



UNIVERSITY OF THESSALY
DEPARTMENT OF MECHANICAL ENGINEERING

***TRANSIT ASSISTED EMERGENCY EVACUATION OF HIGH
DENSITY CLUSTERS IN URBAN AREAS: A CASE STUDY ON
CONTAINER TERMINALS***

by

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Abstract

Emergency evacuation planning is a critical component of life safety. In many hazardous events, the best option is to relocate threatened populations to safer areas, often using transit. Efficient response to natural and man-made disasters requires fast and well organized efforts, which heavily depend not only on proactive planning but also on educated dynamically made decisions. Currently available approaches for addressing evacuation issues are based primarily on proactive planning. A traffic network environment, however, raises more challenges, due to its dynamic structure, making planning ahead less effective in protecting the evacuees.

The work presented in this thesis deals with the issue of transit assisted emergency evacuation procedures in urban clusters using a dynamic network model. The ultimate goal is to present the integration of a state-of-the-art traffic micro-simulation software package with transit based emergency evacuation models, demonstrating the use of transit for emergency evacuation under various conditions.

ΕΚΚΕΝΩΣΗ ΠΕΡΙΟΧΩΝ ΜΕ ΜΕΓΑΛΗ ΠΛΗΘΥΣΜΙΑΚΗ ΚΑΛΥΨΗ ΣΕ ΠΕΡΙΠΤΩΣΕΙΣ ΕΚΤΑΚΤΩΝ ΑΝΑΓΚΩΝ: ΠΙΛΟΤΙΚΗ ΕΦΑΡΜΟΓΗ ΣΕ ΕΜΠΟΡΙΚΟΥΣ ΛΙΜΕΝΕΣ

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Περίληψη

Ο σχεδιασμός της εκκένωσης σε περιπτώσεις εκτάκτων αναγκών είναι ένα κρίσιμο στοιχείο που μπορεί να σώσει ζωές. Σε πολλές περιπτώσεις επικίνδυνων γεγονότων έκτακτης ανάγκης, η καλύτερη επιλογή είναι η μετεγκατάσταση των απειλούμενων πληθυσμών σε ασφαλέστερες περιοχές χρησιμοποιώντας τα μέσα μαζικής μεταφοράς. Η αποτελεσματική αντιμετώπιση των φυσικών και ανθρωπογενών καταστροφών απαιτεί γρήγορη και καλά οργανωμένη προσπάθεια, η οποία εξαρτάται σε μεγάλο βαθμό όχι μόνο από τον ενεργό, προληπτικό σχεδιασμό αντιμετώπισης αλλά και από τη δυνατότητα ορθών αποφάσεων οι οποίες πρέπει να ληφθούν κατά τη διάρκεια των γεγονότων. Οι υπάρχουσες προσεγγίσεις για την αντιμετώπιση θεμάτων εκκένωσης βασίζονται κατά κύριο λόγο στον ενεργό, προληπτικό σχεδιασμό. Ωστόσο, η κίνηση που παρατηρείται σε κάποιο οδικό δίκτυο, παρουσιάζει περισσότερες προκλήσεις, λόγω της δυναμικής δομής και των χαρακτηριστικών του δικτύου, καθιστώντας τον προληπτικό σχεδιασμό λιγότερο αποτελεσματικό για την προστασία των εκκενωθέντων.

Σε αυτή τη μεταπτυχιακή εργασία παρουσιάζουμε την εκκένωση περιοχών μεγάλης πληθυσμιακής κάλυψης με τη βοήθεια των μέσων μαζικής μεταφοράς με τη χρήση ενός μοντέλου δυναμικού δικτύου. Ο απώτερος στόχος είναι να παρουσιάσουμε ολοκληρωμένες λύσεις που συνδυάζουν τα πιο εξελιγμένα πακέτα προσομοίωσης της κυκλοφορίας με μοντέλα βελτιστοποίησης εκκένωσης περιοχών μεγάλης πληθυσμιακής κάλυψης, για να αποδείξουμε τη χρησιμότητα των μέσων μαζικής μεταφοράς στην εκκένωση πληθυσμών υπό διάφορες συνθήκες.

Αρχικά, παρουσιάζουμε μία μικρή εισαγωγή στο πρόβλημα προς επίλυση καθώς και τους λόγους που μας οδήγησαν στη μελέτη και επίλυση του συγκεκριμένου προβλήματος. Στη συνέχεια παρουσιάζουμε τη βιβλιογραφική ανασκόπηση, τα δυναμικά χαρακτηριστικά που συνοδεύουν τις διαδικασίες εκκένωσης καθώς και τα πακέτα προσομοίωσης που υπάρχουν διαθέσιμα.

Στο τρίτο κεφάλαιο, παρουσιάζεται αναλυτικά το πρόβλημα προς επίλυση και αναπτύσσεται η μέθοδος, η οποία βασίζεται στη θεωρία του ακέραιου προγραμματισμού. Η υλοποίηση και η επίλυση του προβλήματος γίνονται με τη βοήθεια της γλώσσας μαθηματικού προγραμματισμού AMPL. Επίσης, παρουσιάζεται η πιλοτική εφαρμογή σε εμπορικούς λιμένες.

Στο τέταρτο κεφάλαιο παρουσιάζονται τα αποτελέσματα και τα συμπεράσματα που προκύπτουν από τη χρήση της μεθόδου. Τα αποτελέσματα δείχνουν ότι η μέθοδος λειτουργεί σωστά και αποτελεσματικά, παρέχει τη βέλτιστη λύση και επομένως είναι δυνατή η μελλοντική εφαρμογή της από τους υπευθύνους διαχείρισης καταστάσεων έκτακτης ανάγκης, έτσι ώστε να καθίσταται γρηγορότερη η εκκένωση πληθυσμών σε περιπτώσεις καταστροφών.

Τέλος, στο πέμπτο κεφάλαιο παρουσιάζονται τα συνολικά συμπεράσματα της παρούσης δουλειάς καθώς και κάποιες κατευθύνσεις για μελλοντική έρευνα.

TABLE OF CONTENTS

TABLE OF CONTENTS	8
LIST OF FIGURES	9
LIST OF TABLES.....	10
1. INTRODUCTION	11
1.1 Introduction and Motivation	11
1.2 Overview of the Postgraduate Thesis	12
2. LITERATURE REVIEW	14
2.1 Literature Review	14
2.2 Dynamics of Evacuation Procedures	17
2.3 Use of Traffic Microsimulation Tools for Emergency Evacuation Decision Making.....	19
3. PROBLEM DEFINITION.....	22
3.1 Problem Definition	22
3.2 The Proposed Integrated Framework.....	24
3.3 Case Study on Container Terminals	31
4. COMPUTATIONAL RESULTS	36
4.1 Transit Vehicle Assignment Module's Results (ETVAM-1)	36
4.2 Heuristic Approach's Results	38
4.3 Transit Vehicle Assignment Module's Results (ETVAM-2)	42
4.4 Comparison between ETVAM-2 and the heuristic algorithm	47
5. CONCLUSIONS	50
Appendix A.....	52
Appendix B.....	53
Appendix C.....	55
REFERENCES	60

LIST OF FIGURES

FIGURE 1 Transit Based Evacuation Traffic Management Framework.	24
FIGURE 2 The cost of the Terminal Evacuation Problem.....	30
FIGURE 3 The Cost of the TSP problem.....	30
FIGURE 4 Case Study Region.	31
FIGURE 5 Demand Profile Estimate at Port Newark-Elizabeth Terminals.	32
FIGURE 6 New Jersey Transit Bus Routes Serving the Study Area.	32
FIGURE 8 Objective Function versus the Number of Evacuation Areas	42
FIGURE 9 Computational Time versus the Number of Evacuation Areas.....	43
FIGURE 10 Objective Function and Computational Time versus the Vehicle Capacity.....	43
FIGURE 11 Objective Function and Computational Time versus the Number of Time Periods.....	44
FIGURE 12 Objective Function and Computational Time versus the Number of Shelters	46
FIGURE 13 Objective Function and Computational Time versus the Number of Vehicles	46
FIGURE 14 Objective Function versus the Number of Vehicles for the Exact Resolution Algorithm and the Heuristic Algorithm	47
FIGURE 15 Computational Time versus the Number of Vehicles for the Exact Resolution Algorithm and the Heuristic Algorithm	48

LIST OF TABLES

TABLE 1 Bus location to evacuation point travel time	36
TABLE 2 Evacuation point to safe shelter travel time.....	37
TABLE 3 Evacuation demand at each terminal	37
TABLE 4 Vehicle Assignment Using CPLEX.....	37
TABLE 5 Vehicle Assignment for Scenario A Using the Heuristic Algorithm	39
TABLE 6 Vehicle Assignment for Scenario B Using the Heuristic Algorithm.....	40
TABLE 7 Vehicle Assignment for Scenario C Using the Heuristic Algorithm.....	40
TABLE 8 Results of the three versions of the proposed heuristic algorithm.....	41
TABLE 9 Objective Function Values for both the Exact and the Heuristic Algorithms.....	47
TABLE 10 Objective Function Values for both the Exact and the Heuristic Algorithms.....	48

1. INTRODUCTION

1.1 Introduction and Motivation

Emergency evacuation planning is a critical component of life safety. In many hazardous events, the best option is to relocate threatened populations to safer areas on foot or using passenger cars or transit vehicles over the transportation system. The latter mode of transportation can play a major role, in providing the means to transport people from evacuated areas to safe locations. Recently, the American Bus Association and the American Highway Users Alliance released a report that highlights the evacuation challenges facing major urban centers. The Report, titled "Emergency Evacuation Report Card 2006; 25 Urban Areas Could Face Greater Challenges than New Orleans Experienced after Hurricane Katrina," evaluates the 37 largest urban areas in the US - those with more than 1,000,000 in population - to identify the evacuation challenges facing planners and residents in each area. According to one of the findings of the study, buses can play an important and significant role to moving large groups of people in times of emergency.

Irrelevant to the mode of evacuation efficient response to natural and man-made disasters requires fast and well organized efforts, which heavily depend not only on proactive planning but also on educated dynamically made decisions. Currently available approaches for addressing evacuation issues are based primarily on proactive planning that involves the development and testing, in advance, different plans for different scenarios, and finding among the available plans the most suitable one to be used whenever an incident occurs. Disasters, however, tend to occur with no or very little warning, they are rare, unique, and overwhelming even for well-equipped societies, which makes them difficult to prepare for and respond to. Static predefined schemes are effective only in situations where the locations of the incidents, the areas to be evacuated and the typical conditions in those areas (e.g., building evacuation) are known with certainty. A traffic network environment, however, raises more challenges, due to its larger and more dynamic structure, making planning ahead less effective in protecting the evacuees. Traffic simulation models used in emergency evacuation planning vary in their

sophistication and ability to realistically capture these traffic dynamics, the interactions between the transit vehicles and the passenger cars, and to model driver behavior under extreme conditions such as an evacuation emergency.

This thesis deals with the issue of *transit assisted emergency evacuation* procedures in high-density areas (e.g., urban clusters), or from large and heavily utilized facilities (e.g., transit hubs, malls, hospitals, business centers, etc.) to remotely located safe sites utilizing a state-of-the-art traffic micro-simulation software package in integration with emergency evacuation models. The ultimate goal is to show the usefulness of such a tool as a decision support tool in responding to emergency situations and present the use of transit for emergency evacuation under various conditions. Having such a tool in place during emergency response is essential. The proposed approach is unique in that it is: a) transit oriented, and b) captures the dynamics of emergency conditions both on the demand and the supply side of the transportation system, as discussed in a later section.

1.2 Overview of the Postgraduate Thesis

This thesis deals with the issue of *transit assisted emergency evacuation* procedures in high-density areas (e.g., urban clusters), or from large and heavily utilized facilities (e.g., transit hubs, malls, hospitals, business centers, etc.) to remotely located safe sites utilizing a state-of-the-art traffic micro-simulation software package in integration with emergency evacuation models.

In Chapter 1 an introduction to the problem addressed in this work is presented as well as an analysis of the reasons led us to deal with the specific issue of emergency evacuation procedures.

In Chapter 2 the literature review, the dynamics of evacuation procedures and the use of traffic micro-simulation tools for emergency evacuation decision making is presented.

Chapter 3 deals with the description of the problem addressed in this work and the development of the solution method based on integer programming theory. The mathematical formulation of the problem along with its implementation on AMPL mathematical programming language is presented. Additionally, a case study on container terminals is presented, in order to demonstrate the usefulness of the proposed framework in practical situations.

In Chapter 4 the experiments and the computational results of the exact resolution algorithms proposed in chapter 3 are presented. Additionally, a heuristic approach for the ETVAM is presented along with its computational results.

Finally, in Chapter 5 some useful conclusions derived from the computational results of this work are presented as well as some points for future research.

2. LITERATURE REVIEW

This chapter deals with the literature review, the dynamics of evacuation procedures, and the use of traffic micro-simulation tools for emergency evacuation decision making. The subject of this thesis has been studied by many researchers during the last decades and it is continuously attracting the interest of the research community due to its dynamic characteristics and the dimension it has been given to it as a result of several terror attacks observed worldwide during the last years.

2.1 *Literature Review*

A vast amount of work in modeling evacuation procedures has been published. Part of it has focused on transit oriented evacuation procedures, which has proven to be an efficient type of response to emergencies. Early studies dealing with traffic management under emergency conditions have been published as early as in 1963 (Givens, 1963) and later in 1975 (Houston, 1975), presenting empirical solutions. Following the partial meltdown of a reactor at the Three Mile Island nuclear power plant in 1979, the Nuclear Regulatory Commission mandated the development of evacuation plans, generating increased interest in relevant literature. As a result, several evacuation models were developed, using various approaches to simulation in evacuation, such as macroscopic simulation, microscopic simulation or mesoscopic simulation.

An evacuation simulator is a traffic simulator, which tries to improve traffic flows in urban areas. The idea is to show what happens as vehicles and people move around a road network (Michael Pidd, et al. 1993). The differences between these three approaches is that the macroscopic simulation does not track the movement of individual vehicles or even convoys of vehicles but estimates the movement of vehicles in unit time intervals across a given road network. NETVAC1 (Sheffi et al., 1981; and Avkowitz and Meyer, 1996) and MASSVAC (Radwan et al., 1985) are ones of the early macroscopic model formulations. Later enough, Han (2005) adapted the NETVAC1 approach in an effort to address different evacuation actions such as rearrangement of gathering points, traffic signal improvement and using partial reversibility lanes on 6-lane highways.

On the other hand, the microscopic simulation tracks the movement of individual vehicles as they move around the network. This type of approach is characterized by the discrete event simulation in which the vehicles are represented as simulation entities whose state representation, such as their current position and speed in the network, their intended route, etc are known.

Finally, the mesoscopic simulation models are in the middle of the other two approaches. They usually divide the traffic flow into convoys of vehicles which are then moved around the network. An example of mesoscopic approach is Barcelo (1993) who describes a simulator which was intended to be part of a real time traffic control system in urban road networks.

Southworth (1991), Rathi and Solanki (1993), Wolshon et al. (2001), Barret et al. (2000) and Alsnih et al. (2004) present reviews of the state-of-the-art and state-of-the-practice in evacuation modeling at the time of their publication. Southworth (1991) reviews traditional planning procedures, including vehicle trip generation, trip departure time, trip destination and trip route selection steps, focusing on limitations of current estimation methods. Rathi and Solanki (1993) give a brief description of the Oak Ridge Evacuation Modeling System (OREMS) which was being developed at the Oak Ridge National Laboratory. The system simulates traffic flow during evacuation and develops evacuation plans for different events and scenarios by considering alternative routes, destinations, traffic control and management practices. Wolshon (2001) presents a state-of-practice review, including application of evacuation strategies and technologies such as use of reverse flow operations, intelligent transportation systems (ITS), methods of information exchanges, and decision-making criteria. Similarities and differences of the various practices are highlighted. The hurricane evacuation problem is reviewed in Barret et al. (2000) which sets up a base for an evacuation model based on a Geographic Information System (GIS). Alsnih et al. (2004) present general evacuation concepts, analysis processes of evacuation behaviors, and model estimation methodologies. Various emergency evacuation models that had been developed since the 1980's are reviewed and the importance of conducting behavioral and transport analyses is emphasized.

Many researchers used traffic simulation models to evaluate different emergency operation plans. Cova et al. (2002) propose a method for using microscopic traffic simulation to develop and test neighborhood evacuation plans in

fire-prone wildlands. Subneighborhood variation in household evacuation travel time under various scenarios is mapped and GIS is used to determine the relative evacuation vulnerability of households. Cova and Johnson (2003) present a network flow model for identifying optimal evacuation routing plans in a complex road network. The model is an integer extension of the minimum cost flow problem, used to generate routing plans that trade total vehicle travel distance against merging conflicts at intersections. Tuydes and Ziliaskopoulos (2004 and 2006) present models of contraflow operations to manage traffic networks during disasters. Contraflow operations provide a temporary capacity increase without any major infrastructure changes and are considered as a primary method to solve the network re-design problem. Contraflow operations are also modeled in Theodoulou and Brian (2004), Zou et al. (2005), and Lim and Wolshon (2005). Murray-Tuite and Mahmassani (2003 and 2004) present evacuation models based on observed household interactions by incorporating household trip-chaining behavior. A series of linear integer programs are proposed to determine household decisions such as meeting location and logistics. Kwon and Pitt (2005) developed a model to evaluate emergency evacuation in large urban areas. Different network configurations corresponding with the evacuation of the Metrodome in Minneapolis, Minnesota during major events are presented. Yuan et al. (2006) present a one-destination concept, used to obtain an optimal destination and route assignment. Li et al. (2006) present a study of developing an integrated emergency evacuation planning system with dynamic traffic flow model within the ArcGIS platform. They develop a time-discrete traffic flow model, which is formulated as the dynamic capacitated multi-commodities flow problem. The traffic flow model produces evacuees' flows that are compatible with the evacuation travel demand and routing behaviors. Several scenarios are developed and evaluated. Sbayti and Mahmassani (2006) present an evacuation-scheduling model to minimize network clearance times. Evacuees are provided with a priori trip information about path assignments and are considered to follow the route guidance in evacuation situations. A modified system-optimal dynamic traffic assignment formulation is proposed and iterative heuristic methods are applied to solve the problem.

Xuwei (2006) estimates the minimum clearance time for evacuation and the number of evacuees who will need to be accommodated in case of the route disruption. The agent-based micro-simulation is used to capture individual and

collective behaviors in a complex and dynamic environment. Emergency evacuation by traffic controls focusing on the Los Alamos National Lab is presented in Jha et al. (2004). Road closures including signal controls around the laboratory are assumed, to prepare for emergency situations. A number of evacuation scenarios are simulated and various measures of effectiveness such as time-dependent progression of evacuation, population at risk and bottleneck locations are presented. Sisiopiku et al. (2004) studied the effect of evacuating a particular building on the traffic network by simulating the evacuation effect as percentage increase in traffic peak hour volume on the road network using micro simulation and suggested that signal optimization for the evacuating traffic decreased the delay resulting from the traffic increase. The results concluded that the computer simulation is a good option for evaluating emergency preparedness' and identifying the possible deficiencies in current evacuation plans.

The following section describes in more detail the dynamics of evacuation procedures, followed by a description of the capabilities of various micro-simulation software packages. The advantages of the application to be used in this project are presented next along with a plan for the proposed research and anticipated benefits.

2.2 Dynamics of Evacuation Procedures

The most common disasters can be classified as either natural or non-natural (man-made) disasters. Natural disasters include earthquakes, hurricanes, floods, volcanic eruptions, fires, tsunamis. Man-made disasters may be accidental, including meltdowns or malfunctions of nuclear power plants or chemical factories, hazardous material spills either during transportation or on-site accidents, or intentional such as terrorist attacks. In developing response plans to such disasters it is important to understand how traffic will be impacted, especially in a densely populated area, for two main reasons: (i) to manage this traffic so that it does not impede with emergency operations and (ii) to develop effective evacuation plans for populations under threat while moving passing-by drivers out of the affected areas. Such models require capturing the fast evolving dynamic conditions taking into consideration street closures and infrastructure failures.

In addition, a catastrophe is an extraordinary event and the drivers confronted with it are not expected to behave, in the commonly accepted in

transportation planning, User Equilibrium and System Optimum behavior. This observation makes existing models not directly applicable to such an application. Finally, the impact of a major catastrophe or threat will impact very large parts of the network, which requires models that can function on large scale regional networks on reasonable computational time.

On the supply side of emergency evacuation modeling, the following issues must be considered:

- There is no possibility of increasing capacity for unusual demand patterns
- Operational modifications for better utilization of the available network capacity may be considered, such as re-design of the network with capacity reversibility (contraflow)
- Even with contraflow evacuation operations, capacity needs to be provided for emergency response vehicles to move toward the disaster location
- The network will typically be occupied by regular users who also need to be guided through the area safely, while minimizing their interaction with the emergency procedures

On the demand side, the following issues need to be considered:

- The O-D patterns change dynamically, as the travelers will be routed and/or re-routed to safer locations and will not necessarily travel to their initial destination
- The behavior of the drivers changes and cannot be captured by the typically used models of user equilibrium. Irrational behavior or guided routing need to be modeled
- The demand on the network (both background traffic and evacuee volume) will depend on the time of the day and day of the week
- Departure time for the evacuees may be part of the optimization procedures, especially in cases of staged operations and when demand mobilization durations are given

To the best of our knowledge no tool exists in the market that can capture all the above mentioned changes and model dynamically large network traffic conditions under threat. Thus, they are not applicable to modeling emergency evacuation traffic conditions. Furthermore, dynamic interactions between passenger cars and transit vehicles are not adequately modeled in the existing tools.

2.3 Use of Traffic Microsimulation Tools for Emergency Evacuation Decision Making

Currently available tools for proactive evacuation planning and analysis include the PBS&J model developed by PBS&J Inc, the Oak Ridge Evacuation Modeling System (OREMS) developed by Oak Ridge National Laboratory (ORNL) and the Dynamic Network Evacuation Planning System (DYNEV) developed by KLD Associate Inc. Currently, these tools are mostly used in the pre-planning analysis (pre-evacuation stage) and in the post-analysis procedure (post-evacuation stage). Given the location of an incident node and the emergency evacuation procedures, algorithms need to be developed for constructing the evacuation routes.

Traffic simulation models are already widely used to evaluate the impacts of highway projects, signal timing changes, and new developments. Microscopic models, such as CORSIM and Synchro/SimTraffic provide more realistic estimates of traffic performance than traditional traffic analysis methods because they simulate the performance of individual vehicles and incorporate the influence of traffic controls and roadway geometry. These models can also provide detailed outputs such as estimated travel times, delays, and travel speeds, measures that are useful for evaluating traffic performance and are more easily understood by non-transportation professionals. As mentioned above, the available evacuation models vary in their sophistication and ability to realistically model driver behavior. The majority of assignment models used as part of these evacuation models are static. These models though are not very adequate to capture the dynamics of an evacuation procedure since vehicles are assigned to specific travel paths at the beginning of a simulation and maintain those paths regardless of prevailing traffic conditions.

At the first level are models like SimTraffic, in which vehicle movements are defined by the user at the beginning of the simulation. Vehicle paths are generated stochastically based upon input turn movements and may not necessarily reflect realistic vehicle movements. For small networks this is ordinarily not a problem and stochastic models like SimTraffic function very well for purposes such as evaluating signal timings or localized traffic impacts.

At the next level are models that permit traffic assignment, such as CORSIM, VISSIM, PARAMICS. Instead of entering turning movements for each

intersection, the user inputs origin-destination trip tables, which specify trip generations and attractions at locations in the network. The model generates traffic volumes using these tables and assigns each vehicle an origin, destination, and optimum path as it enters the network. This tends to generate more realistic vehicle movements across the network and is useful for larger planning models. The limitation of CORSIM is that once a vehicle enters the network it is committed to the path to which it has been assigned, regardless of any traffic congestion or incidents. Over networks that each OD pair has a limited set of competitive paths this limitation may not be significant, but across networks where two or more paths become competitive with an increase in demand such a simplified traffic assignment approach will yield erroneous results. The essence of a traffic assignment model is to yield the potential paths that the travelers will use based on an existing network configuration and congestion. A pure traffic simulator is constrained by the assumption that the selected paths will not respond to changes in demand and/or supply.

Dynamic Traffic Assignment (DTA) models represent the new generation in traffic simulation (Peeta and Ziliaskopoulos, 2001), where vehicle paths are re-evaluated at regular intervals to allow individual vehicles to alter their paths to optimize their travel time. This yields more realistic simulation results by more accurately modeling driver behavior (i.e., choose a route based on available alternatives and current traffic conditions). DTA models therefore offer several advantages, over static simulation models, that include:

- More realistic modeling of vehicle movements and driver behavior,
- Realistic modeling of incidents and disruptions to traffic,
- Realistic modeling of the effects of Intelligent Transportation Systems (ITS) technologies and driver information systems,
- More accurate modeling of how changes to one route can affect traffic on other routes,
- Modeling movement of individual vehicles (i.e. travel time, delays, speed)

In this work, we use a DTA model called VISTA (Visual Interactive System for Transportation Algorithms) that can simulate the movements of multiple modes across large networks, incorporate the effects of ITS and traveler information

systems into driver behavior, and converge at a Dynamic User Equilibrium. As with CORSIM, the user of a DTA model can enter origin-destination trip tables specifying traffic generation for a given network. The DTA model then assigns each vehicle an origin, destination, and optimum path when it enters the network. Unlike CORSIM, a DTA model then re-evaluates vehicle paths at regular intervals and allows individual vehicles to alter paths in order to optimize their travel. This yields more realistic simulation results because it models what drivers actually do (i.e., choose a route based on available alternatives and current traffic conditions) versus what the modeler thinks they ought to do. VISTA is such a DTA model.

One unique feature of the VISTA model is that it is accessible over the Internet. The model is built, hosted, and operated on a cluster of computers accessible by any authorized user at any time over the Internet. Any authorized user can modify the model, run the model, and obtain the results using a typical web browser. Since the software application, model, and the database are located at a remote host the end user is relieved from the need of expensive equipment and software installation and upgrade that is a commonly observed issue with in-house software development. The proposed software setup also ensures a greater consistency in the analysis since all users have access to the same networks and model results. The proliferation of mobile devices (laptops, PDAs) provides an added incentive for users to have up to date VISTA data wherever they are located. This feature is an additional advantage of VISTA in developing and disseminating evacuation plan related information. It also makes it a good tool for table-top exercises and training applications.

In this chapter the literature review, the dynamics of evacuation procedures, and the use of traffic micro-simulation tools for emergency evacuation decision making were presented. The next chapter deals with the definition of the problem, its mathematical formulation and a case study on container terminals.

3. PROBLEM DEFINITION

This chapter deals with the description of the problem addressed in this work and the development of the solution method based on integer programming theory. The mathematical formulation of the problem along with its implementation on AMPL mathematical programming language is presented. Additionally, a case study on container terminals is presented, in order to demonstrate the usefulness of the proposed framework in practical situations.

3.1 *Problem Definition*

Emergency evacuation planning is a complex procedure that involves several tasks which include the following:

- Identifying safe locations to transport the evacuees often called shelters
- Routing the evacuation vehicles which transport the evacuees to shelters
- Designing traffic control over the transportation network

The evacuation routing models are vital to the evacuation planning problem because movement of evacuees may cause congestion on transportation networks. Evacuation planning therefore becomes critically important in order to foster emergency evacuation strategies in defining feasible evacuation routes and their traffic impacts on the existing transportation network.

The specific case of interest in this work is the evacuation of marine terminals during emergency conditions. Such conditions may involve radiological and nuclear threat materials, fire, dangerous chemical spill, weather, or accidental man-made emergencies, to mention a few. As a result of a number of serious natural and man-made disasters, emergency response plans have been developed by various agencies aiming at improving inter and intra-agency coordination and effectively and efficiently responding to emergency situations. Marine terminals have also devised plans for responding to such emergencies, including the evacuation of workers. Following the hazard identification stage, and assuming that evacuation of workers is warranted, this work focuses on the traffic operations portion of emergency response and specifically on the evaluation of traffic conditions during emergency evacuation.

A relevant example is that of the Port of Seattle incident in August of 2006, when a bomb-sniffing dog indicated that two cargo containers from Pakistan could contain explosives, prompting port authorities to set up a perimeter of about a half mile around the terminal. Although no explosives or radioactive materials were found, workers had to be evacuated.

From the perspective of transportation, the scope and breadth of the threat and the amount of advance warning time to move people to safety are keys to determining the size and urgency of an evacuation. During a dangerous chemical spill for example, typical actions include cordoning-off the area, evacuating upwind, informing emergency services and providing for their access to the site, directing traffic away from the incident and setting up roadblocks as necessary. In general, related issues in evacuation as specified by the FHWA include forecasting and modeling of evacuation; travel demand behavior; the costs and benefits of contraflow, secondary routes, intermediate crossovers for contraflow operations; the application of web-based systems for communicating real-time traffic conditions, shelter availability, and route guidance; effective re-entry of areas after evacuation; the development of micro- and macro-level traffic models to analyze bottlenecks and to evaluate scenarios, routing options, and contraflow strategies; and planning mass transit assets for evacuation. Some of these issues are relevant to the case of terminal emergency evacuations and are examined in this work.

One of the most significant issues associated with evacuation is the need to control travel demand. Influencing the number of evacuees on the roads becomes essential, especially given the fact that marine terminals are nearby major metropolitan areas and the highway network surrounding the terminals is typically congested. The adequacy of roadway capacity and mass transit assets needs to be assessed. As evacuation demand has a significant effect on speed and efficiency of operations, the use of large capacity vehicles, such as buses to maximize use of highway infrastructure should be examined. Demand and supply side measures are considered in the analysis presented herein, while enhanced communication and coordination are also key aspects of emergency operations, which are considered to be in place.

3.2 The Proposed Integrated Framework

In this work, we use a DTA model called VISTA (Visual Interactive System for Transportation Algorithms) that can simulate the movements of multiple modes across large networks, incorporate the effects of ITS and traveler information systems into driver behavior, and converge at a Dynamic User Equilibrium.

The proposed VISTA based framework (Tuydes, 2005) follows the typical transportation analysis process as shown in the following figure, with a sequence of trip generation, distribution and assignment of passenger and transit vehicles. However, each of these steps can be updated dynamically, to reflect the dynamic changes occurring on the network, both on the demand and on the supply side.

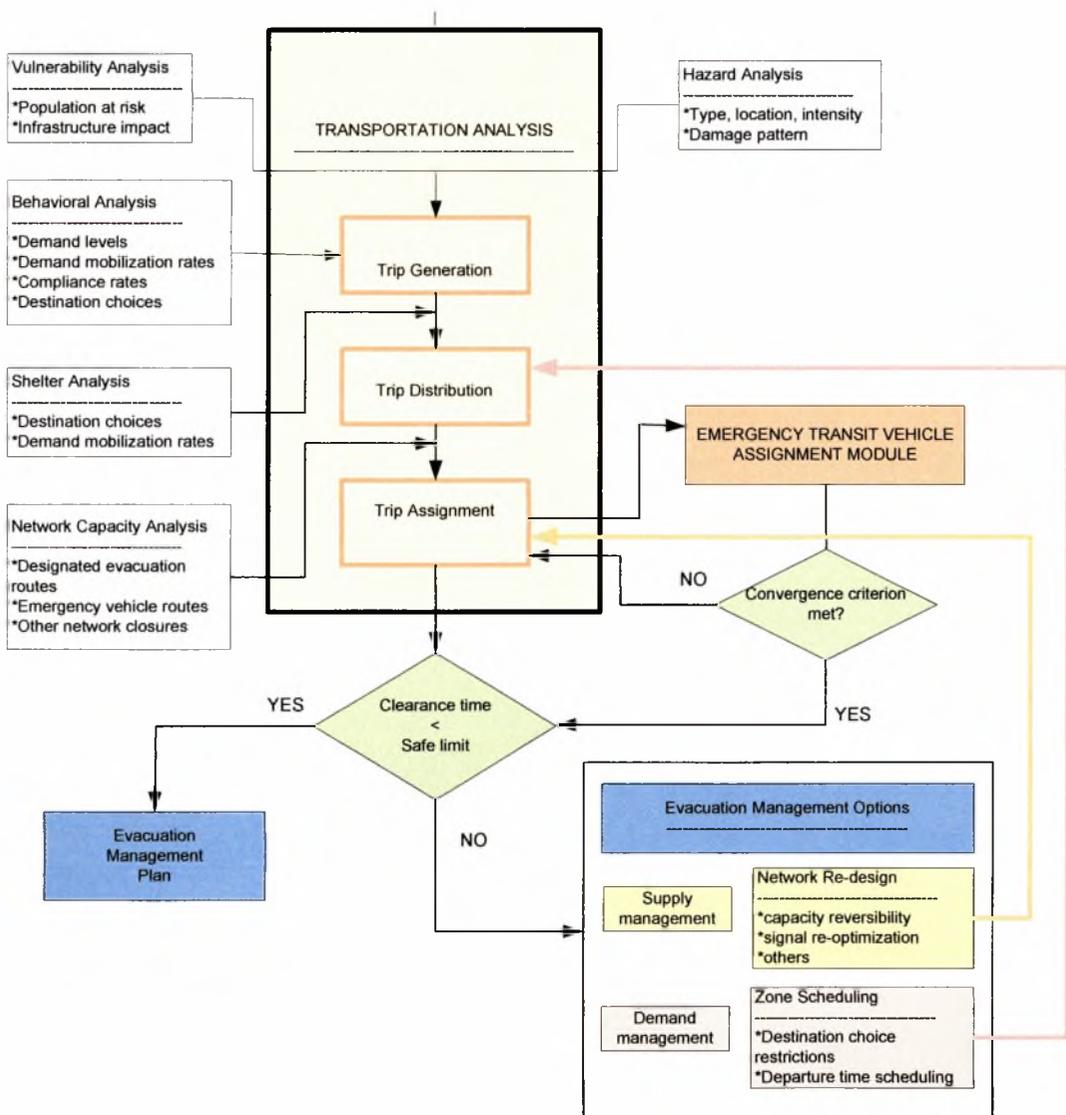


FIGURE 1 Transit Based Evacuation Traffic Management Framework.

The modeling framework, shown in figure 1, includes hazard and vulnerability analysis, which determine the type, location and intensity of the hazard and the damage pattern, as well as the population at risk and infrastructure impact. Behavioral analysis may change the standard trip generation procedure to capture the dynamic levels of demand and mobilization rates, compliance to the provided guidance and changing destination choices. Destination choices may change as a result of not only traveler decisions, but of emergency personnel guidance, which may dynamically define the safe zones and shelters for each cluster of evacuees. The evacuation routes may be updated and emergency vehicle routing and network closures may be captured as well.

An emergency transit vehicle assignment module is integrated with a VISTA-based emergency management framework, to assign each transit vehicle to a terminal evacuation point and after that to an accumulation point (shelter). Once the traffic assignment module has been completed, evacuation points, shelters, location of buses and route travel times are determined and entered into the emergency transit vehicle assignment module. Transit vehicle assignments to evacuation points and shelter sequences are determined and the resulting routes are fed back into the VISTA trip assignment module to re-estimate travel times. These iterations stop once the difference in travel time in subsequent routes becomes negligible. The clearance time is then estimated to determine whether it is within the acceptable limit. If not, various evacuation management options are considered. Otherwise the resulting evacuation management plan is implemented.

The model evaluates these dynamically changing data, under different evacuation management options, to produce evacuation management plans. The model may provide answers to questions such as:

- How long would it take to evacuate a cluster or a hub, given the number of evacuees and the number of evacuation vehicles, profile of the evacuation demand (varying by time of the day), background traffic on the network and time of the day?
- What percentage of the demand will be evacuated within a certain time window (subject to the conditions mentioned above)
- How do we cluster the evacuation region and what is the sequence of evacuation operations among the clusters?

- What is the optimal assignment of transit vehicles to specific clusters based on priority and demand?
- What is the benefit of using transit vehicles, instead of cars, for evacuation of certain clusters, in terms of savings in evacuation time and relief of congestion to the network?
- Decisions about staged evacuation over space and time, as well as evacuee profile.

The emergency transit vehicle assignment module (ETVAM-1) is formulated as follows:

$$\min \sum_i \sum_j \sum_k (VT_{ki} + BT_{ij}) X_{ijk} \quad (1)$$

$$s.t. \sum_j \sum_k C_k X_{ijk} - D_i \geq 0, \forall i \in I \quad (2)$$

$$\sum_i \sum_j X_{ijk} \leq 1, \forall k \in K \quad (3)$$

$$X_{ijk} \text{ binary} \quad (4)$$

Where k : number of transit vehicles

i : terminal evacuation points

j : accumulation points (shelters)

C_k : vehicle capacity

D_i : demand of each terminal evacuation point

VT_{ki} : distance between bus stops and terminal evacuation points

BT_{ij} : distance between terminal evacuation points and accumulation points

The objective function (1) minimizes the time it takes each vehicle to visit the terminal evacuation point and after that to visit the accumulation point (shelter). Constraints (2) ensure that the demand of each terminal evacuation point will be satisfied. Constraints (3) ensure that each vehicle will visit only one terminal evacuation point and constraints (4) ensure that the decision variables are binary.

In the case analyzed above each bus visits each evacuation point only once. In what follows the mathematical formulation for the more general case of the terminal evacuation problems is presented. This formulation considers several evacuation areas with certain demand that need to be evacuated by the same fleet of

vehicles that are operating in a known bus route. The vehicles are considered to be identical. The evacuees will be transferred to several shelter locations each one with infinite capacity that are considered a priori known. The objective of the problem is to transfer all the evacuees to shelter locations in the fastest possible manner.

In order to formulate the problem, we consider a set I of evacuation areas that need to be served and a set J of shelters. In addition, we consider that all vehicles (k) are identical and vehicle travel times are deterministic. The vehicle travel time consists of the time taken for each vehicle to access an evacuation area from its starting point on the bus route (a_{ik}) and the time taken to transfer the evacuees from the evacuation point to a shelter (p_{ij}).

Furthermore, in our problem there are I evacuation areas, J shelters and K vehicles. The location of each vehicle, evacuation area and shelter are considered a priori known. The sequence of visiting each evacuation area and each shelter is crucial in our problem. Therefore we introduced another parameter which denotes the time periods (T). For each time period we assume that the vehicle performs two different transfers. The first one is to visit an evacuation area in order to collect some evacuees and the second one is to visit a shelter in order to transfer the evacuees to a safe location. For this reason, the number of time periods needed in order to complete the evacuation procedure is given as $T_{\max} = I - K + 1$. At this point, it must be referred that the starting and the ending point of the time period, as well as the duration of the time period might differ for each vehicle. The meaning of this parameter is to keep a record of the visiting sequence of each evacuation area and shelter for every vehicle.

The variables of the formulation are all binary. For $i=1, \dots, I$, $j=1, \dots, J$, $k=1, \dots, K$ and $t=1, \dots, T$, let

$$A_{ik} = \begin{cases} 1, & \text{if vehicle } k \text{ is assigned to evacuation area } i \\ 0, & \text{otherwise} \end{cases}$$

$$E_{ijkt} = \begin{cases} 1, & \text{if vehicle } k \text{ is assigned from evacuation area } i \text{ to shelter } j \text{ at time } t \\ 0, & \text{otherwise} \end{cases}$$

$$P_{ijkt} = \begin{cases} 1, & \text{if vehicle } k \text{ is assigned from shelter } j \text{ to evacuation area } i \text{ at time } t \\ 0, & \text{otherwise} \end{cases}$$

$$W_{jkt} = \begin{cases} 1, & \text{if vehicle } k \text{ stops at shelter } j \text{ at time } t \\ 0, & \text{otherwise} \end{cases}$$

The emergency transit vehicle assignment module (ETVAM-2) is formulated as an integer programming model as follows.

min M

$$M \geq \sum_i a_{ik} A_{ik} + \sum_i \sum_j \sum_t p_{ij} (P_{ijkt} + E_{ijkt}), \forall k \quad (1)$$

$$\sum_j E_{ijkt} = A_{ik}, \forall i, k \quad (2)$$

$$P_{ijkt} = 0, \forall i, j, k \quad (3)$$

$$\sum_i A_{ik} \leq 1, \forall k \quad (4)$$

$$\begin{aligned} \sum_j \sum_k \sum_t P_{ijkt} + \sum_k A_{ik} &\leq (D_i / cap) + 1, \forall i \\ \sum_j \sum_k \sum_t P_{ijkt} + \sum_k A_{ik} &\geq (D_i / cap) - 1, \forall i \end{aligned} \quad (5)$$

$$\sum_j \sum_t W_{jkt} \leq 1, \forall k \quad (6)$$

$$\sum_i E_{ijkt} - \sum_i P_{ijkt+1} - W_{jkt} = 0, \forall j, k, t(1, \dots, T-1) \quad (7)$$

$$\sum_j P_{ijkt} - \sum_j E_{ijkt} = 0, \forall i, k, t(2, \dots, T) \quad (8)$$

$$\sum_i \sum_j P_{ijkt} \leq 1, \forall k, t(1, \dots, T) \quad (9)$$

$$\sum_i \sum_j E_{ijkt} \leq 1, \forall k, t(1, \dots, T) \quad (10)$$

$$E_{ijkt}, P_{ijkt}, A_{ik}, W_{jkt} \text{ binary } \forall i, j, k, t \quad (11)$$

The objective function minimizes the quantity M which is constrained by equation (1). Constraints (1) find the maximum time it takes each one of the vehicles to finish with its assigned tasks. Constraints (2) ensure that the vehicle that visited an evacuation area from a start point, the same vehicle will be assigned from that evacuation area to a shelter j . Constraints (3) ensure that the first time period ($t=1$) none of the vehicles will go from any shelter to any evacuation area. Constraints (4) ensure that each vehicle will visit at most one demand point from its initial position. Constraints (5) ensure that the total number of times each demand point will be visited, either by a vehicle which starts from its initial position or by a

vehicle which starts from a shelter depends, on its demand and the vehicle capacity. Constraints (6) ensure that the vehicle that is at a shelter at time period t , will be assigned to an evacuation area at time period $t+1$ from that shelter unless it stopped its operation at time t at that specific shelter. Constraints (7) ensure that a vehicle leaves a shelter to visit an evacuation area at time period $t+1$, if the previous time period t the same vehicle visited the specific shelter unless it stopped at that shelter. Constraints (8) ensure that the vehicle that visits an evacuation area at time period t , will return to a shelter from the specific evacuation area at time period t . Constraints (9) ensure that each vehicle will visit only one evacuation area at a certain time period t . Constraints (10) ensure that each vehicle will visit only one shelter at a certain time period t . Finally, constraints (11) ensure that the decision variables are binary.

The terminal evacuation problem falls in the category of NP hard problems. In what follows, we show that the problem can be transformed to the Traveling Salesman Problem (TSP) to prove NP-completeness. The techniques used for proving NP-completeness vary almost as widely as the NP complete problems themselves. However, there are several general types of proofs that occur frequently and can provide a suggestive framework for deciding how to go about proving a new problem NP-complete. The technique that we use in this work is called “restriction”. An NP-completeness proof by restriction for a given problem $\Pi \in NP$ consists of showing that Π contains a known NP-complete problem Π' as a special case (Garey and Johnson, 1979).

Proposition 1: ETVAM is NP-Complete

Proof: Given an arbitrary instance of the TSP problem, we construct a corresponding instance of the terminal evacuation problem with one transit vehicle and one shelter with infinite capacity. We assume that the demand of each evacuation area is equal or smaller than the capacity of the vehicle. We also assume that the start point of the vehicle is the shelter. Let an arbitrary instance of our problem be given by the graph $G = (V, A)$, where $V = \{s, 1, 2, 3\}$ the nodes and $A = \{s1, s2, s3, 1s, 12, 13, 2s, 21, 23, 3s, 31, 32\}$ the arcs of the graph. Let the costs $C_{ij} \forall i, j \in V$ of the arcs given by the mathematical equation $C_{ij} = C_{ik} + C_{kj} \forall i, j \in V$ (1). We also assume for our problem that $C_{ij} = C_{ji} \forall i, j \in V$, which means that the

costs matrix is symmetric. Then, we suppose that there exists an algorithm A, which gives a sequence of visiting the nodes of the network $t:U \rightarrow \{T,F\}$ satisfying TSP. We show that t can be extended to a truth assignment $t':U' \rightarrow \{T,F\}$ satisfying our problem.

In our problem the vehicle starts from the shelter point (node s) and must visit each other point in the network returning each time at the shelter. This corresponds to a total cost $2 * C_{ij} \forall i = s, j \in V / s$ (Figure 5). The total cost of the TSP problem is given by the equation $C_{si} + C_{ij} + C_{jk} + C_{ks} \forall i, j, k \in V, i \neq j \neq k$ (2). From equation (1) and equation (2) results that the total costs for the TSP is $2 * C_{ij} \forall i = s, j \in V / s$ (Figure 2).

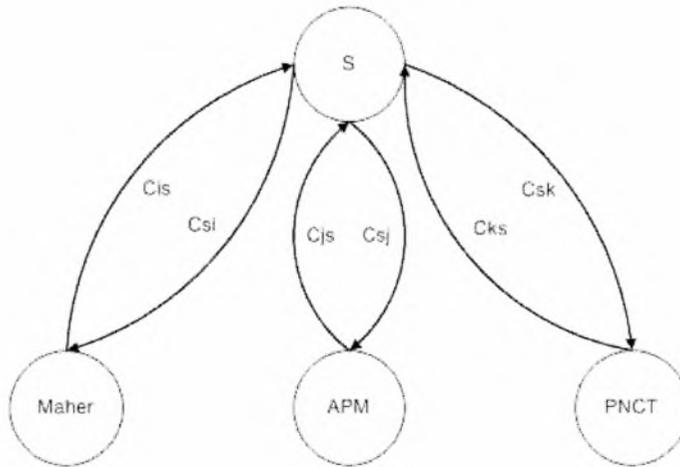


FIGURE 2 The cost of the Terminal Evacuation Problem.

Since the solution resulted from our problem is the solution of the TSP problem, then we can say that this special case of the terminal evacuation problem resulted from the restriction technique is at least as hard as the TSP problem.

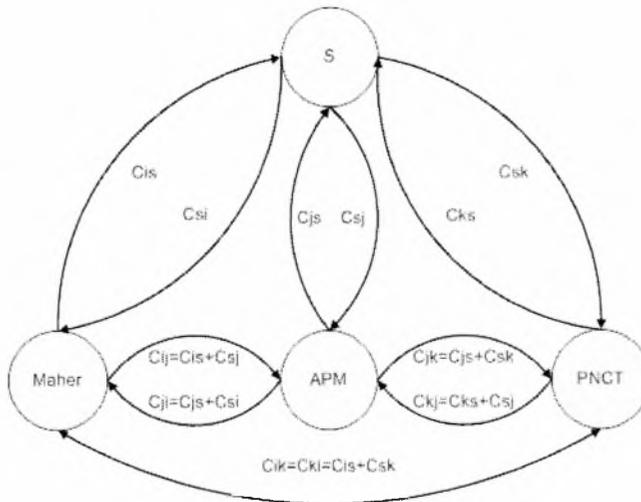


FIGURE 3 The Cost of the TSP problem.

3.3 Case Study on Container Terminals

To demonstrate the usefulness of the proposed framework a case study involving the evacuation of marine terminals, facilities that are typically located nearby densely populated urban areas, is considered in this work.

The region to be studied in this work is modeled after the Port Newark-Elizabeth area, shown in Figure 1. The Port Newark-Elizabeth comprises the PNCT, Maher and APM marine terminals (indicated as points 1, 2 and 3 in figure 4) and other port related facilities. The site is located between the cities of Newark and Elizabeth and is nearby major retail facilities, such as the Jersey Gardens Mall (point B in figure 4) and the IKEA Elizabeth furniture store complex (point A in figure 4). The area of interest is served by a dense transportation system, including the New Jersey Turnpike (I-95), I-78, Rt 1&9 and several other access and local roads. This network is heavily congested during several hours on a typical week day, with small variation in the directional traffic peak. During weekends, the major highways in the area serve recreational and social trips by New Yorkers travelling towards the south part of New Jersey on I-95 and towards Pennsylvania, on I-78.



FIGURE 4 Case Study Region.
(Source: Google Maps)

The terminals operate on a 24-hour basis, meaning that during an emergency, there will be a number of workers to be evacuated. This demand depends on the time of the day and day of the week. For example, terminal gates are

open weekdays, 8am – 12pm and 1pm – 5pm at Maher Terminals, 6am – 4pm at PNCT and 6am – 4:30pm at APM. During hours that the terminal gates are closed, there are waterfront operations taking place. As a result, the profile of demand to be evacuated from the terminals varies by time of the day. A rough estimate of the number of workers at the terminal during a typical week day is shown in figure 5.

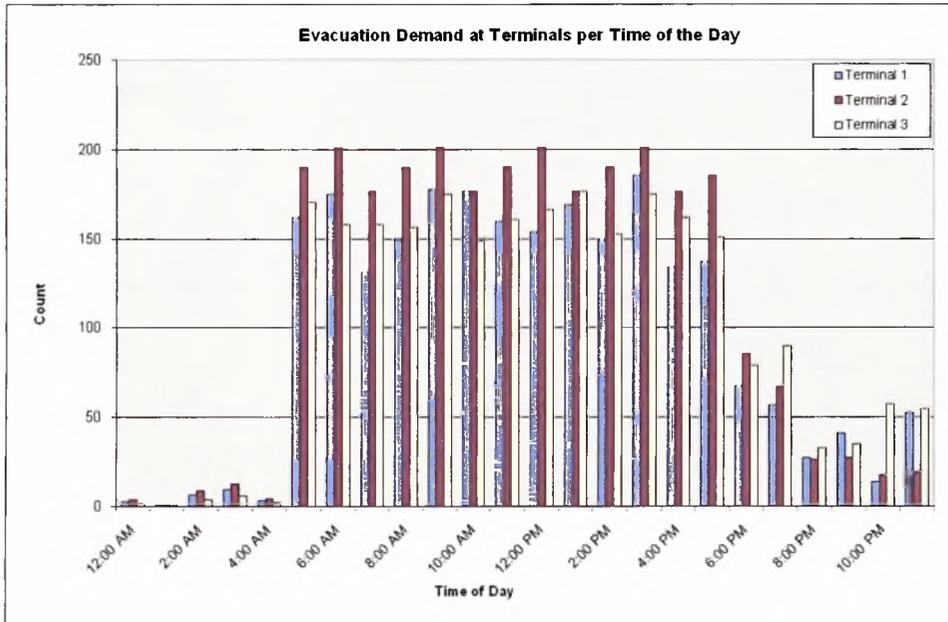


FIGURE 5 Demand Profile Estimate at Port Newark-Elizabeth Terminals.

New Jersey Transit buses operate on the case study network. The transit routes and bus stops for each route are shown in Figure 6.

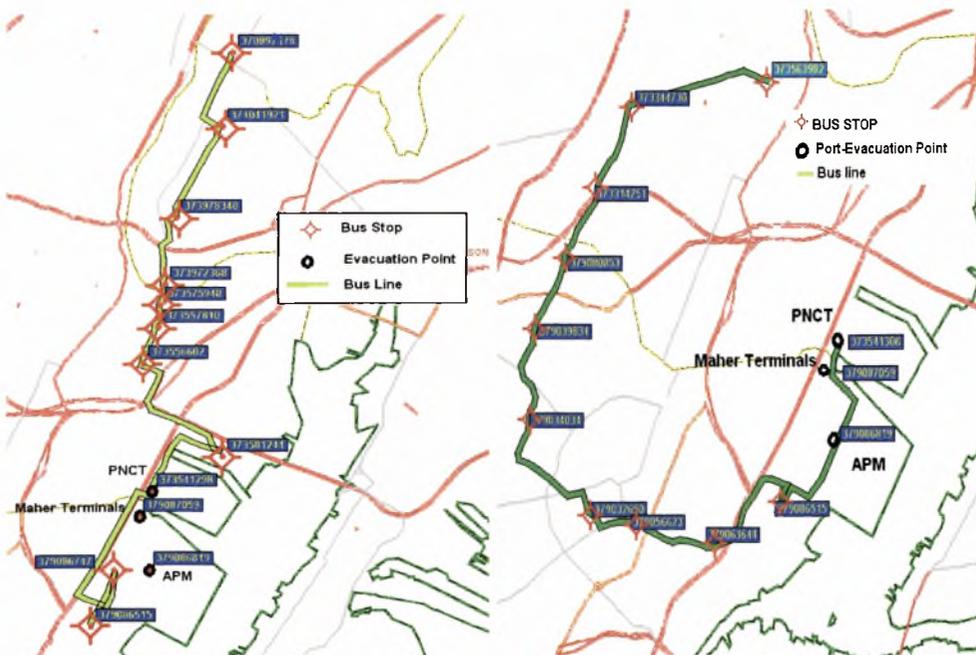


FIGURE 6 New Jersey Transit Bus Routes Serving the Study Area.

Based on the service frequency for the two routes and their scheduled arrivals at each bus stop, VISTA gives the location of vehicles along their routes. We consider the case of a threat that warrants evacuation of all three terminals, with advanced warning. Collection points are specified inside the terminals in case of an incident. Workers are expected to gather at these designated points. For the purpose of this work and to simplify the analysis without loss of generality, we assume that all workers inside each terminal will gather at one point, marked as point 1 (PNCT), 2 (Maher) and 3 (APM) in figure 4. Assuming that the impact of the incident will be felt locally, points A and B are designated as the safe shelters during this operation, which for the purposes of this work are assumed to have infinite capacity.

Once the threat has been assessed and the decision to evacuate the terminals deploying bus transit vehicles has been made, bus drivers are notified. The drivers will go to the nearest bus stop in their route, drop off the passengers and proceed to access one of the collection points at the terminal. Evacuees will board on the vehicles and will be transferred to one of the designated safe shelter sites. Depending on the number of evacuees and the number of buses available and/or deployed during the operation and the response time, a bus may return to the regular transit operation or return to the collection point for a second trip, after dropping off the evacuees. Bus riders that have been dropped off at a bus stop that was not near their intended destination will be picked up by subsequent buses that have not been deployed for the emergency operation, or by the same bus that will return after performing the emergency operation. The collection point and the subsequent safe shelter assignment for each bus is determined based on the location of the bus stop and its distance from each of the points, as well as on traffic conditions on the roadways during that time. The emergency transit vehicle assignment module is used for this purpose. VISTA is used to determine the probable traffic conditions on the roadway during the time of the incident.

The case study region is part of a large scale network micro-simulation model that has been developed in the context of this thesis. Based on this model, the probable traffic conditions in the region at the time of the event may be determined and the fastest route for each of the deployed buses to access the closest collection point and from there the safe shelters is estimated. VISTA has the capability to be used as an on-line tool, receiving real time traffic information. If this feature is

activated, the model will be able to give real time traffic conditions at the time of the event. In this application we use the typical traffic conditions based on historical data. This problem is not trivial as traffic dynamics vary by time of the day and VISTA is used to capture these dynamics and develop the optimal bus routes under different traffic conditions. In addition, the safe shelter location to be assigned to each of the collection points will be determined dynamically, and may vary depending on the directional peak traffic on the highway network.

The time from the bus driver notification to the bus arrival at the assigned collection point, embarkation of evacuees on the buses and arrival to the assigned shelters is estimated. The number of buses to be deployed depends on the demand to be evacuated. Depending on the time of the day, several cases may arise. For example:

- There is adequate number of buses in the vicinity of the terminals and they will all be deployed to perform the evacuation procedures and move terminal workers to the safe location with one trip per bus, in the fastest possible manner. (Buses will then return to the bus stop to resume their transit operations.)
- The bus vehicle capacity is limited compared to the evacuation demand, in which case more than one trips per bus may be required by all buses operating in the area of the event.
- The time window during which the terminals must be evacuated is large enough for a limited number of buses which will perform more than one round trip from the terminal to the shelters to be deployed, leaving additional buses to operate on the regularly scheduled transit routes. In this case the optimal number of buses will be determined.

Depending on the prevailing conditions, the proposed VISTA based framework may be used to answer several questions, including:

- How long it will take from the time the bus drivers are notified till all terminal employees have reached a safe location?
- How long will the dropped off passengers have to wait at the bus stations?

- How many buses from each of the near by bus routes need to be deployed so as to safely evacuate terminal workers while minimizing disruptions in transit operations?
- How many people will be evacuated during a certain time window under different bus deployment scenarios?

In this chapter we presented the problem and proposed two exact resolution algorithms. We show that the problem is NP-Hard and present a case study on container terminals. In the next chapter we present the experiments and the results of the two above-mentioned algorithms.

4. COMPUTATIONAL RESULTS

In this chapter the results of the exact resolution algorithms proposed in chapter 3 are presented. The exact algorithms were implemented in AMPL mathematical language and solved by CPLEX solver. Additionally, a heuristic approach for the ETVAM is presented along with its results. The heuristic algorithm was implemented in FORTRAN. Three different scenarios were modeled and analyzed below.

4.1 *Transit Vehicle Assignment Module's Results (ETVAM-1)*

For demonstration purposes, the first scenario, in which there is adequate number of buses in the vicinity of the terminals and they will all be deployed to perform the evacuation procedures and move terminal workers to the safe location with one trip per bus, in the fastest possible manner is modeled. Considering that one terminal bus will be available at each of the evacuation points and given that VISTA shows another 13 vehicles in the vicinity of the terminals, the travel time from the bus location at the time of the incident to the evacuation point is estimated as shown in Table 1.

TABLE 1 Bus location to evacuation point travel time

VT	Maher	APM	PNCT
Vehicle 1	5	20	20
Vehicle 2	20	5	20
Vehicle 3	20	20	5
Vehicle 4	15.42	9.42	17.1
Vehicle 5	17.58	23.64	16.68
Vehicle 6	20.34	26.4	19.44
Vehicle 7	11.49	14.49	11.01
Vehicle 8	12.42	15.42	11.97
Vehicle 9	16.11	19.11	15.63
Vehicle 10	20.49	23.49	20.01
Vehicle 11	18.57	17.22	16.41
Vehicle 12	15.96	13.26	18.96
Vehicle 13	16.68	15.33	18.21
Vehicle 14	12.99	11.64	14.52
Vehicle 15	18.78	27.48	10.38
Vehicle 16	22.74	20.04	25.74

The travel time from each terminal to each of the safe shelters is given in Table 2 while the number of evacuees at each of the terminals during the time of the incident is given in Table 3.

TABLE 2 Evacuation point to safe shelter travel time

Terminal	Safe Shelter A	Safe Shelter B
Maher	17.1	16.68
APM	18.54	15.33
PNCT	13.62	25.74

TABLE 3 Evacuation demand at each terminal

Terminal	Demand
Maher	200
APM	185
PNCT	170

Considering that vehicle capacity is 60 persons per vehicle, the following vehicle-to-terminal-to-safe shelter assignment results have been obtained using an exact resolution algorithm (CPLEX) and are shown in Table 4. The results indicate that four buses (Vehicle 1, Vehicle 8, Vehicle 9, and Vehicle 13) will serve Maher Terminals and will move the evacuees to shelter B; four buses (Vehicle 2, Vehicle 4, Vehicle 12, and Vehicle 14) will serve APM terminal and will move evacuees to shelter B; and three buses (Vehicle 3, Vehicle 7, and Vehicle 15) will serve PNCT and will move evacuees to shelter A. Based on the conditions considered in the analysis, the fastest evacuation time is that of vehicle 3, which will move people from PNCT to shelter A, while the longest evacuation time is that of vehicle 13, which will move people from Maher Terminal to shelter B. The evacuation will be completed within about 34 minutes, while more than half of the demand will be evacuated within 25 minutes.

TABLE 4 Vehicle Assignment Using CPLEX

Vehicle	Shelter A	Shelter B	Shelter A	Shelter B	Shelter A	Shelter B
	APM		Maher		PNCT	
Vehicle 1	0	0	0	1	0	0
Vehicle 2	0	1	0	0	0	0
Vehicle 3	0	0	0	0	1	0
Vehicle 4	0	1	0	0	0	0
Vehicle 5	0	0	0	0	0	0
Vehicle 6	0	0	0	0	0	0
Vehicle 7	0	0	0	0	1	0
Vehicle 8	0	0	0	1	0	0
Vehicle 9	0	0	0	1	0	0
Vehicle 10	0	0	0	0	0	0
Vehicle 11	0	0	0	0	0	0
Vehicle 12	0	1	0	0	0	0
Vehicle 13	0	0	0	1	0	0
Vehicle 14	0	1	0	0	0	0
Vehicle 15	0	0	0	0	1	0
Vehicle 16	0	0	0	0	0	0

4.2 Heuristic Approach's Results

In order to be able to solve the ETVAM we propose the following heuristic. The algorithmic steps shown in the figure below can be described as follows.

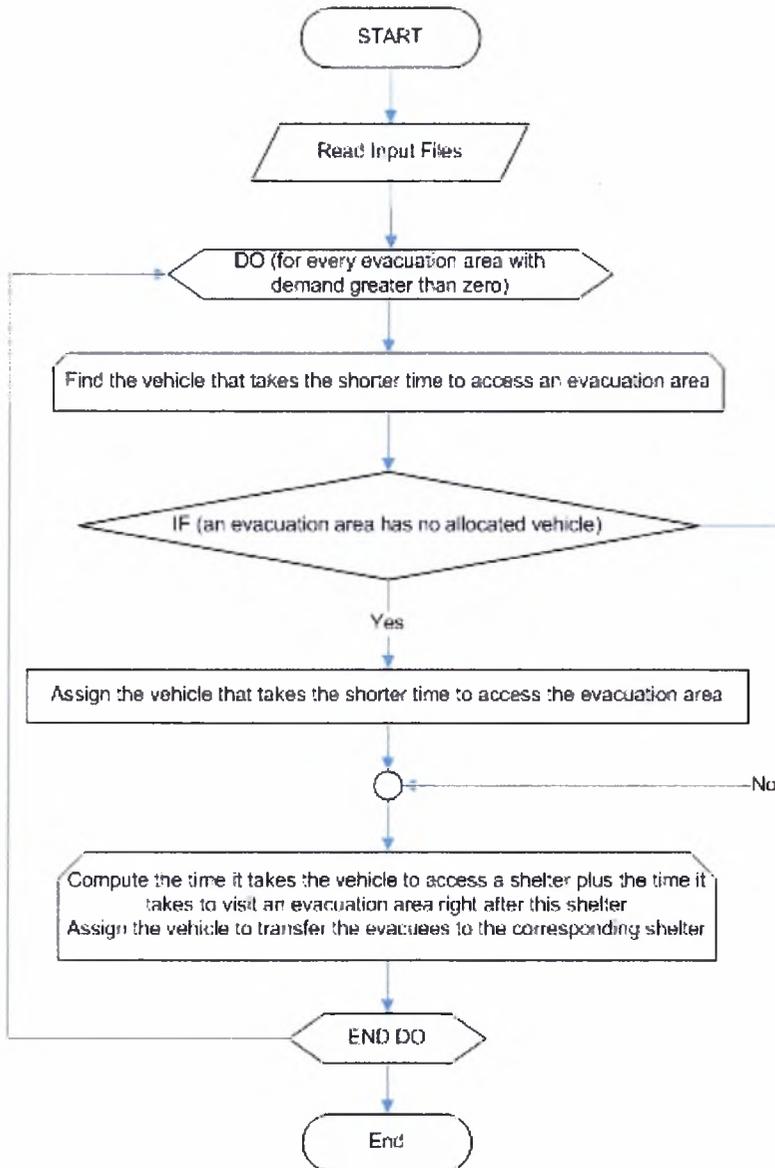


FIGURE 1 Algorithmic Implementation.

Step 1: Check which evacuation areas have demand greater than zero and find the vehicles that are closer to the evacuation areas

Step 2: Check which evacuation areas have no vehicles allocated and assign the vehicle that takes the shorter time to access that evacuation area

Step 3: Compute the time it takes a vehicle to access a shelter including the time it takes to visit the next evacuation area.

The last step forces the algorithm to optimize the distance between an evacuation area and a shelter and at the same time look one step ahead to the next evacuation area that must be visited by the same vehicle and assign the vehicle according to the path with the minimum traveled time. The proposed heuristic was implemented in FORTRAN.

For demonstration purposes, we consider three different scenarios with different number of available evacuation transit vehicles. Under the first scenario an adequate number of buses in the vicinity of the terminals are available so that terminal workers will be moved to the safe locations with one trip per bus, in the fastest possible manner. Under the second scenario these number is reduced to half, and under the third scenario this number is decreased to three. All three scenarios are modeled for peak demand.

Table 5 shows the results obtained from the proposed heuristic algorithm under the first scenario, which was also solved by the exact resolution algorithm above. We see that the results obtained from the exact algorithm are very close to the results obtained from the heuristic algorithm. The evacuation will be completed within 33.36 min while the last evacuees will be picked-up from the evacuation area after 16.68 min the evacuation started.

TABLE 5 Vehicle Assignment for Scenario A Using the Heuristic Algorithm

Vehicle	From	To (Evacuation Area)	Time to Evacuation Area	To (Shelter)	Time to Shelter
Vehicle 1	Start	Maher	5.00	B	21.68
Vehicle 2	Start	APM	8.00	B	23.33
Vehicle 3	Start	PNCT	5.00	A	18.62
Vehicle 4	Start	APM	9.42	B	24.75
Vehicle 5	-	-	-	-	-
Vehicle 6	-	-	-	-	-
Vehicle 7	Start	PNCT	11.01	A	24.63
Vehicle 8	Start	Maher	12.42	B	29.10
Vehicle 9	Start	Maher	16.11	B	32.79
Vehicle 10	-	-	-	-	-
Vehicle 11	-	-	-	-	-
Vehicle 12	Start	APM	13.26	B	28.59
Vehicle 13	Start	Maher	16.68	B	33.36
Vehicle 14	Start	APM	11.64	B	26.97
Vehicle 15	Start	PNCT	10.38	A	24.00
Vehicle 16	-	-	-	-	-

Table 6 shows the same information as table 5, but for the second scenario, where the number of available vehicles are half than the first scenario. Under the second scenario some of the emergency vehicles will need to perform more than one trip. For example vehicle 1 will travel from its original point to Maher Terminal, return to shelter B and then travel back to APM Terminal before ending its tour to shelter B. As expected the evacuation time increases and the evacuation will be completed within 53.99 min.

TABLE 6 Vehicle Assignment for Scenario B Using the Heuristic Algorithm

Vehicle	From	To (Evacuation Area)	Time to Evacuation Area	To (Shelter)	Time to Shelter
Vehicle 1	Start	Maher	5.00	B	21.68
	B	APM	37.01	B	52.34
Vehicle 2	Start	APM	8.00	B	23.33
	B	APM	38.66	B	53.99
Vehicle 3	Start	PNCT	5.00	A	18.62
	A	Maher	35.72	B	52.40
Vehicle 4	Start	APM	9.42	B	24.75
Vehicle 5	Start	Maher	17.58	B	34.26
Vehicle 6	Start	Maher	20.34	B	37.02
Vehicle 7	Start	PNCT	11.01	A	24.63
Vehicle 8	Start	PNCT	11.97	A	25.59

Finally, Table 7 shows the same information as tables 5 and 6, but for the third scenario, where the only available vehicles are the vehicles at the terminals. Similar to the second scenario these vehicles will make more than one trip and the evacuation completion time will increase to 116.36 min.

TABLE 7 Vehicle Assignment for Scenario C Using the Heuristic Algorithm

Vehicle	From	To (Evacuation Area)	Time to Evacuation Area	To (Shelter)	Time to Shelter
Vehicle 1	Start	Maher	5.00	B	21.68
	B	APM	37.01	B	52.34
	B	APM	67.67	B	83.00
	B	Maher	99.68	B	116.36
Vehicle 2	Start	APM	8.00	B	23.33
	B	APM	38.66	B	53.99
	B	Maher	70.67	B	87.35
Vehicle 3	Start	PNCT	5.00	A	18.62
	A	PNCT	32.24	A	45.86
	A	PNCT	59.48	A	73.10
	A	Maher	90.20	B	106.88

Finally, we enhanced our heuristic approach in order to take under consideration some policy issues related to our problem. These policy issues may include service priority of an evacuation area, number of vehicles visiting a specific evacuation area, etc. For this reason, we developed two more versions of the

heuristic approach apart from the first one, which assigns the vehicles according to the closest distance.

The second version of the heuristic, assigns at the start of the evacuation process at least one vehicle to each evacuation area. After the first assignment, the algorithm chooses the next evacuation area to be visited according to the shorter time it takes the vehicle to access a shelter plus the time it takes to visit the next evacuation area.

The third version of the algorithm, is a little more complex than the two previous ones. This version computes every time the number of vehicles to assign according to the demand of the evacuation area. As the algorithm proceeds and the demand is reduced in every step, the algorithm computes the number of vehicles to assign according to the new demand. After having assigned the specified number of vehicles the next job of the vehicle is chosen according to the shortest time it takes the vehicle to access a shelter plus the time it takes to visit the next evacuation area, as in the other two versions. In this way, we assure that each evacuation area will be served by a given priority which is defined by the current demand of evacuees.

Table 8 shows the results we obtained from the three versions of the heuristic algorithm for exactly the same problem. We observe that the three versions of the problem give almost the same results except for the case of the 3rd version with 3 vehicles. In this case we see that the version 3 of the algorithm presents better results regarding the makespan while the computational time remains the same.

TABLE 8 Results of the three versions of the proposed heuristic algorithm

	Version 1		Version 2		Version 3	
	Makespan	Computational Time	Makespan	Computational Time	Makespan	Computational Time
3 vehicles	116.36	0.02 sec	116.36	0.02 sec	113.66	0.02 sec
8 vehicles	53.99	0.02 sec	53.99	0.02 sec	53.99	0.05 sec
16 vehicles	33.36	0.03 sec	33.36	0.02 sec	33.36	0.02 sec

4.3 Transit Vehicle Assignment Module's Results (ETVAM-2)

In this section the data for which the emergency transit vehicle assignment module (ETVAM-2) was solved and the corresponding results are presented. The data are randomly selected and solve small instances of the problem to show its correctness and usefulness.

In the conducted experiments, we want to capture the change of the objective function and the computational time to the change of the problem parameters. Such parameters are the number of evacuation areas, the number of shelters, the number of available vehicles as well as the capacity of the vehicles and the number of time periods needed to complete the evacuation procedures.

In the first experiment we want to capture the change of the objective function and the computational time to the change the number of evacuation areas that need to be served. In order to conduct this experiment, we keep the number of shelters and the number of vehicles constant. Additionally, the capacity of the vehicles remains the same while the number of time periods changes according to the equation used to calculate it. In Figure 8 we see that the objective function increases almost linearly as the number of evacuation areas increases.

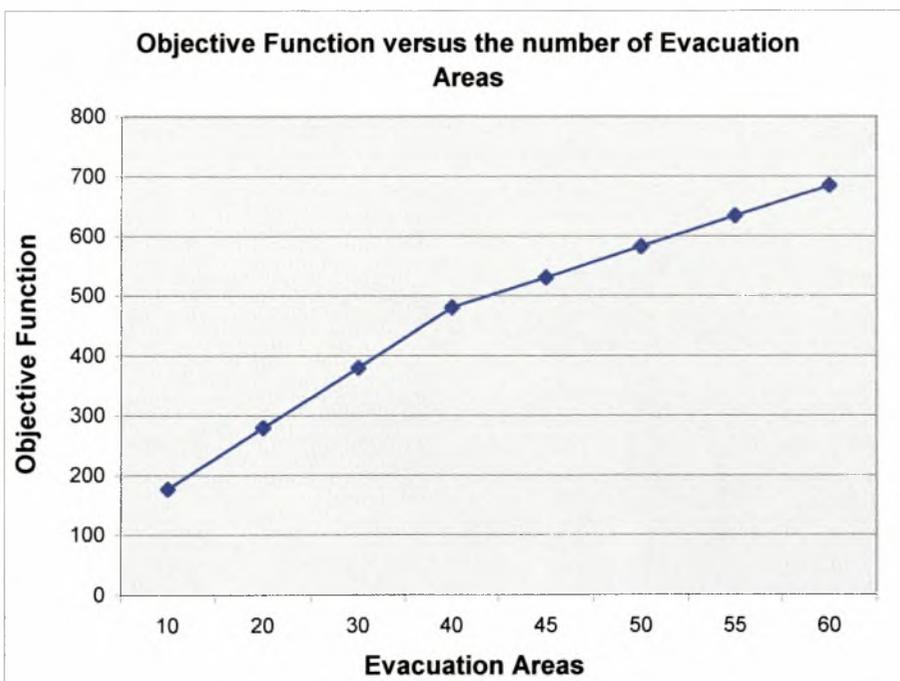


FIGURE 8 Objective Function versus the Number of Evacuation Areas

In Figure 9 we see that the computational time increases as the number of evacuation areas increases.

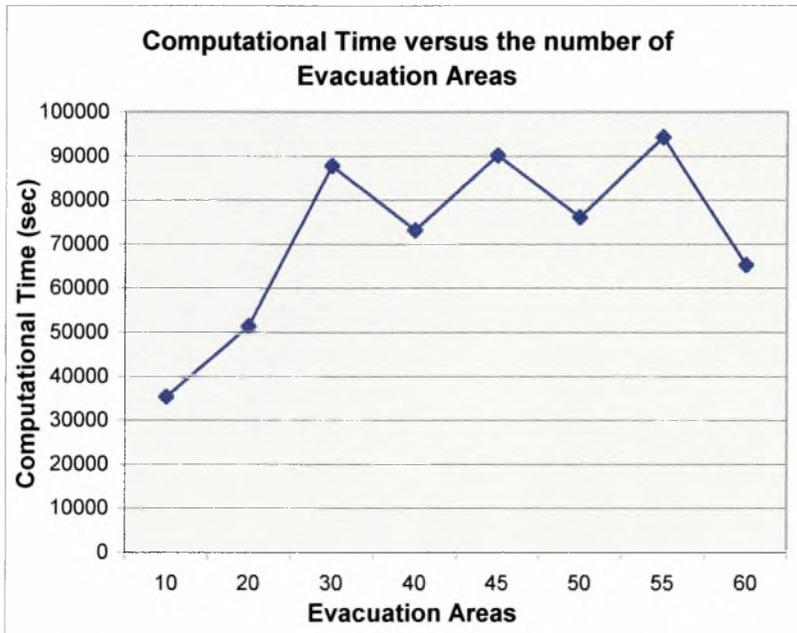


FIGURE 9 Computational Time versus the Number of Evacuation Areas

The next experiments were conducted in order to capture the change of the objective function and the computational time to the change of the vehicle capacity and the number of time periods. The vehicle capacity increases by 10 for each conducted experiment while the minimum vehicle capacity was 50 and the maximum was 100. Figure 10 shows the change of the objective function value and that of the computational time to the increase of vehicle capacity.

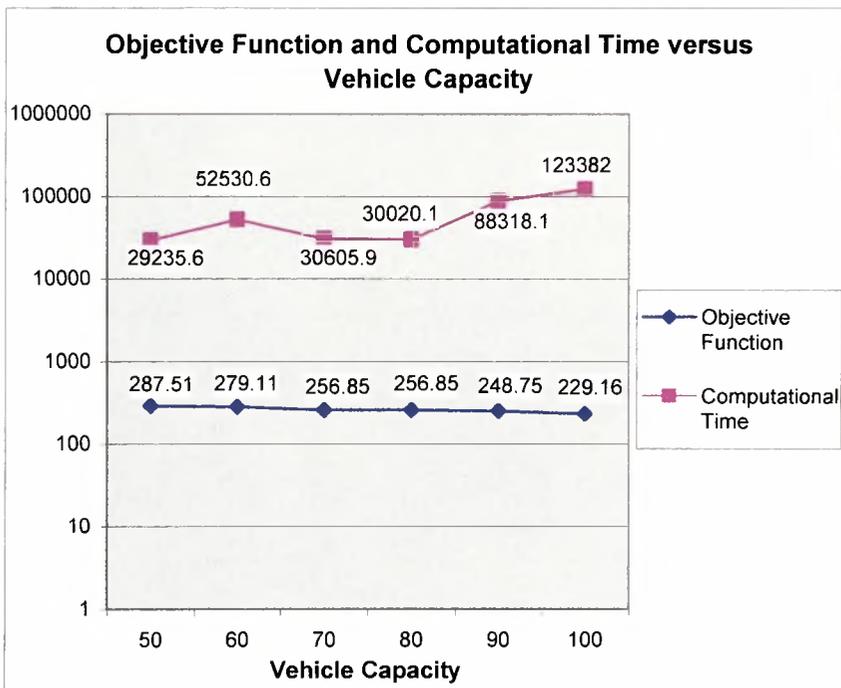


FIGURE 10 Objective Function and Computational Time versus the Vehicle Capacity

As expected the objective function value decreases while the computational time increases as the vehicle capacity increases. For the above and the following plot we used a logarithmic scale on the Y axis, due to the large range of the data.

Figure 11 shows the change of the objective function and that of the computational time to the change of the number of time periods. In the first experiment conducted, the number of time periods is based on the equation proposed to calculate it. This is the maximum number of time periods needed and it was calculated to 18 time periods. The results of the first experiment showed that the evacuation was completed in 11 time periods. This is the reason that the results shown in Figure 11 were computed assuming in each experiment that the number of time periods increases by one.

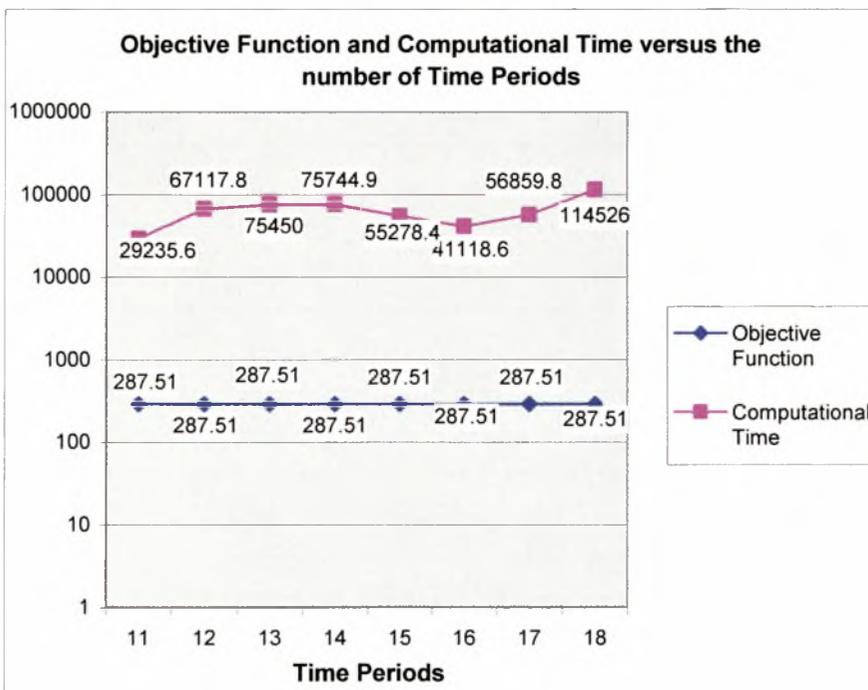


FIGURE 11 Objective Function and Computational Time versus the Number of Time Periods

As expected the results show that the objective function value does not change as the number of time periods increases while the computational time increases.

Until now we see that the computational time increases fast to the change of any parameter of the problem analyzed above. On the other hand, the objective function's value increase or decrease depends on which parameter changes. For example, the objective function value increases as the number of evacuation areas

increases, decreases as the vehicle capacity increases and remains unchanged as the number of time periods increases.

These results are all reasonable and can be justified as follows. The increase in computational time can be easily justified by the fact that we increase the complexity of the problem each time we increase the value of a parameter. The behavior of the objective function's value, however, can be justified if we have a closer look at which parameter changes. The increase in the number of evacuation areas creates more demand, which immediately implies that the available vehicles will have to travel longer distance in order to complete the evacuation. As a result, the value of the objective function which represents the makespan increases. The increase in the vehicle capacity, on the other hand, means that each vehicle can accommodate greater number of evacuees in each trip, which implies that the evacuation will be completed with lower number of trips and thus the total distance traveled will be shorter. This is the reason that we see the objective function value to decrease as the vehicle capacity increases. Finally, the increase in the number of time periods does not change the value of the objective function. This is also reasonable because the algorithm finds the optimal solution for the problem independently of the number of time periods. This number will have an effect on the algorithm and the optimal solution only if it is smaller than the number needed to complete the evacuation. In this case, the algorithm cannot obtain a feasible solution.

The next experiment was conducted to show how the increase in the number of shelters affects the value of the objective function and the computational time. Figure 12 shows that the value of the objective function remains unchanged as the number of shelters increases. This is reasonable since the vehicle visits the shelter that is closer to the evacuation area. Unless no shelter added that is closer to an evacuation area, the optimal solution remains unchanged. The computational time is smaller than the cases presented above and presents some fluctuations.

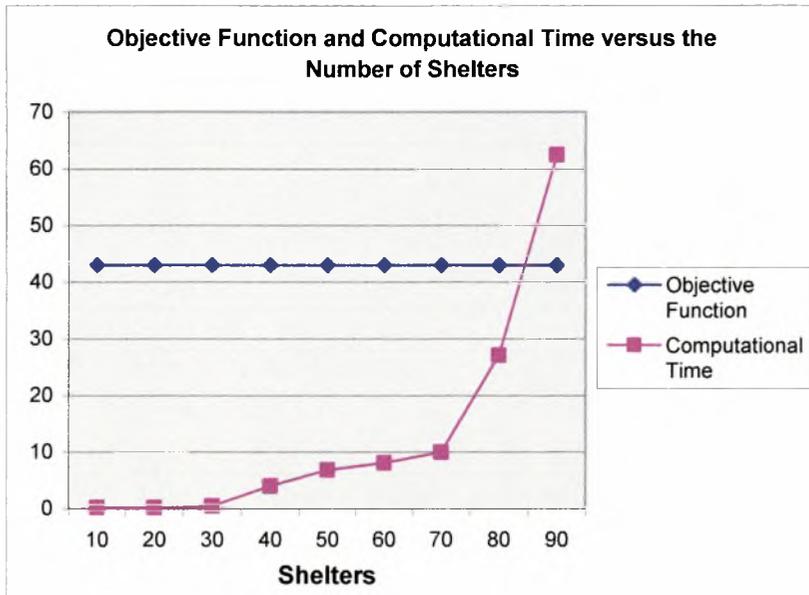


FIGURE 12 Objective Function and Computational Time versus the Number of Shelters

Finally, we conducted some experiments to show the behavior of the objective function value and the computational time to the change of the number of available vehicles. Figure 13 shows that the computational time increases as the number of available vehicles increases, but it remains much smaller than the case where the number of the evacuation areas was increased. The value of the objective function, however, decreases as the number of available vehicles increases up to a number. Above this number, the result of the objective function stabilizes to one particular value.

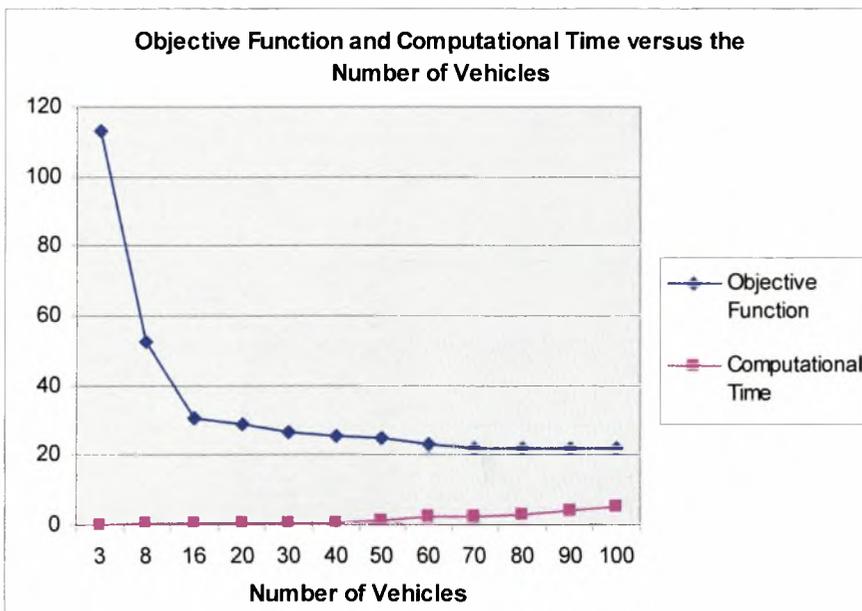


FIGURE 13 Objective Function and Computational Time versus the Number of Vehicles

4.4 Comparison between ETVAM-2 and the heuristic algorithm

In this paragraph the results of the heuristic algorithm compared with the results of ETVAM-2 in order to be able to draw some useful conclusions about their differences in terms of the objective function values and the computational time. For this reason, we compare the results of these two approaches for the three different scenarios analyzed above.

The first experiment conducted in order to see how the objective function values change depending on the approach we use. Figure 14 shows as expected that the exact resolution algorithm outperforms the heuristic algorithm in all the scenarios considered above. The differences, however, do not seem to be so important that could justify large computational times as we see in the next graph. Table 9 shows the values of the objective function for both the exact and the heuristic algorithm.

TABLE 9 Objective Function Values for both the Exact and the Heuristic Algorithms

	Objective Function	
	Exact Resolution Algorithm	Heuristic Algorithm
3 vehicles	113.36	116.36
8 vehicles	52.4	53.99
16 vehicles	30.66	33.36

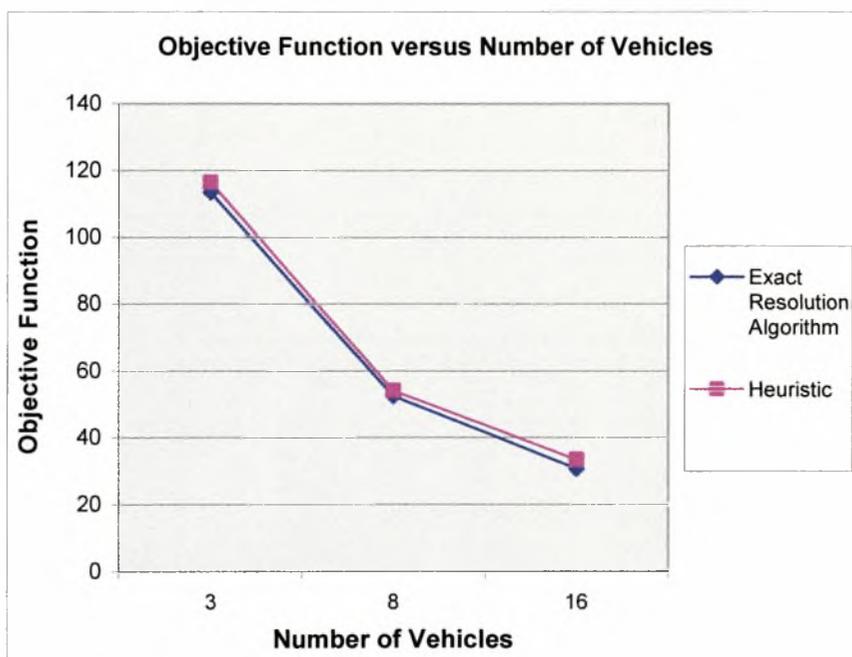


FIGURE 14 Objective Function versus the Number of Vehicles for the Exact Resolution Algorithm and the Heuristic Algorithm

The second experiment conducted in order to see how the computational time changes in the two proposed approaches (Table 10). In figure 15 we observe that heuristic algorithm outperforms the exact resolution algorithm in terms of computational time. This is an expected result as the heuristic algorithms usually outperform the exact algorithms in terms of computational time but their solution is always worst than the optimal solution we obtain by an exact algorithm.

TABLE 10 Objective Function Values for both the Exact and the Heuristic Algorithms

	Computational Time	
	Exact Resolution Algorithm	Heuristic Algorithm
3 vehicles	0.13198	0.02
8 vehicles	1.16282	0.02
16 vehicles	1.88971	0.03

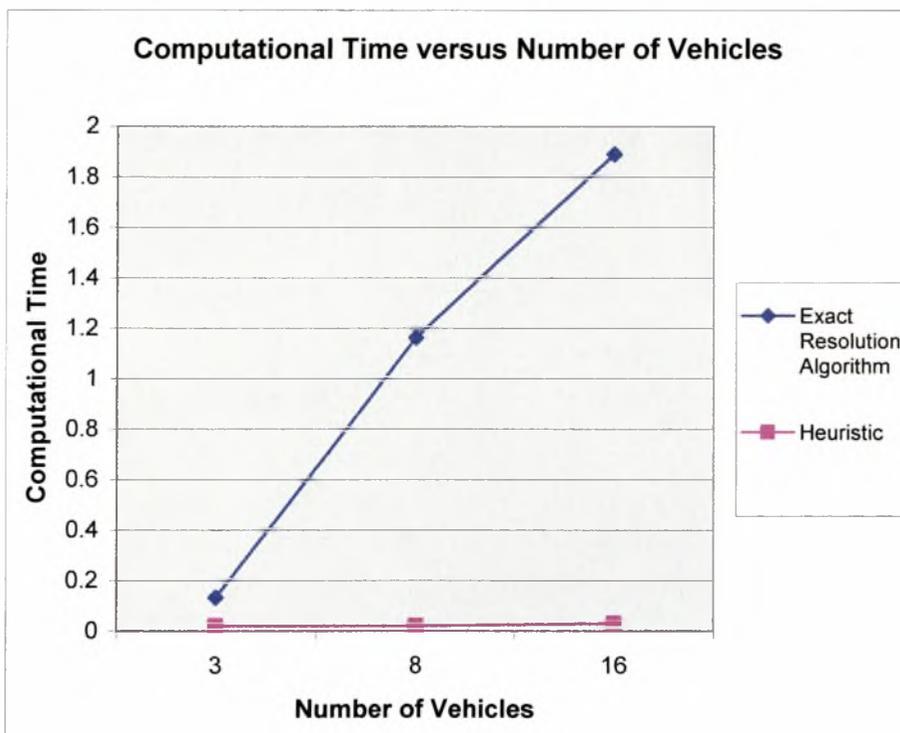


FIGURE 15 Computational Time versus the Number of Vehicles for the Exact Resolution Algorithm and the Heuristic Algorithm

To conclude, the heuristic algorithm outperforms the exact resolution algorithm in terms of computational time but its results are worst than the optimum solution obtained from the exact algorithm. On the one hand, the differences in the values of the objective function between the two approaches are very small, which

means that the proposed heuristic results in very good solutions near the optimal ones. On the other hand, the differences in terms of computational time between the two approaches are not very small, which means that the exact resolution algorithm needs larger computational time to obtain the optimum solution. For this reason, it will be probably preferred during an emergency situation to use the heuristic algorithm instead of the exact resolution algorithm.

5. CONCLUSIONS

An integrated framework for evacuating high-density clusters using transit was presented in this work. For this purpose, a state-of-the-art dynamic traffic assignment module was integrated with transit based emergency evacuation models. The approach was applied for the design of the evacuation of three marine container terminals in the Port Elizabeth-Newark area of the Port of New York and New Jersey. The application focused on the traffic operations portion of emergency response, the evaluation of traffic conditions during emergency evacuation and the routing of transit vehicles.

First, we presented a fairly simple model (ETVAM-1) assuming that there is adequate number of available vehicles in the vicinity of the area, so that each vehicle needs to perform only one trip. After that, we presented an integer formulation of the terminal evacuation problem (ETVAM-2) and the problem proved to be NP-hard. Therefore, a heuristic approach was proposed. The first two models were implemented in mathematical programming language AMPL and the heuristic algorithm was implemented in FORTRAN.

Three different scenarios related to the availability of buses for the evacuation of the terminals were considered. The first scenario assumed that there is adequate number of available vehicles in the vicinity of the terminals. The second scenario assumed that the number of available vehicles is reduced to half, so that some of the emergency vehicles will need to perform more than one trip. Finally, the third scenario assumed that the only available vehicles are the vehicles at the terminals. Similar to the second scenario these vehicles will make more than one trip.

Computational results for demonstration purposes were also presented for the three scenarios analyzed above. The results show that the change in the number of evacuation areas affects both the objective function and the computational time. The experiments conducted to study the change of the objective function value and the computational time to the change of the vehicle capacity show that the objective function value decreases and the computational time increases as the vehicle capacity increases.

The next experiment was conducted to capture the change of the objective function and the computational time to the change of the number of time periods. As expected the results show that the objective function value does not change as the number of time periods increases while the computational time increases.

The next experiment conducted to show how the increase in the number of shelters affects the value of the objective function and the computational time. The results show that the value of the objective function remains unchanged as the number of shelters increases while the computational time is smaller than the cases presented above and presents some fluctuations.

Additionally, we conducted some experiments to show the behavior of the objective function value and the computational time to the change of the number of available vehicles. The results show that the computational time increases as the number of available vehicles increases, but it remains much smaller than the case where the number of the evacuation areas was increased. The value of the objective function, however, decreases as the number of available vehicles increases up to a number. Above this number, the result of the objective function stabilizes to one particular value.

Finally, the comparison of the algorithms showed that the exact algorithms do not differ significantly from the heuristic in terms of the optimum solution but they are greatly differ in terms of computational time. For this reason, it will be probably preferred during an emergency situation to use the heuristic algorithm instead of the exact resolution algorithms.

Future research should focus on the integration of the models with the real-time data of the micro-simulation software package. Additionally, the heuristic approaches should be examined and new techniques able to prove the local optimality of the solutions should be developed.

It also remains open the design of an optimal analytical approach for solving the ETVAM-2 using domain insights to produce tighter bounds during the Branch and Bound process.

Appendix A

ETVAM-1

The model that describes the emergency transit vehicle assignment module (ETVAM-1) for the case that there is an adequate number of available vehicles in the vicinity of the area and each vehicle will perform only one trip is implemented in AMPL as follows:

SETS

set I; # Terminal Evacuation Points
 set J; # Shelters
 set K; # Vehicles

PARAMETERS

param VT{K,I}; #Distance between bus stops and terminal evacuation points
 param BT{I,J}; #Distance between terminal evacuation points and shelters
 param D{I}; # Demand of Terminal Evacuation Points
 param c{K}; #Vehicle Capacity

VARIABLES

var X{I, J, K} >=0 binary;

OBJECTIVE FUNCTION

minimize objective: sum {i in I, j in J, k in K} (VT[k,i]+BT[i,j])*X[i,j,k];

CONSTRAINTS

subject to constr1 {i in I}: sum {j in J, k in K} X[i,j,k]*c[k]-D[i]>=0;
 subject to constr2 {k in K}: sum {i in I, j in J} X[i,j,k]<=1;

Appendix B**ETVAM-2**

The model that describes the emergency transit vehicle assignment module (ETVAM-2) is implemented in AMPL as follows:

SETS

set I; # evacuation points
set J; # shelters
set K; # vehicles

PARAMETERS

param a{I, K}; # distance between start points and terminal evacuation areas
param p {I,J}; # distance between terminal evacuation areas and shelters
param T>1 integer;
param D{I}; #demand of each evacuation area
param cap; # vehicle capacity

VARIABLES

var M;
var A{i in I,k in K} binary;
var W{j in J, k in K, t in 1..T} binary;
var P{i in I, j in J, k in K, t in 1..T} binary;
var E{i in I, j in J, k in K, t in 1..T} binary;

OBJECTIVE FUNCTION

minimize Max_Cost: M;

CONSTRAINTS

subject to M_def{k in K}: M >= sum {i in I} a[i,k]*A[i,k] + sum{i in I, j in J, t in 1..T} p[i,j]*(P[i,j,k,t]+E[i,j,k,t]);

subject to constr1 {i in I, k in K}: sum {j in J} E[i,j,k,1]-A[i,k]=0;

subject to constr2 {i in I, j in J, k in K}: P[i,j,k,1]=0;

subject to constr3 $\{k \text{ in } K\}: \sum\{i \text{ in } I\} A[i,k] \leq 1;$

subject to constr4 $\{i \text{ in } I\}: \sum\{j \text{ in } J, k \text{ in } K, t \text{ in } 1..T\} P[i,j,k,t] + \sum\{k \text{ in } K\} A[i,k] = \text{ceil}(D[i]/\text{cap});$

subject to constr5 $\{k \text{ in } K\}: \sum\{j \text{ in } J, t \text{ in } 1..T\} W[j,k,t] \leq 1;$

subject to constr6 $\{j \text{ in } J, k \text{ in } K, t \text{ in } 1..T-1\}: \sum\{i \text{ in } I\} E[i,j,k,t] - \sum\{i \text{ in } I\} P[i,j,k,t+1] - W[j,k,t] = 0;$

subject to constr7 $\{i \text{ in } I, k \text{ in } K, t \text{ in } 2..T\}: \sum\{j \text{ in } J\} E[i,j,k,t] - \sum\{j \text{ in } J\} P[i,j,k,t] = 0;$

subject to constr8 $\{k \text{ in } K, t \text{ in } 1..T\}: \sum\{i \text{ in } I, j \text{ in } J\} P[i,j,k,t] \leq 1;$

subject to constr9 $\{k \text{ in } K, t \text{ in } 1..T\}: \sum\{i \text{ in } I, j \text{ in } J\} E[i,j,k,t] \leq 1;$

Appendix C

HEURISTIC ALGORITHM

```

program Terminal_Evacuation
implicit none
double precision,allocatable, dimension(:,:): vptea, stea, evats, oevats
double precision,allocatable, dimension(:): tv , maxdemand
double precision makespan, timetoevac, timetoshelter, vehavailtime, vehtimetoevac,
time_evac_to_c_shelter, time_evac_from_c_start
integer, allocatable, dimension(:): evac, vehpos, vehIDs, evacIDs, shelterIDs,
vehstoevac, pvehstoevac, nvehstoevac, fnvehstoevac, inievadIDs,
evac_to_c_shelterID, evac_from_c_startID
integer i,j,k, nov, nofeva, nos, vehID, evacID, shelterID, methodID
real time, tmp, evacsum, vehused, vec

open (1, file='results.dat')
open (2,file='stea.dat')
open (3,file='evats.dat')
open (4,file='evac.dat')
open (5,file='debug.dat')

nov = 16
nofeva = 3
nos = 2
vec = 60

allocate (evac_to_c_shelterID(1), evac_from_c_startID(1), inievadIDs(1),
vptea(nofeva,nov), stea(nofeva,nov), evats(nofeva,nos), oevats(nofeva,nos),
evac(nofeva), tv(nov), maxdemand(1), vehpos(nov), vehIDs(2), evacIDs(nov),
shelterIDs(nofeva), vehstoevac(nofeva), pvehstoevac(nofeva), nvehstoevac(nofeva),
fnvehstoevac(nofeva))

vehpos = 0
tv = 0d0
vptea = 0
vehstoevac = 0
pvehstoevac = 0
nvehstoevac = 0
makespan = 0

do i=1,nofeva
    read (2,*) (stea(i,j), j=1,nov)
enddo

do i=1,nofeva
    read (3,*) (evats(i,j), j=1,nos)
enddo

do i=1,nofeva

```

```

        read (4,*) evac(i)
    enddo

methodID = 0
do while (methodID == 0)
    read*,methodID
end do

do i=1,nofeva
    if (evac(i) == 0) then
        stea(i,:)=stea(i,:) + 10d+5
    endif
enddo

do while (maxval(evac)>0)
    do i=1,nov
        if (vehpos(i) == 0) then
            vptea(:,i) = stea(:,i)
        else
            do j=1,nofeva
                vptea(j,i) = tv(i)+evats(j,vehpos(i))
            enddo
        endif
    enddo
    if (methodID == 1) then
        vehIDs = minloc(vptea)
        vehID = vehIDs(2)
        if (vehpos(vehID) == 0) then
            evacIDs = minloc(stea,dim=1)
            evacID = evacIDs(vehID)
            timetoevac = stea(evacID,vehID)
            stea(:,vehID) = stea(:,vehID) + 10d+5
        else
            evacIDs = minloc(evats(:,vehpos(vehID)))
            evacID = evacIDs(1)
            timetoevac = evats(evacID,vehpos(vehID))
        endif
    else if (methodID == 2) then
        vehused = 1
        if (minval(vehsto evac)<1) then
            inievadIDs = minloc(vehsto evac)
            evacID = inievadIDs(1)
            vehIDs = minloc(vptea(evacID,:))
            vehID = vehIDs(1)
            if (vehpos(vehID) == 0) then
                timetoevac = stea(evacID,vehID)
                stea(:,vehID) = stea(:,vehID) + 10d+5
            else
                timetoevac = evats(evacID,vehpos(vehID))
            endif
        endif
    endif
enddo

```

```

        endif
    else
        vehIDs = minloc(vptea)
        vehID = vehIDs(2)
        if (vehpos(vehID) == 0) then
            evacIDs = minloc(stea,dim=1)
            evacID = evacIDs(vehID)
            timetoevac = stea(evacID,vehID)
            stea(:,vehID) = stea(:,vehID) + 10d+5
        else
            evacIDs = minloc(evats(:,vehpos(vehID)))
            evacID = evacIDs(1)
            timetoevac = evats(evacID,vehpos(vehID))
        endif
    endif
    vehused = 1
else if (methodID == 3) then
    vehstoevac = 0
    evacsum = 0
    vehused = 0

    do i=1,nofeva
        evacsum = evacsum+evac(i)
    end do

    do i=1,nofeva
        tmp = evac(i)/evacsum*nov
        pvehstoevac(i) = FLOOR(tmp)
        tmp = evac(i)*1.0/vec
        nvehstoevac(i) = CEILING(tmp)
        if (pvehstoevac(i)>nvehstoevac(i)) then
            pvehstoevac(i) = nvehstoevac(i)
        end if
        vehused = vehused+pvehstoevac(i)
    end do

    do while (nov-vehused>0)
        tmp = 0.
        Fnvehstoevac = nvehstoevac
        do i=1,nofeva
            nvehstoevac(i) = nvehstoevac(i)-pvehstoevac(i)
            if (nvehstoevac(i)>0) then
                tmp=1
                if (pvehstoevac(i)>0) then
                    nvehstoevac(i) = 10d+5+ nvehstoevac(i)
                else
                    nvehstoevac(i) = nvehstoevac(i)
                end if
            else
                nvehstoevac(i) = 10d+10
            end if
        end do
    end while
end if

```

```

        end if
    end do

    if (tmp == 0) then
        exit
    end if

    evacIDs = minloc(nvehsto evac)
    evacID = evacIDs(1)
    pvehsto evac(evacID) = pvehsto evac(evacID)+1
    vehused = vehused+1
    nvehsto evac = fnvehsto evac
end do
endif

do k=1,vehused
    if (methodID == 3) then
        vehIDs=minloc(vptea)
        vehID=vehIDs(2)
        evacID=vehIDs(1)

        if (vehpos(vehID)==0) then
            timeto evac=stea(evacID,vehID)
            stea(:,vehID)=stea(:,vehID) + 10d+5
        else
            timeto evac=evats(evacID,vehpos(vehID))
        endif
        if ((vehsto evac(evacID)+1)>=pvehsto evac(evacID)) then
            vptea(evacID,:)=vptea(evacID,:) + 10d+5
        end if
    end if

    vehavailtime=tv(vehID)
    veh timeto evac=tv(vehID)+timeto evac
    vehsto evac(evacID)=vehsto evac(evacID)+1

    if (evac(evacID)<=vec) then
        evac(evacID)=0
    else
        evac(evacID)=evac(evacID)-vec
    endif

    oevats=evats

    do i=1,nofeva
        if (evac(i) == 0) then
            oevats(i,:) = oevats(i,:) + 10d+5
        else
            evac_to_c_shelterID = minloc(evats(i,:))
            time_evac_to_c_shelter = evats(i,evac_to_c_shelterID(1))
        end if
    end do
end do

```

```

    evac_from_c_startID = minloc(stea(evacID,:))
    time_evac_from_c_start =
    stea(evacID,evac_from_c_startID(1)) oevats(i,:)=oevats(i,:) +
    evats(evacID,:)
    endif
enddo

shelterIDs=minloc(oevats)
shelterID=shelterIDs(2)
timetoshelter=evats(evacID,shelterID)
tv(vehID)=tv(vehID)+timetoevac+timetoshelter

if (evac(evacID) == 0) then
    evats(evacID,:) = evats(evacID,:) + 10d+5
    stea(evacID,:) = stea(evacID,:) + 10d+5
    if (makespan<veh timetoevac) then
        makespan = veh timetoevac
    endif
endif

write(1,('vehicle",1x,I3,1x,"from ",I3," (t:",F8.2,") ", "-> evacuation
area",I2,1x,(" ",I3,")", "(t:",F8.2,")",1x,"(t:",F8.2,") ""->",1x,"shelter",1x,I1,1x,(" ",
F8.2,")")) vehID, vehpos(vehID), vehavailtime, evacID, evac(evacID),
veh timetoevac, (veh timetoevac-vehavailtime), shelterID, tv(vehID)

vehpos(vehID) = shelterID
if (methodID == 3) then
    vptea(:,vehID) = vptea(:,vehID) + tv(vehID)
end if
end do
enddo

write(1,*) "Vehicles Positions"

do i=1,nov
    write(1,('Vehicle ",I3," at",I3')) i, vehpos(i)
enddo

call CPU_TIME(time)
write (1,('makespan=",F8.2')) makespan
write (1,('computational time=",F5.2,1x,"seconds")) time

stop
end

```

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