
$$\text{if } TransportArcsTrips_{i,j,m} < 1$$
$$\text{then } u_{i,j,m,t} == \sum_{\substack{s \in \{1,\ldots,t\} \\ \text{with } s \geq t+1-\left\lceil \frac{1}{TransportArcsTrips_{i,j,m}} \right\rceil}} z_{i,j,m,s}, \tag{B.17}$$
$$\text{else } u_{i,j,m,t} == z_{i,j,m,t}. \tag{B.18}$$

B.3.6 Constrain the number of transporters

The number of transporters of a specific type being used anywhere in the network at any given time period must respect the upperbound on the total number of transporters available:

$$\text{for all } \{m,t\} \in M \times T :$$
$$\sum_{\{i,j,m\} \in TransportArcs} u_{i,j,m,t} \leq TransQty_m. \tag{B.19}$$

B.3.7 Force the number of trips for a transporter on a particular route and time

An optional constraint is to define the exact number of trips desired for a particular transportation arc and a particular time. This removes the variability for that specific arc and time:

$$\text{for all } \{i,j,m,t\} \in TransportArcs \times T :$$
$$\text{if } FixedTransportTimes_{i,j,m,t} \geq 0$$
$$\text{then } w_{i,j,m,t} == FixedTransportTimes_{i,j,m,t}. \tag{B.20}$$

B.3.8 Site blackout periods

An optional constraint is to indicate time periods where specific sites can neither accept new CEP arrivals nor have CEPs depart. These constraints have no effect on the number of CEPs at that site at that time, only arriving and departing CEPs:

$$\text{for all } \{i,t\} \in Sites \times B :$$
$$\text{if } t > 0 \text{ then } A_{i,t} == 0, \tag{B.21}$$
$$D_{i,t} == 0. \tag{B.22}$$

B.4 Objective functions

Several objective functions are possible and are defined in the following.

B.4.1 Minimize the total number of NEO days

The objective is to complete the NEO as quickly as possible:

$$\text{minimize} \sum_{t \in T} Y_t. \tag{B.23}$$

B.4.2 Minimize the average time people spend in the area of danger

Recall that $IP_{i,t}$ with $i \in SH$ represents the amount of people who have arrived at a safe haven by time t. The objective is to process and move the most people as possible and as soon as possible to a safe haven:

$$\text{minimize} \sum_{\{i,t\} \in SH \times T} -1 \cdot t \cdot IP_{i,t}. \tag{B.24}$$

B.4.3 Minimize the amount of site over-capacity

Recall that $o_{i,t}$ with $\{i,t\} \in SiteTimes$ is a multiplier greater than or equal to one indicating the degree to which site i's capacity is exceeded at time t. $(o_{i,t} - 1) \cdot SiteCapacity_i$ is the number of person time periods (e.g. person days) of site capacity overflow. The objective is to minimize the number of person time periods:

$$\text{minimize} \sum_{\{i,t\} \in SitesTimes} (o_{i,t} - 1) \cdot SiteCapacity_i. \tag{B.25}$$

Annex C: Zimpl formulation file

```
# Zimpl ILP formulation file
# Created by CJOC OR&A: Jean-Denis Caron and Bohdan Kaluzny
# Version date: 5 April 2015

#---------------------------------------------------
# INPUT and SETS and PARAMETERS
#---------------------------------------------------
param SelectObj := read "SelectObj.dat" as "1n" ;
set Three :=  { 1 .. 3 };
param Time[Three] := read "TimeInterval.dat" as "1n" ;
param lastTime := Time[1];
set T := {1 .. lastTime};
set B := {read "Blackout.dat" as "<n+>"};

set AP:={read "AssemblyPoints.dat" as "<1s>"};
set EC:={read "EvacuationCentres.dat" as "<1s>"};
set SH:={read "SafeHavens.dat" as "<1s>"};
set Sites:=AP+EC+SH;

param SiteCapacity[Sites] := read "SiteCapacities.dat" as "<1s>2n";
param ProcessTime[EC] := read "EvacuationCentres.dat" as "<1s>2n";

set M:={read "TransporterTypes.dat" as "<1s>"};
param TransCapacity[M] := read "TransporterTypes.dat" as "<1s>3n";
param TransQty[M] := read "TransporterTypes.dat" as "<1s>2n";
param TransStart[M] := read "TransporterTypes.dat" as "<1s>4n";
param TransEnd[M] := read "TransporterTypes.dat" as "<1s>5n";

param Arrival[Sites*T] := read "Arrival.dat" as "<1s,2n>3n" default 0;
param fixy := Time[2];


set TransportArcs:={read "TransportArcs.dat" as "<1s,2s,3s>"};
param TransportArcsTrips[TransportArcs]
                      := read "TransportArcs.dat" as "<1s,2s,3s>4n";
param TransportArcsMinUse[TransportArcs] := read "TransportArcs.dat" as "<1s,2s,3s>5n";
param TransportArcsMaxUse[TransportArcs] := read "TransportArcs.dat" as "<1s,2s,3s>6n";
param FixedTransportTimes[TransportArcs*T] := read "FixedTimeTransportArcs.dat" as
                                                    "<1s,2s,3s,4n>5n" default -1;
param totalPopulation:= sum <a,t> in Sites*T : Arrival[a,t];

set SitesTimes:= Sites*T;

#---------------------------------------------------
# VARIABLES
#---------------------------------------------------
var z[<i,j,m,t> in TransportArcs*T] integer;
var w[<i,j,m,t> in TransportArcs*T] integer;
```

```
var u[<i,j,m,t> in TransportArcs*T] integer;
var IP[SitesTimes ] real >= 0;
var ip[EC*T ] real >= 0; #number at EC that have been processed and ready to move
var Pr[EC*T] real >= 0; #number processed at site i at time t
var A[SitesTimes ] real >= 0;
var D[SitesTimes ] real >= 0;
var Y[T] binary;
var x[<i,j,m,t> in  TransportArcs*T] real >= 0;
var o[Sites*T] real >= 1;
var Over real;
var AvgTime real;

minimize SelectedObjective:
               if SelectObj == 1 then  sum <t> in T: Y[t]
               else if SelectObj == 2 then sum <i,t> in SH*T : -1*t*IP[i,t]
               else if SelectObj == 3 then Over
               else if SelectObj == 4 then sum <i,j,m,t> in TransportArcs*T:  z[i,j,m,t]
               else sum <i,j,m,t> in TransportArcs*T:  w[i,j,m,t]
               end end end end;

#minimize LastTime:  sum <t> in T: Y[t];
#minimize AvgTimeInverse:  sum <i,t> in SH*T : -1*t*IP[i,t];
#minimize OverFlow: Over;
#minimize Transporters: sum <i,j,m,t> in TransportArcs*T:  z[i,j,m,t];
#minimize TotalTrips: sum <i,j,m,t> in TransportArcs*T:  w[i,j,m,t];

##############################################################################
# Limit on number of days for operation
##############################################################################

subto FixY: Y[fixy] == 0;

##############################################################################
# Used when granularity is to the hour level
##############################################################################

subto EndTime: forall <t> in T do
         totalPopulation - sum <i> in SH: IP[i,t] <=  Y[t]*totalPopulation;

subto EndTimeY: forall <t> in T with (t > 1) do  Y[t-1] >= Y[t];


subto Demand: forall <i,t> in SitesTimes\EC*T do
           if (t > 1) then IP[i,t]  == IP[i,t-1] + A[i,t] - D[i,t] + Arrival[i,t]
           else IP[i,t]  == A[i,t] - D[i,t] + Arrival[i,t]
           end;

##############################################################################
# Used when granularity is to the hour level
##############################################################################
subto Processed: forall <i,t> in EC*T do
```

```
        if (t-ProcessTime[i] >= 1)
        then Pr[i,t] == A[i,t-ProcessTime[i]]+Arrival[i,t-ProcessTime[i]]
        else Pr[i,t] == 0
        end;

subto PrAccount: forall <i,t> in EC*T do
        IP[i,t] == ip[i,t]  + sum <s> in {min((t-ProcessTime[i]+1),t) .. t}
                                    with s > 0 : (A[i,s] + Arrival[i,s]);

subto DemandEC: forall <i,t> in EC*T do
          if (t > 1) then  ip[i,t]  == ip[i,t-1] - D[i,t] + Pr[i,t]
          else ip[i,t] == Pr[i,t] - D[i,t]
          end;

##############################################################################
# Site Capacity
##############################################################################

subto SiteCapacity: forall <i,t> in SitesTimes do IP[i,t] <= SiteCapacity[i]*o[i,t];

subto SiteOverFlow: Over == sum <i,t> in SitesTimes : (o[i,t]-1)*SiteCapacity[i];

##############################################################################
# Departure and Arrival via transport arcs
##############################################################################

subto DepartSite: forall <i,t> in SitesTimes do
         D[i,t] == sum <i,j,m> in TransportArcs : x[i,j,m,t];

subto ArriveSite: forall <i,t> in SitesTimes do
          A[i,t] == sum <j,i,m> in TransportArcs
                 with t > floor(max(0.5/TransportArcsTrips[j,i,m],1)):
                     x[j,i,m,t-floor(max(0.5/TransportArcsTrips[j,i,m],1))];

##############################################################################
# Link travel of people with transporters
##############################################################################

subto TransAccount2:         forall <i,j,m,t> in TransportArcs*T do
          x[i,j,m,t] >=  z[i,j,m,t];

subto TransAccount1:         forall <i,j,m,t> in TransportArcs*T do
          w[i,j,m,t] >=  z[i,j,m,t];

subto TransTripsW2:  forall <i,j,m,t> in TransportArcs*T do
          max(1,floor(TransportArcsTrips[i,j,m]))*z[i,j,m,t] >=  w[i,j,m,t];

subto TransTripsW3:  forall <i,j,m,t> in TransportArcs*T do
          x[i,j,m,t] <= w[i,j,m,t]*TransportArcsMaxUse[i,j,m]*TransCapacity[m];

subto TransTripsW4:  forall <i,j,m,t> in TransportArcs*T do
```

```
          x[i,j,m,t] >= w[i,j,m,t]*TransportArcsMinUse[i,j,m]*TransCapacity[m];

#############################################################################
# Accounting: number of transporters in use at a given time
#############################################################################

subto TransUsage: forall <i,j,m,t> in TransportArcs*T do
        if (TransportArcsTrips[i,j,m] < 1) then  sum <s> in {1..t}
          with s >= (t+1-ceil(1/TransportArcsTrips[i,j,m])): z[i,j,m,s] == u[i,j,m,t]
        else
             z[i,j,m,t] == u[i,j,m,t]
        end;

#############################################################################
# Constraint on number of return trips for assets requiring more
# than one time period of travel
#############################################################################

subto TransTrips: forall <i,j,m,t> in TransportArcs*T do
        if (TransportArcsTrips[i,j,m] < 1) then  sum <s> in {t..lastTime}
        with s <= (t+ceil(1/TransportArcsTrips[i,j,m])-1): z[i,j,m,s] <= TransQty[m]
        end;

#############################################################################
# Force number of trips for a transporter on a particular route/time
#############################################################################
subto ForceTrips: forall <i,j,m,t> in TransportArcs*T do
        if (FixedTransportTimes[i,j,m,t] >= 0)
        then  w[i,j,m,t] == FixedTransportTimes[i,j,m,t]
        end;

#############################################################################
# Constraint on number of transport assets
#############################################################################

subto TransQty:           forall <m,t> in  M*T do
          sum <i,j,m> in TransportArcs:  u[i,j,m,t] <= TransQty[m];

#############################################################################
# Implements blackout periods for arrival and departure at sites
#############################################################################
subto BlackOutA:            forall <i,t> in Sites*B do
                        if (t>0) then A[i,t] == 0
                        end;
subto BlackOutD:            forall <i,t> in Sites*B do
                        if (t>0) then D[i,t] == 0
                        end;

#############################################################################
# Transport departure blackout periods
#############################################################################
```

```
subto TransBlackout: forall <i,j,m,t> in TransportArcs*T do
                if ((t mod Time[3]) <  TransStart[m] or  (t mod Time[3]) >  TransEnd[m])
                      then z[i,j,m,t] == 0
                end;

#############################################################################
# Compute an approximation of the average time in system
#############################################################################
subto AvgTimeCons: AvgTime ==
  sum <a,t> in SH*T : t*A[a,t]/totalPopulation
  - sum <b,s> in Sites*T : s*Arrival[b,s]/totalPopulation;
```

List of acronyms

1st Cdn Div HQ	1st Canadian Division Headquarters
ADM(S&T)	Assistant Deputy Minister Science and Technology
AFIT	Air Force Institute of Technology
AN	Affected Nation
AP	Assembly Point
CAA	Center for Army Analysis
CAF	Canadian Armed Forces
CBSA	Canada Border Services Agency
CECP	Consular Emergency Contingency Plan
CEP	Canadian or Eligible Person
CIC	Citizenship and Immigration Canada
CJOC	Canadian Joint Operational Command
COIC	Commandement des opérations interarmées du Canada
CONPLAN	Contingency Plan
CORA	Centre for Operational Research and Analysis
CPAT	Contingency Planning Assistance Team
CSIS	Canadian Security Intelligence Service
DES	Discrete-Event Simulation
DFATD	Department of Foreign Affairs, Trade and Development
DND	Department of National Defence
DRDC	Defence Research & Development Canada
EC	Evacuation Centre
EM	Eastern Mediterranean
FAC	Forces armées canadiennes
GUI	Graphical User Interface
km	kilometers

MAECD	Ministère des affaires étrangères, du commerce et du développement
MEP	Mission Emergency Plan
M&S	Modelling and Simulation
NATO	North Atlantic Treaty Organization
Nbr	number
NCG	NEO Coordination Group
NEO	Non-Combatant Evacuation Operation
OEN	opération d'évacuation de non-combattants
OPLAN	Operational Plan
OR&A	Operational Research and Analysis
PA	Population Area
PfP	Partnership for Peace
RCMP	Royal Canadian Mounted Police
RS	Repatriation Site
SAS	Systems Analysis and Studies
SH	Safe Haven
STO	Science and Technology Organization
STONE	Simulation Tool for Optimizing Non-Combatant Evacuation
STONE(Opt)	STONE optimization component

This page intentionally left blank.

DOCUMENT CONTROL DATA

(Security markings for the title, abstract and indexing annotation must be entered when the document is Classified or Protected.)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) DRDC – Centre for Operational Research and Analysis Dept. of National Defence, MGen G. R. Pearkes Bldg., 101 Colonel By Drive, 6CBS, Ottawa ON K1A 0K2, Canada	2a. SECURITY MARKING (Overall security marking of the document, including supplemental markings if applicable.) UNCLASSIFIED 2b. CONTROLLED GOODS (NON-CONTROLLED GOODS) DMC A REVIEW: GCEC DECEMBER 2012

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

Simulation Tool for Optimizing Non-Combatant Evacuation (STONE): Optimization of evacuation time and transportation resource utilization

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

Caron, J.-D.; Kaluzny, B. L.

5. DATE OF PUBLICATION (Month and year of publication of document.)	6a. NO. OF PAGES (Total containing information. Include Annexes, Appendices, etc.)	6b. NO. OF REFS (Total cited in document.)
May 2015	74	26

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

Scientific Report

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

DRDC – Centre for Operational Research and Analysis
Dept. of National Defence, MGen G. R. Pearkes Bldg., 101 Colonel By Drive, 6CBS, Ottawa ON K1A 0K2, Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)
FE1-06ac	

10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)
DRDC-RDDC-2015-R074	

11. DOCUMENT AVAILABILITY (Any limitations on further dissemination of the document, other than those imposed by security classification.)

Unlimited

12. DOCUMENT ANNOUNCEMENT (Any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in (11)) is possible, a wider announcement audience may be selected.)

Unlimited

13. ABSTRACT (A brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual.)

A NEO is designed to deploy forces in a short or no-notice situation as a result of a deteriorating situation in an foreign nation where the safety of Canadians abroad is adversely affected. In the event of a rapidly deteriorating civil situation that may overwhelming local authorities, the DFATD may seek assistance from the CAF in order to conduct an evacuation of the Canadians from the affected nation.

In support of CJOC (and by extension DFATD and 1st Canadian Division Headquarters planners), the CJOC OR&A Team initiated the development of the STONE analysis toolset to support NEO planning. This Scientific Report documents the STONE optimization component, STONE(Opt). STONE(Opt) can help to determine the best allocation and utilization of transportation resources and estimate evacuation time.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Non-Combatant; Optimization; Operations; Evacuation; Integer Linear Program

DRDC | RDDC

SCIENCE, TECHNOLOGY AND KNOWLEDGE FOR CANADA'S DEFENCE AND SECURITY

SCIENCE, TECHNOLOGIE ET SAVOIR POUR LA DÉFENSE ET LA SÉCURITÉ DU CANADA

www.drdc-rddc.gc.ca