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**Thesis**

# Supply Chain Management in Humanitarian Aid and Disaster Relief

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## Abstract

Humanitarian aid and disaster relief are delivered in times of crises or natural disasters, such as after a conflict or in response to a hurricane, typhoon, or tsunami. Different from regular aid programs, aid and relief are provided to deal with emergency and immediate local areas, and to shelter affected people and refugees impacted by sudden traumatic events. There is evidence that natural and man-made disasters are increasing in numbers all around the world, affecting hundreds of millions of people every year. In spite of this fact, only in recent years – beginning in 2005 – has management of the supply chain of resources and materials for humanitarian aid and disaster relief been a topic of interest for researchers. Consequently, the academic literature in this field is comparatively new and still sparse, indicating a requirement for more academic studies. As a key part of the C-Change International Community-University Research Alliance (ICURA) project for managing adaptation to environmental change in coastal communities of Canada and the Caribbean, this thesis develops a framework and analytical model for domestic supply chain management in humanitarian aid and disaster relief in the event of severe storm and flooding in the Canadian C-Change community of Charlottetown, Prince Edward Island. In particular, the focus includes quantitative modeling of two specific aspects during the preparedness phase for emergency management: (1) inventory prepositioning and (2) transportation planning. In addition, this thesis proposes and analyses the characteristics of an effective supply chain management framework in practice to assist Canadian coastal communities in improving their preparation and performance in disaster relief efforts. The results indicate Charlottetown system effectiveness and decreased time to assist affected people are improved by distributing central emergency supply among more than one base station.

**Keywords:** supply chain management, humanitarian aid and disaster relief, conceptual framework formulation, inventory prepositioning, transportation planning, linear optimization models evaluation, Charlottetown, Canadian coastal communities

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I must also acknowledge the entire C-Change research team. As one of the research associates, I take advantage of the existing work of the C-Change project and resources at the C-Change website (www.coastalchange.ca) and the ongoing experience of graduate researchers currently working on the C-Change coastal communities as part of that project.

A very special thanks goes out to the five participants in my personal communication: Danny Brouillette, chief of Emergency Preparedness and Response in Public Health Agency of Canada; Denis Guitor, chief of logistics in Public Safety Canada; Laura Johnson-Montigny, provincial director for the Red Cross in Prince Edward Island; Randy MacDonald, emergency measures coordinator and fire chief for the City of Charlottetown; as well as Marilou Poirier, senior manager of logistics in the Canadian Red Cross. The information and materials provided by them make great contribution to the data collection of this thesis.

Last but not the least, thanks goes out to my parents (Guangbin Liu and Chuanlian Yu) and my best friends (Xiaoxi Chang, Meng Jin, and Shuangshuang Kong). Their emotional and spiritual support helps me get through all the difficult times.

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# 1. Introduction

During recent decades, compelling evidence shows that the incidence of disasters has grown at an unprecedented rate all around the world. Consequently, the question of how to improve the performance of humanitarian aid and disaster relief has attracted an increasing attention on a global scale. This chapter introduces current disaster situations, as well as the important role that supply chain management plays in humanitarian aid and disaster relief operations (section 1.1). As well, the research questions and objectives for this thesis research are proposed (section 1.2). Finally, section 1.3 presents the plan of the thesis document by summarizing the key components of this M.Sc. thesis document.

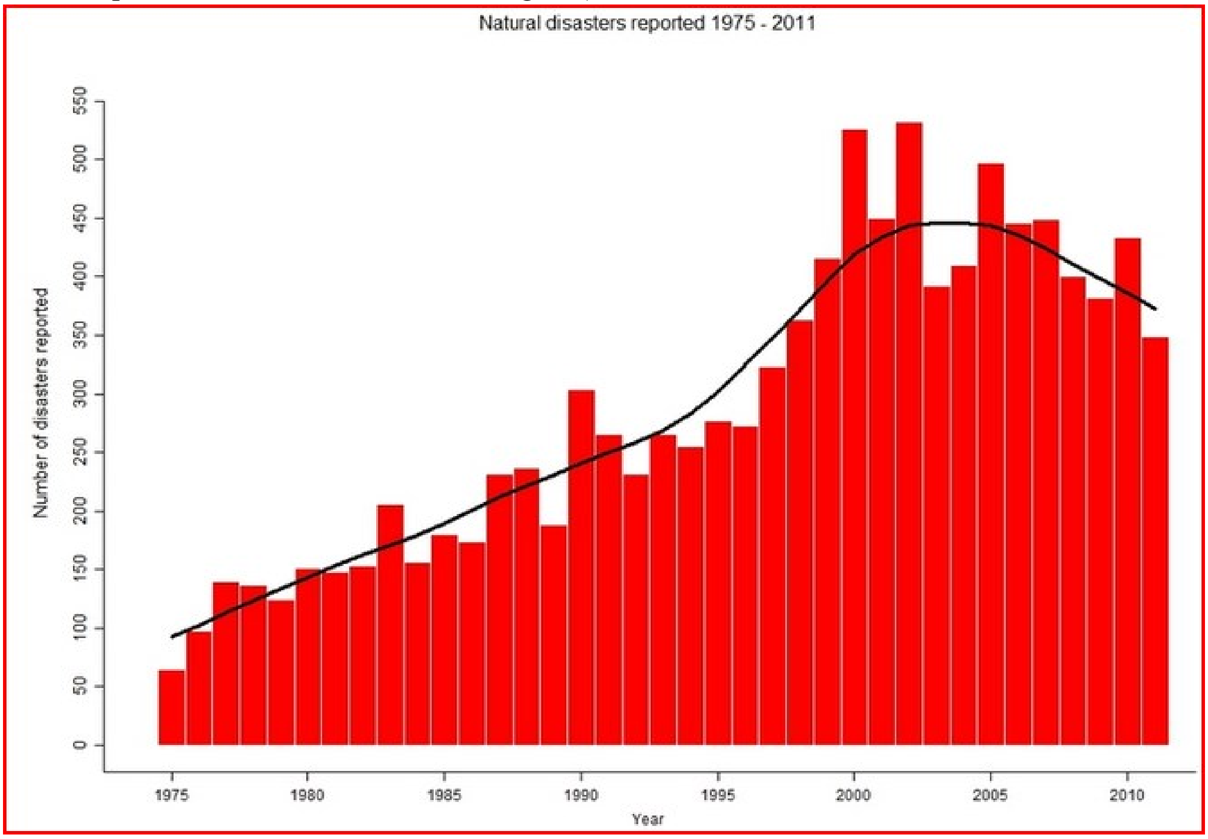
## 1.1. Research Background and Motivation

Among the ten deadliest natural disasters since 1900, the most serious one (in terms of human mortality) was the 1931 China flood that caused estimated 1,000,000 to 4,000,000 death toll (Hough, 2008). Although the continent most influenced by natural disasters, in terms of mortality and occurrence, is Asia, 63% of total 2012 economic losses happened in the Americas due to the significant impact of Hurricane Sandy hitting the Eastern seaboard of the United States, and the drought impacting 62% of the adjacent United States (CRED, 2013). In the past few years, tsunamis in South Asia (2004), Hurricane Katrina in the United States (2005), earthquakes in Pakistan (2005), Java (2006), China (2008), and Haiti (2010), as well as Superstorm Sandy (2012) are some examples of the recent deadly disasters.

Narrowing the scope to Canada, two massive floods cannot be ignored in the year of 2013. On June 20$^{th}$, Alberta experienced heavy rainfall causing catastrophic flooding which is described by the provincial government as the worst in Alberta's history. Flood waters swept over parts of Alberta, touching the lives of more than 100,000 people, leading to the damage of over five billion Canadian dollars, and leaving behind a decade's worth of recovery (CBC News, 2013a). Later, on July 8th, Toronto experienced the most expensive natural disaster in Ontario history. The floods resulted from a severe thunderstorm in the Great Toronto Area (GTA) region (CBC News, 2013b).

All of the above disasters are only a sign of what we can expect in the future. Michel-Kerjan and Slovic (2010) state that over half of the world's twenty costliest catastrophes since 1970 have happened since 2001. These disasters are attributed to the increasing population, the larger focus of assets in high-risk areas, as well as the growing social and economic interdependency. In addition, environmental degradation and rapid urbanization are another two reasons for recent costly disasters (Thomas and Kopczak, 2005). These trends combine to create an environment where disasters are expected to grow in both frequency and intensity. The data in Figure 1.1 illustrates the trend clearly.

**Figure 1.1**: Number of natural disasters reported from 1975 to 2011 (Source: EM-DAT: The OFDA/CRED International Disaster Database, www.emdat.be – Université catholique de Louvain – Brussels – Belgium)



The results of recent disasters not only incur injuries, deaths, and damaged infrastructure, but they also, in the long run, cause changes in economic and social conditions (Ergun et al., 2010). While disasters cannot be prevented, their negative impacts can be reduced by effective preparedness strategies such as humanitarian and disaster operations research. Disasters place special needs on logistical, supply chain, and organizational skills of the affected countries (PAHO/WHO, 2001). For instance, assistance often cannot reach disaster areas due to logistics difficulties with limited infrastructure.

In January 2005, the World Conference on Disaster Reduction in Japan called for better preparedness for humanitarian aid and disaster relief in natural disasters. One preparatory approach is to develop efficient and effective logistics for disasters and emergencies using aspects of operational research and supply chain management. Logistics occupies 80% of humanitarian aid and disaster relief, and supply chain management is needed to maximize the timeliness and efficiency of response operations (Van Wassenhove, 2006).

As noted by Thomas and Kopczak (2005), supply chain management is central to humanitarian aid and disaster relief for three reasons: (i) supply chain management is one of the most expensive parts of a relief effort due to inventory and transportation; (ii) supply chain management plays a critical role in response for major humanitarian programs, such as food, water, shelter, and sanitation; and (iii) supply chain management is the repository of data that can be analyzed to provide post-event learning in that the logistics department is responsible for tracking goods through the chain. Thus, supply chain management is important to the performance of both current and future operations and programs.

Humanitarian aid and disaster relief supply chain operates in a different environment from other supply chains that are more widely known and researched. This enables opportunities and needs for future studies (Clay Whybark et al., 2010). Research in this field tends to concentrate on several particular aspects of the supply chain’s operation, such as location selection, inventory management, or transportation planning, rather than the entire chain all at once. The whole supply chain can be made more effective if manageable portions of the chain are worked on first. As part of this thesis research, in March 2013, two individual interviews were carried out with the Chief of Emergency Preparedness and Response in Public Health Agency of Canada, and the Senior Manager of Logistics in the Canadian Red Cross. Both of the interviewees stated that their logistics teams would sit together with the decision-makers for a large-scale project or disaster now rather than simply operate at the support level. In addition, the logistics teams have become bigger recently because the organizations have realized that logistics is an important component of the success of inventory and transportation in humanitarian aid and disaster relief operations. Similarly, this thesis focuses on two fundamental aspects of supply chain management in humanitarian aid and disaster relief – inventory prepositioning and transportation planning.

**Table 1.1**: Summary of natural disasters in Canada from 1900 to 2013 (Source: EM-DAT: The OFDA/CRED International Disaster Database – www.emdat.be – Université catholique de Louvain – Brussels – Belgium)

| *Natural Disaster* | *# of Events* | *People Killed* | *People Affected* | *Damage (000 US$)* |
|---|---|---|---|---|
| Drought | 5 | — | 55,000 | $ 4,810,000 |
| Seismic activity | 1 | 27 | — | — |
| Epidemic | 7 | 50,562 | 2,008,917 | — |
| Extreme temperature | 3 | 500 | 200 | $ 2,000,000 |
| Flood | 35 | 43 | 179,470 | $ 2,839,900 |
| Mass movement dry | 8 | 305 | 3,591 | — |
| Storm | 40 | 301 | 15,587 | $ 3,405,200 |
| Wildfire | 20 | 119 | 72,600 | $ 6,462,500 |

After a review of the published research in this area, the thesis applies the analysis of the logistics framework for humanitarian aid and disaster relief supply chain to a specific coastal community – Charlottetown, Prince Edward Island. This Canadian community, is subject to coastal flooding from severe storms, aggravated by sea-level rise and storm surge such as the recent natural hazards like Hurricane Gabrielle (2001), Juan (2003), and Igor (2010) (TheStar, 2010). These natural disasters affect the community socially, economically, and alter how community members live. Further, as noted by the above

Table 1.1, such events incur significant damage and are costly to governments to recover. The current situation contributes to the research questions and objectives in the following section 1.2.

## 1.2. Research Questions and Objectives

The overall objective of this thesis research is to reduce the negative impacts caused by disasters through more effective preparedness strategies. However, one of the most unique characteristics of humanitarian aid and disaster relief supply chain is the uncertainty of disasters with respect to the timing and the severity of the events. Thus, it is suitable in this research to adopt a structured approach via scenario planning. Scenario planning takes into account the historical relative frequency of past local events and identifies the uncertain forces that have a potential effect on logistical response efforts. Different scenarios are generated by combining the uncertain forces in different ways to explore possible outcomes. This thesis evaluates the constructed scenarios to define an effective logistics plan for relief efforts. A what-if analysis explores the effects of uncertain forces on robust strategies for relief logistics.

Based on the research background and motivation described in section 1.1, this thesis addresses the following research questions:

1. What are the characteristics of an effective supply chain management framework for humanitarian aid and disaster relief with particular emphasis on the inventory of emergency materials and the transportation logistics of materials and people?
2. What has been the current status of inventory and transportation management in selected Canadian communities with respect to humanitarian aid and disaster relief?
3. How can the existing inventory and transportation management framework for humanitarian aid and disaster relief be improved to assist its operations for the Canadian coastal community of Charlottetown, Prince Edward Island which is subject to more frequent severe storms?

In response to the above research questions, the associated research objectives are as follows:

1. To review the current literature on humanitarian aid and disaster relief with focus on inventory and transportation, and analyze alternative models that have been developed toward constructing an effective supply chain management framework for humanitarian aid and disaster relief.
2. To collect data on specific Canadian communities and examine the experience of managing emergency events, e.g., the recent Alberta and Toronto floods (June and July, 2013), Hurricane Sandy in southern Ontario (October, 2012), the Quebec flooding (May, 2011), Hurricane Igor in Newfoundland (September, 2010), in order to document the experience and evaluate the process of inventory and transportation logistics for relief.
3. To develop a model for inventory and transportation in humanitarian aid and disaster relief scenarios and evaluate alternative logistical strategies (inventory location and capacity, vehicle availability and routing) toward improving emergency preparedness for the C-Change ICURA project coastal community: Charlottetown, Prince Edward Island.

To achieve the research objectives and answer the research questions, the thesis outline is provided in the next section 1.3.

## 1.3. Research Outline

This thesis is made up of seven main chapters and a set of appendices as follows:

- **Chapter 1**: The current chapter is the introduction, including the background of supply chain management in humanitarian aid and disaster relief, the motivation for developing a framework which can be applied to Canadian communities, the specific research questions and objectives, as well as the outline of the thesis.
- **Chapter 2**: The literature review focuses on previous and current research in four

areas: disaster management, general supply chain management, humanitarian aid and disaster relief supply chain management, as well as community relief applications. The literature reviewed that is most related to the thesis and contributes to the research methodology is summarized in the end of this chapter.

- **Chapter 3**: The methodology represents the process for developing a conceptual framework, the approach to collecting data and establishing of linear programming models, the method of policy and decision evaluation for logistics, as well as the process of applying the relief framework to the selected Canadian community application.
- **Chapter 4**: The section of model formulation describes the specific model components, the available community data for Charlottetown, P.E.I., as well as the definition of six different modelling scenarios.
- **Chapter 5**: The model results are presented and analyzed in this chapter. In addition to the evaluation and summary of all results, a what-if analysis of the solution is developed to explore decision robustness.
- **Chapter 6**: This chapter provides conclusions of this thesis as well as an overview of the expected recommendation and consideration for future studies in this area.

The thesis is terminated with a complete Bibliography including all references used directly or indirectly in this thesis. This is followed by the set of appendices designed to offer a complete illustration of the modeling processes and results.

# 2. Literature Review

In this chapter, the existing literature is presented in several topics that are designed to assist in answering the research questions provided in Chapter 1. Research topics include disaster management papers that are classified in section 2.1. Among them, studies in the operations and process area have the closest relationship with this thesis. Section 2.2 discusses papers on four themes in general supply chain management: (i) performance measurement, (ii) critical successful factors, (iii) inventory management, and (iv) transportation management. Subsequently, the corresponding four themes in humanitarian aid and disaster relief context are reviewed in section 2.3. An overview of community relief applications for this thesis is provided in section 2.4. The last section, 2.5 is a summary of the literature reviewed with relevance to the research methodology applied in this research.

## 2.1. Disaster Management

The collection of internationally agreed glossary of basic terms related to disaster is a result of a joint effort of many national institutions, non-governmental organizations, and inter-governmental organizations (United Nations, 1992). Disaster management is defined as "the body of policy and administrative decisions and operational activities which pertain to the various stages of a disaster at all levels" (United Nations, 1992, p. 28). In order to understand the process of managing disasters better, this section gives an illustration from the literature of the three aspects of disasters as presented below: (i) disaster type, (ii) disaster phases, and (iii) operations research in disaster relief.

### 2.1.1. Disaster Types

Before conducting studies on disaster management, researchers need to establish a clear definition of disaster. Among the reviewed literature, different studies define disaster in different ways. As noted by the *Internationally Agreed Glossary of Basic Terms Related to Disaster Management*, the term "disaster" is usually applied to:

> "a serious disruption of the functioning of society, causing widespread human, material or environmental losses which exceed the ability of the affected society to cope using only its own resources" (United Nations, 1992, p. 27).

However, Altay and Green (2006) refer to "disaster" as a catastrophic event excluding daily emergences and situations that are typically responded to by a government organization through standard processes. In contrast, Salkowe and Chakraborty (2009) regard an event as a disaster when a local or state government agency requests a disaster declaration.

The above definitions leave room for subjectivity because it is not clear whether a disruption is serious or not. Quantitative criteria may eliminate the subjectivity. Given that the focus of this thesis is on the disaster management in Canadian communities, the definition of disaster from Public Safety Canada is important. For Public Safety Canada, an event is not regarded as a disaster unless one or more of the following five criteria are met: (i) more than 10 people killed; (ii) over 100 people affected, injured, infected, evacuated, or homeless; (iii) an appeal for national or international assistance; (iv) historical significance; and (v) significant damage or interruption of normal processes such that the community affected cannot recover on its own (Public Safety Canada, 2014).

According to the causes, disasters can be grouped into two main categories: natural or man-made disasters. The former are caused by natural hazards, while the latter are the results of human actions (Ergun et al., 2010). Moreover, each category involves both sudden-onset and slow-onset disasters. Table 2.1 provides some examples for each type of disaster. The World Economic Forum (2013) presents that more than 250 million people are affected by natural disasters every year. However, only 3% of relief operations are devoted to natural disasters (Van Wassenhove, 2006). Thus, more attention needs to be paid to natural disasters.

There are two main streams of humanitarian aid and disaster relief supply chain management: continuous aid work and sudden disaster relief. Famine relief and aid to help develop a poor region is different from that demanded after a sudden catastrophe (Kovacs and Spens, 2007). In short, this thesis only focuses on natural disasters, particularly, sudden-onset relief requirements. No matter what type of disaster, being familiar with the disaster phases is the first step to manage a disaster. Literature on disaster phases is reviewed in the next subsection 2.1.2.

**Table 2.1**: Disaster types and examples

| | **Natural** | **Man-made** |
|---|---|---|
| *Sudden-onset* | Hurricanes, cyclones, tornadoes, and typhoons<br>Floods and tsunamis<br>Earthquakes<br>Volcanic eruption | Terrorist attacks<br>Chemical leaks<br>Coup d'Etat |
| *Slow-onset* | Poverty<br>Drought<br>Famine and food insecurity | Political crisis<br>Refugee crisis |

### 2.1.2. Disaster Phases

Disaster phases, also called disaster cycle or disaster continuum, are pre- and post-disaster stages subdivided into particular actions (OFDA, 1984). Pre-event tasks consist of forecasting and analyzing potential dangers and developing action plans for mitigation (Tufekci and Wallace, 1998). In contrast, post-event efforts include responses that begin when disasters are in progress (Tufekci and Wallace, 1998).

Specific disaster phases vary from research to research. For example, some researchers prefer a four-phase approach – mitigation, preparedness, response and recovery – based on the Comprehensive Emergency Management concept proposed in the 1978 report of the National Governors' Association Emergency Preparedness Project. Differently, Lee and Zbinden (2003), as well as Kovacs and Spens (2007), separate the cycle into three phases: preparedness (preparation), during operation (immediate response), and post operation (reconstruction). Also, there is a two-phase method: disaster mitigation (assessment, prevention, preparedness) including "measures taken in advance of a disaster aimed at decreasing or eliminating its impact on society and environment" (United Nations, 1992, p. 53), and disaster response (relief, rehabilitation, reconstruction) which is "a sum of decisions and actions taken during and after disaster, including immediate relief, rehabilitation, and reconstruction" (United Nations, 1992, p. 29).

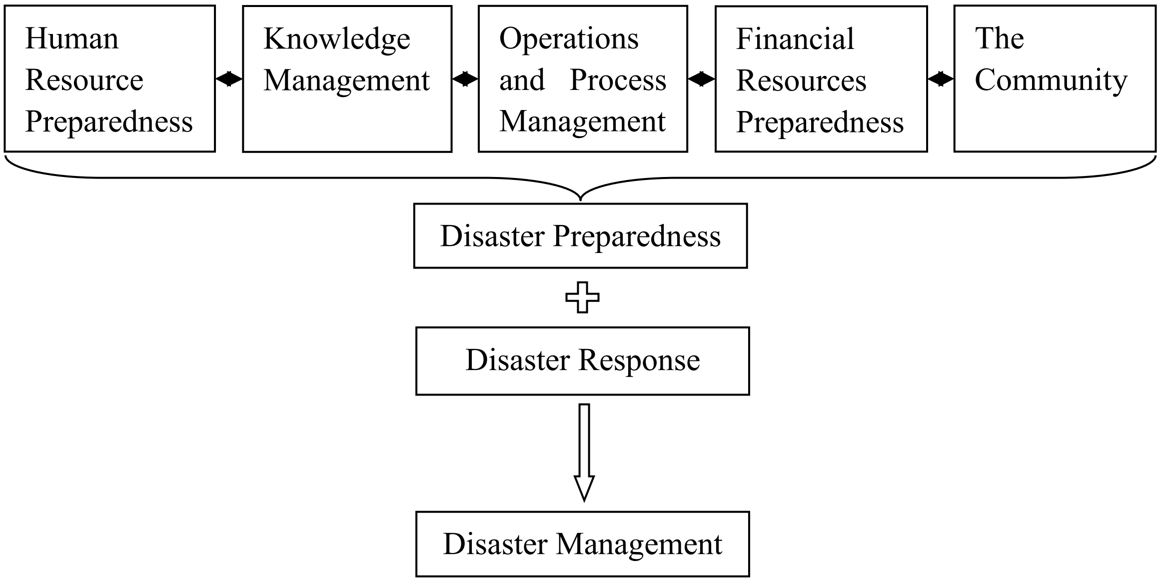
This thesis follows a similar two-phase approach: (i) disaster preparation and (ii) disaster response. The preparation stage consists of all tasks conducted before the disaster strikes, while the response stage includes activities in both immediate response and long-term recovery and reconstruction after the onset of disaster. Since there is no doubt that being better prepared leads to a better response, this thesis concentrates on the pre-disaster phase, that is, disaster preparedness.

In order to produce effective results, disaster preparedness includes five key elements: human resources, knowledge management, operations and process management, financial resources, and the community (Samii et al., 2002). These are explained below:

1. **human resources** preparedness aims to choose trained people who can plan, act, intervene, and coordinate where necessary;
2. **knowledge management** means leaning from previous practices through capturing, codifying, and transferring knowledge on logistics operations;
3. **operations and process management** is about humanitarian aid and disaster relief supply chain management;
4. **financial resources** preparation refers to raising enough money to ensure smooth preparedness and operations; finally,
5. **the community** entails finding effective collaboration methods among key players (Van Wassenhove, 2006).

The interconnection among these five elements as well as the relationships of disaster phases are showed in Figure 2.1.

**Figure 2.1**: Establishing effective disaster management (adapted from Samii et al. (2002))




Humanitarian aid and disaster relief supply chain is a key part of operations and process management and impossible to be improvised at the time of disasters. As a cornerstone of disaster preparedness efforts (PAHO/WHO, 2001), supply chain management in humanitarian aid and disaster relief is the concentration of this thesis. Thus, papers on the disaster operations management are summarized in the subsection 2.1.3.

## 2.1.3. Operations Research in Disaster Management

Researchers have developed new methods in studying disaster management. Analysis and modeling techniques such as risk analysis, operations research, simulation, artificial intelligent systems, decision support systems, and geographic information systems have been used (Tufekci and Wallace, 1998). Operations management means controlling processes or systems that create goods and/or provide services by transforming inputs into outputs. A set of activities are included in operations management, such as forecasting, purchasing, scheduling, capacity planning, production control, quality assurance, inventory management, facility location decision making, and logistics (Heizer and Renser, 2004; Stevenson and Hojati, 2004). Due to the randomness and uniqueness of the impacts and problems in disasters, dynamic, effective, and cost efficient solutions are needed. This topic is suitable for operations research techniques. Disaster operations comprise activities performing before, during, and after a disaster with the aim to decrease human life losses, reduce negative effects on economy, and return to a normal state (Altay and Green, 2006).

A growing number of studies on humanitarian supply chain have been published, and application of operations research to this area has been suggested. Generally, humanitarian aid and disaster relief supply chain is filled with a set of optimization problems combining aspects from classic problems in supply chain management, warehouse location, inventory control, and vehicle routing (Van Hentenryck et al., 2010). Different aspects of the above problems in commercial situations have been studied previously. However, significant complexity is added to the classical problems when it comes to the context of humanitarian aid and disaster relief. Thus, novel research in this area is required to solve these kinds of problems, such as location analysis of shelters in preparation for evacuations, probabilistic and statistic modeling for addressing uncertainties of disaster demands, as well as application of transportation techniques to evacuate victims (Galindo and Batta, 2013).

According to Altay and Green (2006), interest in disasters has increased rapidly since 1990, and the most frequently utilized method in disaster operations management research is mathematical programming which is followed by probability theory and statistics. In contrast, systems dynamics, constraint programming, and soft operations research techniques are underused in disaster operations management research. Based on the phases of disaster management lifecycle, only 21.1% of the research addresses preparation. Altay and Green (2006) summarize three types of knowledge contributions that can be made to the disaster operations management area: (i) model development, (ii) theory development, and (iii) application development. 57.8% of published disaster operations management research uses model development, followed by theory development (26.6%) and application development (15.6%).

The previous statistics provided by Altay and Green (2006) come from a survey of OR/MS papers applied to disaster operations management published between 1980 and 2004. As a continuation, a more recent study covering the timeframe from 2005 to 2010 is conducted by Galindo and Batta (2013). This study explores how OR/MS research in disaster operations management has evolved and to what extent the gaps pointed out by Altay and Green (2006) have been filled. Galindo and Batta (2013) find that there are no radical developments or changes in this field. Most previous trends have remained. For example, the most preferred method is still mathematical programming. Systems dynamics, constraint programming, as well as soft operations research techniques have a low participation in recent research. However, other trends have experienced slight shifts. For instance, the second most popular methodology is conceptual analysis instead of probability theory and statistics; more studies (28.4%) deal with disaster preparation issues; even more research (75.5%) adopts model development, whereas fewer studies select theory (19.3%) or application development (5.2%).

Given the two studies separately conducted by Altay and Green (2006) as well as Galindo and Batta (2013), modeling is the most common type of research contribution while application is the least frequent one. Even though model development is critical in disaster operations management, theory and application are also valuable. On one hand, theory development acts as a base for model development research by helping understand the problems in disaster operations management better (Galindo and Batta, 2013). On the other hand, application development plays an important role in offering a tool for putting theoretical and analytical research into practice (Galindo and Batta, 2013). Thus, this thesis aims to cover the important gap by combining two contributions together; that is, developing a mathematical model first and then applying the model to the case of a specific coastal community.

Literature on disaster management is represented in this section 2.1. Before moving to the focus of this thesis – humanitarian aid and disaster relief supply chain management, it is necessary to review the articles on general supply chain management (section 2.2).

## 2.2. Supply Chain Management

The definition of logistics and supply chain management varies from area to area. In the military area, supply chain management means:

> "…the science of planning and carrying out the movement and maintenance of forces" [dealing with:] "(a) design and development, acquisition, storage, movement, distribution, maintenance, evacuation, and disposition of material; (b) movement, evacuation, and hospitalization of personnel; (c) acquisition or construction, maintenance, operation, and disposition of facilities; and (d) acquisition or furnishing of services" (Department of Defense, 2005, p. 313).

In the commercial domain, supply chain management is defined as a planning framework for managing materials, services, information, and capital flows to convey superior customer value at the least cost (Van Wassenhove, 2006). In commercial context, factories, processing centres, warehouses, distribution centres, and retail stores all belong to facilities. Functions and activities involve forecasting, scheduling, procurement, production, quality assurance, delivery, inventory management, distribution, information management, as well as customer service. Stevenson and Hojati (2004, p.462) define supply chain management in the business context as "the sequence of organizations – their facilities, functions, and activities – that are involved in producing and delivering a product or service." Overall, commercial supply chain aims to link all the above components to meet market demand as efficiently as possible through the entire chain (Stevenson and Hojati, 2004).

Finally, in the humanitarian context, the Fritz Institute defines supply chain management as:

> "…the process of planning, implementing, and controlling the efficient, cost-effective flow and storage of goods, and materials, as well as related information, from point of origin to the point of consumption for the purpose of alleviating the suffering of vulnerable people." (Thomas and Kopczak, 2005, p. 2).

Overall, the literature records that there is commonality among these definitions, and that supply chain management consists of preparedness, planning, procurement, transportation, inventory, warehousing, tracking, allocation, and recipient satisfaction. In accordance with the goals of this thesis, research on four specific supply chain management streams is included in this section: (2.2.1) performance measurement, (2.2.2) critical successful factors, (2.2.3) inventory management, and (2.2.4) transportation management.

### 2.2.1. Performance Measurement

Academic and practical papers have studied the various processes of the supply chain. Growing attention has been recently placed on the performance, design, and analysis of the supply chain as a whole (Beamon, 1998). Performance measurement is defined as "the process of quantifying the efficiency and effectiveness of action" (Neely et al., 1995, p. 80). Effectiveness measures the extent to which customer demands are met, while efficiency refers to how economically an organization's resources are used when offering a given level of customer satisfaction (Neely et al., 1995). Parker (2000) points out six reasons for measuring performance: (i) identify success; (ii) identify whether customer requirements are met; (iii) make organizations to understand the operations process better; (iv) identify where bottlenecks exist and where improvements are needed; (v) ensure decisions are made according to fact; and (vi) demonstrate whether planned improvements actually happen.

With the ability of offering insight to identify success and potential opportunities, appropriate performance measures can make a supply chain more efficient and more effective (Chan and Qi, 2003; Gunasekaran et al., 2001; Persson and Olhager, 2002). Since no one measure is sufficient for supply chain management performance (Chow et al., 1994), researchers attempt to examine a set of measures that collectively capture most of the performance dimensions. Available literature has identified some important performance measurement to characterize systems, in particular, production, distribution, and inventory systems (Beamon, 1999).

Beamon (1998) summarizes two broad types of performance measurements in the existing literature: qualitative and quantitative. Qualitative performance measurements include customer satisfaction, flexibility, information and material flow integration, effective risk management, and supplier performance. Quantitative performance measurements include cost (inventory and operating cost), and customer responsiveness (lead-time, stock-out probability, and fill rate). Some studies follow the main stream of using quantitative performance measurements. For example, Petrovic et al. (1998) adopt total cost and fill-rate when fuzzy modeling and simulating a typical, serial supply chain with infinite capacity.

Some researchers follow a three-part framework developed for the selection of supply chain performance measurement: resource, output, and flexibility measures (Beamon, 1999). Resource measures assess the efficient level of resources used to meet the goals, such as total cost, distribution cost, manufacturing cost, inventory cost, and return on investment (Beamon, 1999). Output measures evaluate the effectiveness with which supply chains can supply, including sales, profit, fill rate, on-time deliveries, backorder/stock-out, customer response time, manufacturing lead time, shipping errors, and customer complaints (Beamon, 1999). Flexibility measures examine the range of possible operating conditions profitably achievable by the chain, for example, volume flexibility, delivery flexibility, mix flexibility, and new product flexibility (Beamon, 1999). For example, the supply chain design of Persson and Olhager (2002) chooses cost and inventory as resource measures, uses lead-time and lead-time availability as both output measures and flexibility measures. Angerhofer and Angelides (2006) also use this framework to measure the collaborative supply chain performance and identify areas for improvement.

Different from the above studies, Gunasekaran et al. (2001) build a framework to assess a supply chain at strategic, tactical, and operational levels, respectively. A list of key performance measurement is proposed for each level, mainly dealing with supplier, delivery, customer service, inventory cost, and logistics cost. Based on the research of Gunasekaran et al. (2001), Shepher and Günter (2006) also state that supply chain performance needs to be evaluated at these three levels and assign five categories of measures to the first level: cost, quality, time, flexibility, and innovativeness. Time and quality indicate the capacity of a supply chain to deliver a high customer service, while flexibility and innovativeness reflect the ability of dealing with rapid changes in supply or demand.

However, little research on supply chain performance measurement addresses system design and measure selection. Thus, Chan and Qi (2003) adopt an innovative process-based system-thinking approach to measuring the holistic performance of complex supply chains, aiming to contribute to the performance improvement. Chan and Qi (2003) build a process and performance hierarchy, and then discuss measurement from three dimensions: inputs (time and cost), outputs (delivery reliability and customer responsiveness), and composite (productivity, efficiency, and utilization). Overall, performance measurement of commercial supply chain management can be summarized under the general framework built by Beamon (1999) as Table 2.2. To improve the performance level, Critical Successful Factors (CSFs) need to be identified and papers related to CSFs are summarized in the next subsection 2.2.2.

**Table 2.2**: Performance measurement of commercial supply chain management (summarized from Angerhofer and Angelides, 2006; Beamon, 1998; Beamon, 1999; Chan and Qi, 2003; Gunasekaran et al., 2001; Persson and Olhager, 2002; Petrovic et al., 1998; Shepher and Günter, 2006)

| **Performance measurement** | *Specific objectives and measures* |
|---|---|
| **Resource measurement** (Assess the efficient level of resources used to meet the goals) | -cost minimization<br>-inventory investment minimization<br>-return on investment maximization<br>-function duplication minimization<br>-equipment utilization maximization<br>-personnel allocation optimization |
| **Output measurement** (Evaluate the effectiveness with which supply chains can supply) | -sales maximization<br>-profit maximization<br>-fill rate maximization<br>- lead time minimization<br>-product lateness minimization<br>-customer response time minimization<br>-product quality optimization<br>-customer satisfaction maximization |
| **Flexibility measurement** (Examine the ability to respond to a changing environment) | -risk management optimization<br>-available system capacity maximization (volume, delivery, mix, and new product flexibility) |

### 2.2.2. Critical Successful Factors

The concept of success factors is developed by Daniel (1961) of McKinsey & Company, and refined into Critical Successful Factors (CSFs) by Rockart (1979). CSFs have been examined in a variety of areas such as human resource management, information technology, small business management, project management, and supply chain management (Oloruntoba, 2010). Among various studies, the classical definition considers CSFs as those characteristics, conditions, or variables that when properly sustained, maintained, or managed can have a significant effect on the performance and the endeavor of an organization (Leidecker and Bruno, 1984).

This section reviews the research on CSFs in commercial supply chain management, since identifying CSFs plays an important role in improving the performance of an organization. Specifically, CSFs can help organizations set and convey goals to everyone, assist managers in holding people responsible for progress against the goals, as well as proactively deal with productivity and performance gaps (Oloruntoba, 2010). In order to provide an overall impression of CSFs in commercial supply chain management, Table 2.3 (in the end of this subsection) summarizes and lists ten CSFs consistently identified in the literature.

Overall, the ten CSFs can be classified into three levels: macro, micro, and mutual levels. The first two factors – strategic planning and supply chain strategy – belong to the macro level. After further refinement of the macro-level factors, seven micro-level factors are defined: inventory management, transportation planning, capacity planning, participative management, information management, technology utilization, and relationship development. The last factor is continuous improvement which is a mutual-level factor connecting macro- and micro-level factors.

From the macro perspective, managing an organization requires **strategic planning** including making long-term decisions on operations (Gunasekaran and Ngai, 2003; Petitt and Bereford, 2009). In particular, **supply chain strategies** are identified for managing the logistics operations in the organization. These decisions involve but are not limited to the strategies on the location of distribution centres, the nature of logistics processes, outsourcing, and the budget for operating the logistics business (Gunasekaran and Ngai, 2003). Furthermore, macro strategic planning needs to consider standards establishment (Razzaque and Sheng, 1998), performance measurement identification (Rao Tummala et al., 2006), and performance monitoring against the criteria (Razzaque and Sheng, 1998).

In the micro level, specific factors need to be considered, as follows.

- **Inventory management**, also known as resource management, involves planning, coordinating and controlling the materials flow along the supply chain (Gunasekaran and Ngai, 2003). In order to be responsive to the changing market demands, different methods are adopted to optimize the utilization of resources. For example, material requirement planning, just-in-time methodology, and vendor managed inventory (Power et al., 2001).

- **Transportation planning** consists of transportation modes, utilization of available capacity, planning of transportation equipment, and maintenance of transportation facilities (Gunasekaran and Ngai, 2003). Well-planned transportation can help reduce lead time (the time interval between placing an order and receiving the order), as well as enhance a supply chain's reliability (the ability of delivering products in right quantities without damage) and flexibility (the capacity of arranging urgent deliveries) (Korpela and Tuominen, 1996).
- **Capacity planning** is driven by both long-term and short-term demand for products along the chain (Gunasekaran and Ngai, 2003). Decisions of capacity planning are on the amount and capacity of warehouses, distribution centres, transportation vehicles, as well as personnel (Gunasekaran and Ngai, 2003).
- **Participative management** is the special management of personnel. Specific methods are composed of cultural development, motivational aids, systematical training and education (Wong, 2005), as well as internal and external communication (Razzaque and Sheng, 1998). Once the personnel work as a team with common goals, the supply chain will be more cost-effectiveness (the ability to meet the customers' requirements) and value-added (the ability to offer services exceeding the basic requirements) (Korpela and Tuominen, 1996; Power et al., 2001). The role of computer-based technologies has attracted significant attention in supply chain management.
- **Information management** deals with the managing of effective strategic and operational information systems with the purpose of offering accurate information on the utilization of resources for value-adding activities and on the performance of various areas of a supply chain (Korpela and Tuominen, 1996; Gunasekaran and Ngai, 2003).
- **Technology utilization** exists in different parts of a logistics system, such as e-procurement, e-commerce, data mining, data warehousing, and electronic data interchange (Korpela and Tuominen, 1996; Gunasekaran and Ngai, 2003).

- **Relationship development** including long-term and contractual relationships with both customers and providers of logistics services is the last factor at the micro level due to the emphasis on coordination and collaboration (Korpela and Tuominen, 1996). Good customer-supplier relationships are critical for agile supply chain management (Power et al., 2001; Rao Tummala et al., 2006) and outsourcing logistics activities (Razzaque and Sheng, 1998).

The only factor in the mutual-level is **continuous improvement** which assists with activity integration of all areas by collecting data on the performance and utilization of resources, and then making required changes to logistics operations (Gunasekaran and Ngai, 2003). An organization that is needed to reengineer material flows (Rao Tummala et al., 2006) or reengineer complex relationships (Power et al., 2001) can benefit from a holistic and continuous improvement.

In summary, the above ten CSFs in commercial supply chain management area can contribute to three goals: (i) effective logistics strategic management systems, (ii) integrated customer-oriented logistics processes, and (iii) flexible logistics organizations (Korpela and Tuominen, 1996). Two of the ten CSFs are the concentration of this thesis – inventory management and transportation management; therefore, literature on these two factors is explored separately in the following subsections 2.2.3 and 2.2.4.

**Table 2.3:** Critical Successful Factors (CSFs) in commercial supply chain management

| **CSFs** | *Alternate Terms* | *Key Activities* | *References* |
|---|---|---|---|
| | | ***Macro-level Factors*** | |
| **Strategic planning** | Corporate/business strategy development, long-term decision making | Organizational infrastructure and corporate culture creation, budget, market segment analysis, product/service selection, customer focus, target setting and performance monitoring | Gunasekaran and Ngai, 2003; Korpela and Tuominen, 1996; Petitt and Bereford, 2009; Power et al., 2001; Rao Tummala et al., 2006; Razzaque and Sheng, 1998; Wong, 2005 |
| **Supply chain** | Logistics | Process integration, | Korpela and |

| | | | |
|---|---|---|---|
| **strategy** | strategic management | outsourcing, just-in-time strategy, balance of leanness and agility | Tuominen, 1996; Petitt and Bereford, 2009; Power et al., 2001; Razzaque and Sheng, 1998; Wong, 2005 |
| | | ***Micro-level Factors*** | |
| **Inventory management** | Production planning, order management, resource management, material flow re-engineering | Demand forecasting; location selection; network consulting; slotting/layout design; planning, coordinating and controlling of materials flow, volumes, timings, and consolidation | Gunasekaran and Ngai, 2003; Petitt and Bereford, 2009; Power et al., 2001; Rao Tummala et al., 2006; Wong, 2005 |
| **Transportation planning** | Shipping planning, transportation availability and limitation | Transportation mode selection, available capacity utilization, transportation equipment planning, transportation facilities maintenance, contract delivery, load tendering and brokering | Gunasekaran and Ngai, 2003; Petitt and Bereford, 2009 |
| **Capacity planning** | Capacity mapping; storage, processing and transportation capacity | Long-term and short-term demand analysis, warehouse capacity, capacity of transportation vehicles, material handling equipment capacity, human resources | Gunasekaran and Ngai, 2003; Petitt and Bereford , 2009 |
| **Participative management** | Human resource management, human factor management | Internal and external communication, training and education, motivational aids, culture development | Petitt and Bereford, 2009; Power et al., 2001; Razzaque and Sheng, 1998; Wong, 2005 |
| **Information management** | Strategic and operational information management, enterprise resource planning | Integration, data collection on performance and utilization of resources, data mining | Gunasekaran and Ngai, 2003; Korpela and Tuominen, 1996; Petitt and Bereford, 2009; Power et al., 2001; Umble et al, 2003; Wong, 2005 |
| **Technology utilization** | Technology implementation | Implementing information and communication technology, innovation and adaptation, interfacing | Korpela and Tuominen, 1996; Petitt and Bereford, 2009; Power et al., |

| | | | |
|---|---|---|---|
| | | | 2001; Rao Tummala et al., 2006; Wong, 2005 |
| **Relationship development** | Coordination and collaboration | Long-term and contractual relationships, supplier relations development, building customer-supplier relations | Korpela and Tuominen, 1996; Petitt and Bereford, 2009; Power et al., 2001; Rao Tummala et al., 2006; Razzaque and Sheng, 1998 |
| ***Mutual-level Factor*** | | | |
| **Continuous improvement** | Benchmarking | Reliability, lead time, flexibility, cost-effectiveness, value-added, performance measurement | Korpela and Tuominen, 1996; Petitt and Bereford, 2009; Power et al., 2001 |

### 2.2.3. Inventory Management

In the 17th Annual State of Logistics Report, Wilson (2006) reviews the trends in inventory costs, transportation costs, and total logistics costs since 1984 in the United States. The report points out that inventory carrying costs account for 33% or so of the over one trillion dollars spent on logistics (Wilson, 2006). As a stock of goods kept for sale or use in the future (Stevenson and Hojati, 2004), inventory plays a role of staple in most supply chains (Zhang, 2013). Therefore, inventory management is an indispensable part of supply chain management.

The main goal of inventory management is balance – too much adds unnecessary costs, while too little causes delays or disrupts schedules (Stevenson and Hojati, 2004). Basically, inventory management includes two functions: (i) how to classify inventory items and maintain accurate inventory records (Heizer and Render, 2004), as well as (ii) how to decide the amount and time to order items (Stevenson and Hojati, 2004). Since scholars in different areas try to advance the theories and practices in inventory management, inventory management research has long been central to academic literature. Related studies in the field of supply chain management are examined in this subsection. Overall, there are three themes: traditional inventory management models, collaborative inventory management models, and just-in-time (JIT) inventory management strategy.

***Traditional Inventory Management Models***

A majority of the research on inventory management in supply chain concentrates on traditional inventory control models (Williams and Tokar, 2008). Generally, there are five inventory models for independent demand: (i) the basic Economic Order Quantity (EOQ) model; (ii) the Re-order Point (ROP) model; (iii) the Economic Production Quantity (EPQ) model; (iv) the quantity discount model; and (v) the Fixed Order-interval (FOI) model (Heizer and Render, 2004; Stevenson and Hojati, 2004). The first four models, assume the demand for a single product is known and constant, and belong to fixed-quantity system, or Q system. The same fixed amount (Q units) is added to inventory every time an inventory decreases to the reorder point (Heizer and Render, 2004). If organizations use the fixed-quantity system, they will need a continuous inventory review system to keep track of each addition or withdrawal to inventory (Heizer and Render, 2004).

In contrast, in the fixed-period system, or P system (Heizer and Render, 2004), the FOI (Fixed Order-interval) model is suitable when demand is unknown but can be specified by a probability distribution (Heizer and Render, 2004; Stevenson and Hojati, 2004). In this kind of model, various amounts of items are ordered at regular time intervals (P) to raise inventory up to the target value (T) (Heizer and Render, 2004; Stevenson and Hojati, 2004).

According to Williams and Tokar (2008), most research in inventory management assumes the approach of the Q system. Moreover, there are studies extending the Q system in several aspects. Specifically, additional elements like transportation factors (Swenseth and Godfrey, 2002), short lead times (Mattsson, 2007), as well as emergency conditions (Beamon and Kotleba, 2006b) are taken into consideration. On the other hand, some authors evaluate the Q system approach under particular demand and lead-time distribution. For instance, Namit and Chen (1999) build an accurate and efficient algorithm that does not need tabulated values for solving the inventory model in the Q system with gamma lead-time demand.

However, the method of the P system has not been studied as widely as the Q system in the logistics literature. Some authors assume the P system approach as either the sole inventory management policy, or one of several policies. To illustrate, Sezen (2006) uses a simulation approach to explore the effects on the performance of a periodic review inventory model while changing the length of the review period with lost sales under normally distributed demands.

Some researchers integrate diverse logistics factors into this policy. For example, Qu et al. (1999) propose an integrated inventory-transportation system with modified periodic policy for multiple products. A heuristic decomposition approach is used to deal with a multi-item joint replenishment problem in a stochastic setting, aiming to minimize the long-run total average costs and make the decisions on inventory control as well as transportation planning at the same time (Qu et al., 1999). Graves and Willems (2000) build a framework for modeling strategic safety stock placement in a supply chain subject to uncertain demand or forecast. A key assumption is that Graves and Willems (2000) regard supply chain as a network and every single stage operates with a periodic-review base-stock replenishment policy.

***Collaborative Inventory Management Models***

The above-mentioned literature shows that researchers pay attention to integrating logistics considerations into traditional inventory management models. Giunipero and Eltantawy (2004) state that traditional buffer strategies against risks use multiple sources for strategic items and holding safety inventories, while new methods include identifying potential losses, understanding the likelihood of potential losses, and assigning significance to the losses. Applying this concept to supply chain management means enhancing performances by integrating internal functions within an organization and linking them with external operations of suppliers, channel members and customers (Giunipero and Eltantawy, 2004).

From the perspective of inventory management, researchers in the supply chain management area focus on how collaboration among business entities affects inventory policy decisions in an organization. According to Williams and Tokar (2008), four widely used collaborative methods are Continuous Replenishment Planning (CRP), Vendor Managed Inventory (VMI), Efficient Consumer Response (ECR), and Quick Response (QR). Some researchers try to find the determinants and enablers of successful collaborative inventory relationships. For example, Borade et al. (2013) identify seven factors and 50 sub-factors which are critical to VMI, and build an Analytical Hierarchy Process (AHP)-based framework for VMI adoption. In contrast, others concentrate on testing the benefits of collaborative inventory relationships for supply chain entities. For instance, Yao and Dresner (2008) make an analysis of benefits in terms of inventory cost savings to both manufacturers and retailers under information sharing, CRP, or VMI.

***Just-in-time (JIT) Inventory Management Strategy***

Usually, inventory in supply chain management exists just-in-case (JIC) something goes wrong, and extra inventory is used to cover problems (Heizer and Render, 2004). Nonetheless, efficient and effective inventory management strategy needs just-in-time (JIT) rather than JIC. JIT inventory is the minimum inventory necessary to keep a perfect system running, and the exact number of items arrives at the moment the items are needed (Heizer and Render, 2004). Recently, more researchers focus on the JIT inventory management strategy. For example, Hoque and Goyal (2000) propose an optimal solution process for the single-vendor, single-buyer, production-inventory system with both equal and unequal sized shipments from vendor to buyer under the limitation of transportation equipment capacity.

In short, three major streams of studies are classified in this subsection and the next subsection 2.2.4 is about those papers on transportation management.

### 2.2.4. Transportation Management

Transportation cost growth is the single largest rise of business logistics in the United States and accounts for six percent of nominal GDP in 2006 (Wilson, 2006). As a physical link between supplier and customer enabling the flow of resources, transportation is a key function in supply chain management (Naim et al., 2006). Transportation planning is interrelated with inventory strategy and warehouse management. There is a contradictory relationship between transportation efficiency and inventory efficiency (Zhang, 2013). All of the costs, methods, and routes of transportation can have impacts on inventory level. After reviewing the literature in transportation management, three research streams are identified in this area: attribute identification, decision process development, and supply chain integration.

***Attribute Identification***

Research with focus on attribute identification identifies critical properties for the transportation mode choice and carrier selection. Flexibility is a major performance measure in supply chain management, especially under uncertainties. From a logistics perspective, Naim et al. (2006) develop a framework to rationalize transportation flexibility into fourteen elements: mode, fleet, vehicle, node, link, temporal, capacity, routing, communication, product, mix, volume, delivery, and access. Understanding these elements, then the time and degree of required transportation flexibility are determined.

From a fresh perspective, Voss et al. (2006) point out that the topic of importance of carrier attributes needs to be reevaluated because of increasing demand for carrier preparation under an unforeseen environment, as well as growing emphasis on transport costs reduction and supply chain security. As a result, Voss et al. (2006) apply the Theory of Reasoned Action (TRA) since TRA can assist with the forecast of behavioral intentions under various situations; that is, TRA might be helpful in evaluating shippers' intention to purchase transportation services from carriers with certain attributes. Finally, the top two carrier selection criteria are identified: delivery reliability and rates.

***Decision Process Development***

Developing qualitative or quantitative models to support the logistics decision procedure of transportation mode choice and carrier selection is the purpose of this research stream. McGinnis (1989) investigates four general types of transportation choice models in the literature:

1. the classical economic model identifies the distance breakpoint between competing modes such as rail and truck shipments by cost issues;
2. the inventory-theoretic model makes trade-offs among freight rates, transit time, reliability, and en-route lossage, as well as determines the optimal model relying on total costs of ordering, transportation, and inventory;
3. the trade-off model identifies the best model according to the total of transportation costs and quantifiable non-transportation costs; and
4. the constrained optimization model makes the choice by minimizing transportation costs subject to both quantitative and qualitative non-transportation constraints such as production constraint, distribution pattern restrict, and service need limitation.

Other researchers build models first and then apply to a real problem. For instance, deJong and Ben-Akiva (2007) develop a micro-simulation (firm-to-firm level) multi-nominal logit choice model of shipment size, segment number in transport chain, as well as use of consolidation and distribution centres for water, road, rail, and air transport. The purpose is to minimize the total annual logistics costs such as order, transport and inventory. DeJong and Ben-Akiva (2007) apply this model to the national freight transportation forecasting systems in Norway and Sweden.

***Supply Chain Integration***

The last category of studies is related to supply chain integration in which organizations collaborate to integrate transportation choices into other supply chain decisions. Supply chain management includes a series of activities such as demand management, order fulfillment management, manufacturing flow management, and customer relationship management (Meixell and Norbis, 2008). These activities involve transportation choice at several points (Meixell and Norbis, 2008). Different authors consider different initiatives in supply chain activities. For example, Miller and deMatta (2003) build an integrated production and transportation scheduling model for a geographically separated multi-echelon manufacturing network. Aiming to minimize the total cost, the model generates a line-by-line and product-by-product production schedule, as well as a transportation schedule for shipments between separated plants. Unlike Miller and deMatta (2003), Liao and Rittscher (2007) combine transportation choice with lot sizing and supplier selection. A multi-objective programming model is formulated to: (i) decide the time and quantity to order under dynamic demand conditions, (ii) pick suppliers and determine the order amount from each selected supplier, and (iii) choose specific carriers for the selected suppliers. The purpose of the model is to minimize the total logistic cost, total quality rejected items, and late deliveries constrained to demand satisfaction and capacity issue.

Esper and Williams (2003) address nearly all of the above issues. Esper and Williams (2003) develop a conceptual framework and quantifiable measures for Collaborative Transportation Management (CTM) and illustrate the importance of information technology in CTM procedures, aiming to reduce transaction costs, improve service capacities, and realize a more streamlined chain via third-party logistics and transportation service providers or collaborative relationships. An important concept of CTM is to transfer the order forecast established by Collaborative Planning, Forecasting and Replenishment (CPFR), into shipments forecast along with accurate fulfillment. It is a meaningful approach to dealing with issues on inventory reduction, underutilized carrier equipment, or even the overall operation performance.

The research on general supply chain management is relatively mature, as reviewed in this section. In contrast, studies with the focus on supply chain management in aid and relief context are sparse. In order to make up this research gap, it is necessary to identify the significant articles in humanitarian supply chain area, as described in the following section 2.3.

## 2.3. Humanitarian Aid and Disaster Relief Supply Chain Management

Humanitarian aid and disaster relief supply chain management is described as "sense-and-respond", and includes a series of activities: planning, preparedness, procurement, transportation, warehousing, tracking, last mile delivery, and customer clearance (Thomas, 2007; Thomas and Kopczak, 2005). Thomas and Kopczak (2005) explain the process specifically: once a disaster happens, experts will be sent to assess the extent of damage and the number of affected people, helping identify both the kinds and the quantities of relief items required. Emergency stocks of standard relief items are sent from the nearest warehouses. When the relief items arrive, local transportation, warehousing, and distribution need to be organized as part of this problem situation.

However, few organizations have prioritized the development of high-performing supply chain operations for humanitarian aid and disaster relief. These operations are judged as being not as effective and efficient as they could be (Thomas and Kopczak, 2005). Thus, it is important to improve the performance of supply chain management and then enhance the whole humanitarian aid and disaster relief operations. Logisticians participating in Fritz Institute's Humanitarian Logistics Conference identified several topics: managing a humanitarian response, humanitarian supply chains, procurement, warehousing and inventory management, transportation, fleet management, and import/export procedures (Thomas and Kopczak, 2005). The focus of this thesis is on the topics that include facility location selection, inventory management, and transportation planning. With the similar structure of the above section 2.2, this section is organized as follows: (2.3.1) performance measurement aid and relief, (2.3.2) critical successful factors aid and relief, (2.3.3) inventory repositioning, and (2.3.4) transportation planning.

### 2.3.1. Performance Measurement Aid and Relief

Since logistics occupy 80% of disaster relief (Van Wassenhove, 2006), measuring the performance of logistics operations and more precisely supply chain management is significant for humanitarian aid and disaster relief. An effective performance measurement system can help practitioners make relief decisions, and can enhance the efficiency and effectiveness of relief operations. Performance measurement can improve the transparency and accountability of disaster responses (Beamon and Balcik, 2008). However, research has not widely developed and systematically implemented performance measurement systems in humanitarian aid and disaster relief supply chain due to the uniqueness and complexity of the disaster relief environment (Beamon and Balcik, 2008).

A recent exception is the research conducted by Davidson (2006) that proposes a performance measurement framework of relief logistics for the International Federation of Red Cross and Red Crescent Societies. The framework is based on four indicators which measure supply chain performance in terms of the trade-offs of speed, cost and accuracy: appeal coverage, donation-to-delivery time, financial efficiency, and assessment accuracy. Despite the fact that this research is performed with an international non-profit humanitarian organization in mind, the principles of measurement are related to other organizations that take part in disaster relief operations such as non-governmental organizations and governmental agencies.

Particular characteristics in humanitarian aid and disaster relief supply chain can be divided into three parts: strategic goals, demand characteristics, and customer characteristics. To start with, the strategic goal of commercial supply chain is to produce maximum profits and high quality goods or services, while the ultimate objective of humanitarian aid and disaster relief supply chain is to save lives and reduce human suffering (Beamon and Balcik, 2008). In addition, the demands in commercial supply chain are products or services, but the demands in humanitarian aid and disaster relief are relief items and human resources (Beamon and Balcik, 2008). The demand within a commercial supply chain is generally assumed to be more stable and predictable, while the demand in humanitarian aid and disaster relief supply chain is changeable in terms of type, time, location, and quantity (Beamon and Balcik, 2008). Finally, customers in humanitarian aid and disaster relief supply chain are aid recipients who do not have rich choices for supplies (Beamon and Balcik, 2008).

In spite of the differences mentioned above, general concepts in commercial supply chain management can be applied to humanitarian aid and disaster relief situation. As for performance measurement, three broad types of measures in commercial supply chain management have been summarized above in Table 2.2; that is, resource, output, and flexibility measurement. Similarly, performance of humanitarian aid and disaster relief supply chain management can also be measured from the same three aspects. Nevertheless, the difference is that specific objectives need to be adjusted.

First of all, resource measurement indicates the efficiency level of humanitarian aid and disaster relief supply chain. Inefficient resource utilization can discourage donor funding. In commercial context, cost is the major resource measure. Although saving money is not the priority in humanitarian situation, a budget constraint exists and efficient resource utilization can lead to more people helped per dollar spent. Three dominating costs in humanitarian aid and disaster relief are: (i) supply cost, (ii) distribution cost, and (iii) inventory cost (Beamon and Balcik, 2008). Apart from costs, resources also include: personnel, facilities, information, and materials. Efficient allocation of personnel, utilization of equipment, and integration of process can improve the performance level of the whole chain.

Output measurement can directly evaluate the characteristics of supply which is the primary goal of any supply chain. In humanitarian aid and disaster relief, time is an important dimension and poor output can cause more suffering and even death. The objective of aid output is to minimize product lateness and response time (instead of maximizing commercial sales and profits). Other measures in commercial supply chain such as fill rate can be used for assessing the performance of permanent warehouses in humanitarian aid and disaster relief background (Beamon and Balcik, 2008). The distinctive distribution concern in disaster operation means equity (Beamon and Balcik, 2008). These specific output measures can be combined together to improve the demand satisfaction.

Finally, inherent uncertainties and the high variability of humanitarian aid and disaster relief environment call for high flexibility levels. In the commercial situation, as discussed above, there are four types of flexibility: (i) volume flexibility – the ability to change the volume of output, (ii) delivery flexibility – the capacity of adjusting assumed dates of delivery, (iii) mixed flexibility – the ability of changing the variety of produced products in a given time period, and (iv) new product flexibility – the capacity in modifying existing products or introducing new ones (Slack, 2005). With the exception of the last item, enhancing anyone of the other three types of flexibility can improve risk management in humanitarian aid and disaster relief. As noted by Beamon and Balcik (2008), volume flexibility implies the ability of responding to different magnitudes of disasters; delivery flexibility indicates the response time to disasters; and mixed flexibility represents the capacity of offering various relief items. Table 2.4 (comparable to Table 2.2 above for commercial supply chain performance) summarizes the performance measurement of humanitarian aid and disaster relief supply chain management. Parallel subsection 2.2.2, subsection 2.3.2 below identifies the Critical Successful Factors (CSFs) for humanitarian aid and disaster relief supply chain management to improve the overall performance.

**Table 2.4**: Performance measurement of humanitarian aid and disaster relief supply chain management

| **Performance measurement** | *Specific objectives and measures* |
|---|---|
| **Resource measurement** | -cost minimization<br>-personnel allocation optimization<br>-equipment utilization maximization<br>-function duplication minimization |
| **Output measurement** | -product lateness minimization<br>-response time minimization<br>-fill rate maximization<br>-distribution equity maximization<br>-demand satisfaction maximization |
| **Flexibility measurement** | -volume flexibility maximization<br>-delivery flexibility maximization<br>-mixed flexibility maximization |

## 2.3.2. Critical Successful Factors Aid and Relief

Similar to commercial supply chain management, CSFs are the characteristics and conditions that impact the improved performance of humanitarian aid and disaster relief efforts. Despite the complexity of the environment where humanitarian aid and disaster relief supply chain operates, the basic activities in this kind of supply chain are not fundamentally different from those in commercial supply chain (Pettit and Beresford, 2009). Thus, the ten CSFs in Table 2.3 for commercial supply chain management are all relevant to humanitarian aid and disaster relief supply chain management. These CSFs are discussed in the relief context blow with the merger of two CSFs (information management and technology utilization); in other words, the original ten CSFs reduced to nine for humanitarian circumstance.

***1) Strategic Planning***

Strategic planning dealing with long-term decision needs to be addressed at the highest level of an organization (Pettit and Beresford, 2009). Different from logistics operations in commercial supply chain (which can be planned regularly in advance of demand), logistics decisions in humanitarian aid and disaster relief supply chain have to be made within short time frames (Balcik and Beamon, 2008). The assessment and planning for the Asian Tsunami was insufficient in many organizations, causing problems in the performance of an effective response (Fritz Institute, 2005). Thus, long-term scheduling plays an important role in realizing a high-performance disaster response. Below the organizational level, strategic planning deals with critical attributes related to various stages of disaster planning (Pettit and Beresford, 2009). Resources and capacities vary in three phases: (i) preparation, (ii) immediate response, and (iii) reconstruction (Kovacs and Spens, 2007). Hence, strategic planning requirements are also different in each phase. Overall, without strategic planning, it is improbable that individual aspects of a humanitarian aid and disaster relief business, such as supply chain management, can be fully achieved (Pettit and Beresford, 2009).

***2) Inventory Management***

There are two kinds of systems in a supply chain: the push system and the pull system. A push system means that suppliers produce products according to the prediction of customers' demands (Zhang, 2013). In contrast, a pull system begins with customers' real orders and suppliers only make enough products to fulfill customers' orders (Zhang, 2013). A commercial supply chain is controlled by a pull system to decrease inventory (Clay Whybark, 2007). However, a humanitarian aid and disaster relief supply chain pushes inventory into strategic storage locations before a pull system is implemented to reach the precise area of need (Clay Whybark, 2007). A variety of methods have been used in commercial organizations to optimize resource utilization. Some methods may be proper for humanitarian aid and disaster relief, such as just-in-time and vendor-managed inventory. Time is one of the most important factors in any humanitarian aid and disaster relief operation. In order to offer humanitarian aid and disaster relief rapidly, we need logistics capabilities to deploy inventory as soon as possible (Clay Whybark, 2007). Therefore, pre-positioning – the storage of inventory at or near the disaster location for seamless delivery of critical goods – plays a critical role in the inventory process (Ukkusuri and Yushimoto, 2008). Developing a collaborative warehouse network (Fritz Institute, 2005) which is supported by transportation capacity can also save time.

***3) Transportation Planning***

Instead of primary infrastructure and a stable vehicle fleet as in commercial supply chain management, the infrastructure for relief is often destabilized and the fleet has to be organized at the disaster location from available resources in humanitarian aid and disaster relief circumstances (Kovacs and Spens, 2007). In the disaster area, physical infrastructures including bridges, roads, railways, and airports are often destroyed. Transportation capacity becomes limited or even non-existent (Thomas and Kopczak, 2005). A full range of delivery choices are needed including sea, road, and air. Hence, the planning of transportation and the delivery in the preparedness phase is important in humanitarian aid and disaster relief.

***4) Participative Management***

The effectiveness and the capacity of distributing relief aid is impacted by how an organization organizes its staff (Pettit and Beresford, 2009; Thomas and Kopczak, 2005). However, the personnel in humanitarian organizations come from diverse backgrounds and most staff with logistics responsibilities do not have training in logistics (Thomas and Kopczak, 2005). A survey following the Asian Tsunami shows that 88% of organizations had to reallocate the most experienced logisticians from other assignments to staff the relief efforts (Fritz Institute, 2005). The professionalization of logistics is not smooth because field experience may be more meaningful than formal training (Thomas and Kopczak, 2005). Since the availability of trained logistics professionals to promote effective humanitarian aid response is important, there is a need to create a pool of trained and experienced logistics professionals – who share common processes, standardization, and vocabulary – at international, national, and local levels to be deployed on short notice (Fritz Institute, 2005; Thomas and Kopczak, 2005).

***5) Supply Chain Strategy***

In commercial supply chain, researchers pay attention to lean logistics and agile logistics. Leanness entails establishing a value stream to remove waste including time and to enable a level schedule (Naylor et al., 1999). Agility means using market knowledge and virtual companies to develop profitable chances in an unstable marketplace (Naylor et al., 1999). It is important to identify the most proper concepts from established commercial supply chain frameworks (Pettit and Beresford, 2009) and then use those concepts to improve the performance of humanitarian aid and disaster relief. The lean thinking paradigm suggests doing more with less. This concept is suitable for situations with stable demand, low variety, and high volume (Christopher, 2000). It is difficult to apply the lean concept to humanitarian aid and disaster relief environment. In contrast, the key to agility is the flexibility in responding quickly to changes in demand in terms of variety and volume (Christopher, 2000). It is helpful to improve the demand satisfaction in humanitarian aid and disaster relief supply chain performance. Nevertheless, an agile supply chain is less cost-effective than a lean one. Therefore, some researchers also try to combine these two concepts into 'leagility' (Naylor et al., 1999), aiming to bring the advantages of lean and agile supply chain together. In addition, outsourcing non-core activities like just-in-time may also be a useful strategy (Razzaque and Sheng, 1998).

***6) Information Management and Technology Utilization***

In the general supply chain context, information management and technology utilization are often regarded as enablers for knowledge management in an organization (Wong, 2005). Similarly, information technology plays an important role in the humanitarian aid and disaster relief environment. The use of information systems to track and trace relief items helps improve the effectiveness of aid delivery and waste minimization (Fiedrich et al., 2000; Pettit and Beresford, 2009). In addition, specific communication systems and decision support systems are critical in handling relief operations (Pettit and Beresford, 2009). For example, geographical information systems can help analyze transportation lifelines, map resources, and identify highly damaged areas (Fiedrich et al., 2000). The Humanitarian Supply Management System (SUMA) can assist in classification of available resources (PAHO/WHO, 2001). However, supply chain management in humanitarian aid and disaster relief sector is still largely manual (Lee and Zbinden, 2003; Thomas and Kopczak, 2005). Only 26% of organizations have access to track and trace software (Fritz Institute, 2005). Therefore, there is a common need for developing flexible technology solutions to support procurement, tracking and tracing inventory, distribution through a pipeline, robust reporting and connectivity in the field (Fritz Institute, 2005). Moreover, advanced information systems can form a foundation for knowledge management, performance measurement, and organization learning (Thomas and Kopczak, 2005). Overall, four major functions must be included in humanitarian logistics software: (i) mobilization, (ii) procurement, (iii) transportation and tracking, as well as (iv) reports (Lee and Zbinden, 2003).

***7) Relationship Development***

In the immediate response to the Asian Tsunami, a considerable inter-organization conflict existed and it was not until this was addressed that improved collaboration was achieved (Pettit and Beresford, 2009). This is an example revealing the fact that poor collaboration can affect many other success factors such as inventory management, transportation planning, and capacity planning. Thus, building relationships by collaboration is a key factor in best supply chain practice and in logistics network integration (Power et al., 2001). According to the Fritz Institute (2005), the result is overall positive once collaboration happens. For example, collaborative warehousing strategy can make relief provision more effective and therefore save more people. In a sudden onset natural disaster, relationships on the basis of trust have to be established quickly. Therefore, the development of swift trust, "the willingness to rely upon team members to perform their formal and informal roles in a hastily formed temporary team" (Zolin, 2002, p.4), is a significant enabler.

***8) Capacity Planning***

Capacity planning is influenced by demand and has an effect on decisions about numbers of warehouses, distribution centres, vehicles, employees, and other equipment (Pettit and Beresford, 2009). Four key activities which can affect capacity are warehousing, transportion, material handling, and personnel resources (Gunasekaran and Ngai, 2003). Maximizing the use of capacity is a key to humanitarian aid and disaster relief supply chain management (Gunasekaran and Ngai, 2003). Generally speaking, capacity planning of the aid and relief network can be enhanced by collaboration. Also, capacity planning can involve the ability of ports and airports to hold relief items under different scenarios (Pettit and Beresford, 2009).

### *9) Continuous Improvement*

In supply chain management, organizations need to concentrate on having a continuous and holistic improvement method to meet the demands of customers (Power et al., 2001). Performance measurement is useful in this process, tracking key factors in supply chain performance and benchmarking activities against key performance indicators (Koeprla and Tuominen, 1996). Humanitarian aid and disaster relief supply chain can learn from this process to improve itself and achieve greater success. Continuous improvement such as transformational or incremental change is an essential part of disaster management practices at all levels to minimize the recurrence of problems (Government of Canada, 2011a). After a disaster happens, a systematic method can be used to learn lessons from the experience, to increase effectiveness, and to improve disaster management practices and processes (Government of Canada, 2011a). For instance, using information technology, the performance measurement system can evaluate the overall effectiveness of the supply chain (Fritz Institute, 2005).

**Table 2.5**: CSFs in humanitarian aid and disaster relief supply chain management

| **CSFs** | *Enablers or strategies* | *References* |
|---|---|---|
| **1-Strategic planning** | Target setting, strategic alliance forming, aggregate planning, partner selection, getting support of top management, capital acquirement | Balcik and Beamon, 2008; Fritz Institute, 2005; Gunasekaran and Ngai, 2003; Petitt and Bereford, 2009 |
| **2-Inventory management** | Demand forecast, push and pull system combination, facility location selection, pre-positioning, just-in-time, vendor-managed inventory, centralized purchasing, collaborative warehousing network development | Clay Whybark, 2007; Fritz Institute, 2005; Gunasekaran and Ngai, 2003; Petitt and Bereford, 2009; Zhang, 2013 |
| **3-Transportation planning** | Transport mode selection, total productive maintenance, vehicle routing optimization, contract delivery, centralized purchasing | Gunasekaran and Ngai, 2003; Kovacs and Spens, 2007; Petitt and Bereford, 2009; Thomas and Kopczak, 2005 |

| | | |
|---|---|---|
| **4-Participative management** | Improved standardized education and field training, professional logistics community creation | Fritz Institute, 2005; Petitt and Bereford, 2009; Thomas and Kopczak, 2005 |
| **5-Supply chain strategy** | Outsourcing non-core activities, integration the concepts of leanness and agility | Christopher, 2000; Naylor et al., 1999; Petitt and Bereford, 2009; Razzaque and Sheng, 1998 |
| **6-Information management and Technology utilization** | Development of flexible technology solutions, process integration, data mining, data collection on performance, data warehousing | Fiedrich et al., 2000; Fritz Institute, 2005; Gunasekaran and Ngai, 2003; Lee and Zbinden, 2003; Petitt and Bereford, 2009; Thomas and Kopczak, 2005; Wong, 2005 |
| **7-Relationship development** | Long-term and contractual relationships, collaboration establishment; swift trust building | Fritz Institute, 2005; Petitt and Bereford, 2009; Power et al., 2001; Zolin, 2002 |
| **8-Capacity planning** | Long-term and short-term demand analysis; aggregate capacity planning; collaboration building; improving utilization of warehouses, materials, equipment, and personnel | Gunasekaran and Ngai, 2003; Petitt and Bereford, 2009 |
| **9-Continuous improvement** | Development of performance measurement system, benchmarking | Fritz Institute, 2005; Korpela and Tuominen, 1996; Petitt and Bereford, 2009; Power et al., 2001 |

Taking the above into consideration, the nine CSFs in humanitarian aid and disaster relief are listed in Table 2.5 above. In particular, specific enablers or strategies which can help achieve each factor are classified and summarized along with the respective reference to the published literature. This thesis research pays attention to the inventory and transportation factor. Thus, more published studies are explored further in the next two subsections 2.3.3 and 2.3.4.

### 2.3.3. Inventory Prepositioning

Controlling disaster relief inventories is challenging. On the one hand, organizations may experience stock-outs for responding to demand surge without sufficient inventory. On the other hand, large amount of excess inventory can be commonplace due to an inactive period of extreme event disasters. Within the disaster preparedness phase, facility location and stock prepositioning decisions are two important parts that require long-term planning to achieve a high-performance disaster response (Balcik and Beamon, 2008). Recently, some humanitarian aid and disaster relief organizations have pre-positioned relief items in strategic locations to improve the ability of delivering sufficient items in a short period. Although much literature is available on enterprise inventory control, there is little research of humanitarian aid and disaster relief inventory management (Beamon and Balcik, 2006a; Clay Whybark, 2007). An exception exists in the health service area. For example, Bechtel et al. (2000) explore how to manage disaster relief inventories of blood, medicine, and medical supplies.

Different kinds of relief items are needed at different times. Thus, some items which are immediately needed during the earliest phases of relief operations should be pre-positioned; while those which can be safely provided in later phases can be postponed. Pre-positioned items include food items, e.g., ready-to-eat meals; non-food items such as blankets, tents and jerry cans; medical supplies; as well as equipment such as telecommunication equipment (Balcik and Beamon, 2008). The prepositioning system should keep a balance between costs against risks in humanitarian aid supply chain, and increase the benefits to the affected population (Balcik and Beamon, 2008). Inventory prepositioning theory includes two broad categories: one is inventory theory which appraises stock levels needed at various nodes along a supply chain; the other is related to facility location which uses a facility location model to identify optimal locations for stocks (Ukkusuri and Yushimito, 2008).

***Inventory Theory***

Generally, research on humanitarian aid and disaster relief concentrates on solving decision problems from the view of non-government and not-for-profit organizations, leaving out the for-profit, private sector organizations. For example, Beamon and Kotleba (2006a) build a stochastic single-item multi-supplier inventory management model to determine optimal order quantities and reorder points. The analysis depends on a case study of a single humanitarian organization operating a pre-positioned warehouse in Lockichoggio, Kenya and responding to the south Sudan crisis.

Similarly, Beamon and Kotleba (2006b) build three single-item inventory management models for pre-positioned stocks supporting long-term relief response in south Sudan: (i) a mathematical model optimizing reorder quantity and level according to the costs of reordering, holding, and backorder; (ii) a heuristic model deciding reorder quantity based on reordering and holding costs; and (iii) a naïve model relies on convenience and implementation ease. A humanitarian relief simulation model, and a relief-specific performance measurement system are proposed. According to the research analysis, Beamon and Kotleba (2006b) identify the factors important to the performance of the inventory system. Additional details and analysis about the first model have been demonstrated in Beamon and Kotleba (2006a).

The previous two papers of Beamon and Kotleba are from the perspective of an NGO focusing on long-term humanitarian aid and disaster relief operations. Other research focuses on for-profit and private sector organizations particularly. Using a newsvendor-type of analysis, Lodree and Taskin (2008) model the uncertainty of a potential threat to identify proper inventory levels. Lodree and Taskin (2008) develop variations to the classical newsvendor solution to plan the inventory for initial disaster response. In addition, an insurance policy framework is built to prepare for demand surge caused by potential disaster relief activities or supply chain disruption in the context of inventory control. However, Lodree and Taskin (2008) do not take the facility location and the possibility of inventory being destroyed into account.

Lodree and Taskin (2009) formulate the inventory control problem as an optimal stopping problem with Bayesian updates for a single-supplier, single-retailer supply chain. An unofficial hurricane prediction model is introduced. Moreover, Lodree and Taskin (2009) present a method to determine when to order and how much to order non-priority products by a manufacturer. No location decisions are considered.

Taskin and Lodree (2010) formulate a stochastic programming model to specify cost minimizing inventory strategies for meeting demands prior to the hurricane season and preparing for potential demand surge during the season. Specifically, Taskin and Lodree (2010) consider the information updating problem which is similar to Advance Booking Discount program in commercial supply chain. Decision makers can modify inventory policy based on the updated hurricane season demand information, and when the pre-season demand realizations happen.

Taskin and Lodree (2011) build a sequential Bayesian decision model to help private sector manufacturing firm to minimize expected costs of inventory control in response to an observed tropical cyclone. Taskin and Lodree (2011) deal with a single-supplier, multi-retailer supply chain system with a random demand at each retailer location. An official hurricane prediction model used by the National Hurricane Centre (NHC) is included.

Different from all the above studies, models built by some research can be applied to both not-for-profit and for-profit organizations. For example, Ozbay and Ozguven (2007) develop a realistic model of time-dependent inventory planning and management problem which can be used for developing efficient pre- and post-disaster plans. This model aims to determine the minimal safety stock level while allowing a continuous consumption without disruption.

***Facility Location***

Inventory management involves three basic questions: how much to order, when to order, and where to store it. In disaster relief inventory area, the question of where to store inventory is more critical (Clay Whybark, 2007). Dekle et al. (2005) test where to locate Disaster Recovery Centres (DRCs) for a single county in Florida. First, a standard set-covering model is built. Then, other site locations are identified close to those chosen by the set-covering model. However, no inventory decisions are considered.

Campbell and Jones (2011) point out that inventory and facility locations are intertwined, while all research mentioned above concentrates on the inventory control strategy. Several studies integrate the facility location decision into the inventory control problem. Chang et al. (2007) propose two stochastic programming models to help government departments to make decisions for urban flood emergency logistics preparation, including locations of relief items storehouse, required quantities, and distribution of relief equipment. Chang et al. (2007) study how to optimize the expected performances in all scenarios and combine scenario planning with flood emergency logistics preparation modeling. However, Chang et al. (2007) do not consider the vehicle scheduling problem.

Balcik and Beamon (2008) build a mathematical model which is a variant of the maximal covering location model. Balcik and Beamon (2008) combine facility location and inventory prepositioning together, deciding the number and location of the warehouses first, and then determining the amount of relief items to be stocked in each warehouse. The model provides an integrated global stock prepositioning system for humanitarian aid and disaster relief supply chain responding to sudden-onset disasters. However, there are two assumptions of the model: (i) multiple disasters do not happen simultaneously, and (ii) there is no possibility of inventory being destroyed.

Closely related to Balcik and Beamon (2008), Duran et al. (2011) build a mixed integer programming inventory location model for CARE to decide the optimal number and location of pre-positioning warehouses as well as the quantity of inventory in each warehouse. Nevertheless, two differences exist: (i) multiple events can happen during a replenishment period, and (ii) the probability of demand for every item relies on local conditions and natural disaster type.

Based on dynamic hurricane information, Salas et al. (2012) start from building a stochastic programming inventory model of perishable products for government or non-profit organizations to minimize costs and maximize demand satisfaction. A process is proposed to transform the first model into a deterministic mixed integer programming model.

Most research in the humanitarian aid context determines location decisions and stocking levels aiming to minimizing goals within limited scenarios. The research of Campbell and Jones (2011) is the first to consider both inventory level and risk without using scenarios. Campbell and Jones (2011) explore where to pre-position relief items in preparation for a disaster and how much to pre-position at each location. However, there is an assumption that the destruction probability of each facility location is independent.

To sum up, the prepositioning of relief resources is a common focus of inventory management in humanitarian aid and disaster relief. The two important decisions on inventory prepositioning are the facility location and the stock level. Even though managing relief inventory efficiently plays a critical role in response to a disaster, it is also important to deploy the resources timely by effective transportation planning. The subsection 2.3.4 below is a recap of literature on transportation planning.

### 2.3.4. Transportation Planning

Transportation is the second largest overhead cost to humanitarian aid and disaster relief operations after personnel (Pedraza Martines et al., 2011). Main operational decisions on transportation involve allocation of relief supply, planning of vehicle delivery, and scheduling of vehicle routing (Balcik et al., 2008). The Asian Tsunami in 2004 led to the public acknowledgement of the role of logistics in effective relief efforts (Fritz Institute, 2005; Thomas and Kopczak, 2005). Specifically, the total number of cargo-laden humanitarian flights overwhelmed the ability of handling goods at the airport in Sri Lanka, and transportation pipelines were bottlenecked in India. “Last mile” challenges were experienced during the transportation of humanitarian goods to less developed regions of the world. Thus, improving the distribution of relief items effectively is a key point in humanitarian aid and disaster relief.

As early as the year of 1988, Knott (1988) conducted a research focusing on the last mile delivery of multiple food stocks from distribution centres to various camps. The author proposes a knowledge-based approach to schedule vehicles, combining Operations Research heuristics with Artificial Intelligence techniques. The knowledge bases include information on camps that will be supplied, types of trucks, individual trucks available to planners, and types of relief items to be supplied. The program proposed is able to deal with several operations, including various vehicle types and capabilities, discrete truck fleets, a variety of relief items, different types of roads and terrains, as well as changeable priorities for different consignments.

However, the relief items include not only food, but also other commodities (e.g., clothing, medical supplies, relief personnel). The transportation of relief items and relief personnel needs to be done efficiently to minimize operation costs and maximize the survival rate of affected people. There are plenty of transportation modes that may not be proper for every commodity. Thus, Haghani and Oh (1996) propose a multi-commodity, multi-modal network flow problem with time windows as a single objective linear programming model. Multi-commodity, multi-modal network flow problems seek to deliver different commodities via different modes of transportation as soon as possible to the disaster areas (Barbarosoğlu and Arda, 2004; Haghani and Oh, 1996). The model decides the detailed routing and scheduling of the available transportation modes, delivery plans for a variety of commodities, and load schedules of every transportation mode. Particularly, mode transfer during relief operations is taken into consideration. Haghani and Oh (1996) aim to minimize the sum of supply or demand carry-over costs, transfer costs, commodity flow costs, and vehicle flow costs totals over all time periods. Among the above costs, demand carry-over costs indicate the penalty costs for late deliveries that help achieve the timeliness of emergency response. The model assumes that the quantity of supplies and demands are known. Moreover, the model is only tested by artificially generated data.

As the time and magnitude of disasters are unpredictable, there are many uncertainties related to both resource requirements, and transportation system's capacities. Barbarosoğlu and Arda (2004) build a two-stage and scenario-based stochastic linear programming model to plan the transportation of important first-aid commodities, such as food, clothing, medicine, and machinery, as well as relief personnel for the case of earthquakes. Although Barbarosoğlu and Arda (2004) also attempt to solve the multi-commodity, multi-modal network flow problem to meet requirements by minimizing cost, the research extends the problem of Haghani and Oh (1996) by (i) considering uncertainties of supplies, demands, and route capacities, as well as (ii) using actual data of the August 1999, M-7.4, Marmara earthquake in Turkey to validate the model. The assumed randomness inherent in the scenarios is twofold: (i) the determination of the epicenter and the magnitude, and (ii) the estimation of the impact scenarios. The model built in this research will provide the best plan that compromises diverse response actions to plenty of random expectations if the impact scenarios are accurately estimated.

Some papers in this area use utilitarian policies that maximize the amount of satisfied demand without considering the access to goods or the equality of delivery (de la Torre et al., 2012). For instance, Özdamar et al. (2004) build a linear and integer multi-period multi-commodity network flow model which can be integrated into a natural disaster logistics Decision Support System, aiming to search for vehicle routes to minimize the delay in the arrival of commodities to aid centres. The model deals with the dynamic time-dependent transportation problem that needs to be addressed repetitively at given time intervals during ongoing aid delivery. The emergency supply chain plan generated by this model consists of optimal pick-up and delivery schedules for vehicles, optimal quantities and types of loads picked up and delivered on the routes. Specially, vehicles are regarded as commodities accompanying the actual relief items. Also, the model built by Özdamar et al. (2004) can regenerate existing plans according to new information on demands, supplies, and vehicle availability, without route-specific restrictions.

Similarly, in order to minimize delay in providing prioritized commodities for survivors and offering health care services to injured people, Yi and Kumar (2007) decompose the original humanitarian aid and disaster relief supply chain problem into two phases: the vehicle route construction and the multi-commodity dispatch. Different kinds of vehicles are used to serve the transportation demands. However, Yi and Kumar (2007) assume a single transportation mode and a corresponding heterogeneous fleet valid for that mode to achieve simplicity.

In contrast to utilitarian policies, egalitarian policies require that an equal amount of demand for all targeted population are satisfied to maximize the equality of a measure including delivery speed or quantity (de la Torre et al., 2012). Different from the above papers that minimize total unsatisfied demand without considering delivery equality, the following articles integrate egalitarian policies into utilitarian policies. Tzeng et al. (2007) adopt a multi-objective programming approach to build a fuzzy relief-distribution programming model for designing a relief delivery system for a real case study. The model considers three aspects: minimal total costs (economical), shortest total travel time (effective), and maximal satisfaction of fairness (fair). The objective is to minimize the maximum unsatisfied demand over all beneficiaries while minimizing total travel time. In short, an egalitarian measure for delivery quantity is combined with a utilitarian measure for delivery speed.

On the contrary, Van Hentenryck et al. (2010) use a utilitarian measure of delivery quantity and an egalitarian measure of delivery speed, that is, minimizing the latest arrival time is along with minimizing the total amount of unsatisfied demand. The research considers the single commodity allocation problem for disaster recovery, combining warehouse routing, resource allocation, and vehicle fleet routing together. Specifically, an multi-stage hybrid-optimization decomposition using the strengths of mixed integer programming is proposed for commodity storage and customer allocation; constrain programming, for repository routing; large neighborhood search, for minimizing the latest delivery time of overall routing. Moreover, Van Hentenryck et al. (2010) validate the approach on the delivery of potable water for hurricane recovery using a disaster scenario.

Balcik et al. (2008) also minimize the maximum unsatisfied demand over all beneficiaries. With the aim to minimize the sum of transportation costs and penalty costs for unsatisfied and late-satisfied demand for various relief items, a flexible and generalized two-phase mixed integer programming modeling approach is adopted to determine a delivery plan for every vehicle and to make inventory allocation decisions via considering supply, vehicle capacity, and delivery time restrictions. In addition, a rolling-horizon framework is used to capture the multiperiodicity of the problem, as well as the uncertainty of supply and demand. Specially, Balcik et al. (2008) categorize relief items into two main groups based on the demand characteristics. The first type of commodities are those whose demand occurs at the beginning of the planning horizon, such as blankets and tents; while the second type of commodities are those used regularly, and for which demand occurs periodically over planning horizon, including food and hygiene kits.

Balcik et al. (2008) present the difficulties of studying the underlying differences in route design occurring in humanitarian aid and disaster relief while modeling last-mile logistic operations with all related complexities. Huang et al. (2010) simplify the modeling into a more stylized setting and focus on a single period problem where every vehicle performs at most one trip to deliver one type of item. Despite being more restricted than Balcik et al. (2008), Huang et al. (2010) still successfully represents the important characteristics of the last-mile delivery problem. Particularly, the model fits the relief operations in rural areas where each vehicle can only take one trip per period and supplies are delivered in the form of standard packages. The setting of this model allows Huang et al. (2010) to gain insights into different objectives: (i) efficiency (transportation costs), (ii) effectiveness (route structures and quick response), and (iii) equity (deviation among recipients in efficacy).

Two exceptional papers combine inventory prepositioning and transportation planning together. Ukkusuri and Yushimoto (2008), regard the prepositioning of items as a location routing problem and take travel reliability into consideration. In the other paper, Mete and Zabinsky (2010), build a two-stage stochastic programming model to select warehouse location and inventory level for medical supplies in preparation for disasters. Subsequently, the subproblem in the model is used to suggest detailed loading and routing of vehicles to transport medical supplies for disaster response.

All the research mentioned above has taken the view of a central planner without exploring transportation implementation. Pedraza Martines et al. (2011) adopt a case-based descriptive exploratory approach to obtaining primary data for vehicle fleet management from humanitarian in-country programs. The research makes three contributions by: (i) exploring how humanitarian organizations manage vehicle fleets, (ii) identifying critical factors affecting field vehicle fleet management, and (iii) analyzing how field vehicle fleet management affects program delivery. Obviously, most research on transportation planning in humanitarian aid and disaster relief supply chain focuses on distributing limited relief resources to a disaster area. The objectives, parameters, and variables chosen by previous research are summarized in Table 2.6 on the next page.

In summary, this section includes the previous research related to the supply chain management under humanitarian circumstance. In practice, it is meaningful to apply the theories mentioned in sections 2.1 to 2.3 to the real world. The next section 2.4 examines the applications of community relief.

**Table 2.6**: Summary of humanitarian aid and disaster relief transportation modeling

| **Objective** | **Parameters** | **Variables** | **Reference** |
|---|---|---|---|
| Cost minimization | budget;<br>supply and demand amount;<br>warehouse investment and maintenance cost;<br>inventory holding and shortage cost;<br>depot setup cost;<br>shipping, mode-shifting, and vehicular flow cost;<br>penalty cost for late delivery and unsatisfied demand;<br>capacity of warehouse, vehicle, and route;<br>route duration;<br>commodity package size;<br>earliest pick-up and delivery time period;<br>arrival time;<br>commodity satisfaction score;<br>availability of site and vehicle;<br>scenario probability | candidate warehouse;<br>candidate transfer depot;<br>route for commodity;<br>delivery plans;<br>transportation mode load schedules;<br>vehicle delivery schedules;<br>shortage and excess of commodities at demand;<br>warehouse inventory levels;<br>warehouse utilization;<br>unsatisfied demand | Balcik et al., 2008; Barbarosoğlu and Arda, 2004; Haghani and Oh, 1996; Huang et al., 2010; Tzeng et al., 2007; Van Hentenryck et al., 2010 |
| Demand satisfaction maximization | budget;<br>time-related supply or demand;<br>wounded population;<br>wounded person average unit weight;<br>availability of site, vehicle, and maximum commodity;<br>capacity of warehouse and vehicle;<br>commodity package size and unit weight;<br>warehouse investment, maintenance, and operating cost;<br>depot setup cost;<br>time-related shipping and vehicular flow cost;<br>penalty cost for unsatisfied demand; | candidate warehouse;<br>candidate transfer depot;<br>route for commodity;<br>delivery plans;<br>vehicle delivery schedules;<br>unsatisfied commodity demand;<br>warehouse inventory levels;<br>warehouse utilization;<br>served and unserved wounded population;<br>route schedules | Balcik et al., 2008; Mete and Zabinsky, 2010; Özdamar et al., 2004; Tzeng et al., 2007; Van Hentenryck et al., 2010; Yi and Kumar, 2007 |

| | | | |
|---|---|---|---|
| | time-related satisfaction score for commodity;<br>serving priority and per period service rate for wounded people;<br>satisfying demand priority of commodity;<br>upper limit of unsatisfied demand;<br>route duration and travel time;<br>scenario probability | | |
| Response time minimization | budget;<br>time-related supply and demand;<br>site availability;<br>capacity of warehouse and vehicle;<br>time-related route capacity;<br>time-related vehicle amount;<br>depot setup cost;<br>warehouse investment and maintenance cost;<br>shipping, mode-shifting, and vehicular flow cost;<br>inventory holding cost;<br>penalty cost for late delivery;<br>commodity package size;<br>travel time;<br>arrival time;<br>earliest pick-up and delivery time period;<br>time-related satisfaction score for commodity;<br>scenario probability | candidate transfer depot;<br>candidate warehouse;<br>route for commodity;<br>warehouse inventory levels;<br>warehouse utilization;<br>delivery plans;<br>transportation mode load schedules;<br>vehicle delivery schedules;<br>unsatisfied demand | Haghani and Oh, 1996; Huang et al., 2010; Tzeng et al., 2007; Van Hentenryck et al., 2010 |
| Travel reliability maximization | demand amount;<br>capacity of warehouse and vehicle;<br>vehicle amount;<br>fixed warehouse cost;<br>route cost, duration, and availability | the most reliable path | Ukkusuri and Yushimoto, 2008 |

## 2.4. Community Relief Applications

Natural disasters can strike anywhere, as evidence by recent history (Figure 1.1). Thus, regardless of location, history, or culture, communities need to be well-prepared for disasters. This subsection presents applications focused on community relief applications in Canada in general terms (2.4.1), specific recent Canadian disaster applications (2.4.2), and the case of community preparation for relief applications in Charlottetown, Prince Edward Island (2.4.3).

### 2.4.1. Current Situation in Canada

Even though federal and provincial governments actively engage in emergency planning, municipal governments play a central role in Canadian emergency management because specific operational measures must be implemented locally (Henstra, 2011). Those communities which are well-trained psychologically, socially, and culturally are better prepared and more effective in response to the consequence of disasters (Mathbor, 2007). Different communities face different hazards and vulnerabilities; thus, local officials are arguably best positioned to decide the proper mix of preparedness measures (Henstra, 2011).

The Standing Senate Committee on National Security and Defence published a report of emergency preparedness in Canada in 2008. Based on the testimony of over 110 witnesses from 2001 to 2008 and two emergency preparedness surveys, the Committee examined Canadian governments' efforts on improving the ability of disaster preparedness and response (Government of Canada, 2008). In consequence, twelve problems of emergency preparedness in the Canadian system were identified: (1) lack of emergency management; (2) use of the Canadian Forces for domestic emergencies; (3) hidden emergency caches; (4) lack of funding for equipment and training; (5) poor collaboration among governments; (6) lessons learned but not remembered and lack of leadership on best practices; (7) emergency public communications; (8) lack of first responder interoperability; (9) first responders ignored; (10) poor federal leadership on critical infrastructure protection; (11) emergency ad hockery; and (12) policy during emergencies (Government of Canada, 2008).

The Committee has recommended that Public Safety Canada involve the Canadian Forces Militia into the national inventory of emergency preparedness resources, as well as offer details of the Militia's assets and capabilities to first responders (Government of Canada, 2008). Good communication between local emergency management officials and the Canadian Forces is beneficial, while only 32% of responding municipalities have included the Canadian Forces Reserves in the emergency plans (Government of Canada, 2008). It is because any communications between municipalities and federal government must trickle back and forth through the provinces. According to the concept of Territorial Defence Battalion Groups declared by the former Defence Minister Gordon O'Connor, these units need to be located in 12 Canadian cities to be able to come to the rescue following natural disasters (Government of Canada, 2008). In spite of this initial commitment, no battalions have been established.

When it comes to inventory management, the Public Health Agency of Canada maintains a National Emergency Stockpile System (NESS) consisting of a central depot in Ottawa, eight warehouses, and 1,300 pre-positioned supply centres strategically located throughout Canada, under the combined management of the provinces and federal government (PHAC, 2012). In addition, the pre-positioned supply centres have a mix of supplies relying on the facility locations and the anticipated disasters (PHAC, 2012). However, first responders usually do not know the locations and contents of emergency caches (Government of Canada, 2008). As well, first responders have virtually no input into what goes into the vital caches (Government of Canada, 2008). In reality, local responders are first on the scene and operate without help from provincial or federal governments until assistance is requested (Government of Canada, 2008).

With the purpose of improving the emergency preparedness system in Canada, it is necessary to explore the current relief operations first and identify the gaps that can be made up. The most recent disaster relief applications of Canadian communities are illustrated in the following subsection 2.4.2.

### 2.4.2. Canadian Disaster Relief Applications

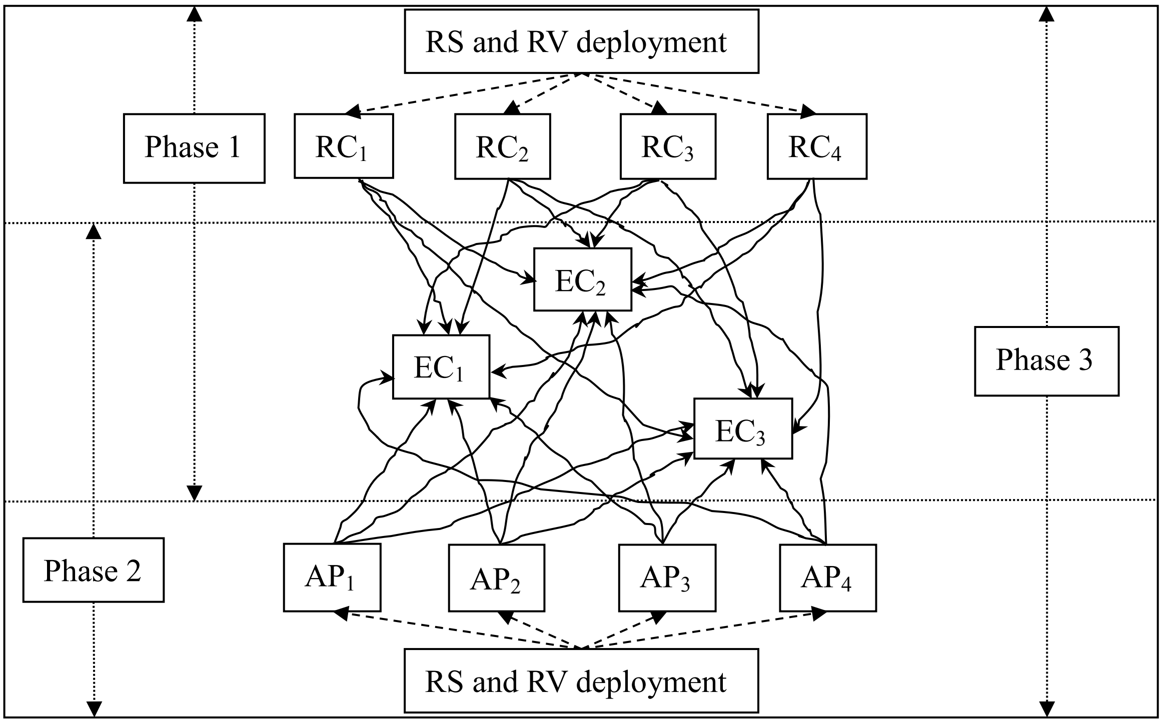
According to the statistics in Canadian Disaster Database, floods are the most costly natural disasters in Canada in terms of property damage (Public Safety Canada, 2013). Floods can happen in any region at any time of the year and have affected hundreds of thousands of Canadians. Heavy precipitation on steep slopes of mountains in western Canada often causes flooding; tropical storms and hurricanes in eastern Canada carry the risk of heavy rain; spring ice break-up results in floods in most of the Yukon and Northwest Territories. In addition, there is potential for floods in urban areas since Canadian cities, e.g., Calgary, Toronto, and Vancouver are developed along coastal harbors, rivers, and lakes due to the historical convenience of commerce and transportation. In recent history, the worst floods are the Central and Southern Alberta flood in June 2013 and the Manitoba's Red River flood in May 1997 (Public Safety Canada, 2013). Thus, in order to gain insight into current disaster management system in Canada, it is suitable to choose the latest 2013 Alberta flood as the base case scenario.

In June 2013, Alberta was devastated by the flooding of 31 communities directly affected. Nearly 120,000 people forced out of homes (Government of Alberta, 2013b). According to the day-by-day updated timeline recorded by the Government of Alberta (2013b), the whole process of humanitarian aid and disaster relief can be generalized as follows:

- A slow-moving weather system in Saskatchewan attacked northern Alberta on June 8$^{th}$. Fort McMurray declared an emergency state on June 11$^{th}$. On the same day, evacuation orders went into effect and Alberta Health Services issued boil water advisories.

- Rescue work did not stop until flood warnings were downgraded to flood watches in the northeast on June 15th. However, torrential downpour started up again over southern Alberta on June 19th.
- The immediate response lasted from June 20th to June 23rd. During those four days, states of local emergency, evacuations, and 'shelter in place' orders were initiated in multiple communities.
- Key tasks included setting up evacuation centres, evacuating affected people (distressed residents, acute care patients, and stranded travelers), delivering essential commodities (food and water), as well as deploying relief staff (officials, doctors, volunteers, and military personnel) and vehicles. From June 23rd, recovery and reconstruction work continued (Government of Alberta, 2013b).

**Figure 2.2**: Supply chain management activities in 2013 Alberta flooding response (RS-Relief Staff, RV-Relief Vehicle, RC-Relief Commodity, EC-Evacuation Centre, AP-Affected People)




According to the description of the base case emergency management scenario, there are three phases of activities from the perspective of humanitarian aid and disaster relief supply chain:

- Phase 1) Deploy Relief Staff (RS) and Relief Commodities (RCs) via Relief Vehicles (RVs) to stock Evacuation Centres (ECs) with required resources;
- Phase 2) Arrange Relief Staff (RS) and transportation resources (RVs) to help carry out evacuation orders of Affected People (AP); and
- Phase 3) Monitor and replenish, as required, Relief Staff (RS) and Relief Commodities (RCs) at Evacuation Centres (ECs) according to the updated information of real demand, as well as conduct more rounds of evacuation if necessary.

This process is demonstrated in Figure 2.2 above.

As noted by the Chief of Emergency Medical Services for the City of Calgary, Tom Sampson, “the municipal authority must deal with the first five to seven days of any major disaster, at which time additional assistance will be available” (Sampson, 2007). However, nearly all of Canadian communities can merely sustain themselves for at most four days before outside help is required (Government of Canada, 2008). As reported in the Senate study, government systems seemingly responsible on paper are not always working well in the field.

The latest community disaster relief operations process in Canada is illustrated by the 2013 Alberta flood. Since the community focused by this thesis is Charlottetown, P.E.I., reviewing the humanitarian aid and disaster relief efforts in this coastal community is important as well. Specific details are included in the subsection 2.4.3.

### 2.4.3. Charlottetown Flood Relief

The City of Charlottetown is a community of over 34,500 people located on south shore of Prince Edward Island. Situated on Charlottetown Harbour which opens onto the Northumberland Strait and which is formed by the confluence of three rivers (C-Change, 2009), this capital city is vulnerable to coastal flooding from storm surges, sea level rise, and loss of sea ice (Government of Canada, 2014).

As noted by Government of Canada (2014), the most intense storm event in Charlottetown's history was 'No Name 2000' happened on January 21, 2000. A record water level of 4.23 metres above chart datum was produced by a storm surge coincided with a high tide. The waterfront of Charlottetown experienced a flood at 3.60 metres above chart datum. Most historical development of Charlottetown including heritage building stock, municipal infrastructure, and street network is located at relatively low-lying neighborhoods. As a result, this severe storm event led to an estimate $20 million in damage to infrastructure and property throughout Prince Edward Island (P.E.I.) and impacted P.E.I.'s coastline over the last ten years. This flood and the successive storms have increased the local awareness of the importance of humanitarian aid and disaster relief operations.

As for the aid and relief operations, a general process is defined by the *Emergency Measures Plan* (City of Charlottetown, 2009) that should be executed in full or in part in preparation for an impending or an actual disaster in the city of Charlottetown or a distinct or geographical area in the city. To begin with, the situation of a disaster is analyzed by the Emergency Measures Coordinator and the On-Scene Commander to determine the probability of an evacuation. Once an evacuation is necessary, the actions should be taken as follows:

- determine the evacuation reason;
- identify the Affected Areas (AAs) need to be evacuated;
- assess the number of Affected People (AP) to be evacuated;
- determine the availability of Relief Vehicles (RVs), pick-up points, and evacuation routes;
- set up Evacuation Centres (ECs);
- issue warning to the public in the AAs;
- police the evacuated area;

- establish a communication system with ECs;
- ensure Relief Staff (RS) and Relief Commodities (RCs) are adequate at ECs;
- build a downwind danger area as well as an inner and outer perimeter danger area;
- update the applicable provincial government department periodically (City of Charlottetown, 2009).

On the whole, this section outlines the current status of humanitarian aid and disaster relief applications in the Canadian communities. The general relief phases identified in subsection 2.4.2 (Figure 2.2) contribute to the research methodology in Chapter 3. The rest is the last section of Chapter 2 that makes a summary of all the reviewed literature.

## 2.5. Summary

At the highest level, a supply chain consists of two basic and integrated processes: (i) production planning and inventory control process, (ii) distribution and logistics process (Beamon, 1998). These two processes interact with each other to produce an integrated supply chain. The design and management of the two processes can determine the extent to which the supply chain works as a unit to meet the required performance objectives (Beamon, 1998).

The unpredictable nature of natural disasters and the large casualties at stake make supply chain management a key part of humanitarian aid and disaster relief operations. One important issue is the agility in mobilizing resources and the effectiveness in distributing resources (Duran et al., 2011). However, research related to this issue is limited (Van Wassenhove, 2006). Most research on humanitarian aid and disaster relief supply chain focuses on how to distribute limited relief resources to a disaster area after a disaster has happened (Chang et al., 2007). Thus, more attention needs to be paid on the preparedness phase because better preparation can improve response performances.

Preparedness can be defined from different perspectives. When it comes to humanitarian aid and disaster relief supply chain, preparedness is related to several logistics issues such as facility location, inventory management, and transportation planning (Clay Whybark, 2007; Duran et al., 2011). Studies in facility location in humanitarian aid and disaster relief context concentrate on the spatial aspects of operations that investigate the impacts of geographical location on costs and response time (Duran et al., 2011). Since this thesis focuses on inventory and transportation management, reviewed studies include those integrating facility location decisions into either of these two parts. Most researchers conduct studies on a two-stage issue: warehousing location and stocking level (Balcik and Beamon, 2008; Campbell and Jones, 2011; Chang et al., 2007; Dekle et al., 2005; Duran et al., 2011; Salas et al., 2012); or warehousing location and delivery plan (Mete and Zabinsky, 2010; Van Hentenryck et al., 2010).

Research in inventory management mainly addresses problems such as demand estimation, purchasing quantity, order frequency, and stock level. Apart from the above papers that consider facility location element in inventory prepositioning decision, some research focuses on inventory control (Beamon and Kotleba, 2006a; Beamon and Kotleba, 2006b; Lodree and Taskin, 2008; Lodree and Taskin, 2009; Ozbay and Ozguven, 2007; Taskin and Lodree, 2010; Taskin and Lodree, 2011).

Given the decisions on location and inventory, the next step is transporting items. Most of the reviewed literature pays attention to the building of humanitarian aid and disaster relief distribution models. (Balcik et al., 2008; Barbarosoğlu and Arda, 2004; Haghani and Oh, 1996; Huang et al., 2010; Knott, 1988; Mete and Zabinsky, 2010; Özdamar et al., 2004; Tzeng et al., 2007; Ukkusuri and Yushimoto, 2008; Van Hentenryck et al., 2010; Yi and Kumar, 2007). Only Pedraza Martines et al. (2011) use a qualitative method to explore the practice of vehicle fleet management in humanitarian organizations.

Although studies summarized above pay attention to the operational logistical activities in humanitarian aid and disaster relief supply chain, aiming to optimize the flow of supplies through existing distribution network, little attention is paid to learning best practices from commercial supply chain. Recently, an increasing number of research compares commercial supply chain with humanitarian aid and disaster relief supply chain, and recognizes the challenges and opportunities of applying supply chain management practices in commercial situations to that in humanitarian aid and disaster relief context (Clay Whybark, 2007; Oloruntoba and Gray, 2006; Pettit and Beresford, 2009; Thomas, 2007; Thomas and Kopczak, 2005; Van Wassenhove, 2006).

**Table 2.7**: Comparison of commercial with humanitarian aid and disaster relief supply chain (Clay Whybark, 2007; Tzeng et al., 2007)

| **Comparison item** | *Commercial supply chain* | *Humanitarian aid and disaster relief supply chain* |
|---|---|---|
| **Research** | Extensive | Limited |
| **Objective** | Profit maximization | Efficiency, effectiveness, fairness |
| **Inventory** | Few unknown demand peaks<br>Storage location and inventory usage are business decisions<br>Information available to control expiry<br>Obsolescence defined by business needs<br>Pull system used | High uncertainty of future demand<br>Storage location and inventory usage are political decisions<br>Information on inventory not integrated<br>Obsolescence defined by infrastructure<br>Pull system not permitted by demand knowledge |
| **Transportation** | Theory available for quantification<br>Dimensional roles include factories, distribution centres, and customers<br>Commercial transportation used<br>Round-trip or circulating delivery | Very little theory to guide decisions<br>Dimensional roles involve collection points, transfer depots, and demand points<br>Special transportation sometimes needed<br>Round-trip delivery |

Directly applying practices that work well in commercial supply chain management to humanitarian aid and disaster relief settings may be improper. It is because the environment in which humanitarian aid and disaster relief supply chain operates is extremely uncertain and dynamic. The unique characteristics are as follows: (1) demand unpredictability associated with type, time, location, and quantity; (2) sudden-occurring demand of relief items in large amounts and short lead times; (3) lack of transportation capacity; (4) high stakes related to timely and sufficient delivery (Balcik and Beamon, 2008). The first two characteristics put forward higher requirements to inventory, and the latter two, demand more of the transportation system. Many researchers also mention other challenges such as financial limitation; shortage of logistics experts; inadequate use of technology; poor assessment and planning; limited collaboration and coordination; new supply chain formation and donor independence issue; shifting overall priorities; supply chain evolution; self-initiated participants; press coverage and publicity (Balcik and Beamon, 2008; Clay Whybark et al., 2010; Fritz Institute, 2005; Thomas and Kopczak, 2005). Table 2.7 above compares the characteristics in commercial supply chain and those in humanitarian aid and disaster relief supply chain with a focus in this thesis on inventory management and transportation planning.

Despite not necessarily directly transferrable, many functions in commercial supply chain are similar to those in humanitarian aid and disaster relief context. Thus, the important challenge in real humanitarian aid and disaster relief situations is to recognize the most proper concepts from established commercial frameworks and to ignore those inappropriate and irrelevant concepts (Pettit and Beresford, 2009). This thesis focuses on how to help humanitarian aid and disaster relief supply chains learn from commercial ones. Some concepts, such as agility and leagility can be applied into humanitarian aid and disaster relief operations.

One typical example is about agility which is defined as “the ability to thrive and prosper in an environment of constant and unpredictable change” (Maskell, 2001, p. 5). Applying the agility concept to the context of humanitarian aid and disaster relief means that the supply chain needs to handle the unstable nature of funding (Bennett and Kottasz, 2000), and to ensure rapid deployment on demand (Van Wassenhove, 2006). Oloruntoba and Gray (2006) discuss the extent to which certain concepts of agility in commercial supply chain can apply to humanitarian aid and disaster relief. A model of an agile supply chain is built for humanitarian aid and disaster relief. For inventory, there are two strategies:

prepositioning and postpone. Prepositioning is a type of advanced planning, meaning storing supplies at or near the places where they are likely to be required (Oloruntoba and Gray 2006). On the contrary, postponement aims to delay inventory commitment until receiving customer orders (Bowersox and Gloss, 1996).

Overall, humanitarian aid and disaster relief supply chain can indirectly learn from existing inventory and transportation theory in commercial supply chain (Clay Whybark, 2007). For acquisitions, enterprises make the decision on the time and amount of ordering inventory by the estimations of future demand, while this logic cannot be applied to disaster relief inventory. Moreover, the ownership of relief inventory is decentralized. It is difficult to know the aggregate disaster relief inventory. However, disaster relief inventory can learn from medicine inventory, because the uncertainty of location and demand.

For storage, choosing the location of relief inventory needs to consider the time and cost of transportation to demand area. Relief inventory can learn from commercial inventory – continuously monitoring time-dependent inventories such as food and medicine which have expiry dates, as well as inventories subject to technological obsolescence such as medical and communication equipment. For distribution, relief inventory cannot use the pull system as in the commercial situation. Instead, the inventory has to be pushed out to the storage locations during disaster planning activities.

In addition, research in humanitarian aid and disaster relief operations mainly concentrates on strategic and operative planning issues, such as facility location planning, inventory planning, vehicle routing, and delivery planning (Rottkemper et al., 2011). Maximum covering models, various optimization methods, and network flow or shortest path models are adapted to solve these problems respectively (Rottkemper et al., 2011). Nearly no research integrates these issues together. One exception is the research of Ukkusuri and Yushimito (2008) which regards the prepositioning of items as a location routing problem. The reliability of the ground transportation network is included in the model. However, an integrated approach to various logistics functions can make a distribution system efficient (Qu et al., 1999). Thus, more research needs to consider the decisions of warehouse location, stock level, and the transport plan together.

According to Altay and Green (2006), there are three research methods in operations management: model development, theory development, and application development. Studies building an analytical model to solve a problem or to estimate an outcome are in the first group. Articles testing hypotheses, exploring system behaviors, or developing a framework and advancing our understanding of phenomenon belong to the second group. Research in which a prototype is developed or a computer tool is produced is placed into the last group. Corbett and Van Wassenhove (1993, p. 3) state that “the basic disciplines provide knowledge for the applied sciences to use, whereas the applied sciences signal to the basic disciplines which areas are in need of deeper research”. The area of research combining theory with application carries the true spirit of operations research, but it is well-underpopulated in humanitarian aid and disaster relief context (Corbett and Van Wassenhove, 1993). The community of operations research recognizes the importance of using new research to solve the problems in humanitarian aid and disaster relief. Therefore, this thesis uses both model development and the application development.

Humanitarian aid and disaster relief is a large-scale process requiring the coordination and collaboration of various organizations. For instance, in Canada, participants involve Public Safety Canada, Public Health Agency of Canada, Transport Canada, Canadian Forces, Canadian Red Cross as well as local groups. Usually, these organizations operate in a complex environment. Unpreparedness may cause the inability to handle chaos, and therefore increase the number of deaths. In the emergency management system of Canada, municipal governments are key players. The quality and comprehensiveness of local disaster preparedness largely determines the effectiveness of response efforts when disaster occurs (Henstra, 2011). The major objectives of community disaster operation management are to protect people and property from disasters, to minimize losses related to disasters, and to ensure a swift and effective recovery from disaster (Henstra, 2011).

This chapter has reviewed a wide breath of publications on disaster management, supply chain management, humanitarian aid and disaster relief supply chain management, and applied community relief operations. The summary above captures those key references that are most pertinent to the thesis. These references provide the foundation of the research methodology described in the next chapter.

# 3. Methodology

The purpose of this chapter is to explain the research methodology applied in this thesis to evaluate and improve the logistical effectiveness of humanitarian aid and disaster relief in Canadian communities. Specifically, the research process will: (3.1) define performance measurement and Critical Successful Factors (CSFs) for humanitarian aid and disaster relief supply chain management; (3.2) identify the specific enablers or strategies that can help achieve an outstanding performance level on a certain CSF; (3.3) illustrate a general modeling approach and define the process; (3.4) analyze the current situation of Canadian communities and define an illustrative model; (3.5) evaluate alternative facility location, inventory and transportation policies.

A conceptual framework of performance measurement and CSFs in humanitarian aid and disaster relief supply chain management is defined in section 3.1. Performance measurement is used to measure the efficiency, effectiveness, and fairness of the whole chain. Then, specific indicators of the measurement are selected in section 3.2. Meanwhile, this thesis narrows the focus to the preparedness of inventory and transportation. In addition to determining the inventory and transportation plan, this thesis takes one step further and aims to apply the results to a coastal Canadian community. The modeling approach is illustrated in section 3.3 which is followed by the definition of a small-scale centralized example problem in section 3.4. Finally, section 3.5 presents the method of evaluation and decision making. These elements of the research process are defined in further detail below.

## 3.1. Conceptual Framework Development

Establishing proper performance measurement is critical in the design and analysis of a supply chain, because proper measures can be used to determine the efficiency and effectiveness of an existing system, or to compare competing alternative systems

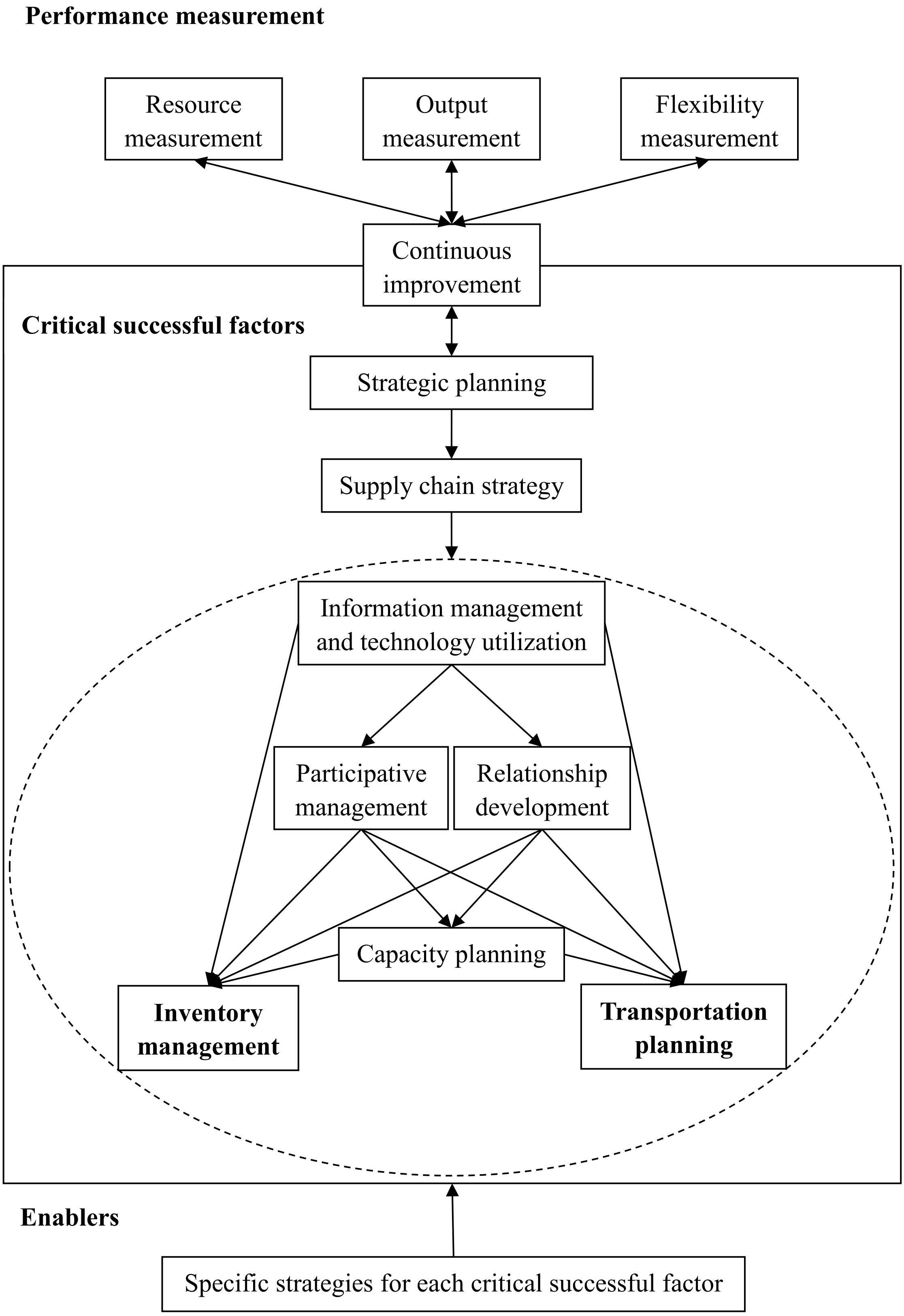
(Beamon, 1998). Moreover, proper measures can help design the proposed system by determining the values of decision variables which yield the most desirable level of performance (Beamon, 1998). In order to achieve higher performance level, successful factors need to be explored and improved. In the literature review, three types of performance measurement, and nine CSFs were identified for humanitarian aid and disaster relief supply chain management.

Since the nine CSFs can influence each other, improving one or more factors can optimize the effectiveness of the whole chain. For the preparedness for humanitarian aid and disaster relief, two basic components are the need to efficiently use resources and the need to have an effective delivery plan. The two components respectively correspond to the two identified CSFs: inventory management and transportation planning. According to the previous analysis and research focus, the conceptual framework developed in this thesis demonstrates part of the relationships among all the elements, as shown in Figure 3.1 in the next page.

No matter what kind of humanitarian aid and disaster relief efforts is needed, there is a budget limitation. Adopting proper supply chain strategies can help make the most use of financial and inventory sources (Brouillette, D., 2013; Poirier, M., 2013). Specific supply chain strategies can help achieve the other six CSFs in the ellipse, such as cooperate strategy (outsourcing non-core activities), location of distribution centres (centralized or localized), resource deployment (relief items and personnel), and effective use of organizational capacity.

Among the six factors in the ellipse, the effective use of information technology can help build a platform for knowledge sharing which can enhance participative management and improve relationship development. Subsequently, collaboration both intra- and inter-organization can assist in maximizing the use of capacity. Given that capacity planning has an effect on decisions about numbers of warehouses, distribution centres, vehicles, employees, and other equipment, there is a close relationship between capacity planning and the management of inventory and transportation.

**Figure 3.1**: Conceptual framework for humanitarian aid and disaster relief supply chain management



There are some other direct influences on inventory and transportation. First, since it is necessary to find an optimal plan for assigning resources in space and time to the Affected Area (AA), information technology can help assess and process all incoming information in an adequate manner, as well as track and trace Relief Commodities (RCs) and Vehicles (RVs). Second, participative management can assist in controlling human resources including Relief Staff (RS) related to inventory and transportation. Finally, relationship development may help coordinate relief items and vehicles.

To conclude, this section establishes a general conceptual framework to display the relationships among the three performance measures and the nine CSFs. Among all the nine CSFs, the most two basic factors are inventory management and transportation planning. Exploring the specific enablers for inventory and transportation can improve the performance of the whole chain. Thus, the specific strategy options for these two CSFs are selected in the next section 3.2.

## 3.2. Performance Indicators Selection

There are many performance measures for commercial supply chain management. However, unique characteristics and additional complexity of humanitarian aid and disaster relief supply chain make some measures unsuitable. According to the conceptual framework of Figure 3.1, three broad types of performance measurement are defined: (i) resource measurement, (ii) output measurement, and (iii) flexibility measurement. Each of these contains various indicators as discussed below.

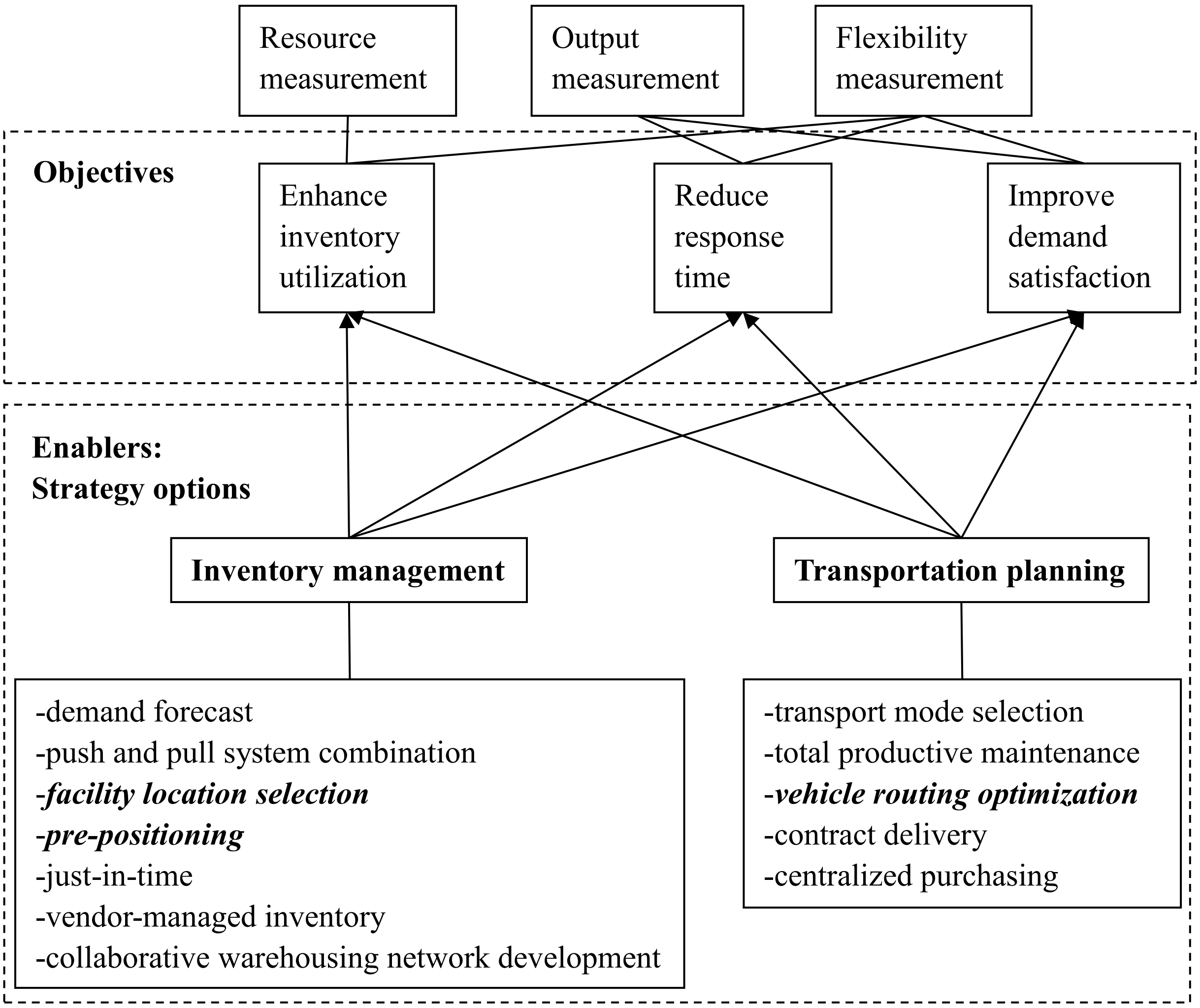
First of all, resources considered in this thesis include three parts: Relief Staff (RS), Relief Commodities (RCs), and Relief Vehicles (RVs). Ideally, cost is the least important factor in humanitarian aid and disaster relief. Nevertheless, any relief effort is constrained by specific budgets in practice, in turn, limited relief inventory (RS, RCs, or RVs). For instance, the research conducted by Balcik and Beamon (2008) shows the effects of pre- and post-disaster relief funding on relief performance in terms of satisfied demand proportion and response time. Thus, efficient resource management is critical to aid and relief efforts. Poor resource management leads to a lower utilization of the certain amount of relief inventory or even a reduced relief rate in a disaster. This thesis recognizes inventory utilization as an indicator for resource measurement.

Second, the ultimate goal in humanitarian aid and disaster relief is to save people and minimize suffering. Output measurement can be defined from two respects: response time and demand satisfaction. Time is one of the most critical measures of relief performance since it is related to life and death emergencies. In practice, budgets and relief resources are limited. Many papers aim to prioritize the demands of the most vulnerable people (de la Torre et al., 2012). The amount of Relief Staff (RS), Relief Commodities (RCs), and Relief Vehicles (RVs) delivered to disaster areas is related to demand satisfaction. The more rapid and timely demand satisfaction, the more effective the humanitarian aid and disaster relief supply chain management. Therefore, response time and demand satisfaction are two indicators for output measurement.

Last but not the least, flexibility in the humanitarian aid and disaster relief supply chain management is also an important indicator of performance. According to Beamon (1999), flexibility can measure the capacity of a system in responding to fluctuation and shift in schedule. In humanitarian aid and disaster relief supply chain management, both the availability of resources (RS, RCs, RVs) and the demand of Affected People (AP) vary from disaster to disaster. Volume flexibility can be used to measure the fraction of available cycles experiencing an emergency order given available budget. In this thesis research, volume flexibility is similar to the resource measure, that is, inventory utilization. Delivery flexibility can be selected to measure minimum response time. Mixed flexibility represents the capacity of offering various relief items to meet different demands and parallels demand satisfaction improvement.

To achieve a higher performance level in general supply chain management, strategic enablers need to be identified. Inventory management enablers are well-studied (Williams and Tokar, 2008). In general, for the disaster relief context, enablers for efficient inventory include: the ability to predict needs (demand forecast), facility location selection, pre-positioning of emergency materials and availabilities in stock, and collaborative warehousing networks. For transportation planning, effective methods are noted by: appropriate transport mode selection under emergency conditions, productive maintenance, vehicle routing optimization, and contracted and timed delivery (Qu et al., 1999). Figure 3.2 demonstrates the relationship between the specified indicators and enablers (strategy options) for the thesis research. The enablers examined in this thesis are shown in bold and italic type.

**Figure 3.2**: Relationships between indicators and enablers



A theoretical framework is completed by combining the Figures 3.1 and 3.2. The next step is to put those theories into practice. Section 3.3 below defines a general linear programming spreadsheet modeling approach.

## 3.3. Modeling Approach and Process Definition

Operations research is an application of quantitative techniques to aid in decision making (WebFinance, 2013). For example, linear programming, dynamic programming, and the critical path method are adopted in managing complex information in inventory control, resource allocation, reorder quantity determination, and project management. Simulation and statistical forecasting methods are used in situations with high uncertainty such as market trends and traffic patterns (WebFinance, 2013). The linear programming modeling method is used in this thesis study and related special case linear problem formulation for the transportation and assignment problems associated with moving relief resources and Affected People (AA) into Evacuation Centres (ECs) with minimum response time. A spreadsheet model is used to formulate and solve the linear programming problems as outlined in Figure 3.3 (Hillier and Hillier, 2008).

To begin the formulation of a linear programming model, three questions are posed:

1. What are the decisions to be made?
2. What are the constraints on these decisions?
3. What is the overall measure of performance (single valued objective) for these decisions?

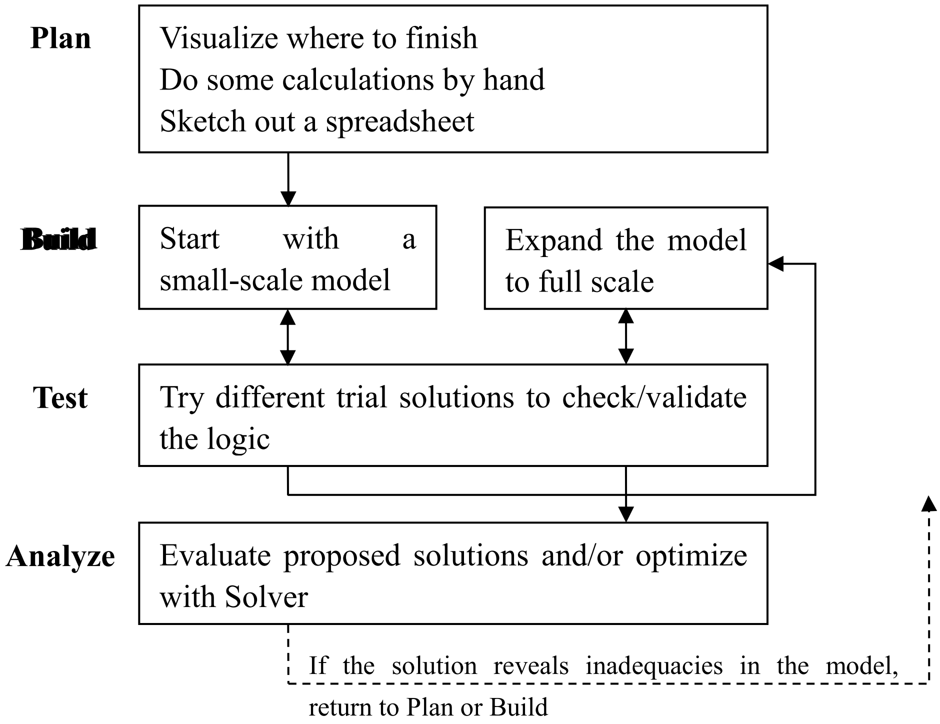
The situation in humanitarian aid and disaster relief supply chain considers three unique characteristics:

1. the disaster situation is high-stakes and needs to balance several objective goals, including inventory utilization, response time, and demand satisfaction;
2. random side constraints exist, such as deficient preparation of budgets, limited relief

items, fixed vehicle fleets, and restricted delivery time; and

3. preparedness plans of natural disasters have to be robust with regard to different scenarios because natural disasters are inherently stochastic and unpredictable (Van Hentenryck et al., 2010).

**Figure 3.3**: A general spreadsheet modeling process for linear programming using EXCEL (Source: Hillier and Hillier, 2008)




As a first step in planning, visualizing where to end up is helpful at this point (Figure 3.3). For instance, what relief resources need to be shipped (people, blankets, clothes, water, food, medical)? What are the shipment sources (emergency base warehouses, distribution centres) and destinations (evacuation centres, shelters, hospitals, hotels)? What kinds of relief vehicles are involved (vans, trucks, buses, cars, boats, helicopters)? The answers to these questions help to get the modeling procedure started. Hand calculations can clarify what functions are needed for the results. Before using a spreadsheet modeler such as EXCEL, it is useful to sketch a layout of the spreadsheet. A logical progression begins with data on the top and moves through the model development toward the result analysis on the bottom (Figure 3.3). With the general modeling process proposed in this section, a small-scale illustrative model is built in the following section 3.4.

## 3.4. Illustrative Model Establishment

A post-operational review of recent disasters provides evidence for understanding the emergency response system and the applied processes for emergency relief (Government of Alberta, 2013a). With the aim to create a framework and build a model for Canadian communities, an inductive approach is adopted, based on observations from the recent Alberta and Toronto floods (June and July, 2013). To the end, data have been collected that have enabled a description of the Emergency Operations Centres (EOC) procedures for dealing with emergencies. Inputs and decision outputs for staged inventory and transportation analyses in emergencies are modelled through the phased application of assignment and transportation problem formulations built in an EXCEL spreadsheet toward developing a generalized framework. The illustrative model scenario is designed to understand a community's current situation and the ability to improve.

In March of this year, the federal government initiated a restricted policy writing cheques after damage were incurred rather than develop preparedness programs or to intervene with operational help to Canadians in the case of disasters (Kenny, 2013). The federal government has discontinued funding to emergency management projects – the Joint Emergency Preparedness Program (JEPP), leaving the provinces and municipalities to prepare for disasters themselves (Kenny, 2013). The Government of Alberta has responded to the federal cut by coming up with a one-time $400,000 grant to the Calgary Heavy Urban Search and Rescue (HUSAR) teams that helped search for endangered occupants of buildings during the 2013 Alberta flood (Kenny, 2013). In addition, financial donations and volunteers were accepted since June 21st, 2013. These facts reveal the constraint of relief inventory in the municipal response process.

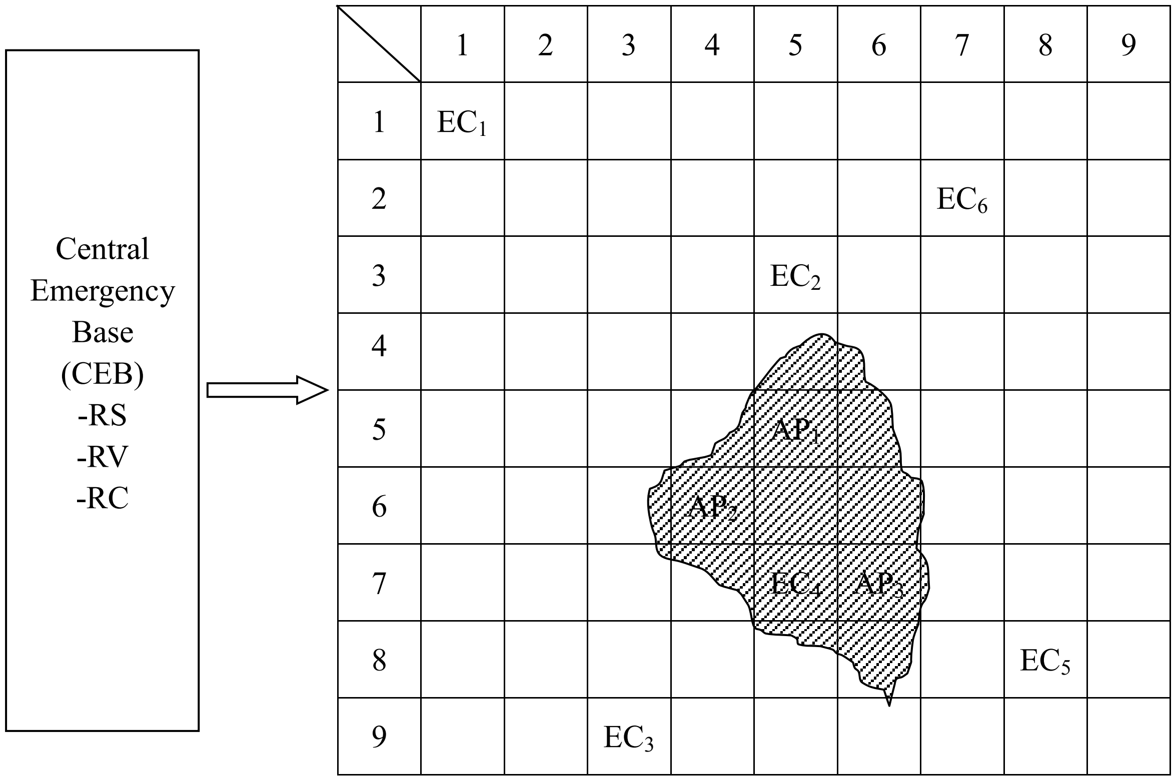
Since many roads are made impassable or destroyed by the flood, transportation means may include other modes of transport, e.g., helicopters, heavy equipment, and trucks. In the case of Alberta floods, as well as in order to improve the inventory utilization and the demand satisfaction, all provincial resources were brought together via the Alberta Emergency Management Agency. In accordance with Phases 1 and Phase 2 displayed in subsection 2.4.2 (Figure 2.2), the two objectives of the observed community flood response process are: (i) the delivery of Relief Staff (RS) and Relief Commodities (RCs) via Relief Vehicles (RVs); and (ii) the transportation of Affected People (AP). Whether Phase 3 needs to be conducted or not relies on the real data. Thus, the current goal of humanitarian aid and disaster relief supply chain is represented as a network aiming to find the best strategy to deploy required relief inventory and the shortest routes to evacuate affected people.

The details of the illustrative model are described as follows: (3.4.1) define the illustrative model scenario, (3.4.2) collect the parameters and inputs of the illustrative model, as well as (3.4.3) analyze the results of the illustrative model.

### 3.4.1. Illustrative Model Scenario

Generally speaking, the current emergency relief situation in Canadian municipalities is described as a centralized emergency response system. Figure 3.4 illustrates the typical base case of approach as observed in the Alberta and Toronto floods. On the left side of the diagram, a single Central Emergency Base (CEB) is denoted. The CEB contains Relief Staff (RS), Relief Vehicles (RVs), and Relief Commodities (RCs). On the right side of the diagram, a 9x9 grid map indicates the known location of the Evacuation Centres (ECs). AP represents the Affected People who need to be evacuated from the indicated Affected Area (AA) (shaded cells). It is noted that the EC4 is in AA, and therefore it is not functional as an operational EC.

**Figure 3.4**: A grid map of the illustrative of centralized emergency base case with designated Evacuation Centres, and the Affected Area (shaded cells)




## 3.4.2. Illustrative Model Data

In order to build the linear programming models for the phased application of assignment and transportation problems formulations, a series of parameters are needed and listed in the Tables 3.1 to 3.3 below. Parameter values are set to illustrate the phase application of the methodology. Table 3.1 contains some basic information about every EC: (i) EC capacity – the number of evacuees can be held; (ii) the distance from the CEB to the EC; and (iii) the distance from the EC to the centre of AA. Table 3.2 lists: (i) the amount of available Relief Staff (RS) groups; and (ii) the Relief Vehicles (RVs) in the CEB over the time period. Table 3.3 shows (i) the number of people affected (AP) in specific cells of the AA, as well as (ii) their distances to each EC.

**Table 3.1**: Parameters about ECs

| Evacuation centres | $EC_1$ | $EC_2$ | $EC_3$ | $EC_4$ | $EC_5$ | $EC_6$ |
|---|---|---|---|---|---|---|
| Full capacity (#people) | 20 | 40 | 30 | 30 | 50 | 20 |
| Distance from CEB (kilometers) | 5 | 9 | 7 | 9 | 12 | 11 |
| Distance to AA (kilometers) | 7.07 | 1.00 | 4.24 | 0 | 2.00 | 3.61 |

**Table 3.2**: The time availability of RS and RVs in the CEB

| Time period | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Relief staff (#group) | 7 | 3 | 4 | 5 | 2 | 3 | 5 | 3 | 2 | 2 |
| Relief vehicle (#available) | 4 | 5 | 7 | 4 | 6 | 8 | 4 | 5 | 3 | 2 |

**Table 3.3**: The number of AP in specific locations and the distance between AP and EC

| Location | $AP_1$ $Cell_{55}$ | $AP_2$ $Cell_{64}$ | $AP_3$ $Cell_{76}$ |
|---|---|---|---|
| Number of affected people | 50 | 70 | 40 |
| Distance to $EC_1$ (kilometers) | 7.07 | 7.75 | 9.22 |
| Distance to $EC_2$ (kilometers) | 3.00 | 4.47 | 5.39 |
| Distance to $EC_3$ (kilometers) | 5.83 | 4.47 | 5.00 |
| Distance to $EC_4$ (kilometers) | 3.00 | 2.82 | 2.00 |
| Distance to $EC_5$ (kilometers) | 6.40 | 5.83 | 3.61 |
| Distance to $EC_6$ (kilometers) | 5.00 | 6.40 | 6.32 |

In order to consider more factors (e.g., what if the relief ability varies among staff), Phase 1 defined in Figure 2.2 is separated into two steps. Relief Staff (RS) and Relief Commodities (RCs) are delivered successively instead of concurrently. Therefore, the timeline of supply chain management in humanitarian aid and disaster relief for the small-scale illustrative model is:

- Phase 1a) Assign given RS groups to a designated set of ECs to open them. At the end of this phase, several ECs are fully or partly opened.
- Phase 1b) Operationalize the designated ECs with RS groups; that is, ship RV truckloads of RCs from the CEB to the open ECs.
- Phase 2) Evacuate the AP to the open and operating ECs.

The above phases may be considered the 'first round' that must be executed in a timely and repeated fashion in order to respond to the ongoing and renewed potential demand for relief related to the progression of the emergency. From historical evidence, the initial requirements are less than the follow-up surge demand and available supply; thus, more rounds are often necessary to complete the relief exercise. The loop (Phase 3 in Figure 2.2) of the three phases will not end until all the demands (evacuations of Affected People) are satisfied. Specific details are illustrated in the following paragraphs.

Phase 1a is modeled as an assignment problem that deploys groups of RS to ECs in order to maximize total assignment scores. In the illustrative model, it is assumed that one RS group can serve ten evacuees. Although each group of RS has at least the minimal capacity to perform humanitarian aid and disaster relief, these groups may differ considerably in how efficient and how effective they can handle all the services. Thus, the groups can be divided into three levels: $RS_1$ (good), $RS_2$ (medium), and $RS_3$ (weak). The unit value (satisfaction score) along each arrow are decided by the service level of RS group, the holding capacity of EC, the distance between CEB and EC, as well as the distance between EC and AA. Table 3.4 shows the data for Phase 1a formulated as an assignment problem. Since $EC_4$ is not functional, the satisfaction scores are indicated as $-\infty$. At this time, the limitation is the number of available RS groups.

**Table 3.4**: Unit satisfaction score for assignment problem

| Unit satisfaction score | $EC_1$ | $EC_2$ | $EC_3$ | $EC_4$ | $EC_5$ | $EC_6$ |
|---|---|---|---|---|---|---|
| $RS_1$ | 4 | 6 | 7 | $-\infty$ | 7 | 6 |
| $RS_2$ | 6 | 5 | 6 | $-\infty$ | 7 | 8 |
| $RS_3$ | 3 | 5 | 3 | $-\infty$ | 5 | 6 |

Phases 1b and 2 are formulated as minimum cost transportation problems with the purpose of shipping RCs to the open ECs, and the delivery of AP to the open ECs. It is assumed for illustration purpose that each RV can transport ten AP at a time. The unit shipping cost along each route from CEB to EC site depends on the distance between them (Table 3.1). Similarly, the unit delivery cost along each route between AP to EC relies on the distance between them, the road condition, and the accessibility of specific location (Table 3.3). Table 3.5 illustrates the unit cost for Phase 1b and Phase 2 formulated as transportation problems. The cost related to $EC_4$ is represented by sign $+\infty$ to denote that it is not functional. During Phase 1b, the constraint is the amount of available RVs since the RCs are assumed to be enough. However, two limits exist in Phase 2: the extent to which ECs have been opened, and the amount of available RVs.

**Table 3.5**: Unit shipping cost for the Phases 1b and 2 in transportation problems

| Shipping Cost (dollars) | $EC_1$ | $EC_2$ | $EC_3$ | $EC_4$ | $EC_5$ | $EC_6$ |
|---|---|---|---|---|---|---|
| CEB | $10 | $50 | $30 | $+\infty$ | $70 | $60 |
| $AP_1$ | $50 | $10 | $50 | $+\infty$ | $40 | $40 |
| $AP_2$ | $50 | $20 | $20 | $+\infty$ | $40 | $40 |
| $AP_3$ | $60 | $40 | $40 | $+\infty$ | $30 | $50 |

### 3.4.3. Illustrative Model Results

**Table 3.6**: Specific modelling information about each phase within one round

| | *Phase 1a-Designate ECs* | *Phase 1b-Operationalize ECs* | *Phase 2-Evacuate AP* |
|---|---|---|---|
| **Objectives** | Maximize the total satisfaction score | Minimize the total shipping cost | Minimize the total delivery cost |
| **Constraints** | The amount of available RS and RV | The amount of available RV | The amount of available RV and the extent to which a potential EC is opened |
| **Parameters** | The supply of RS in CEB; the demand of RS in each EC; the unit satisfaction score along each assignment approach | The supply of RV in CEB; the demand of RC in each open EC; the unit shipping cost along each route | The holding capacity of each open EC; the number of available RV; the amount of AP needed to be evacuated; the unit delivery cost along each route |
| **Variables** | Whether or not a potential EC is opened; the extent to which a potential EC is opened; assignment of RS to each EC | Delivery plan of RC to each open EC | Evacuation plan of AP to each open EC |

Generally speaking, the illustrative model data can be collected from performance in ordinary days, feedback during disasters, as well as analyses among previous experience. After data collection and model development, the last step is evaluation and decision making. In order to find the solution for both assignment and transportation problems in all phases, the EXCEL spreadsheet add-in function Solver of linear programming problems is used for the base case problem. The Table 3.6 above summarizes the objectives, constraints, parameters, and variables in each phase of the problem.

The completed small-scale centralized problem is presented and solved for illustration purposes to demonstrate the methodology for the disaster relief problem. This illustration of the application of the assignment and transportation optimization problem formulations correspond to the sample data provided in Table 3.1 to 3.5 above. The specific evaluation and decision making details are included in Appendix A "Illustrative Model Results for the Phased Assignment and Transportation Problems". The Appendix A includes the network representation of the centralized example problem used to illustrate the application of the research methodology and process.

In the first round, not all demands are met in the illustrative problem. At the end of T=1, no RS groups are delivered to $EC_1$ and $EC_2$, thus, they are still closed. Two RS groups are deployed to $EC_3$ and three to $EC_5$, but the demand of RS groups in both of them are still not satisfied; therefore, these two ECs are partly opened. Only $EC_6$ is totally opened since its demand is fully met. The results in assignment problem help decide the number of AP that can be delivered to each EC in Phase 2.

After assigning RS groups, RCs need to be shipped to the open ECs. In the illustrative problem, there is an assumption that RCs are enough in CEB because emergency agency can bring all provincial resources together. Hence, the only limitation is the amount of available RVs. During T=2, there are five RVs and the demand is greater than the supply. At the end of this period, the demands in $EC_3$ and $EC_6$ are fully met, while the needs in $EC_5$ just partly satisfied and the unsatisfied needs (two full truckloads of RCs) will be added to Phase 1b in the second round.

With deployed RS groups and RCs, AP can be transported to operational ECs. Based on the extent to which each EC is opened, the supplies in T=3 are determined. In addition, the number of AP that can be evacuated also depends on the amount of available RVs. At the end of T=3, no AP in $Cell_{55}$ are evacuated and part of AP in $Cell_{64}$ and $Cell_{76}$ are evacuated successfully. Thus, second or more rounds are proceeded following the above steps.

Similar phases are conducted in both round 2 and round 3. At the end of round three, all ECs are opened and the demands of RCs in each EC are satisfied. However, due to the shortage of available RVs in T=9, not all AP are evacuated successfully. In consequence, it is necessary to do round 4 and only conduct Phase 2. After round 4, the humanitarian aid and disaster relief effort is done.

This section provided a single modeling scenario for illustration. Different scenarios need to be modelled and evaluated to help make the best decision. Thus, the last section in this chapter suggests the evaluation and decision making process.

## 3.5. Evaluation and Decision Making

This research aims to build a model to improve the existing supply chain management in humanitarian aid and disaster relief for a specific Canadian community – Charlottetown, Prince Edward Island. Historically, linear programming was the first term for optimization that is the selection of a best plan regarding some criteria from some set of feasible alternatives (Dantzig, 2014). In addition, a majority of the reviewed literature uses optimization to evaluate the results. In consequence, this thesis research adopts the approach of optimization for each modeling phase to find the optimal plan with the aim to minimize response time.

The strategic pre-position of sites for Relief Staff (RS), Relief Commodities (RCs), and

Relief Vehicles (RVs), as well as the options to coordinate and transport Relief Commodities (RCs) are explored as alternative policies. Emergency situations are simulated using different combinations of alternative policies. Reduced response time and decreased delay of evacuation and commodity delivery from characterized policies in emergency scenarios are defined by examining alternative scenarios and strategies for relief inventory deployment and affected people transportation. Once the assignment and transportation modeling under alternative designs are completed, single-criteria (response time) evaluation is used to find the optimal plan and make the final decision.

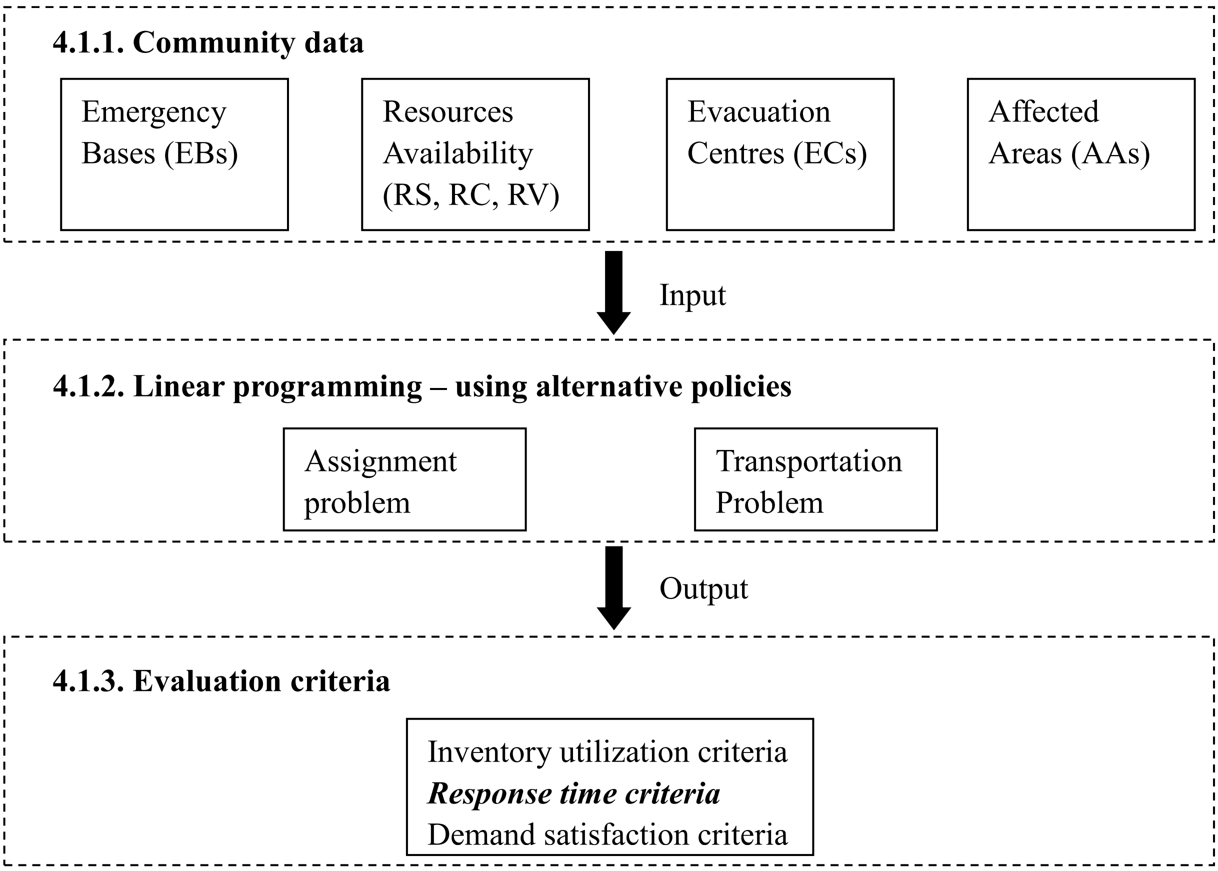
To sum, Chapter 3 proposes the research methodology for this thesis. This modelling approach is applied to the coastal Canadian community – Charlottetown, Prince Edward Island. The scenarios and inputs of the application model are provided in the next Chapter 4.

# 4. Application Model Formulation

This chapter applies the general methodology illustrated in Chapter 3 to a particular Canadian coastal community: Charlottetown, Prince Edward Island. Charlottetown is a community member of the C-Change International Community-University Research Alliance (ICURA) research project (C-Change, 2009). Specific model components are represented in section 4.1. Section 4.2 examines the current situation of Charlottetown subject to critical flooding from storm surge. According to the available information in section 4.2, six different model scenarios are defined in section 4.3 for Charlottetown emergency relief. Section 4.4 provides a summary of the formulation of the application model.

## 4.1. Model Components

**Figure 4.1**: Model components



Model components include the parameter inputs, the formulated linear programming models, and the model outputs. Figure 4.1 above provides a visual overview of the model components. Each of these components identified in Figure 4.1 is described in further detail in the following subsections below.

### 4.1.1. Community Data

Available and required community data have to be collected to constitute the inputs of the model. Generally speaking, the inputs include four pillars: (i) Emergency Bases (EBs); (ii) Resources Availability (RS, RCs, RVs); (iii) Evacuation Centres (ECs); and (iv) Affected Areas (AAs). The principle sources for these input data for the case of the C-Change community Charlottetown include: Statistics Canada, the Government of Prince Edward Island, the City of Charlottetown, the C-Change project, the Guardian newspaper, and two personal communications with the Provincial Director for the Red Cross in Prince Edward Island and the Emergency Measures Coordinator and City of Charlottetown Fire Chief. With the available community data, the linear programming model can be built as described in the next subsection 4.1.2.

### 4.1.2. Linear Programming Model

As noted in Chapter 3, this thesis develops nonexperimental modeling for emergency management of inventory and transportation scenarios as experienced in recent periods in Canadian communities, with focus here on Charlottetown. This modeling includes the data collection, formulation, analysis, and evaluation of linear optimization models using special case applied linear programming models, namely, the assignment problem and the transportation problem models. In the formulation and solution of the assignment and transportation problems for emergency relief in Charlottetown, alternative policies are adopted and reported here designed for operational application in the event of an emergency evacuation of flooded community members. These policies are described below in section 4.3 for alternative problem scenarios. The results produced by the linear programming model are evaluated by the criteria posed in the following subsection 4.1.3.

### 4.1.3. Evaluation Criteria

Model outputs are used to evaluate and compare the alternative policies. The primary function of this thesis is to identify an optimal plan for each phase of community emergency relief logistics. In accordance to the conceptual and illustrated framework (Figure 3.2) built in Chapter 3, three evaluation criteria are considered: (i) inventory utilization, (ii) response time, and (iii) demand satisfaction. The units of measure are different among these three criteria. Identifying their relationships can help include the three in one objective. Response time is indicated as the most important criteria because the ultimate goal of effectively using inventory is to reduce response time, and shorter response time indicates higher satisfaction. Thus, five response time indicators are calculated to reflect the criteria: (i) maximum inventory delivery time, (ii) total Evacuation Centres (ECs) set up time, (iii) average person wait time, (iv) total Affected People (AP) transport time, and (v) total relief response time. These measures are used to compare and rank alternative policies developed in section 4.3 for Charlottetown relief.

## 4.2. Current Situation of Charlottetown

To improve the effectiveness of humanitarian aid and disaster relief supply chain management in Charlottetown, it is necessary to have a comprehensive understanding of its current situation. Specifically, Charlottetown inputs include the following set of parameters:

1. location of Emergency Bases (EBs);
2. basic information about each Evacuation Centre, EC (location, capacity, and distance);
3. amount of available Relief Commodities (RCs), transportation equipment (RVs), and

personnel resources (RS);

4. location of the Affected (Charlottetown flooded) Areas (AAs); and
5. location and number of Affected People (AP).

The following subsections identify the specifics for these Charlottetown inputs (Figure 4.1).

### 4.2.1. Emergency Bases (EBs)

According to the information provided by Emergency Measures Coordinator and City of Charlottetown Fire Chief, MacDonald (2014), the Charlottetown Emergency Operations Centre (EOC) has a contract with different organizations, including the Red Cross and the Salvation Army. As part of the largest humanitarian network in the world (i.e., the International Red Cross and Red Crescent Movement), the Canadian Red Cross aims to mobilize the humanitarian power in Canada and around the world to improve the lives of vulnerable people. The Red Cross in Prince Edward Island provides emergency and disaster services (Canadian Red Cross, 2013a).

During Phase 1 of the natural disaster response, the Relief Staff (RS) and Relief Commodities (RCs) are sent from the Red Cross in Charlottetown to the designated Evacuation Centres (ECs). In the base case, the local branch of Red Cross in Charlottetown is considered as the Central Emergency Base (CEB). The location of the current CEB is 62 Prince Street in Charlottetown.

In fact, the Red Cross is preparing to move its headquarters, including its CEB, to a new location at Paramount Drive in Charlottetown. The new site is expected to be operational before the end of summer in 2014 according to the provincial director for the Red Cross in Prince Edward Island (Johnson-Montigny, 2014). The new EB will provide more flexibility than the current headquarters, including wheelchair accessibility, and a preparedness centre for disaster management training (The Guardian, 2013b).

### 4.2.2. Evacuation Centres (ECs)

The *Emergency Measures Plan* of Charlottetown (City of Charlottetown, 2009) lists eleven Evacuation Centres (ECs) in the city. Table 4.1 represents the specific location and capacity of the eleven ECs. The accurate locations of the eleven ECs are indicated by a star on the Google Map of Figure 4.2. Distance data between every two ECs (Table 4.2) are calculated by Google Earth and used for the transportation modelling in these locations. Similarly, Table 4.3 displays the distance between the 62 Prince Street CEB and each Evacuation Centre (EC). Table 4.4 displays the distance between the future CEB at Paramount Drive to each EC.

**Table 4.1**: Location and capacity of evaluation centres in Charlottetown

| *EC* | *Name* | *Location* | *Capacity* |
|---|---|---|---|
| $EC_1$ | West Royalty Community Centre | 1 Kirkdale Road, Charlottetown, PE | 100 |
| $EC_2$ | Hillsborough Park Community Centre | 199 Patterson Drive, Charlottetown, PE | 50 |
| $EC_3$ | East Royalty Community Centre | 1 Avonlea Drive, Charlottetown, PE | 50 |
| $EC_4$ | Charlottetown Civic Centre | 46 Kensington Road, Charlottetown, PE | 100 |
| $EC_5$ | Sherwood Recreation Hall | 56 Maple Avenue, Charlottetown, PE | 50 |
| $EC_6$ | Charlottetown Rural High School | 100 Raider Road, Charlottetown, PE | 300 |
| $EC_7$ | Colonel Gray High School | 175 Spring Park Road, Charlottetown, PE | 300 |
| $EC_8$ | Birchwood Junior High School | 49 Longworth Avenue, Charlottetown, PE | 300 |
| $EC_9$ | Queen Charlotte Junior High School | 150 North River Road, Charlottetown, PE | 300 |
| $EC_{10}$ | Stone Park Junior High School | 50 Pope Avenue, Charlottetown, PE | 300 |
| $EC_{11}$ | HMCS Queen Charlotte | 210 Water Parkway, Charlottetown, PE | 200 |

**Figure 4.2**: Eleven Evacuation Centres (ECs) indicated by stars in Google Map of Charlottetown (Source: Google Maps 2014.)

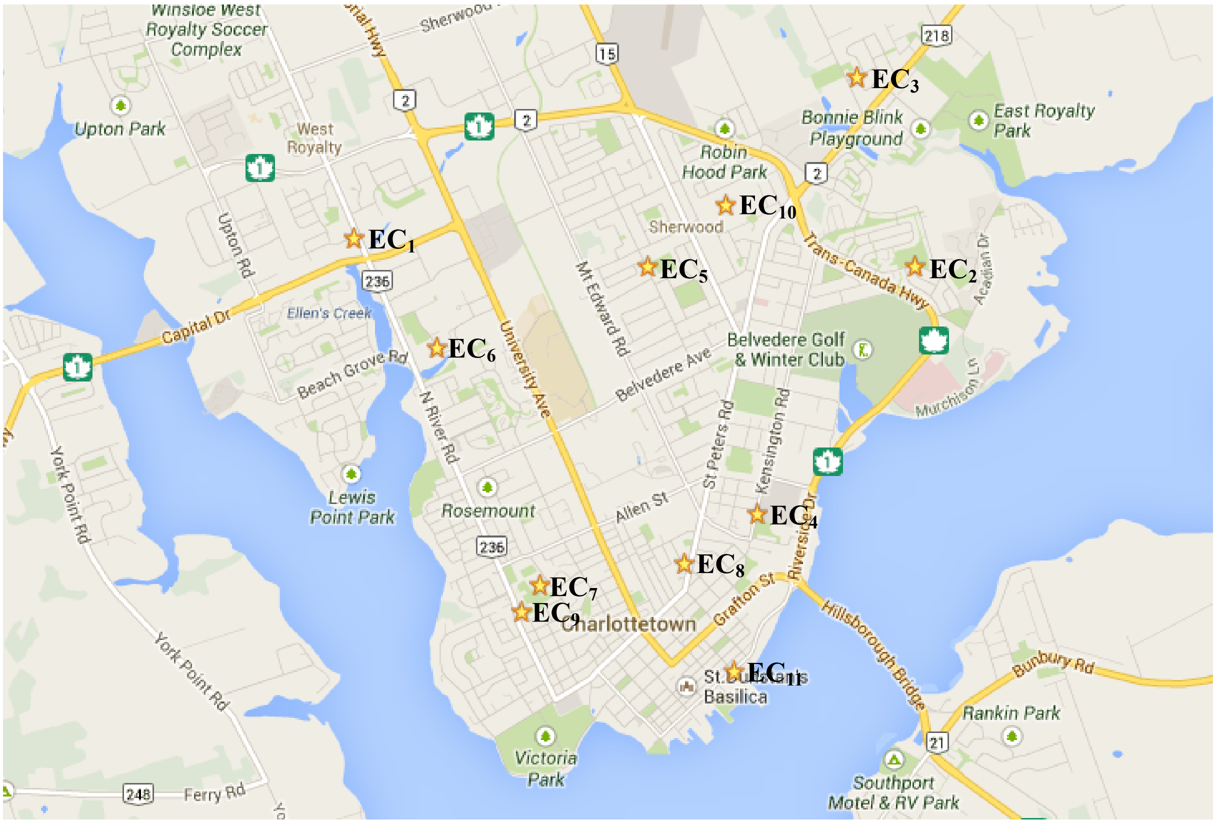



**Table 4.2**: Distance adjacency matrix between Evacuation Centres (ECs) in Charlottetown

| Km | $EC_1$ | $EC_2$ | $EC_3$ | $EC_4$ | $EC_5$ | $EC_6$ | $EC_7$ | $EC_8$ | $EC_9$ | $EC_{10}$ | $EC_{11}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $EC_1$ | — | | | | | | | | | | |
| $EC_2$ | 6.3 | — | | | | | | | | | |
| $EC_3$ | 6.3 | 2.6 | — | | | | | | | | |
| $EC_4$ | 5.3 | 3.4 | 3.9 | — | | | | | | | |
| $EC_5$ | 4.5 | 4.5 | 4.3 | 3.1 | — | | | | | | |
| $EC_6$ | 1.3 | 6.9 | 6.7 | 4.4 | 3.9 | — | | | | | |
| $EC_7$ | 3.4 | 5.5 | 5.4 | 2.6 | 3.8 | 3.5 | — | | | | |
| $EC_8$ | 5.1 | 4.4 | 4.3 | 1.0 | 2.8 | 4.1 | 1.9 | — | | | |
| $EC_9$ | 3.3 | 5.9 | 5.8 | 2.9 | 4.2 | 3.0 | 1.0 | 2.4 | — | | |
| $EC_{10}$ | 4.7 | 2.7 | 2.6 | 2.9 | 0.8 | 4.7 | 4.5 | 3.0 | 4.9 | — | |
| $EC_{11}$ | 5.6 | 4.4 | 6.2 | 2.3 | 3.9 | 4.6 | 2.5 | 1.1 | 2.7 | 4.7 | — |

**Table 4.3**: Distance (in km) between 62 Prince Street CEB to the designated 11 ECs in Charlottetown

| Km | $EC_1$ | $EC_2$ | $EC_3$ | $EC_4$ | $EC_5$ | $EC_6$ | $EC_7$ | $EC_8$ | $EC_9$ | $EC_{10}$ | $EC_{11}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Current Central Emergency Base | 5.3 | 4.8 | 6.6 | 1.6 | 3.9 | 4.3 | 1.8 | 1.1 | 2.4 | 5.1 | 0.29 |

**Table 4.4**: Distance (in km) between Paramount Drive CEB to the designated 11 ECs in Charlottetown

| Km | $EC_1$ | $EC_2$ | $EC_3$ | $EC_4$ | $EC_5$ | $EC_6$ | $EC_7$ | $EC_8$ | $EC_9$ | $EC_{10}$ | $EC_{11}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| New Central Emergency Base | 3.4 | 4.2 | 4.1 | 5.4 | 2.9 | 3.9 | 5.6 | 4.7 | 6.2 | 2.6 | 7.8 |

### 4.2.3. Resources Availability (RS, RCs, RVs)

With regard to resources availability, Relief Staff (RS) and commodities (RCs) are considered together, while there is a constraint related to the number of Relief Vehicles (RVs) for Charlottetown. Currently, only two Red Cross vans are available at the Prince Street EB to be used to deploy resources to set up Evacuation Centres (ECs). Once the new Paramount Drive EB is completed, there will be three vans available. For transporting Affected People (AP) to operational ECs, 65 buses can be used under contract with the city to commercial (public and other) and school buses. These are located in three different bus centres (MacDonald, 2014). The location, amount, and capacity of evacuation buses are shown in Table 4.5.

**Table 4.5**: Location, number and capacity of Relief Vehicles (RVs) for evacuation (MacDonald, 2014)

| | *Location* | *Number* | *Capacity per vehicle* |
|---|---|---|---|
| Public transportation bus | Mount Edward Road, Charlottetown | 15 | 50 |
| School bus | North River Road, Charlottetown | 30 | 50 |
| Other | Riverside Drive, Charlottetown | 20 | 50 |

### 4.2.4. Affected Areas (AAs)

Information about the population of Charlottetown is collected from Statistics Canada. In order to calculate the number of Affected People (AP) from an emergency flooding event, this thesis adopts the Dissemination Area (DA) as the designator of local city zones where flooded coastal areas can be more directly defined.

Statistics Canada (2011a) defines a DA as

> "a small, relatively stable geographic unit composed of one or more adjacent dissemination blocks" and is "the smallest standard geographic area for which all census data are disseminated" (Statistics Canada, 2011a, p. 114).

Figure 4.3 is the map of Charlottetown with numbered DAs. Data collected from the 2011 Canada Census are used. The map of Charlottetown with three-meter flooded line is shown in Figure 4.4.

**Figure 4.3**: The map of Charlottetown with numbered DAs (Source: Statistics Canada, 2011b)

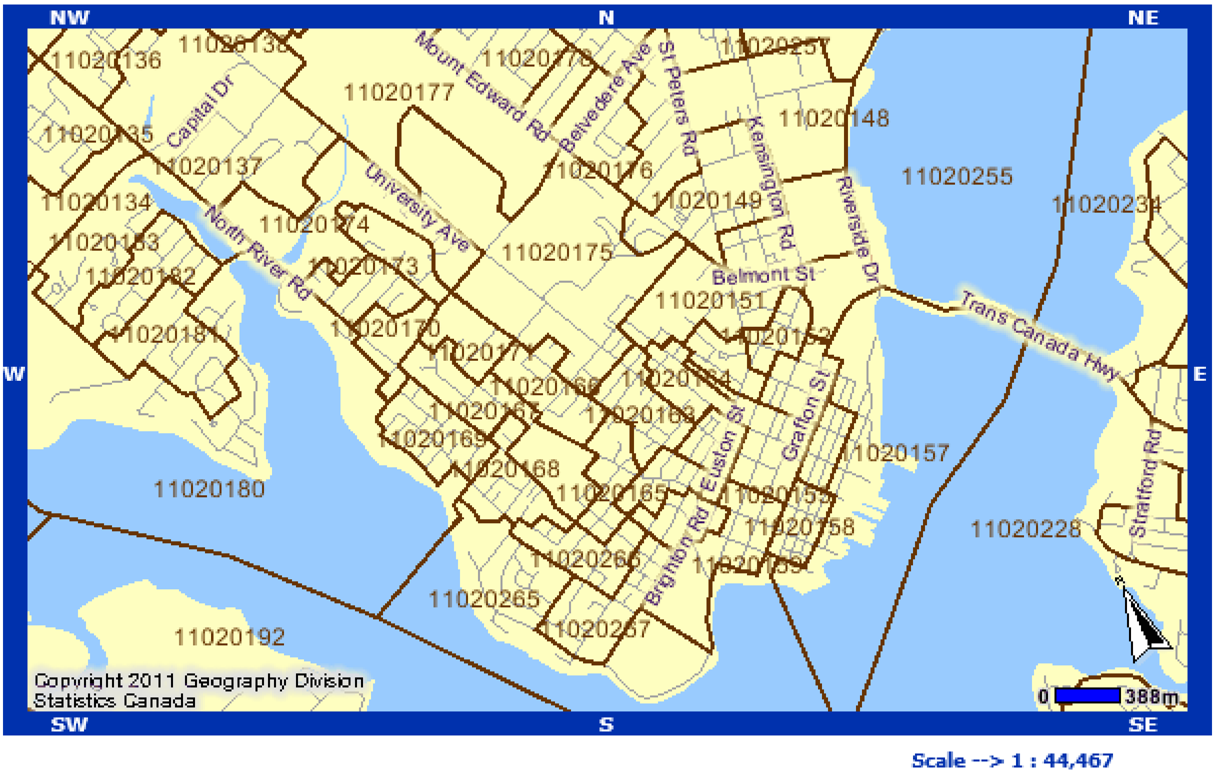


**Figure 4.4**: The map of Charlottetown with three-meter flooded line (Source: ArcGIS 2013)


Data about flooded areas and affected people are calculated by comparing the above two maps of Figures 4.3 and 4.4. In this analysis, 20 coastal DAs are considered (the DAs inland are not expected to be flooded in the event of storm surge). The range of flooded proportion of each DA is estimated. The centre of flooded area in each DA is pinpointed in Google Earth (Figure 4.5). Since the total population in each DA is known (Statistics Canada, 2011b), the number of Affected People (AP) is calculated by the equation (4.1) below:

$$Number\ of\ Affected\ People (AP)$$
$$\approx \left(\frac{Lower\ Limit\ of\ Flooded\ Area\ Proportion + Upper\ Limit\ of\ Flooded\ Area\ Proportion}{2}\right)$$
$$* (Total\ Population\ in\ DA) \quad (4.1)$$

**Figure 4.5**: Centre of flooded area in each DA of Charlottetown (Source: Google Earth 2014)


Table 4.6 lists the specific information about the coastal DAs subject to flooding. Distance data between the centre of each Affected Area (AA), and each Evacuation Centre (EC) are calculated by Google Earth and shown in Table 4.7. From Table 4.6, the expected total affected population from a 3m level of maximum observed water level for Charlottetown is approximately 2,000 people (1842). Given the location of the affected dissemination areas, AA, the distance from each EC can be calculated using Google Earth. These distance data are presented in Table 4.7.

**Table 4.6**: Specific information about DAs in Charlottetown (Source: Statistics Canada, 2011b)

| No. | Geographic code of DA | Estimated flooded proportion | DA population | Estimated affected people | Centre of affected area |
|---|---|---|---|---|---|
| 1 | 11020148 | 5%~7% | 487 | (25,35)-30 | 46° 15' 6.22" N 63° 6' 33.68" W |
| 2 | 11020150 | 14%~16% | 483 | (68,78)-73 | 46° 14' 45.83" N 63° 6' 47.48" W |
| 3 | 11020152 | 6.5%~8.5% | 518 | (34,45)-40 | 46° 14' 30.77" N 63° 7' 9.56" W |
| 4 | 11020154 | 16.5%~18.5% | 552 | (92,103)-98 | 46° 14' 22.76" N 63° 7' 11.97" W |
| 5 | 11020156 | 12.5%~14.5% | 480 | (60,70)-65 | 46° 14' 10.21" N 63° 7' 11.69" W |
| 6 | 11020157 | 75%~77% | 586 | (440,452)-446 | 46° 14' 8.68" N 63° 7' 7.57" W |
| 7 | 11020158 | 3%~5% | 533 | (16,27)-22 | 46° 13' 55.83" N 63° 7' 30.13" W |
| 8 | 11020159 | 8%~10% | 606 | (49,61)-55 | 46° 13' 57.28" N 63° 8' 4.81" W |
| 9 | 11020160 | 25%~27% | 492 | (123,133)-128 | 46° 14' 8.15" N 63° 8' 6.14" W |
| 10 | 11020161 | 10%~12% | 474 | (48,57)-53 | 46° 14' 13.79" N 63° 8' 5.86" W |
| 11 | 11020174 | 9%~11% | 946 | (86,105)-96 | 46° 15' 27.98" N 63° 9' 0.28" W |
| 12 | 11020180 | 7.5%~9.5% | 917 | (69,88)-79 | 46° 14' 59.74" N 63° 9' 32.13" W |
| 13 | 11020183 | 8%~10% | 667 | (54,67)-61 | 46° 15' 50.38" N 63° 9' 34.34" W |
| 14 | 11020255 | 40%~42% | 483 | (194,203)-199 | 46° 14' 34.11" N 63° 6' 49.01" W |
| 15 | 11020256 | 4.5%~6.5% | 841 | (38,55)-47 | 46° 16' 15.93" N 63° 5' 40.18" W |
| 16 | 11020257 | 13%~15% | 628 | (82,95)-89 | 46° 15' 27.64" N 63° 6' 25.56" W |
| 17 | 11020258 | 10%~12% | 554 | (55,83)-69 | 46° 16' 23.05" N 63° 5' 49.29" W |
| 18 | 11020261 | 9%~11% | 807 | (73,89)-81 | 46° 16' 11.10" N 63° 5' 29.58" W |
| 19 | 11020265 | 15%~17% | 498 | (75,85)-80 | 46° 13' 44.69" N 63° 8' 25.20" W |
| 20 | 11020267 | 5.5%~7.5% | 469 | (26,36)-31 | 46° 13' 50.80" N 63° 8' 41.26" W |

**Table 4.7**: Distance (in km) between each Affected Area (AA) and each Evacuation Centre (EC) (Source: Google Earth 2014)

| AA\EC | $EC_1$ | $EC_2$ | $EC_3$ | $EC_4$ | $EC_5$ | $EC_6$ | $EC_7$ | $EC_8$ | $EC_9$ | $EC_{10}$ | $EC_{11}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $AA_1$ | 8.2 | 2.6 | 4.4 | 1.2 | 2.8 | 8.7 | 3.2 | 2.2 | 3.6 | 2.6 | 2.1 |
| $AA_2$ | 8.6 | 2.9 | 4.8 | 0.95 | 3.5 | 4.8 | 3.2 | 1.5 | 3.8 | 3.3 | 1.4 |
| $AA_3$ | 5.6 | 3.5 | 4.4 | 0.5 | 3.2 | 4.5 | 2.3 | 0.65 | 2.8 | 3.4 | 1.6 |
| $AA_4$ | 5.6 | 4.0 | 5.8 | 0.85 | 3.6 | 4.6 | 2.2 | 0.8 | 2.7 | 4.3 | 1.4 |
| $AA_5$ | 6.2 | 4.5 | 6.4 | 1.6 | 4.1 | 4.7 | 2.7 | 1.2 | 2.9 | 4.9 | 0.19 |
| $AA_6$ | 6.2 | 4.2 | 6.1 | 1.8 | 3.9 | 6.0 | 2.8 | 1.0 | 3.0 | 4.6 | 0.25 |
| $AA_7$ | 5.5 | 4.8 | 6.7 | 2.4 | 4.4 | 5.3 | 1.6 | 1.5 | 2.2 | 5.2 | 0.5 |
| $AA_8$ | 4.6 | 5.9 | 7.7 | 2.2 | 4.3 | 4.3 | 1.3 | 1.5 | 1.3 | 4.5 | 1.6 |
| $AA_9$ | 4.4 | 5.6 | 7.4 | 2.2 | 4.3 | 4.1 | 0.9 | 1.2 | 1.1 | 4.3 | 1.7 |
| $AA_{10}$ | 4.4 | 5.6 | 7.4 | 2.2 | 4.2 | 4.1 | 0.7 | 1.2 | 1.1 | 4.2 | 1.8 |
| $AA_{11}$ | 1.4 | 6.7 | 6.6 | 4.2 | 3.8 | 0.12 | 3.4 | 4.0 | 3.1 | 5.0 | 4.5 |
| $AA_{12}$ | 2.4 | 9.6 | 9.6 | 5.7 | 5.2 | 2.1 | 3.6 | 5.5 | 3.5 | 6.0 | 6.2 |
| $AA_{13}$ | 0.35 | 6.2 | 6.2 | 7.5 | 4.9 | 1.2 | 3.3 | 5.0 | 3.1 | 4.6 | 5.9 |
| $AA_{14}$ | 8.9 | 3.3 | 5.1 | 0.85 | 3.8 | 5.3 | 2.9 | 1.2 | 3.4 | 3.6 | 1.0 |
| $AA_{15}$ | 8.0 | 1.7 | 4.2 | 4.0 | 6.1 | 8.5 | 6.0 | 5.1 | 6.4 | 4.3 | 5.0 |
| $AA_{16}$ | 7.3 | 1.6 | 3.4 | 1.8 | 5.3 | 7.7 | 3.8 | 2.8 | 4.2 | 1.7 | 2.7 |
| $AA_{17}$ | 6.9 | 3.2 | 1.4 | 4.5 | 4.9 | 7.4 | 6.1 | 4.9 | 6.4 | 3.2 | 6.8 |
| $AA_{18}$ | 8.0 | 1.7 | 4.2 | 4.0 | 6.1 | 8.5 | 6.0 | 5.1 | 6.4 | 4.3 | 5.0 |
| $AA_{19}$ | 4.7 | 6.6 | 8.4 | 2.9 | 5.4 | 4.4 | 1.9 | 2.3 | 1.4 | 5.2 | 2.3 |
| $AA_{20}$ | 4.6 | 6.5 | 6.4 | 3.1 | 5.4 | 4.3 | 1.9 | 2.1 | 1.3 | 5.1 | 2.4 |

This section displays all the input data for the application model of Charlottetown. With these community data, the modeling scenarios and processes are defined in the next section 4.3.

## 4.3. Scenario Definition

As described in section 4.1, several alternative policies are considered during the linear programming process. The first policy is regarding the facility location of inventory. The current Charlottetown Emergency Base (EB) is the Red Cross headquarters at 62 Prince Street. Given that the Red Cross headquarters are moving to Paramount Drive, this analysis explores the efficiency of the current facility location and the future one operating individually as a CEB, as well as both EBs operating together.

At present, there are only two available vans in Prince Street EB. Once a new EB is built in Paramount Drive, another van will be introduced. Thus, three vans (RVs) will be available in total. Different combinations of the three vans at each EB, or in the combined EBs are analyzed. Overall, six scenarios (I through VI) as presented in Table 4.8 are proposed relying on various combinations. (The Government of Prince Edward Island is currently considering the building of a new bus garage within the next five years (The Guardian, 2013a). Although the province has expressed interest in an area of land close to the airport, the accurate location is to be determined. Therefore, this thesis does not take the alternatives of government garage location into consideration.)

**Table 4.8**: Brief summary of six scenarios for the assignment of Red Cross vans (RVs) to the designated Emergency Base (EB)

| **Scenario** | *Inventory prepositioning type* | *Facility location and available vans* |
|---|---|---|
| **I** | Centralization (1 EB operating only) | Prince Street EB with two vans (Status Quo) |
| **II** | | Paramount Drive EB with two vans |
| **III** | | Prince Street EB with three vans |
| **IV** | | Paramount Drive EB with three vans (Proposed) |
| **V** | Decentralization (2 EBs operating) | Prince Street EB with two vans and Paramount Drive EB with one van |
| **VI** | | Prince Street EB with one van and Paramount Drive EB with two vans |

In accordance with the modeling process defined in Chapter 2 (Figure 2.2) and Chapter 3 (section 3.4), the operation of humanitarian aid and disaster relief in Charlottetown involves two phases:

- Phase 1) Deliver Relief Staff (RS) and Relief Commodities (RCs) to set up potential Evacuation Centres (ECs), as well as
- Phase 2) Deploy buses from Bus Centres (BCs) to Affected Areas (AAs) and then transport Affected People (AP) to the operational ECs.

The second phase will not start until the first phase has been completed for all ECs. Due to the constraint of relief resources, ECs need to be opened in sequence rather than all at once. Therefore, it is necessary to make a ranking list to order the deployment of RS and RCs to the ECs. The criteria used to rank ECs are based on the three performance indicators defined in Figure 3.2 (inventory utilization, response time, and demand satisfaction):

1. According to the *Emergency Measures Plan* of Charlottetown (City of Charlottetown, 2009), there are five primary ECs with kitchen and six secondary ones with cafeteria. The Emergency Operations Centre (EOC) designates higher set up priority to the primary ECs because the inventory utilization can be enhanced by operating the ECs with better amenities. In the application model, initial scores indicate the set up priority of each EC: primary ECs score 10 and secondary ones score 5.
2. The larger the full capacity of an EC has, the higher the demand satisfaction the EC can provide. The full capacity of an EC indicates the demand satisfaction in the application model.
3. The travel distance of a van represents the response time. The application model can choose either the distance between EB and EC or the shortest distance between EC and AA. The former criteria can set up ECs faster, so the evacuation can be started earlier. Although the latter one may lead to a later start of evacuation, less time will be needed to transport AP. No matter which type of distance is chosen, shorter is better.

Thus, the following equation is used to calculate the satisfaction score of each EC:

$$Satisfaction\ Score = \frac{Initial\ Score * Full\ Capacity}{Distance} \tag{4.2}$$

As described above, initial score and full capacity are constants, while there are two choices to define distance. In short, EC with higher satisfaction score should be set up earlier.

After making a ranking list, the last policy is about the delivery strategy of RS and RCs. There are two alternatives: "together" deployment strategy and "unique" deployment strategy. "Together" means all the available vans continue delivering RS and RCs to the same EC until the total demand of that EC is satisfied. In contrast, "unique" entails one van is specifically responsible for one EC. Combining different ranking criteria with different deployment strategies, four set-up strategies, as defined in Table 4.9, are applied to Phase 1 in the six scenarios proposed above (Table 4.8).

**Table 4.9**: Four strategies of setting up ECs

| **Strategy** | *Distance used in satisfaction score equation* | *Deployment strategy* |
|---|---|---|
| **1** | Distance between EB and EC | "Together" to EC |
| **2** | | "Unique" to EC |
| **3** | Shortest distance between EC and AA | "Together" to EC |
| **4** | | "Unique" to EC |

The following subsections provide detailed model formulation of each Scenario I through Scenario VI. The application of Phase 1 in each scenario is different. Subsections 4.3.1 to 4.3.6 illustrate six scenarios separately. On the contrary, Phase 2 is similar among all the scenarios and described in subsection 4.3.7.

## 4.3.1. Scenario I

The first scenario represents the current situation ("Status Quo") for Charlottetown: only one centralized Emergency Base (EB) with two available vans (RVs) located at 62 Prince Street. Demand for RS and RCs in all potential ECs needs to be satisfied by the central EB in sequence in Phase 1. Thus, the first step is to calculate the satisfaction score for each EC and schedule staffing and stocking of the ECs according to the selected EC ranking list. Two different EC ranking lists can be determined based on the two kinds of distances used in satisfaction score equation. Only ten ECs are functional because $EC_{11}$ is in the Affected Area (AA) (Figure 4.4). If the satisfaction scores of several ECs are equal, the rank will be made by the importance defined in the *Emergency Measures Plan* of

Charlottetown (City of Charlottetown, 2009). For example, although $EC_4$ and $EC_9$ have the same score of 625, $EC_4$ is ranked 3 and $EC_9$ is ranked 4 since $EC_4$ is one of the primary ECs but $EC_9$ belong to the secondary list. Table 4.10 and Table 4.11 illustrate the calculation process for the alternative EC rankings.

**Table 4.10**: Satisfaction scores calculated by distance (in km) between the Prince Street EB and the Charlottetown ECs

| **Select distance between Prince Street EB and EC** | | | | | |
|---|---|---|---|---|---|
| *EC* | *Initial score* | *Full Capacity (# people)* | *Distance* | *Satisfaction score* | *Rank* |
| $EC_1$ | 10 | 100 | 5.3 | 188.6792 | 7 |
| $EC_2$ | 10 | 50 | 4.8 | 104.1667 | 9 |
| $EC_3$ | 10 | 50 | 6.6 | 75.7576 | 10 |
| $EC_4$ | 10 | 100 | 1.6 | 625 | 3 |
| $EC_5$ | 10 | 50 | 3.9 | 128.2051 | 8 |
| $EC_6$ | 5 | 300 | 4.3 | 348.8372 | 5 |
| $EC_7$ | 5 | 300 | 1.8 | 833.3333 | 2 |
| $EC_8$ | 5 | 300 | 1.1 | 1363.6364 | 1 |
| $EC_9$ | 5 | 300 | 2.4 | 625 | 4 |
| $EC_{10}$ | 5 | 300 | 5.1 | 294.1176 | 6 |
| $EC_{11}$ | Not functional (in AA) | | | | |

**Table 4.11**: Satisfaction scores calculated by shortest distance (in km) between the EC and the closest AA

| **Select shortest distance between EC and AA** | | | | | |
|---|---|---|---|---|---|
| *EC* | *Initial score* | *Full Capacity (# people)* | *Distance* | *Satisfaction score* | *Rank* |
| $EC_1$ | 10 | 100 | 0.35 | 57.1429 | 2 |
| $EC_2$ | 10 | 50 | 1.6 | 6.25 | 9 |
| $EC_3$ | 10 | 50 | 1.4 | 7.1429 | 8 |
| $EC_4$ | 10 | 100 | 0.5 | 40 | 5 |
| $EC_5$ | 10 | 50 | 2.8 | 3.5714 | 10 |
| $EC_6$ | 5 | 300 | 0.12 | 250 | 1 |
| $EC_7$ | 5 | 300 | 0.7 | 42.8571 | 4 |
| $EC_8$ | 5 | 300 | 0.65 | 46.1538 | 3 |
| $EC_9$ | 5 | 300 | 1.1 | 27.2727 | 6 |
| $EC_{10}$ | 5 | 300 | 1.7 | 17.6471 | 7 |
| $EC_{11}$ | Not functional (in AA) | | | | |

After making the ranking list, the second step in Phase 1 is to apply the two deployment strategies (“together” or “unique”). Table 4.12 and Table 4.13 illustrate the application process of the "together" (Strategy 1 in Table 4.9) and the "unique" (Strategy 2 in Table 4.9) deployment strategies for the Charlottetown EC set up operation in Scenario I. Although the RV vans in the EB have uniform standards, a number (e.g., 1, 2…) is designated to each RV van to facilitate calculating separate deployment time.

**Table 4.12**: Illustration of RV van "together" deployment strategy (Strategy 1 in Table 4.9)

| Rank | EC | Capacity | Total demand (van) | Van# | No. Round trips | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Van1 deployment time (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC8 | 300 | 6 | 1,2 | 3 | 6.6 | 6.6 | 90 | 96.6 | 96.6 | 96.6 |
| 2 | EC7 | 300 | 6 | 1,2 | 3 | 10.8 | 10.8 | 90 | 100.8 | 197.4 | 197.4 |
| 3 | EC4 | 100 | 2 | 1,2 | 1 | 3.2 | 3.2 | 30 | 33.2 | 230.6 | 230.6 |
| 4 | EC9 | 300 | 6 | 1,2 | 3 | 14.4 | 14.4 | 90 | 104.4 | 335 | 335 |
| 5 | EC6 | 300 | 6 | 1,2 | 3 | 25.8 | 25.8 | 90 | 115.8 | 450.8 | 450.8 |
| 6 | EC10 | 300 | 6 | 1,2 | 3 | 30.6 | 30.6 | 90 | 120.6 | 571.4 | 571.4 |
| 7 | EC1 | 100 | 2 | 1,2 | 1 | 10.6 | 10.6 | 30 | 40.6 | 612 | 612 |
| 8 | EC5 | 50 | 1 | 1 | 1 | 7.8 | 7.8 | 30 | 37.8 | 649.8 | |
| 9 | EC2 | 50 | 1 | 2 | 1 | 9.6 | 9.6 | 30 | 39.6 | | 651.6 |
| 10 | EC3 | 50 | 1 | 1 | 0.5 | 6.6 | 6.6 | 30 | 36.6 | 686.4 | |

Strategy 1 uses the distance between the Prince Street EB and the EC to rank ten available ECs. The first two columns are the ranking list made by the satisfaction score calculated in Table 4.10. "Capacity" is the maximum number of Affected People that can be held in the EC and is converted to the corresponding total demand of vans. "Van#" illustrates the vans used to set up the EC. According to the nature of "together" deployment strategy described in Table 4.9, Van 1 and Van 2 go together to deliver RS and RCs to set up the highest ranked EC ($EC_8$). Once the demand in $EC_8$ is totally satisfied, two vans go together again to set up the rest ECs in the ranking list in sequence. When the total demand of the EC is less than the total supply of available vans, two vans do not have to go together anymore. For example, $EC_5$, $EC_2$, and $EC_3$ only need one van to deploy RS and RCs. The two available vans go separately to set up each of the last three ECs. The total time used in Phase 1 is determined by the longer deployment time between the two vans.

**Table 4.13**: Illustration of RV van "unique" deployment strategy (Strategy 2 in Table 4.9)

| Rank | EC | Capacity | Total demand (van) | Van# | No. Round trips | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Van1 deployment time (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC8 | 300 | 6 | 1 | 6 | 13.2 | 13.2 | 30 | 193.2 | 193.2 | |
| 2 | EC7 | 300 | 6 | 2 | 6 | 21.6 | 21.6 | 30 | 201.6 | | 201.6 |
| 3 | EC4 | 100 | 2 | 1 | 2 | 6.4 | 6.4 | 30 | 66.4 | 259.6 | |
| 4 | EC9 | 300 | 6 | 2 | 6 | 28.8 | 28.8 | 30 | 208.8 | | 410.4 |
| 5 | EC6 | 300 | 6 | 1 | 6 | 51.6 | 51.6 | 30 | 231.6 | 491.2 | |
| 6 | EC10 | 300 | 6 | 2 | 6 | 61.2 | 61.2 | 30 | 241.2 | | 651.6 |
| 7 | EC1 | 100 | 2 | 1 | 2 | 21.2 | 21.2 | 30 | 81.2 | 572.4 | |
| 8 | EC5 | 50 | 1 | 1 | 1 | 7.8 | 7.8 | 30 | 37.8 | 610.2 | |
| 9 | EC2 | 50 | 1 | 1 | 1 | 9.6 | 9.6 | 30 | 39.6 | 649.8 | |
| 10 | EC3 | 50 | 1 | 1 | 0.5 | 6.6 | 6.6 | 30 | 36.6 | 686.4 | |

The ranking policy in both Table 4.12 and Table 4.13 uses the distance between the Prince Street EB and the EC. The first two columns are the same in Tables 4.12 and 4.13. Different from Strategy 1, Strategy 2 illustrates the "unique" deployment strategy described in Table 4.9. Each van is assigned responsibility for the highest ranked, single EC and executes trips to complete the EC set up. For example, Van 1 delivers RS and RCs to $EC_8$ and Van 2 is used to set up $EC_7$ because $EC_8$ and $EC_7$ are the two highest ranked ECs. When the demand in $EC_8$ is satisfied, Van 1 will go to set up $EC_4$ that is ranked the third highest. Similarly, Van 2 will go to set up $EC_9$ in sequence once Van 2 completes setting up $EC_7$. The total time used in Phase 1 is determined by the longer deployment time between the two vans.

Tables 4.12 and 4.13 are used to demonstrate the different characteristics and application process of "together" and "unique" deployment strategies in Phase 1. The results in the tables are described and analyzed further in Chapter 5.

## 4.3.2. Scenario II

Since the Charlottetown Red Cross headquarters are being moved to a new location at Paramount Drive, Scenario II is defined with EB at the new location (versus the Prince Street EB of Scenario I). Consequently, the modeling steps are as same as those described in subsections 4.3.1. The EC satisfaction scores are calculated, since the distances between the new EB and the ECs are different from those used in Table 4.10. The new ranking list is provided in Table 4.14 on the next page. However, since the Affected Area (AA) has not changed, the AA is the same region; therefore, the EC-AA ranking is the same as shown in Table 4.11.

The four strategies in Table 4.9 are now applied. Comparing the results between Scenario I and Scenario II, the research can find out which location is better for one central EB. A specific analysis of the results of this scenario is provided in Chapter 5.

**Table 4.14**: Satisfaction scores calculated by distance (in km) between the Paramount Drive EB and the Charlottetown ECs

| **Select distance between Paramount Drive EB and EC** | | | | | |
|---|---|---|---|---|---|
| *EC* | *Initial score* | *Full Capacity (# people)* | *Distance* | *Satisfaction score* | *Rank* |
| $EC_1$ | 10 | 100 | 3.4 | 294.1176 | 4 |
| $EC_2$ | 10 | 50 | 4.2 | 119.0476 | 10 |
| $EC_3$ | 10 | 50 | 4.1 | 121.9512 | 9 |
| $EC_4$ | 10 | 100 | 5.4 | 185.1852 | 7 |
| $EC_5$ | 10 | 50 | 2.9 | 172.4138 | 8 |
| $EC_6$ | 5 | 300 | 3.9 | 384.6154 | 2 |
| $EC_7$ | 5 | 300 | 5.6 | 267.8571 | 5 |
| $EC_8$ | 5 | 300 | 4.7 | 319.1489 | 3 |
| $EC_9$ | 5 | 300 | 6.2 | 241.9355 | 6 |
| $EC_{10}$ | 5 | 300 | 2.6 | 576.9231 | 1 |
| $EC_{11}$ | Not functional (in AA) | | | | |

### 4.3.3. Scenario III

The Provincial Director for the Red Cross in P.E.I. has indicated that a new (third) van will be added to the RV since the new Paramount Drive EB is larger and can provide more services (Johnson-Montigny, 2014). For the purpose of this analysis, this scenario looks at the impact of adding the new van to the current Prince Street EB. Thus, the third scenario is one central EB in Prince Street with three available vans.

Scenario III is similar to the analysis of Scenario I except for the addition of the new van.

The ranking lists applied in this scenario are exactly the same as those defined in Scenario I (section 4.3.1). In addition, the same four strategies of Table 4.9 are applied to Scenario III. The results of this scenario are presented in Chapter 5.

### 4.3.4. Scenario IV

In contrast to Scenario III, the fourth scenario displays the planned action to be taken by the Red Cross, i.e., moving the EB to Paramount Drive and storing three vans there. The EC ranking lists in this situation are the same as those in Scenario II. The four deployment strategies of Table 4.9 are applied to Scenario IV. The results of Scenario IV are given in Chapter 5.

### 4.3.5. Scenario V

The above four scenarios all consider the situation of only one central Emergency Base (EB). The centralized single EB may be considered risky if there is a possibility the EB is flooded. Therefore, it may be more appropriate to consider two EBs: one in Paramount Drive, and the other maintained at the current Prince Street location. If there are two EBs, the three available vans need to be assigned separately: either two vans at Prince Street, or two vans at Paramount Drive. Scenarios V (two vans at Prince Street) and VI (two vans at Paramount Drive) illustrate these two situations of decentralized EBs separately.

Since it is assumed that no one EB can meet the total demand in all ECs, a separation needs to be made among the ten ECs. In the case of two EBs, the RS and RCs come from different origins to set up ECs. The supply of each EB is proportional to the number of available vans stored. In Scenario V, two vans are in Prince Street EB and one van is located at the Paramount Drive EB. Since the total demand requirement (to staff the ten Charlottetown ECs) is 37 full truckloads of RS and RCs, 24 full truckloads of supply come from the two vans at the Prince Street EB, and another 12 full truckloads are provided by the single van at the Paramount Drive EB. The 37th full truckload of supply can be offered by either of the two EBs. This separation decision is made by a transportation problem that is described in Chapter 5.

After making the separation, Evacuation Centres (ECs) supplied by each EB are ranked according to Table 4.10, Table 4.11, or Table 4.14. For Scenario V, Strategy 1 and 2 are based on the ranking made in Table 4.10 and Table 4.14, while strategy 3 and 4 rely on the ranking in Table 4.11. Different from Scenario I to IV, these four strategies need to be applied twice: one for adding the 37th full truckload demand to the Paramount Drive EB and the other for adding the final extra demand to the Prince Street EB.

### 4.3.6. Scenario VI

Scenario VI also considers decentralized EBs with three available vans. Different from Scenario V, this scenario assumes that two vans are in Paramount Drive EB and one van is in Prince Street EB. Thus, the Prince Street EB only provides 12 full truckloads of RS and RCs, while Paramount Drive EB offer another 24 full truckloads of supplies. Similarly, a transportation problem is built to make a segment among all ECs. More details are provided in Chapter 5.

The second step is as the same as that described in Scenario V. Evacuation Centres are ranked according to Tables 4.10, 4.11, or 4.14. For Scenario VI, Strategy 1 and 2 depend on the ranking made in Table 4.10 and Table 4.14, while strategy 3 and 4 rely on the ranking list in Table 4.11. The four strategies also need to be applied twice: one for adding the 37th full truckload demand to Prince Street EB and the other for adding the final extra demand to Paramount Drive EB.

### 4.3.7. General Application of Phase 2

Subsections 4.3.1 to 4.3.6 represents the application of Phase 1, setting up ECs, in six different model scenarios. Phase 2 for evacuating Affected People (AP) is similar in all scenarios. It is because the parameters of Bus Centres (BCs), Affected Areas (AAs), and Evacuation Centres (ECs) do not change. This subsection describes the application of Phase 2 generally.

The capacity of each bus is 50 people, thus, the number of buses needed in each AA can be calculated according to the number of AP in the area, and the total demand is 45 buses. In the case of the three-meter maximum water level, the $BC_3$ in Table 4.3 is flooded. Therefore, only two BCs can send buses to pick up AP and the supply of buses is exactly equal to 45 buses. Since the affected population in each specific AA is not always a multiple of 50, some buses are not fully loaded. The total demand for buses, the number of fully loaded buses, and the remainders on partially full buses are shown in Table 4.15.

**Table 4.15**: Total demand of buses, number of full buses, and remainders on partially full buses

| AA | Total demand | #Full buses | #Remainders | AA | Total demand | #Full buses | #Remainders |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 30 | 11 | 2 | 1 | 46 |
| 2 | 2 | 1 | 23 | 12 | 2 | 1 | 29 |
| 3 | 1 | 0 | 40 | 13 | 2 | 1 | 11 |
| 4 | 2 | 1 | 48 | 14 | 4 | 3 | 49 |
| 5 | 2 | 1 | 15 | 15 | 1 | 0 | 47 |
| 6 | 9 | 8 | 46 | 16 | 2 | 1 | 39 |
| 7 | 1 | 0 | 22 | 17 | 2 | 1 | 19 |
| 8 | 2 | 1 | 5 | 18 | 2 | 1 | 31 |
| 9 | 3 | 2 | 28 | 19 | 2 | 1 | 30 |
| 10 | 2 | 1 | 3 | 20 | 1 | 0 | 31 |

In Phase 2, the first step is to formulate a transportation problem to deploy buses to the AAs. Distances between BCs and AAs are in Table 4.16 on the next page. Then, the second step is to use another transportation problem to deliver fully loaded buses in AAs to open ECs. Finally, people in partially loaded buses are sent to ECs that are not fully occupied by developing an assignment problem since there is at most one partially fully loaded bus in each AA. Specific results analysis is provided in Chapter 5.

The modeling scenarios and strategies are illustrated in this section. Subsections 4.3.1 to 4.3.6 discuss the modeling procedures in Phase 1 for different scenarios. A general Phase 2 modeling process is described in subsection 4.3.7. The next section 4.4 is a summary of the above model formulation.

**Table 4.16**: Distances between BCs and AAs

| Distance (km) | $BC_1$ | $BC_2$ | $BC_3$ | Distance (km) | $BC_1$ | $BC_2$ | $BC_3$ |
|---|---|---|---|---|---|---|---|
| $AA_1$ | 1.8 | 5.1 | 0.95 | $AA_{11}$ | 3.6 | 0.2 | 5.4 |
| $AA_2$ | 1.2 | 5.8 | 0.18 | $AA_{12}$ | 5 | 2.1 | 7.1 |
| $AA_3$ | 0.8 | 4.6 | 0.75 | $AA_{13}$ | 4.6 | 1.1 | 8.6 |
| $AA_4$ | 1.1 | 4.7 | 0.85 | $AA_{14}$ | 1.2 | 5.4 | 0.18 |
| $AA_5$ | 1.4 | 4.8 | 1.2 | $AA_{15}$ | 4.4 | 8.7 | 3.6 |
| $AA_6$ | 1.4 | 4.9 | 1.1 | $AA_{16}$ | 2.5 | 7.9 | 1.5 |
| $AA_7$ | 2 | 4.5 | 1.7 | $AA_{17}$ | 4.6 | 7.6 | 5.6 |
| $AA_8$ | 1.9 | 4.2 | 2.4 | $AA_{18}$ | 4.4 | 8.7 | 3.6 |
| $AA_9$ | 1.7 | 4 | 2.5 | $AA_{19}$ | 2.7 | 4.3 | 3.4 |
| $AA_{10}$ | 1.7 | 4 | 2.5 | $AA_{20}$ | 2.6 | 4.2 | 3.3 |

## 4.4. Model Formulation Summary

This chapter has represented the analysis applied to the case of coastal flooding from storm surge in Charlottetown, P.E.I. With the availability of the community data, six linear programming modeling scenarios are proposed, as described in Table 4.8. Consistent with Phase 1 and Phase 2 illustrated in Figure 2.2, the humanitarian aid and disaster relief operations in the city of Charlottetown include: (i) assign Relief Vehicle (RV) vans to deploy Relief Staff (RS) and Relief Commodities (RCs) from the Emergency Bases (EBs) to set up ten designated Evacuation Centres (ECs), as well as (ii) send RV buses to Affected Areas (AAs) to pick up Affected People (AP) and evacuated AP to operating ECs.

Four RS and RCs deployment strategies illustrated in Table 4.9 are applied to Phase 1 in the six scenarios separately. The goal in Phase 1 is to minimize the total deployment time of RV vans. An automated EXCEL spreadsheet algorithm is used to determine the successive RV van schedules (more details are in Appendix B). In order to seek for the optimal strategy in each scenario, the results of deployment time are compared among the four strategies within the same scenario. After identifying the optimal strategy, the next step is to analyze and find the scenario in which the optimal strategy operates best. At the end of Phase 1, ten designated ECs are open and evacuation starts.

The operation of Phase 1 varies from scenario to scenario. In contrast, Phase 2 is similar in the six scenarios. In Phase 2, a transportation table linear programming problem is developed to send RV buses from Bus Centres (BCs) to AAs, with the aim to minimize the total travel distance. AP can start getting on and then wait on the RV buses once the buses arrive at the AAs. These two steps can be executed concurrent with Phase 1. There is a possibility that the RV bus in the AA is not full because the number of AP varies. Another transportation problem is built to determine the evacuation schedule of the full RV buses, with the goal of minimizing the total travel distance. An assignment problem is constructed with the same objective, total travel distance minimization, to determine the evacuation plan of the remainders on the partially full RV buses. The actual time cost in Phase 2 depends on the longest route in these two concurrent evacuation schedules.

Finally, the total response time is the sum of the deployment time in Phase 1 and the evacuation time in Phase 2. Specific results analysis is illustrated in Chapter 5 and all the EXCEL spreadsheets are included in Appendix B “Automated EXCEL Spreadsheet Algorithm for Successive RV van Schedule in Phase 1” and Appendix C “General Phase 2 EXCEL Solver Results”.

# 5. Analysis and Results

In this Chapter 5, the final results of the application model of Chapter 4 are presented and analyzed. Microsoft EXCEL and EXCEL Solver are adopted to assist in the data process and results output. The two phases of the modelled humanitarian aid and disaster relief operations include:

- Phase 1) Delivery of Relief Staff (RS) and Relief Commodities (RCs) via Relief Vehicles (RVs) from Emergency Bases EB(s) to set up Evacuation Centres (ECs). Four strategies are applied to the six scenarios presented in Chapter 4. Strategies 1 to 4 are illustrated by Scenarios I to IV (sections 5.1 to 5.4) in sequence. Scenarios I to IV simulate the situation with one centralized EB, thus four strategies can be applied directly and 16 results arise. In contrast, Scenarios V and VI model the situation with two decentralized EBs. Therefore, four strategies need to be applied twice to each scenario according to two kinds of ECs' separation, as illustrated in sections 5.5 and 5.6.
- Phase 2) Deployment of buses from Bus Centres (BCs) to Affected Areas (AAs) and then transportation of Affected People (AP) to operational ECs. One general result is obtained for the six scenarios because the evacuation of AP is not influenced by the number and the location of EB(s). Details about Phase 2 are displayed in section 5.7.

In short, the results are presented and analyzed below by scenario and designated strategy for the two phases. Sections 5.1 through 5.6 present the Phase 1 results for the six different scenarios; and section 5.7 presents the same Phase 2 results for all scenarios. Finally, section 5.8 makes a comparison and summary of the results. The entire data process and results output are included in Appendix B "Automated EXCEL Spreadsheet Algorithm for Successive RV van Schedule in Phase 1" and Appendix C "General Phase 2 EXCEL Solver Results".

## 5.1. Scenario I

In the first scenario, there is one EB in Prince Street with two vans. Table 5.1 is the representation of the application of Strategy 1 – EC ranking based on distance from EB and vans "together" schedule. The first two columns list the rank of the ten operational ECs. EB in Scenario I is at Prince Street, thus the EC ranking list is determined from Table 4.10. "Capacity" is the maximum number of people that can be held in ECs. To facilitate the calculating process, the "Capacity" is converted to the equivalent number of vans – "Total demand (van)" – with the assumption that RS and RCs in each van can serve 50 AP. "No. Vans" is either the amount of available vans or the number of vans needed to set up the EC. With the constraint of the amount of vans, ECs cannot be set up at once. As a result, vans need to go back and forth to replenish supplies. The "No. Round trips" column is calculated by the "Total demand" in each EC and the "No. Vans". "Trip distance" is the one-way distance from EB to EC. "Total distance" is calculated through multiplying the "No. Round trips" by twice the one-way distance. However, the last trip is a one-way trip, because once all ECs are set up, Phase 2 can start without returning the van to the EB.

The goal of Phase 1 is to calculate the total EC setup time including three component parts: (i) loading time of the RV at the EB supply point; (ii) travel time from the EB to the designated EC; and (iii) unloading time of the RV supplies at the EC. The speed limit in Charlottetown is 60 kilometers per hour or 1 kilometer per minute. "Travel time" is calculated according to the "Total distance". Setup time (RV loading and unloading of supplies) per trip for Charlottetown is estimated as a function of van capacity at 30 minutes. This includes the total time for both loading and unloading. The "Total setup time" multiplies 30 by the "No. Round trips". Finally, "Total time" is the sum of "Travel time" and "Total setup time".

During the process, the time used by each van is displayed in the last four columns. Although the two vans in Prince Street EB are exactly the same, a number (e.g., 1, 2…)

is designated to help calculate the deployment time of each van. The total time for EC set up in Phase 1 is the maximum deployment time between the two vans, or 686.4 minutes as shown in Table 5.1.

**Table 5.1**: Strategy 1 in Scenario I

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC8 | 300 | 6 | 2 | 3 | 1.1 | 6.6 | 6.6 | 90 | 96.6 | 0 | 96.6 | 0 | 96.6 |
| 2 | EC7 | 300 | 6 | 2 | 3 | 1.8 | 10.8 | 10.8 | 90 | 100.8 | 96.6 | 197.4 | 96.6 | 197.4 |
| 3 | EC4 | 100 | 2 | 2 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 197.4 | 230.6 | 197.4 | 230.6 |
| 4 | EC9 | 300 | 6 | 2 | 3 | 2.4 | 14.4 | 14.4 | 90 | 104.4 | 230.6 | 335 | 230.6 | 335 |
| 5 | EC6 | 300 | 6 | 2 | 3 | 4.3 | 25.8 | 25.8 | 90 | 115.8 | 335 | 450.8 | 335 | 450.8 |
| 6 | ECQ | 300 | 6 | 2 | 3 | 5.1 | 30.6 | 30.6 | 90 | 120.6 | 450.8 | 571.4 | 450.8 | 571.4 |
| 7 | EC1 | 100 | 2 | 2 | 1 | 5.3 | 10.6 | 10.6 | 30 | 40.6 | 571.4 | 612 | 571.4 | 612 |
| 8 | EC5 | 50 | 1 | 1 | 1 | 3.9 | 7.8 | 7.8 | 30 | 37.8 | 612 | 649.8 | 612 | 612 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.8 | 9.6 | 9.6 | 30 | 39.6 | 649.8 | 649.8 | 612 | 651.6 |
| 10 | EC3 | 50 | 1 | 1 | 1 | 6.6 | 6.6 | 6.6 | 30 | 36.6 | 649.8 | 686.4 | 651.6 | 651.6 |

## 5.2. Scenario II

Similar to Scenario I, there is only one centralized EB in Scenario II with the two vans located at the Paramount Drive EB. This section illustrates the details of Strategy 2 – EC ranking based on distance from EB and van "unique" schedule. The only difference between Strategy 1 described in section 5.1 and Strategy 2 is the way of deployment. Table 5.2 shows the calculation of Strategy 2 in Scenario II.

**Table 5.2**: Strategy 2 in Scenario II

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ECQ | 300 | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 0 | 211.2 | 0 | 0 |
| 2 | EC6 | 300 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 211.2 | 211.2 | 0 | 226.8 |
| 3 | EC8 | 300 | 6 | 1 | 6 | 4.7 | 56.4 | 56.4 | 180 | 236.4 | 211.2 | 447.6 | 226.8 | 226.8 |
| 4 | EC1 | 100 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 447.6 | 447.6 | 226.8 | 300.4 |
| 5 | EC7 | 300 | 6 | 1 | 6 | 5.6 | 67.2 | 67.2 | 180 | 247.2 | 447.6 | 447.6 | 300.4 | 547.6 |
| 6 | EC9 | 300 | 6 | 1 | 6 | 6.2 | 74.4 | 74.4 | 180 | 254.4 | 447.6 | 702 | 547.6 | 547.6 |
| 7 | EC4 | 100 | 2 | 1 | 2 | 5.4 | 21.6 | 21.6 | 60 | 81.6 | 702 | 702 | 547.6 | 629.2 |
| 8 | EC5 | 50 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 702 | 702 | 629.2 | 665 |
| 9 | EC3 | 50 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 702 | 702 | 665 | 703.2 |
| 10 | EC2 | 50 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 702 | 736.2 | 703.2 | 703.2 |

The ranking list demonstrated in the first two columns is made depending on the distance between EB and EC. However, the location of EB becomes Paramount Drive rather than Prince Street. The following list comes from Table 4.14. Different from Table 5.1, there is always only one van in the fifth column because of the characteristic of the "unique" deployment strategy. Different vans are responsible for a different EC, and each van keeps delivering RS as well as RCs to one EC until that EC's demand is satisfied. On return to the EB, the van goes immediately to set up the next ranked EC. The total time for EC set up in Phase 1 is the maximum deployment time between the two vans, or 736.2 minutes as shown in Table 5.2.

## 5.3. Scenario III

The third new van is introduced for the remainder of the Scenarios III through VI. This section takes Scenario III as an example to explain how Strategy 3 – EC ranking based on shortest distance from AA to EC and vans "together" schedule – works. In Scenario III, there is still only one centralized EB at Prince Street with three vans available. Table 5.3 records the calculation results.

Different from Strategies 1 and 2, the ranking list is made by the shortest distance between EC and AA in Strategy 3. In consequence, the first two columns in Table 5.3 are from Table 4.11. Since both Strategy 3 and Strategy 1 use "together" deployment strategy, three vans go together to set up the same EC. There is an exception that three vans will go to different ECs when the demand of an EC is less than three van truckloads of RS and RCs. For example, only two vans ("No. Vans" column) deliver RS and RCs to $EC_1$ after setting up $EC_6$ since the demand of $EC_6$ can be met by one time delivery of two vans. Finally, the total set up time is also the longest deployment time used by Van 1, or 466.5 minutes in Table 5.3.

**Table 5.3**: Strategy 3 in Scenario III

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC6 | 300 | 6 | 3 | 2 | 4.3 | 17.2 | 17.2 | 60 | 77.2 | 0 | 77.2 | 0 | 77.2 | 0 | 77.2 |
| 2 | EC1 | 100 | 2 | 2 | 1 | 5.3 | 10.6 | 10.6 | 30 | 40.6 | 77.2 | 117.8 | 77.2 | 117.8 | 77.2 | 77.2 |
| 3 | EC8 | 300 | 6 | 3 | 2 | 1.1 | 4.4 | 4.4 | 60 | 64.4 | 117.8 | 182.2 | 117.8 | 182.2 | 77.2 | 141.6 |
| 4 | EC7 | 300 | 6 | 3 | 2 | 1.8 | 7.2 | 7.2 | 60 | 67.2 | 182.2 | 249.4 | 182.2 | 249.4 | 141.6 | 208.8 |
| 5 | EC4 | 100 | 2 | 2 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 249.4 | 282.6 | 249.4 | 249.4 | 208.8 | 242 |
| 6 | EC9 | 300 | 6 | 3 | 2 | 2.4 | 9.6 | 9.6 | 60 | 69.6 | 282.6 | 352.2 | 249.4 | 319 | 242 | 311.6 |
| 7 | ECQ | 300 | 6 | 3 | 2 | 5.1 | 20.4 | 20.4 | 60 | 80.4 | 352.2 | 432.6 | 319 | 399.4 | 311.6 | 392 |
| 8 | EC3 | 50 | 1 | 1 | 1 | 6.6 | 13.2 | 13.2 | 30 | 43.2 | 432.6 | 432.6 | 399.4 | 399.4 | 392 | 435.2 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.8 | 9.6 | 9.6 | 30 | 39.6 | 432.6 | 432.6 | 399.4 | 439 | 435.2 | 435.2 |
| 10 | EC5 | 50 | 1 | 1 | 1 | 3.9 | 3.9 | 3.9 | 30 | 33.9 | 432.6 | 466.5 | 439 | 439 | 435.2 | 435.2 |

## 5.4. Scenario IV

The last strategy (Strategy 4 – EC ranking based on shortest distance from AA to EC and vans "unique" schedule) is illustrated by the application in Scenario IV. Similar to Scenario III, three vans are available in a centralized EB. The difference is that the location of EB is at Paramount Drive instead of Prince Street. The EC ranking list is the same for both Strategy 3 and Strategy 4 because both of the two strategies use the same distance between AA and EC in the EC ranking score calculation. Thus, the first two columns in Table 5.4 are from Table 4.11 as well. In this strategy, initially, the three available vans are sent to different ECs; that is, the same "unique" deployment strategy as in Strategy 2. The van that returns earliest is sent to the next ranked EC. In Table 5.4, the maximum set up time is made by Van 1: 519.6 minutes.

Different from Tables 5.1 to 5.3, there is a big gap of time among the three vans in Table 5.4. Van 2 finishes at the earliest time point. It is not reasonable to make Van 2 idle. In the automated spreadsheet, Van 2 does not return to the EB after sending enough RS and RC to $EC_5$. Consequently, Van 2 needs to come back from $EC_5$ to the EB first, and then deploy one more truckload of RS and RCs to $EC_{10}$ so as to reduce the time used by Van 1.

The one-way distance between $EC_5$ and Paramount Drive EB is 2.9 km. In addition, the round-trip distance between Paramount Drive EB and $EC_{10}$ is 5.2 km and 30 minutes need to be used to load and unload all materials. As a result, one more deployment occupies 35.2 minutes. After applying this modification, Van 2 needs 430.3 + 2.9 + 35.2 = 468.4 minutes and Van 1 needs 519.6 – 35.2 = 484.6 minutes. Since Van 3 needs 490.8 minutes that is the longest time used among three vans, Van 3 delivers the last truckload of demand and does not need to go back to EB. Therefore, the time used by Van 3 is 490.8 – 6.2 = 484.6 minutes. In the end, the maximum deployment time becomes 484.6 minutes which is much better than 519.6 minutes for Strategy 4. The similar modification is applied in other scenarios (details are in Appendix B) if there is a big gap among the deployment time used by different vans.

**Table 5.4**: Strategy 4 in Scenario IV

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC6 | 300 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 0 | 226.8 | 0 | 0 | 0 | 0 |
| 2 | EC1 | 100 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 226.8 | 226.8 | 0 | 73.6 | 0 | 0 |
| 3 | EC8 | 300 | 6 | 1 | 6 | 4.7 | 56.4 | 56.4 | 180 | 236.4 | 226.8 | 226.8 | 73.6 | 73.6 | 0 | 236.4 |
| 4 | EC7 | 300 | 6 | 1 | 6 | 5.6 | 67.2 | 67.2 | 180 | 247.2 | 226.8 | 226.8 | 73.6 | 320.8 | 236.4 | 236.4 |
| 5 | EC4 | 100 | 2 | 1 | 2 | 5.4 | 21.6 | 21.6 | 60 | 81.6 | 226.8 | 308.4 | 320.8 | 320.8 | 236.4 | 236.4 |
| 6 | EC9 | 300 | 6 | 1 | 6 | 6.2 | 74.4 | 74.4 | 180 | 254.4 | 308.4 | 308.4 | 320.8 | 320.8 | 236.4 | 490.8 |
| 7 | ECQ | 300 | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 308.4 | 519.6 | 320.8 | 320.8 | 490.8 | 490.8 |
| 8 | EC3 | 50 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 519.6 | 519.6 | 320.8 | 359 | 490.8 | 490.8 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 519.6 | 519.6 | 359 | 397.4 | 490.8 | 490.8 |
| 10 | EC5 | 50 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 519.6 | 519.6 | 397.4 | 430.3 | 490.8 | 490.8 |

## 5.5. Scenario V

Four strategies can be applied to Scenarios I to IV directly. However, the situation becomes more complex in Scenarios V and VI. As the modeling process described in subsection 4.3.5, an EC separation decision needs to be made before applying the four strategies. This is a transportation problem with the purpose of minimizing the total travel distance. A dummy variable is introduced to determine where the 37$^{th}$ truckload of demand comes from and help make decisions. Table 5.5 is the representation of the transportation table linear programming problem. As the results shown in the changing cells, Prince Street EB (EB1) is responsible for $EC_4$, $EC_6$, $EC_7$, $EC_8$, and $EC_9$. Paramount Drive EB (EB2) is in charge with $EC_1$, $EC_2$, $EC_3$, $EC_5$, $EC_6$, and $EC_{10}$. The 37$^{th}$ truckload of demand is in $EC_2$. Different from Scenario I to IV, the four strategies need to be applied twice: one for adding the 37$^{th}$ full truckload demand in $EC_2$ to the Prince Street EB (Scenario Va) and the other for adding the final extra demand to the Paramount Drive EB (Scenario Vb).

**Table 5.5**: Transportation problem table for separation of ECs to EB in Scenario V

| # Supply | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from EB | | Supply in EB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 0 | 0 | 0 | 2 | 0 | 4 | 6 | 6 | 6 | 0 | 24 | = | 24 |
| EB2 | 2 | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 6 | 12 | = | 12 |
| EBD* | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| Total to EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| | = | = | = | = | = | = | = | = | = | = | | | |
| EC Demand | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| Total travel distance (km) | | | | | | | | | | | | = | 89.4 |

*EBD denotes Dummy Emergency Base

After making the separation, for EB1, the Evacuation Centres: $EC_4$, $EC_6$, $EC_7$, $EC_8$, and $EC_9$ are ranked according to Table 4.10 or Table 4.11. Similarly, for EB2: $EC_1$, $EC_2$, $EC_3$,

$EC_5$, $EC_6$, and $EC_{10}$ are ranked based on Table 4.14 or Table 4.11. Strategies 1 and 2 are based on the ranking made in Table 4.10 and Table 4.14, while Strategies 3 and 4 rely on the ranking in Table 4.11. The data processes of the four strategies are illustrated in Sections 5.1 to 5.4 by Scenarios I to IV. Thus, this section only takes the optimal strategy in Scenario V – Strategy 4 in Scenario Va (Table 5.6) – as an example to display the result analysis.

**Table 5.6**: Optimal van schedule in Scenario V

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC6 | 4 | 1 | 4 | 4.3 | 34.4 | 34.4 | 120 | 154.4 | 0 | 154.4 | 0 | 0 |
| | 2 | EC8 | 6 | 1 | 6 | 1.1 | 13.2 | 13.2 | 180 | 193.2 | 154.4 | 154.4 | 0 | 193.2 |
| | 3 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 154.4 | 356 | 193.2 | 193.2 |
| | 4 | EC4 | 2 | 1 | 2 | 1.6 | 6.4 | 6.4 | 60 | 66.4 | 356 | 356 | 193.2 | 259.6 |
| | 5 | EC9 | 6 | 1 | 6 | 2.4 | 28.8 | 28.8 | 180 | 208.8 | 356 | 356 | 259.6 | 468.4 |
| | 6 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 356 | 390.8 | 468.4 | 468.4 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 0 | 75.6 | | |
| | 2 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 75.6 | 149.2 | | |
| | 3 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 149.2 | 360.4 | | |
| | 4 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 360.4 | 398.6 | | |
| | 5 | EC5 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 398.6 | 431.5 | | |

The determination of van schedule in EB1 is by Strategy 4 – EC ranking based on shortest distance from AA and vans "unique" schedule. The values in "No. Vans" column are always "1" because two vans in EB1 need go to set up a different EC concurrently. There is only one van available in EB2. Thus, this van keeps delivering RS and RCs to set up all ECs in sequence. The total EC set up time is determined by the longest time used among the three vans, or 468.4 minutes used by Van 2 in Table 5.6

Similar to the exceptional circumstance illustrated in section 5.4, there is a big gap of time between the two vans in Prince Street EB (EB1). In the automated spreadsheet, Van 1 does not return to the EB1 after sending enough RS and RC to $EC_2$. Consequently, Van 1 needs to return from $EC_2$ to EB1 first, and then deploy one more truckload of RS and RCs to $EC_9$ so as to reduce the time used by Van 2. The one-way distance between $EC_2$ and EB1 is 4.8 km. In addition, the round-trip distance between EB1 and $EC_9$ is 4.8 km and 30 minutes need to be used to load and unload all materials. As a result, one more deployment occupies 34.8 minutes. After applying this modification, Van 1 needs 390.8 +

4.8 + 34.8 = 430.4 minutes and Van 2 needs 468.4 – 34.8 = 433.6 minutes. Since Van 2 still uses more time than Van 1, Van 2 delivers the last truckload of materials and does not need to go back to EB in the end. Therefore, the time used by Van 2 is 433.6 – 2.4 = 431.2 minutes. The maximum deployment time becomes 431.2 minutes.

## 5.6. Scenario VI

Similar to Scenario V, an EC separation decision is also made by a transportation linear programming problem for Scenario VI, as described in subsection 4.3.6. The results are shown in Table 5.7. According to the changing cells, Prince Street EB (EB1) is responsible for $EC_4$, $EC_7$, and $EC_9$. Paramount Drive EB (EB2) is in charge with $EC_1$, $EC_2$, $EC_3$, $EC_4$, $EC_5$, $EC_6$, $EC_8$ and $EC_{10}$. The final extra truckload of demand comes from $EC_9$. As well, the four strategies need to be applied twice: one for adding the 37$^{th}$ full truckload demand in $EC_9$ to Prince Street EB (Scenario VIa) and the other for adding the final extra demand to Paramount Drive EB (Scenario VIb).

**Table 5.7**: Transportation problem table for separation of ECs to EB in Scenario VI

| # Supply | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from EB | | Supply in EB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 0 | 0 | 0 | 1 | 0 | 0 | 6 | 0 | 5 | 0 | 12 | = | 12 |
| EB2 | 2 | 1 | 1 | 1 | 1 | 6 | 0 | 6 | 0 | 6 | 24 | = | 24 |
| EBD* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| Total to EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| | = | = | = | = | = | = | = | = | = | = | | | |
| EC Demand | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| Total travel distance (km) | | | | | | | | | | | | = | 115 |

*EBD denotes Dummy Emergency Base

The second step is as the same as that described in Scenario V (section 5.5). Evacuation Centres: $EC_4$, $EC_7$, and $EC_9$ are ranked according to Table 4.10 or Table 4.11; $EC_1$, $EC_2$,

$EC_3$, $EC_4$, $EC_5$, $EC_6$, $EC_8$, and $EC_{10}$ are ranked based on Table 4.14 or Table 4.11. Strategies 1 and 2 depend on the ranking made in Table 4.10 and Table 4.14, while Strategies 3 and 4 rely on the ranking list in Table 4.11. The optimal plan in this scenario is Strategy 1 in Scenario VIa, as illustrated in Table 5.8. The total EC set up time is the longest time used by Van 2, or 449 minutes in Table 5.8.

**Table 5.8**: Optimal van schedule in Scenario VI

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 0 | 201.6 | | |
| | 2 | EC4 | 1 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 201.6 | 234.8 | | |
| | 3 | EC9 | 6 | 1 | 6 | 2.4 | 26.4 | 26.4 | 180 | 206.4 | 234.8 | 441.2 | | |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
| | 1 | ECQ | 6 | 2 | 3 | 2.6 | 15.6 | 15.6 | 90 | 105.6 | 0 | 105.6 | 0 | 105.6 |
| | 2 | EC6 | 6 | 2 | 3 | 3.9 | 23.4 | 23.4 | 90 | 113.4 | 105.6 | 219 | 105.6 | 219 |
| | 3 | EC8 | 6 | 2 | 3 | 4.7 | 28.2 | 28.2 | 90 | 118.2 | 219 | 337.2 | 219 | 337.2 |
| | 4 | EC1 | 2 | 2 | 1 | 3.4 | 6.8 | 6.8 | 30 | 36.8 | 337.2 | 374 | 337.2 | 374 |
| | 5 | EC4 | 1 | 1 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 374 | 414.8 | 374 | 374 |
| | 6 | EC5 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 414.8 | 414.8 | 374 | 409.8 |
| | 7 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 414.8 | 414.8 | 409.8 | 448 |
| | 8 | EC2 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 414.8 | 449 | 448 | 448 |

Sections 5.1 to 5.6 illustrate the results of Phase 1 in the six scenarios separately. The next section 5.7 provides the general and the same Phase 2 results for all scenarios.

## 5.7. General Results of Phase 2

The previous six sections represent the results of the six Phase 1 scenarios and the four alternative strategies to set up the ECs. In this section, the focus is on Phase 2 – the evacuation of Affected People (AP) from the Affected Areas (AAs) to the operational ECs. Compared to Phase 1, this phase is similar to all scenarios and facilitated by the Solver add-in function in Microsoft EXCEL. Generally, two transportation problems and one assignment problem can cover the Phase 2 requirements.

The first step in Phase 2 is to deploy buses from the Bus Centres (BCs) to the 20 Affected Areas (AAs). Since the government bus garage is flooded in the three-meter maximum water level case, there are only two available BCs (Table 4.5). This step is a transportation problem aiming to minimize the total travel distance, as shown in Table 5.9. The demand of buses in each AA is in Table 4.15 and the supply of buses by each BC is from Table 4.5. The results in Table 5.9 determine the bus schedule. The bus deployment time is determined by the longest routes in Table 5.9. The distance (in km) between AA and BC is in Table 4.16. Combining the parameters in Table 4.16 with the results in Table 5.9, the longest route is from $BC_2$ to $AA_{17}$, or 7.6 km. Thus, the time of sending buses to AAs is 7.6 minutes with the Charlottetown speed limit 60 km/h.

**Table 5.9**: Deployment of buses to AAs

| Number of buses | $BC_1$ | $BC_2$ | Total to AA | | Demand in AA |
|---|---|---|---|---|---|
| $AA_1$ | 0 | 1 | 1 | = | 1 |
| $AA_2$ | 2 | 0 | 2 | = | 2 |
| $AA_3$ | 1 | 0 | 1 | = | 1 |
| $AA_4$ | 2 | 0 | 2 | = | 2 |
| $AA_5$ | 0 | 2 | 2 | = | 2 |
| $AA_6$ | 1 | 8 | 9 | = | 9 |
| $AA_7$ | 0 | 1 | 1 | = | 1 |
| $AA_8$ | 0 | 2 | 2 | = | 2 |
| $AA_9$ | 0 | 3 | 3 | = | 3 |
| $AA_{10}$ | 0 | 2 | 2 | = | 2 |
| $AA_{11}$ | 0 | 2 | 2 | = | 2 |
| $AA_{12}$ | 0 | 2 | 2 | = | 2 |
| $AA_{13}$ | 0 | 2 | 2 | = | 2 |
| $AA_{14}$ | 4 | 0 | 4 | = | 4 |
| $AA_{15}$ | 1 | 0 | 1 | = | 1 |
| $AA_{16}$ | 2 | 0 | 2 | = | 2 |
| $AA_{17}$ | 0 | 2 | 2 | = | 2 |
| $AA_{18}$ | 2 | 0 | 2 | = | 2 |
| $AA_{19}$ | 0 | 2 | 2 | = | 2 |
| $AA_{20}$ | 0 | 1 | 1 | = | 1 |
| Total from BC | 15 | 30 | | | |
| | = | = | | | |
| Supply in BC | 15 | 30 | | | |
| | | | Total travel distance (km) | = | 151.4 |

Once buses arrive at the AAs, the AP start getting on the buses. Adding the get-on time of people, which is assumed to be 20 minutes per bus, can get the AP pick up time, 7.6 + 20 = 27.6 minutes. Since 27.6 minutes is much less than the set up time in any strategy in

Phase 1 (over hundreds minutes), AP can get on and wait on the buses during the operation of Phase 1.

**Table 5.10**: Transport fully loaded buses to ECs

| # Full buses | $EC_1$ | $EC_2$ | $EC_3$ | $EC_4$ | $EC_5$ | $EC_6$ | $EC_7$ | $EC_8$ | $EC_9$ | $EC_{10}$ | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $AA_1$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| $AA_2$ | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| $AA_4$ | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_5$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| $AA_6$ | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 6 | 0 | 0 | 8 | = | 8 |
| $AA_7$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| $AA_8$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| $AA_9$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | = | 2 |
| $AA_{10}$ | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_{11}$ | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_{12}$ | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_{13}$ | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_{14}$ | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 0 | 0 | 0 | 3 | = | 3 |
| $AA_{15}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| $AA_{16}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| $AA_{17}$ | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_{18}$ | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_{19}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| $AA_{20}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| Total to EC | 1 | 1 | 1 | 2 | 0 | 2 | 6 | 6 | 5 | 1 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | | |
| Supply in EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| Total travel distance (km) | | | | | | | | | | | | = | 37.27 |

After completing Phase 1, the second step in Phase 2 is to determine the number of buses that need to be sent to each EC. As described in subsection 4.3.7, it is necessary to break down the second step into two problems: a transportation problem and an assignment problem. The transportation problem formulation is defined within Table 5.10 above to send fully loaded buses to open ECs. The demand in AA is from Table 4.15 and the supply in EC is from Table 4.1. The constraint in the bottom of the table is that the number of buses is no more than the capacity of ECs, since all ECs cannot be totally occupied at this time.

**Table 5.11**: Assignment problem formulation and solution matrix

| Partially full buses | $EC_1$ | $EC_2$ | $EC_3$ | $EC_4$ | $EC_5$ | $EC_6$ | $EC_7$ | $EC_8$ | $EC_9$ | $EC_{10}$ | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $AA_1$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| $AA_2$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| $AA_3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| $AA_4$ | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_5$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| $AA_6$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| $AA_7$ | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_8$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| $AA_9$ | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_{10}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| $AA_{11}$ | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_{12}$ | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_{13}$ | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_{14}$ | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_{15}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| $AA_{16}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| $AA_{17}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| $AA_{18}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| $AA_{19}$ | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| $AA_{20}$ | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| Total to EC | 50 | 0 | 0 | 0 | 49 | 195 | 0 | 0 | 48 | 250 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | |
| Supply in EC | 50 | 0 | 0 | 0 | 50 | 200 | 0 | 0 | 50 | 250 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 64.52 |

According to the results in Table 5.10, the remaining capacity of each EC can be calculated. For example, only one fully loaded bus is sent to $EC_1$ but $EC_1$ can accept two full buses (100 AP); thus, $EC_1$ can still accept 50 remainders on the partially fully loaded buses. An assignment problem is developed to determine the evacuation of the remainders on the partially fully loaded buses, as displayed in Table 5.11 above. The demand in AA is from Table 4.15 and the remaining supply in EC is calculated by the results in Table 5.10. Similarly, the objective of this assignment problem is to minimize the total travel distance.

Although the evacuation of AP from AAs to ECs is separated into two problems, these two problems happen concurrently according to the results shown in Tables 5.10 and 5.11. The time cost in Phase 2 depends on the longest evacuation route. Considering the parameters in Table 4.7 (distance between AA and EC) as well as the results in Tables 5.10 and 5.11 together, the longest route is from $AA_1$ to $EC_7$ (5.5 km). In other words, the actual evacuation time used in Phase 2 is 5.5 minutes with the speed limitation 60km/h.

Among the six scenarios proposed in Chapter 4, the evacuation time is constant. Thus, the time to set up all ECs is the determinant of the total response time. Choosing the shortest setup strategy for Phase 1 can help reduce the total response time and then save more people. The evaluation of different strategies in the six scenarios is summarized in the following section 5.8.

## 5.8. Model Results Summary

The results of the analyses provided above are on policy advice for coastal communities' facility location strategies for inventory and transportation resources, characterize effective operational strategies for dealing with the expected impacts of disaster relief and humanitarian aid for coastal communities. Table 5.12 is a summary table for all the results in Phase 1 because the time in Phase 2 is always 5.5 minutes that does not influence the evaluation process.

**Table 5.12**: Total Phase 1 time to set up all ECs

| *Total time cost in phase one (min)* | **Strategy 1** | **Strategy 2** | **Strategy 3** | **Strategy 4** |
|---|---|---|---|---|
| **Scenario I** | 686.4 | 686.4 | 685.5 | ***674.4*** |
| **Scenario II** | 735.6 | 736.2 | 736.7 | ***722.6*** |
| **Scenario III** | 466.4 | 461.4 | 466.5 | ***455.5*** |
| **Scenario IV** | 498.8 | 490.8 | 499.9 | ***484.6*** |
| **Scenario V a** | 447 | 445.2 | 447 | ***431.2*** |
| **Scenario V b** | 468.6 | 468.6 | 469.9 | 469.9 |
| **Scenario VI a** | ***449*** | 449.4 | 450.6 | 455 |
| **Scenario VI b** | 484.8 | 481.8 | 485.9 | 483.4 |

Character "a" means the final extra demand is supplied by Prince Street EB, and "b" entails Paramount Drive EB.

First of all, the shortest setup time along each row is the best option for each scenario. The setup time is more than 650 minutes in the first two scenarios, while less than 500 minutes in the other four scenarios. It is because only two vans are available in Scenarios I and II, but a third van is added to the other scenarios. The more vans are available, the shorter the setup time will be.

Within the first four scenarios, EB is at Prince Street in Scenario I and III, while at Paramount Drive in Scenario II and IV. In addition, the number of available vans is the same in Scenarios I and II, Scenarios III and IV. With the constant amount of vans, comparing Scenario I and II can find that the setup time is 48.2-minute shorter in Scenario I. Similarly, the setup time in Scenario III is 29.1-minute shorter than that in Scenario IV. In consequence, Prince Street is a better location for the centralized EB.

In the last two Scenarios V and VI, the results in Scenario Va are better than those in Scenario Vb. The same phenomenon occurs between Scenario VIa and Scenario VIb. The standard used to separate each scenario into two situations is the supply of the last extra demand. Situation a is always better than b because the extra demand is from Prince Street EB and the overall distances are shorter between Prince Street EB and ECs. Consequently, the extra demand should be assigned to the EB which is closer to all ECs.

Among all the scenarios, Strategy 4 is the best solution except for Scenario VI. Although Strategy 1 is the best for Scenario VI, there is only a slight difference between Strategy 1 and Strategy 4: Strategy 4 needs 6 more minutes. It is because all potential ECs are designated to two EBs in this scenario and the condition is that each EB is responsible for the ECs that are closer to it. Moreover, Strategy 1 uses the distance between EB and EC to rank all ECs. Thus, the results give preference to the first strategy. As a result, this thesis makes a conclusion that Strategy 4 is the most preferable solution; that is, decision makers are supposed to use the shortest distance between EC and AA to rank all potential ECs, as well as to adopt "unique" deployment strategy. It makes sense that opening ECs closer to AAs earlier can help evacuate AP faster.

**Table 5.13**: Start time, duration, end time, and source of setting up ECs (EB1 is in Prince Street and EB2 is in Paramount Drive)

| *EC* | *Start time (min)* | *Duration (min)* | *End time (min)* | *Source of RS and RCs* |
|---|---|---|---|---|
| $EC_6$ | 0 | 154.4 | 154.4 | $EB_1$ and $EB_2$ |
| $EC_8$ | 0 | 193.2 | 193.2 | $EB_1$ |
| $EC_1$ | 75.6 | 73.6 | 149.2 | $EB_2$ |
| $EC_{10}$ | 149.2 | 211.2 | 360.4 | $EB_2$ |
| $EC_7$ | 154.2 | 201.6 | 356 | $EB_1$ |
| $EC_4$ | 193.2 | 66.4 | 259.6 | $EB_1$ |
| $EC_9$ | 259.6 | 174 | ***431.2*** | $EB_1$ |
| $EC_2$ | 356 | 34.8 | 390.8 | $EB_1$ |
| $EC_3$ | 360.4 | 38.2 | 398.6 | $EB_2$ |
| $EC_5$ | 398.6 | 32.9 | 431.5 | $EB_2$ |

To the end, among all of those results, the best one is 431.2 minutes which is Strategy 4 applied to Scenario Va. Details about the best solution are summarized below. In Phase 1, RS and RCs have to be delivered to ten ECs as soon as possible. According to the EXCEL spreadsheet of Strategy 4 in Scenario Va, the duration of setting up each EC can be calculated. Table 5.13 above displays the specific start time, duration, and end time. Furthermore, two EBs provide the RS and RCs. The source of RS and RCs is pointed out in the table. $EC_1$ indicates Prince Street EB and $EC_2$ represents Paramount Drive EB. Based on the end time in the Table 5.13, the opening order of ten ECs is: $EC_1$, $EC_6$, $EC_8$, $EC_4$, $EC_7$, $EC_{10}$, $EC_2$, $EC_3$, $EC_5$, and $EC_9$.

In Phase 2 of Scenario Va, the buses are sent to 20 AAs in the beginning. As shown in Table 5.9, the origin and amount of buses sent to each AA are solved by a transportation problem. Buses in $BC_1$ are sent to eight AAs: $AA_2$, $AA_3$, $AA_4$, $AA_6$, $AA_{14}$, $AA_{15}$, $AA_{16}$, and $AA_{18}$. Meanwhile, $BC_2$ deploys buses to thirteen AAs: $AA_1$, $AA_5$, $AA_6$, $AA_7$, $AA_8$, $AA_9$, $AA_{10}$, $AA_{11}$, $AA_{12}$, $AA_{13}$, $AA_{17}$, $AA_{19}$, and $AA_{20}$. Since all buses leave for AAs at the same time, the longest distance among the above routes determines the total travel time of bus deployment. According to Table 4.16, the longest distance is from $BC_2$ to $AA_{17}$ which is 7.6 km; therefore, the duration is 7.6 minutes with the speed of 60km/h. In addition, 20 more minutes are needed for AP to get on the buses. Thus, 27.6 minutes are cost. To save time, the AP pick-up process and the EC set-up process can happen simultaneously. Obviously, 27.6 minutes are far more less than 431.2 minutes. As a result, all AP can get on buses before ECs open.

**Table 5.14**: Amount of buses sent from AAs to ECs

| Number of buses | $EC_1$ | $EC_2$ | $EC_3$ | $EC_4$ | $EC_5$ | $EC_6$ | $EC_7$ | $EC_8$ | $EC_9$ | $EC_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $AA_1$ | | | | | | | | | | 1 |
| $AA_2$ | | | | 1 | | | | | | 1 |
| $AA_3$ | | | | | | | | | 1 | |
| $AA_4$ | | | | | | 1 | 1 | | | |
| $AA_5$ | | | | | | | | | 1 | 1 |
| $AA_6$ | | | | | | | 2 | 6 | | 1 |
| $AA_7$ | 1 | | | | | | | | | |
| $AA_8$ | | | | | | | | | 2 | |
| $AA_9$ | 1 | | | | | | | | 2 | |
| $AA_{10}$ | | | | | | | 1 | | 1 | |
| $AA_{11}$ | | | | | | 2 | | | | |
| $AA_{12}$ | | | | | | 2 | | | | |
| $AA_{13}$ | 1 | | | | | 1 | | | | |
| $AA_{14}$ | | | | 1 | 1 | | | | | |
| $AA_{15}$ | | | | | | | | | | 1 |
| $AA_{16}$ | | | | | | | | | | 2 |
| $AA_{17}$ | | | 1 | | | | | | | 1 |
| $AA_{18}$ | | 1 | | | | | | | | 1 |
| $AA_{19}$ | | | | | | 1 | | | 1 | |
| $AA_{20}$ | | | | | | 1 | | | | |

The last step is to send AP to open ECs. Combining the decision making processes in Table 5.10 and Table 5.11, the number of buses sent to each EC is summarized in Table 5.14 above. Similarly, the total transportation time depends on the longest distance between AAs and ECs. According to the distance data in Table 4.7, the longest route is between $AA_7$ and $EC_1$, 5.5 kilometers. With the 60km/h speed limit, the total evacuation time is 5.5 minutes. Adding to the setting up time in Phase 1, the total response time in the best scenario (Scenario Va) is 431.2 + 5.5 = 436.7 minutes.

Taking the above into consideration, five reasons can explain why the strategy described in detail is the most preferable.

1. Scenario V represents the situation of decentralized EBs with two vans at Prince Street and one van at Paramount Drive. Decentralized EBs is better than centralized EB because there is always a backup source of supplies during a disaster. Comparing the result in Scenario III which indicates the situation of three vans all at Prince Street EB, Scenario Va can save 455.5 – 431.2 = 24.3 minutes.
2. In practice, RS and RCs should be stored in the EB nearer to the ECs. Scenario VIa has all the same conditions as Scenario Va except that two vans are stored in Paramount Drive EB. However, Scenario VIa costs 449 – 431.2 = 17.8 more minutes. Scenario Va is better because Prince Street EB is closer to ECs and has two vans to deliver more relief materials.
3. Va means the extra demand comes from Prince Street EB because the extra demand needs to be stored in the EB closer to all ECs to save time. Once the extra demand is from Paramount Drive EB, the period takes 468.6 – 431.2 = 37.4 more minutes which is Strategies 1 and 2 in Scenario Vb.
4. Strategy 4 uses the shortest distance between ECs and AAs to rank ECs and then adopts the “unique” deployment strategy. Ranking ECs according to the distance between ECs and AAs is better since open ECs closer to AAs earlier can help start evacuation earlier.
5. “Unique” indicates different vans need to deploy RS and RCs to different ECs. It is better to open different ECs at the same time because AAs are dispersed.

In consequence, Scenario Va is the optimal plan which means the Red Cross headquarters should continue being moved to Paramount Drive and maintain the current EB at Prince Street. For this best scenario, a what-is analysis is conducted and the details are in the section below (section 5.9).

## 5.9. What-if Analysis

With the ability to offer insights into the likely results of pursuing different managerial options under various assumptions on future conditions, linear programming research can be used to assist in guiding management's final decisions. In addition, most critical insights are gained by making analysis after finding an optimal solution for the original model. This kind of analysis is called the what-if analysis aiming to deal with questions on what would happen to the optimal solution if different assumptions were made (Hiller and Hiller, 2008).

As noted by Hiller and Hiller (2008), there are three benefits of what-if analysis:

1. Since many parameters of a linear programming model are only estimates of quantities, what-if analysis can reveal how close each estimate needs to be to avoid getting an incorrect optimal solution and then identify the sensitive parameters.
2. There is a possibility that conditions change after the research has been finished, therefore what-if analysis can be used to indicate whether the optimal solution will be different when a parameter of the model changes.
3. If some parameters of the model signify managerial policy decisions, what-if analysis can give guidance to management about the impact of changing these policy decisions.

According to the results of the original model, the optimal solution occurs in Scenario Va with two vans at Prince Street EB and one van at Paramount Drive EB. The supply of each EB is proportional to the number of available vans stored. In addition, the extra demand of relief resources is always supplied by the Prince Street EB when the total demand is not the multiple of three. Thus, this section makes a what-if analysis for Scenario Va with the following four different assumptions:

1. What if the flood prevents certain routes to be used?
2. What if van1 in Prince Street EB is out of use?
3. What if three ECs are flooded and unavailable?
4. What if the number of Affected People decreases or increases?

Specific analyses are illustrated from subsections 5.9.1 to 5.9.4.

### 5.9.1. Assumption I

In the original model, the distances from Emergency Bases (EBs) to Evacuation Centres (ECs), from Bus Centres (BCs) to Affected Areas (AAs), and from AAs to ECs are the shortest routes identified by Google Earth. However, in reality, certain routes may be flooded and cannot be used any more. For example, it is probable that the area around Grafton Street will be flooded since this area is near the waterfront. Thus, other longer routes need to be chosen to replace the original ones.

Based on the map of Charlottetown, the original routes from Prince Street EB ($EB_1$) to $EC_4$ and $EC_8$, from $AA_4$ and $AA_5$ to $EC_4$, from $AA_3$ and $AA_4$ to $EC_8$ need to be changed. Table 5.15 displays the original and new distances ("—" means the original routes is still available). The ranking list of ECs in Strategies 1 and 2 are calculated by the distances from EBs to ECs and the ranking list of ECs in Strategies 3 and 4 are calculated by the distances from AAs to ECs. Once the distances change, the ranking list may change. Calculating the satisfaction score by equation (4.2) in section 4.3, the original and new ranking lists of ECs are shown in Table 5.16.

**Table 5.15**: Original and new parameters of distances

| Km | $EB_1$ | $AA_3$ | $AA_4$ | $AA_5$ |
|---|---|---|---|---|
| $EC_4$ (Original) | 1.6 | — | 0.85 | 1.6 |
| $EC_4$ (New) | 2.4 | — | 2.7 | 3.0 |
| $EC_8$ (Original) | 1.1 | 0.65 | 0.8 | — |
| $EC_8$ (New) | 1.4 | 1.5 | 1.7 | — |

**Table 5.16**: Original and new ranking lists of ECs for what-if analysis assumption I

| *Distance used in satisfaction score equation* | *Ranking list of ECs* |
|---|---|
| Distance from $EB_1$ to EC (Original) | $EC_8$, $EC_7$, $EC_4$, $EC_9$, $EC_6$, $EC_{10}$, $EC_1$, $EC_5$, $EC_2$, $EC_3$ |
| Distance from $EB_1$ to EC (New) | $EC_8$, $EC_7$, $EC_9$, $EC_4$, $EC_6$, $EC_{10}$, $EC_1$, $EC_5$, $EC_2$, $EC_3$ |
| Shortest distance from AA to EC (Original) | $EC_6$, $EC_1$, $EC_8$, $EC_7$, $EC_4$, $EC_9$, $EC_{10}$, $EC_3$, $EC_2$, $EC_5$ |
| Shortest distance from AA to EC (New) | $EC_6$, $EC_1$, $EC_7$, $EC_4$, $EC_8$, $EC_9$, $EC_{10}$, $EC_3$, $EC_2$, $EC_5$ |

Running the model with the above altered parameters, the new results are shown in Table 5.17 that are compared with the original results. In Phase 1, the best plan for Scenario Va with Assumption I is still Strategy 4 (433.2 min). However, the time of setting up all ECs in Phase 1 becomes longer overall. It is because the vans have to deliver RS and RCs via longer routes. However, the decisions made in Phase 2 (5.5 min) are still the same since the routes replaced are not used in the original model. In consequence, the total response time is 2-minute longer (caused by Phase 1) than the original decision. Details of EXCEL spreadsheet results of both Phase 1 and Phase 2 are included in Appendix D1 "Results of Assumption I –What if the flood prevents certain routes to be used".

**Table 5.17**: Comparable results between original case and Assumption I case for Scenario Va

| Minutes | **Phase 1** | | | | **Phase 2** |
|---|---|---|---|---|---|
| | *Strategy 1* | *Strategy 2* | *Strategy 3* | *Strategy 4* | |
| **Scenario Va (Original)** | 447 | 445.2 | 447 | ***431.2*** | 5.5 |
| **Scenario Va (Assumption I)** | 450.4 | 440.4 | 450.4 | ***433.2*** | 5.5 |

### 5.9.2. Assumption II

The vans stocked in the Red Cross of Charlottetown are specifically for emergencies. The emergencies happen irregularly and the vans do not need to be used constantly, thus some vans may be just out of use when a natural disaster occurs suddenly. In the original Scenario Va, there are two vans in Prince Street EB ($EB_1$) and one van in Paramount Drive EB ($EB_2$). This section considers the situation that one van in $EB_1$ is broken and then the new Scenario Va has two separate EBs with only one available van in each EB.

Due to the change of the number of vans, the demand among ten ECs needs to be reassigned between two EBs. Originally, the demand in ECs provided by $EB_1$ is twice as those supplied by $EB_2$ since the number of vans in $EB_1$ is twice as that in $EB_2$. Now, either EB only has one van. The demand needs to be separated evenly between the two EBs. A dummy EB is introduced to decide where the $37^{th}$ demand comes from. As the results conclusions in section 5.8, the extra demand always comes from the Prince Street EB ($EB_1$) that is nearer to the demand. In this case, the last demand is in $EC_9$. Thus, $EB_1$ supplies 19 van truckloads of RS and RCs while $EB_2$ provides the other 18 van thuckloads of RS and RCs. However, the delivery routes are the same; thus, the ranking lists of ECs do not change. This case is a simplified version because there is no difference between “together” or “unique” deployment strategies. The only van in each EB keeps setting up ECs until the total demand is met. As a result, Strategies 1 and 2 can be combined, so do Strategies 3 and 4.

After making the above changes of parameters, the results in Phase 1 change as well. However, the evacuation time in Phase 2 is still the same since there is no change of parameters for Phase 2. The new results are shown in Table 5.18 that are compared with the original results. In Phase 1, the shortest total EC setup time becomes 659.2 minutes (Strategies 1 and 2) which is much longer than the original 431.5 minutes. Since only one van is available in each EB, there is no difference between “together” and “unique” deployment strategy. In the new case with Assumption II, Strategy 4 is not preferred because Strategies 1 and 2 use the distance between EB and EC to rank ECs. The shorter the distance, the less the EC set up time. There is no change in Phase 2. In consequence, there is a fact that the cost of total response time is caused by Phase 1, 227.2 minutes, once one van is out of use.

**Table 5.18**: Comparable results between original case and Assumption II case for Scenario Va

| Minutes | **Phase 1** | | | | **Phase 2** |
|---|---|---|---|---|---|
| | *Strategy 1* | *Strategy 2* | *Strategy 3* | *Strategy 4* | |
| **Scenario Va (Original)** | 447 | 445.2 | 447 | ***431.2*** | 5.5 |
| **Scenario Va (Assumption II)** | ***659.2*** | ***659.2*** | 660.5 | 660.5 | 5.5 |

Moreover, it is meaningful to compare this case with Scenario I and II since those two scenarios also only two available vans. Scenario I represents that two vans are in Prince Street EB and Scenario II assumes two vans are in Paramount Drive EB. The time used to set up all ECs is 674.4 minutes and 722.6 minutes, separately. As a result, decentralized EB is more efficient than centralized one. Details of EXCEL spreadsheet results are included in Appendix D2 “Results of Assumption II –What if van1 in Prince Street EB is out of use”.

## 5.9.3. Assumption III

In the case of three-meter maximum water level, $EC_{11}$ is flooded. The total full capacity of the other ten ECs is nearly the same of the total number of Affected People (AP). Looking at the map of Charlottetown, $EC_1$ and $EC_6$ are probably to be flooded since these two ECs are along the bay. Once these two ECs are also unavailable, the full capacity of $EC_1$ and $EC_6$ needs to be dispersed to the other eight remaining ECs. Originally, $EC_1$ can hold 100 people and $EC_6$ can hold 300 people. Now, each of the other eight ECs should accept 50 more people. The new full capacity and demand in each EC are displayed in Table 5.19. Since the full capacity of all available ECs changes, the ranking lists of ECs change correspondingly. Table 5.20 represents the new ranking lists of ECs.

**Table 5.19**: New capacity and demand in available ECs

| | $EC_2$ | $EC_3$ | $EC_4$ | $EC_5$ | $EC_7$ | $EC_8$ | $EC_9$ | $EC_{10}$ |
|---|---|---|---|---|---|---|---|---|
| Capacity (#people) | 100 | 100 | 150 | 100 | 350 | 350 | 350 | 350 |
| Demand (#van) | 2 | 2 | 3 | 2 | 7 | 7 | 7 | 7 |

**Table 5.20**: New ranking lists of eight available ECs

| *Distance used in satisfaction score equation* | *Ranking list of ECs* |
|---|---|
| Distance from $EB_1$ to EC (New) | $EC_8$, $EC_7$, $EC_4$, $EC_9$, $EC_{10}$, $EC_5$, $EC_2$, $EC_3$ |
| Distance from $EB_2$ to EC (New) | $EC_{10}$, $EC_8$, $EC_5$,$EC_7$, $EC_9$, $EC_4$, $EC_3$, $EC_2$ |
| Shortest distance from AA to EC (New) | $EC_4$, $EC_8$, $EC_7$, $EC_9$, $EC_{10}$, $EC_3$, $EC_2$, $EC_5$ |

Adapting the above changes to the original model, the new results are shown in Table 5.21 that are compared with the original results. In Phase 1, the best the plan for Scenario Va with Assumption III is still Strategy 4 (431.8 min). The time of setting up all ECs in Phase 1 becomes 431.8 minutes instead of 431.5 minutes. The time is longer since two more ECs ($EC_1$ and $EC_6$) are flooded in the new situation.

**Table 5.21**: Comparable results between original case and Assumption III case for Scenario Va

| Minutes | **Phase 1** | | | | **Phase 2** |
|---|---|---|---|---|---|
| | *Strategy 1* | *Strategy 2* | *Strategy 3* | *Strategy 4* | |
| **Scenario Va (Original)** | 447 | 445.2 | 447 | ***431.2*** | 5.5 |
| **Scenario Va (Assumption III)** | 435.2 | 431.8 | 435.6 | ***431.8*** | 5.2 |

In this situation, the results of Phase 2 change too. Since people in those Affected Areas (AAs) that are close to $EC_1$ and $EC_6$ have to be transported to further available ECs, the evacuation time should become longer. However, following the same steps in section 5.7, the longest transportation distance is from $AA_{12}$ to $EC_5$; that is 5.2 kilometers. Thus, the evacuation time is 5.2 minutes rather than the original 5.5 minutes. It is because the original longest distance is from $AA_7$ to $EC_1$ and this longest distance is avoided when the full capacity of other ECs is increased. Details of EXCEL spreadsheet results are included in Appendix D3 "Results of Assumption III –What if three ECs ($EC_1$, $EC_6$, $EC_{11}$) are flooded and unavailable".

### 5.9.4. Assumption IV

The original natural disaster considered in this thesis is the three-meter maximum observed water level with 1842 people affected. However, the severity of natural disaster varies irregularly. This section makes a what-if analysis on the fluctuation of the affected population: increase or decrease. According to the results summarized in section 5.8, Strategy 4 is the most preferred solution in Phase 1. Thus, this section only focuses on Strategy 4 for Phase 1.

One possibility is what if the number of Affected People (AP) increases. Originally, the population of AP is 1842. Once this number is increased by 500, the total number of AP will be 2342 and the full capacity of each EC will increase by 50 people (one more van of RS and RCs is needed in each EC). If this number is increased by 1000, the total number of AP will be 2842 and the full capacity of each EC will increase by 100 people (two more van of RS and RCs is needed in each EC). Since the full capacity of ECs is changed, the ranking list of ECs will change too. Table 5.22 compares the original and new ranking lists.

**Table 5.22**: Comparison of original and new ranking of ECs

| *Distance used in satisfaction score equation* | *Ranking list of ECs* |
|---|---|
| Shortest distance from AA to EC (1842 AP) | $EC_6$, $EC_1$, $EC_8$, $EC_7$, $EC_4$, $EC_9$, $EC_{10}$, $EC_3$, $EC_2$, $EC_5$ |
| Shortest distance from AA to EC (2342 AP) | $EC_6$, $EC_1$, $EC_4$, $EC_8$, $EC_7$, $EC_9$, $EC_{10}$, $EC_3$, $EC_2$, $EC_5$ |
| Shortest distance from AA to EC (2842 AP) | $EC_6$, $EC_1$, $EC_4$, $EC_8$, $EC_7$, $EC_9$, $EC_{10}$, $EC_3$, $EC_2$, $EC_5$ |

The other possibility is what if the number of AP decreases. Once the original AP population is decreased by over 500, it is impossible to decrease the full capacity evenly among ten ECs since the smallest capacity of EC is 50 people. The alternative strategy is open the ECs in the ranking list one by one until the total capacity is no less than the total AP. According to the original ranking list, six ECs are needed to be opened once the total number of AP is decreased by 500 and four ECs are needed if the number is decreased by 1000. Table 5.23 displays the extent to which EC needs to be opened.

**Table 5.23**: The number and the extent to which EC needed to be opened

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1342 AP | ECs needed to be opened | $EC_6$ | $EC_1$ | $EC_8$ | $EC_7$ | $EC_4$ | $EC_9$ |
| | Open extent (# people) | 300 | 100 | 300 | 300 | 100 | 250 |
| 842 AP | ECs needed to be opened | $EC_6$ | $EC_1$ | $EC_8$ | $EC_7$ | — | — |
| | Open extent (# people) | 300 | 100 | 300 | 150 | — | — |

Given that the total affected population is changed, the number of AP in each AA should be changed. The varied number of AP is dispersed among the 20 AAs evenly. For example, there will be 25 more people affected in each AA when the total affected population is increased by 500. Subsequently, the number of full buses in each AA and the number of remainders on partially full buses change too. Specific parameters in Phase 2 are illustrated from Table 5.24 to Table 5.27. The results are displayed in Table 5.28. Details of EXCEL spreadsheet results are included in Appendix D4 "Results of Assumption IV –What if the number of Affected People decreases or increases".

**Table 5.24**: Parameters in Phase 2 when the number of AP is increased to 2342

| AA | Total demand | #Full buses | #Remainders | AA | Total demand | #Full buses | #Remainders |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 1 | 5 | 11 | 3 | 2 | 21 |
| 2 | 2 | 1 | 48 | 12 | 3 | 2 | 4 |
| 3 | 2 | 1 | 15 | 13 | 2 | 1 | 36 |
| 4 | 3 | 2 | 23 | 14 | 5 | 4 | 24 |
| 5 | 2 | 1 | 40 | 15 | 2 | 1 | 22 |
| 6 | 10 | 9 | 21 | 16 | 3 | 2 | 14 |
| 7 | 1 | 0 | 47 | 17 | 2 | 1 | 44 |
| 8 | 2 | 1 | 30 | 18 | 3 | 2 | 6 |
| 9 | 4 | 3 | 3 | 19 | 3 | 2 | 5 |
| 10 | 2 | 1 | 28 | 20 | 2 | 1 | 6 |

**Table 5.25**: Parameters in Phase 2 when the number of AP is increased to 2842

| AA | Total demand | #Full buses | #Remainders | AA | Total demand | #Full buses | #Remainders |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 1 | 30 | 11 | 3 | 2 | 46 |
| 2 | 3 | 2 | 23 | 12 | 3 | 2 | 29 |
| 3 | 2 | 1 | 40 | 13 | 3 | 2 | 11 |
| 4 | 3 | 2 | 48 | 14 | 5 | 4 | 49 |
| 5 | 3 | 2 | 15 | 15 | 2 | 1 | 47 |
| 6 | 10 | 9 | 46 | 16 | 3 | 2 | 39 |
| 7 | 2 | 1 | 22 | 17 | 3 | 2 | 19 |
| 8 | 3 | 2 | 5 | 18 | 3 | 2 | 31 |
| 9 | 4 | 3 | 28 | 19 | 3 | 2 | 30 |
| 10 | 3 | 2 | 3 | 20 | 2 | 1 | 31 |

**Table 5.26**: Parameters in Phase 2 when the number of AP is decreased to 1342

| AA | Total demand | #Full buses | #Remainders | AA | Total demand | #Full buses | #Remainders |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 5 | 11 | 2 | 1 | 21 |
| 2 | 1 | 0 | 48 | 12 | 2 | 1 | 4 |
| 3 | 1 | 0 | 15 | 13 | 1 | 0 | 36 |
| 4 | 2 | 1 | 23 | 14 | 4 | 3 | 24 |
| 5 | 1 | 0 | 40 | 15 | 1 | 0 | 22 |
| 6 | 9 | 8 | 18 | 16 | 2 | 1 | 14 |
| 7 | 0 | 0 | 0 | 17 | 1 | 0 | 44 |
| 8 | 1 | 0 | 30 | 18 | 2 | 1 | 6 |
| 9 | 3 | 2 | 3 | 19 | 2 | 1 | 5 |
| 10 | 1 | 0 | 28 | 20 | 1 | 0 | 6 |

**Table 5.27**: Parameters in Phase 2 when the number of AP is decreased to 842

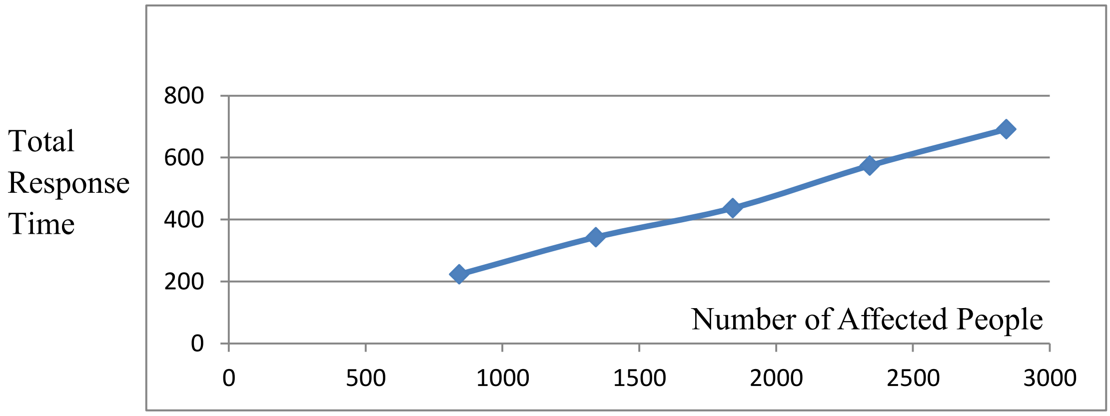
| AA | Total demand | #Full buses | #Remainders | AA | Total demand | #Full buses | #Remainders |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 11 | 1 | 0 | 46 |
| 2 | 1 | 0 | 23 | 12 | 1 | 0 | 29 |
| 3 | 0 | 0 | 0 | 13 | 1 | 0 | 11 |
| 4 | 1 | 0 | 48 | 14 | 3 | 2 | 49 |
| 5 | 1 | 0 | 15 | 15 | 0 | 0 | 0 |
| 6 | 7 | 6 | 16 | 16 | 1 | 0 | 39 |
| 7 | 0 | 0 | 0 | 17 | 1 | 0 | 19 |
| 8 | 1 | 0 | 5 | 18 | 1 | 0 | 31 |
| 9 | 2 | 1 | 28 | 19 | 1 | 0 | 30 |
| 10 | 1 | 0 | 3 | 20 | 0 | 0 | 0 |

**Table 5.28**: Summary of response time

| Number of AP | EC setup time (Phase 1) | Evacuation time (Phase 2) | Total response time |
|---|---|---|---|
| 842 | 214.8 minutes | 8.0 minutes | 222.8 minutes |
| 1342 | 335.1 minutes | 8.0 minutes | 343.1 minutes |
| 1842 | 431.5 minutes | 5.5 minutes | 437.0 minutes |
| 2342 | 568.0 minutes | 5.3 minutes | 573. minutes |
| 2842 | 686.3 minutes | 5.3 minutes | 691.6minutes |

Figure 5.1 shows how the total response changes corresponding to the fluctuation of AP. When the number of AP is doubled, the demand among all ECs will double and then the EC set up time will double. Compared to the EC set up time, the evacuation time is too small to influence the total response time. Thus the total response time will nearly double too. That is the reason why the line in Figure 5.1 is close to linear.

**Figure 5.1**: Relationship between total response time and number of Affected People




### 5.9.5. What-if Analysis Results Summary

In summary, the results of the first three assumptions are compared with the original results in Table 5.29: Strategy 4 is still the most preferable choice for Phase 1 and there are not obvious differences in Phase 2. For the last assumption, Figure 5.1 displays the relationship between the total response time and the number of affected people. The analyses of results are described in Chapter 5. The next Chapter 6 makes the conclusions for the whole thesis research and suggests future recommendations.

**Table 5.29**: Results comparison among what-if assumptions I to III and original best plan

| *Minutes* | *Phase 1* | *Phase 2* | *Total response time* |
|---|---|---|---|
| **Original** | 431.5 (Strategy 4) | 5.5 | 437 |
| **Assumption I** | 433.2 (Strategy 4) | 5.5 | 438.7 |
| **Assumption II** | 659.2 (Strategy 1&2) | 5.5 | 664.7 |
| **Assumption III** | 431.8 (Strategy 4) | 5.2 | 437 |

# 6. Conclusions and Recommendations

## 6.1. Research Conclusions

Recent events in Canada have uncovered the deficiencies of the existing supply chain system in humanitarian aid and disaster relief in the face of large-scale natural disasters. First, in Canada, the most important objective is to reduce the disaster relief response time because it is not proper to have relief items lay idle in the system to save costs (Tzeng et al., 2007). In addition, the pre-position site of inventory is centralized and there is no backup emergency base, the response procedures cannot be applied if the only centralized EB is affected by the disaster. These shortcomings cause long response time, which in turn lead to the delay of commodity delivery and expected evacuation, and even the death of potential survivors. Thus, this thesis research builds a linear programming optimization model to reduce the total response time from two aspects: inventory management and transportation planning.

In the aspect of inventory management, strategic prepositioning is critical. However, it is not possible to place relief commodities and relief personnel everywhere. Two approaches appear reasonable: one is prepositioning inventory close to the probable affected areas in which natural disasters may occur; the other one is decentralizing inventory facilities to enable partial coverage of multiple affected areas by a facility and full coverage of every affected area by multiple facilities (En Shen, 2006). In Chapter 4, scattered inventory are aggregated in one centralized emergency base and then be deployed in the first four scenarios. In addition, the situation with two decentralized emergency bases are considered and evaluated in the last two scenarios. A comparison is made to evaluate these two strategy and the results show that decentralized prepositioning strategy is better which is in accordance with the conclusion made by Oloruntoba and Gray (2006) in Chapter 2 (section 2.5).

When it comes to transportation planning, instead of minimizing the cost, the objective of the linear programming model built in this thesis is to minimize total travel distance, that is, total response time. It is because each second wasted in the situation of humanitarian aid and disaster relief may increase the mortality rate. This goal can be realized by decreasing the total operation rounds (Phase 3 in Figure 2.2) or reducing the operation time of each phase (Phases 1 and 2 in Figure 2.2).

Overall, a practical problem is studied in this thesis by combining several disciplines, such as disaster management, supply chain management, and community relief applications. The three research questions proposed in Chapter 1 are answered by the following responding results:

1. an effective conceptual framework developed for humanitarian aid and disaster relief supply chain management, as well as an illustrative scenario modelled for inventory and transportation aid in Chapter 3;
2. an application model formulated for selected Canadian community – Charlottetown, P.E.I. in Chapter 4; and
3. a result analysis for linear optimization of coastal emergency results in Chapter 5.

Despite of the data limitation, the objective of this thesis is fulfilled and the designed model can help policy makers and community planners for policy planning.

## 6.2. Future Recommendations

Future recommendations focus on how to lead this current research to more complete and more accurate future studies. For this thesis, there are several future study opportunities.

To start with, future analyses and testing may improve the model and data to achieve further realism. This thesis uses the historical data. The objective of the illustrative model established in Chapter 3 is to minimize cost while the application model formulated in Chapter 4 is to minimize response time. It is because no historical cost data are available

of Charlottetown, P.E.I. Future study can try to collect data from survey to first responders because limited data collection can hinder the real goal of distribution.
Currently, the major aim is to minimize the total response time. Due to the finance constraint, cost minimization can be weighted as an objective along with other objectives. For example, other plausible objectives could be minimizing operational costs given a desired level of response time and demand satisfaction. However, the values of these three aspects are not expressed in the same units, making it challenging to combine all into a single objective function (Van Hentenryck et al., 2010). Thus, penalty cost can be used to measure delayed response time or unsatisfied demand.

Furthermore, the two relief phases are done separately in this thesis. The Affected People will not be transported until all Evacuation Centres are open. However, the two phases can be done overlapping since the vans used to set up ECs are different from the buses used to transport people. Future studies can adopt different strategy to calculate the total response time. The travelling salesman problem can be another option.

In addition, since the current model is used to create local operational procedures, future study can integrate this model into a comprehensive decision support system for humanitarian aid and disaster relief. Meanwhile, a graphical user interface could be offered to facilitate the input of data and display of outcomes. Then, the model may be used by personnel who are not familiar with evaluation techniques.

To the end, this thesis focuses almost entirely on what relief organizations need to do. These relief organizations include but are not limited to the local government departments, the Canadian Red Cross, and other voluntary sector agencies. In the future, researchers can widen the concentration on what the Canadian public can do to protect themselves, their families, and their neighbors. The suggested preparedness activities for ordinary Canadians involve three parts: (i) understand the potential natural disasters and the general evacuation plan in the community, (ii) make a specific plan for evacuating people's own homes and practice the plan regularly, as well as (iii) keep a 72 hour kit on hand and rotate some items such as fresh water annually (Canadian Red Cross, 2014).

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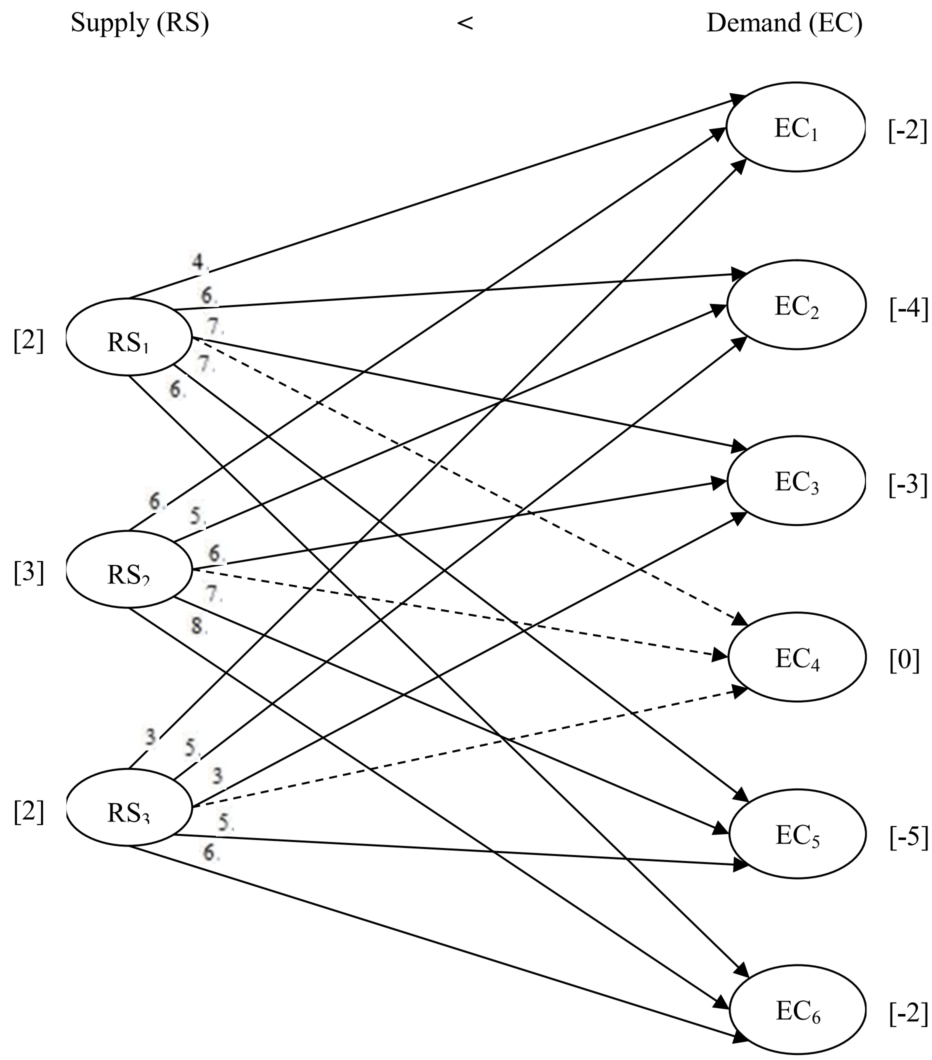
# Appendix A: Illustrative Model Results for the Phased Assignment and Transportation Problems

The appendix includes the network representation of the centralized example problem along the timeline and the progressive calculation results showed in EXCEL.

**Round 1:**

**T=1 (Phase 1):** Usually, the supply of relief items is short during the immediate response stage. There are seven RS groups in CEB at t=1: 2 good ones, three medium ones, and two weak ones. The supply of each type of RS groups is displayed in the bracket on the left side. Based on the rule set in the example problem, each group can serve ten evacuees. The full capacity of every EC determines its total demand of RS groups. The demand in each EC is showed in the bracket on the right side with a negative sign. Particularly, the dotted arrows illustrate that $EC_4$ is not functional because it is in the AA. Unit satisfaction scores are indicated along solid arrows, decided by the service level of RS group, the holding capacity of EC, the distance between CEB and EC, as well as the distance between EC and AA.

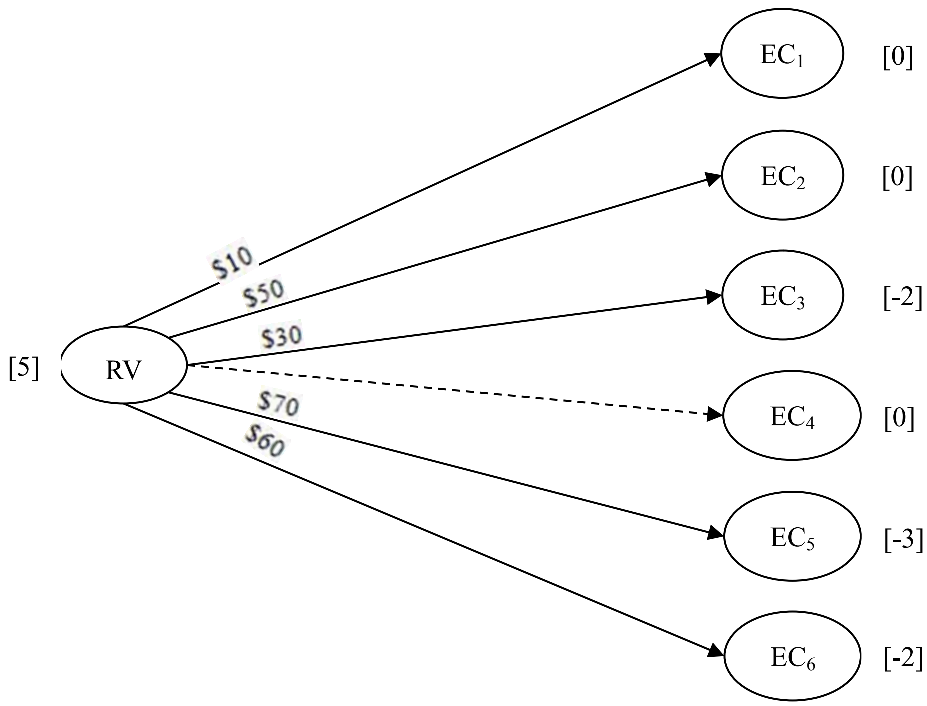



In order to maximize the total satisfaction score, the Solver function in EXCEL optimizes the following assignment plan: two good RS groups are sent to $EC_3$, three RS groups (one medium and two weak ones) are sent to $EC_5$, and two medium RS groups are sent to $EC_6$. Thus, the supply of RS groups can open the above three ECs: $EC_3$ and $EC_5$ are partly opened while $EC_6$ can be fully opened. Other unsatisfied demands need to be met at phase 1 in round 2.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| T=1 Phase 1: Assignment Problem | | | | | | | | | | |
| | | | | | | | | | | |
| Unit Satisfaction Score | | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | | | |
| | RS1 | 4 | 6 | 7 | - | 7 | 6 | | | |
| | RS2 | 6 | 5 | 6 | - | 7 | 8 | | | |
| | RS3 | 3 | 5 | 3 | - | 5 | 6 | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| Assignment | | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | Total Assignments | | Supply |
| | RS1 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | = | 2 |
| | RS2 | 0 | 0 | 0 | 0 | 1 | 2 | 3 | = | 3 |
| | RS3 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | = | 2 |
| | Total Assigned | 0 | 0 | 2 | 0 | 3 | 2 | | | |
| | | <= | <= | <= | <= | <= | <= | | | |
| | Demand | 2 | 4 | 3 | 0 | 5 | 2 | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | Total Satisfaction Score | 47 | |

**T=2 (Phase 2):** Since each RS group can serve ten AP and every ten AP need one full truckload of RCs, the demand of RCs is decided by the extent to which an EC is opened. In the example problem, the demand of RCs is exactly equal to the number of RS groups sent to the EC. The unit shipping costs are marked along solid arrows which depend on the distance between CEB and EC. There is an assumption that RCs are enough in CEB because emergency agency can bring all provincial resources together. Hence, the only limitation is the amount of available RVs.

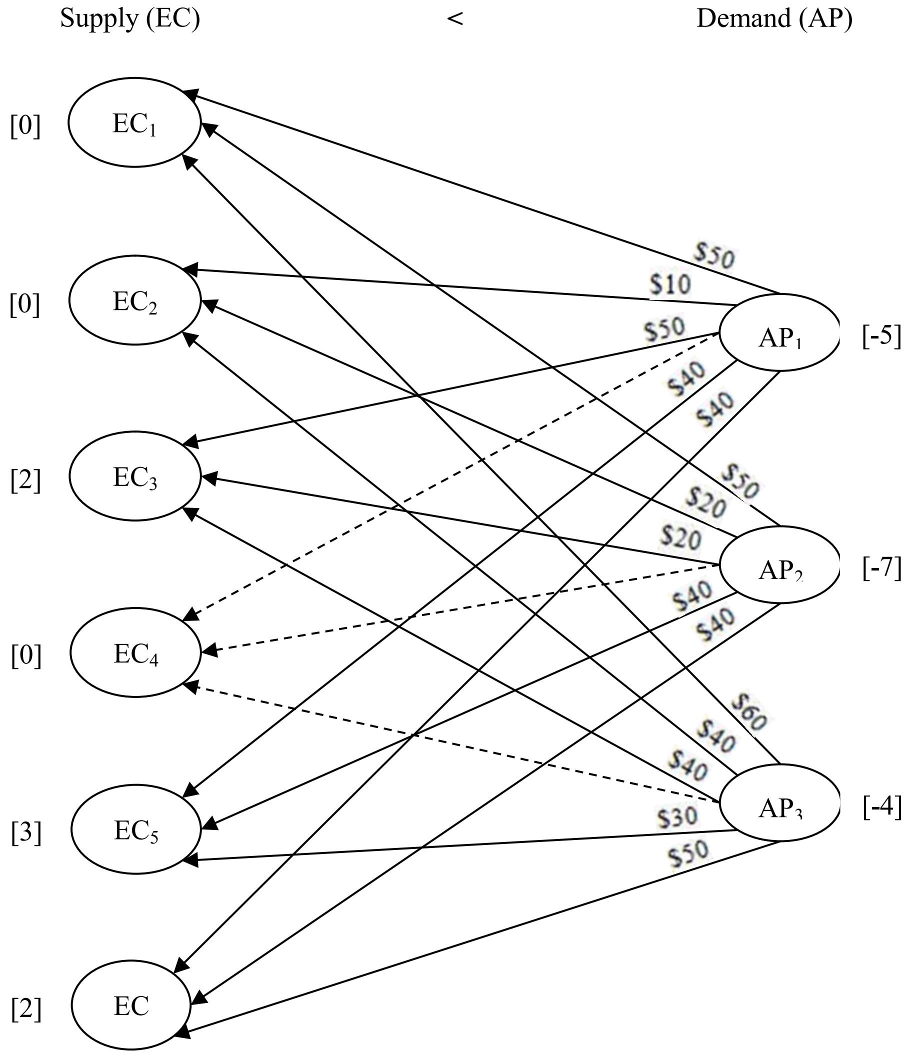
Supply (RV) < Demand (EC)




To minimize the total shipping cost, two truckloads of RCs are shipped to $EC_3$, one truckload to $EC_5$, and two truckloads to $EC_6$. Thus, the demand in $EC_3$ and $EC_6$ is fully met but the demand in $EC_5$ is just partly satisfied. The unsatisfied demand will be added to $EC_5$ at phase 2 in round 2.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T=2 Phase 2: Transportation Problem of Relief Commodities | | | | | | | | | | | |
| | | | | | | | | | | | |
| Unit Shipping Cost | | | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | | | |
| | | RV | $10 | $50 | $30 | - | $70 | $60 | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| Shipment Quantity | | | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | Total Shipped | | Supply |
| (truckload) | | RV | 0 | 0 | 2 | 0 | 1 | 2 | 5 | = | 5 |
| | | Total Received | 0 | 0 | 2 | 0 | 1 | 2 | | | |
| | | | <= | <= | <= | <= | <= | <= | | | |
| | | Demand | 0 | 0 | 2 | 0 | 3 | 2 | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | Total Cost | 250 | |

**T=3 (Phase 3):** Those open ECs with a certain level of RCs can accept evacuees at this time. Each RV can deliver ten AP per time. In the example problem, the number of AP that can be evacuated is decided by the extent to which ECs are opened instead of the amount of RCs in ECs, because it is better to hold AP in ECs without enough RCs than to leave them at AA. Unit delivery costs along solid arrows rely on the distance between AP and EC. Another constraint is the amount of available RVs at this time.

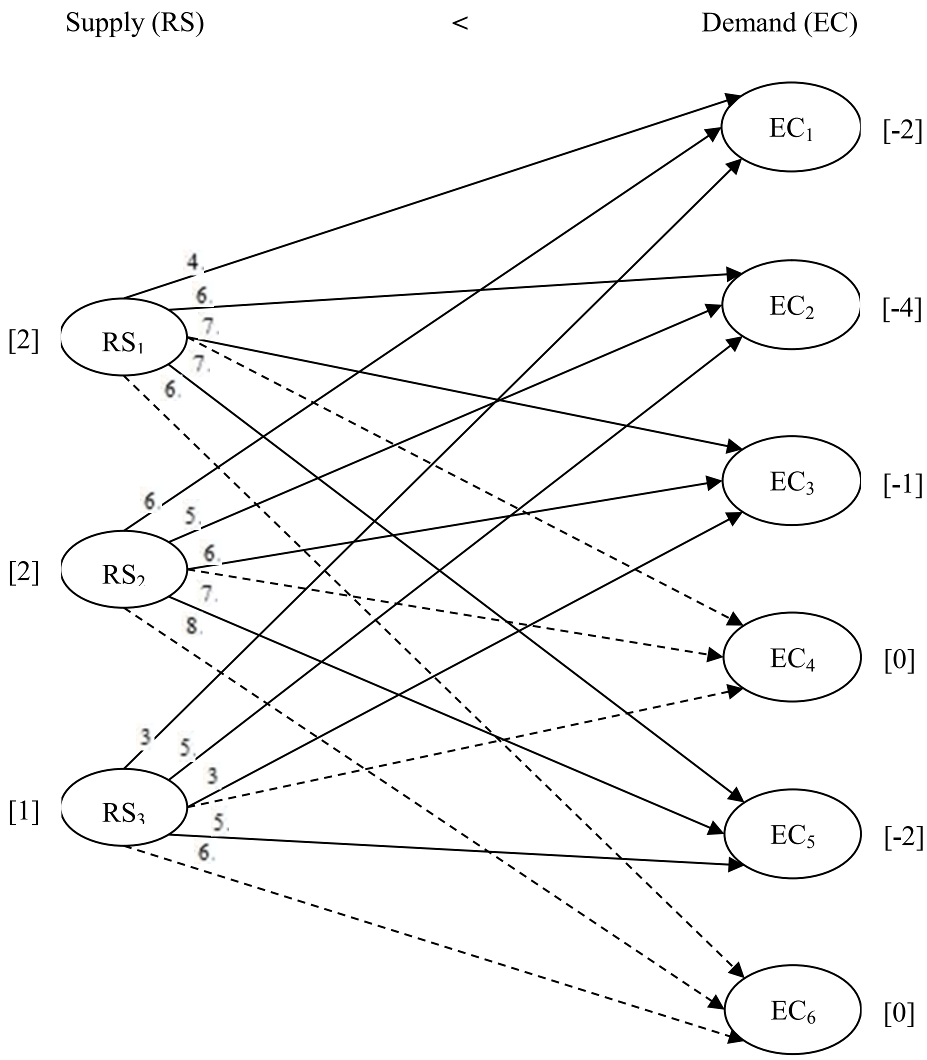



With the aim of minimize the total delivery cost, 40 people in $AP_2$ are evacuated (20 are to $EC_3$, 20 are to $EC_6$) and 30 people in $AP_3$ are evacuated to $EC_5$. Until now, the amount of AP in $EC_6$ is up to its full capacity because only $EC_6$ is fully opened and contains enough RCs.

| T=3 Phase 3: Transportation Problem of Evacuation | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| Unit Delivery Cost | | | AP1 | AP2 | AP3 | | | |
| | | EC1 | $50 | $50 | $60 | | | |
| | | EC2 | $10 | $20 | $40 | | | |
| | | EC3 | $50 | $20 | $40 | | | |
| | | EC4 | - | - | - | | | |
| | | EC5 | $40 | $40 | $30 | | | |
| | | EC6 | $40 | $40 | $50 | | | |
| | | | | | | | | |
| | | | | | | | | |
| Shipment Quantity | | | AP1 | AP2 | AP3 | Total Received | | Supply |
| (truckload) | | EC1 | 0 | 0 | 0 | 0 | = | 0 |
| | | EC2 | 0 | 0 | 0 | 0 | = | 0 |
| | | EC3 | 0 | 2 | 0 | 2 | = | 2 |
| | | EC4 | 0 | 0 | 0 | 0 | = | 0 |
| | | EC5 | 0 | 0 | 3 | 3 | = | 3 |
| | | EC6 | 0 | 2 | 0 | 2 | = | 2 |
| | | Total Delivered | 0 | 4 | 3 | | | |
| | | | <= | <= | <= | | | |
| | | Demand | 5 | 7 | 4 | | | |
| | | | | | | | | |
| | | RV Needed | 7 | | | | | |
| | | | <= | | | | | |
| | | RV Available | 7 | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | Total Cost | 210 | |

**Round 2:**

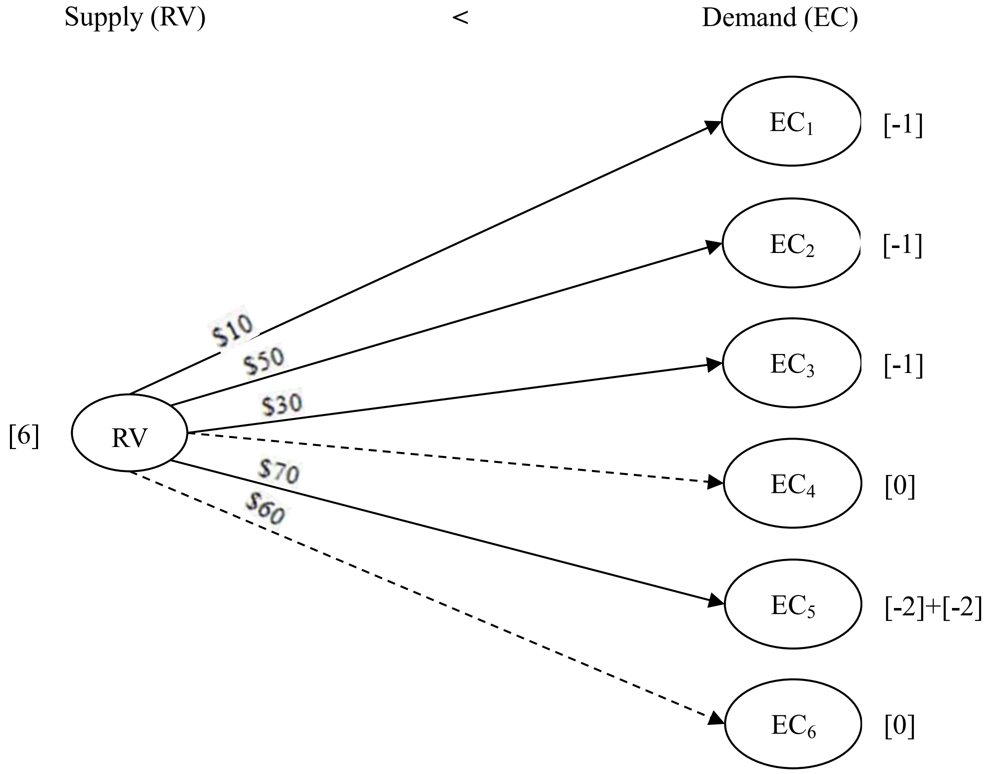
**T=4 (Phase 1):** After the response in round 1, $EC_6$ has been already fully opened and fully satisfied, it is not within the scope of consideration any more. Similar to $EC_4$, dotted arrows are used for $EC_6$. At this period, the supply of RS groups is still not sufficient. Among five RS groups, two of them are good, two are medium, and one is weak.




To achieve the maximization of the total satisfaction score, one medium group is assigned to $EC_1$, one weak group is assigned to $EC_2$, one good group is assigned to $EC_3$, and two groups (a good one and a medium one) are assigned to $EC_5$. After this time period, all the available ECs are opened ($EC_1$ and $EC_2$ are just partly opened; $EC_3$ and $EC_5$ are fully opened).

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T=4 Phase 1: Assignment Problem | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| Unit Satisfaction Score | | | | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | | | |
| | | | RS1 | 4 | 6 | 7 | - | 7 | 6 | | | |
| | | | RS2 | 6 | 5 | 6 | - | 7 | 8 | | | |
| | | | RS3 | 3 | 5 | 3 | - | 5 | 6 | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| Assignment | | | | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | Total Assignments | | Supply |
| | | | RS1 | 0 | 0 | 1 | 0 | 1 | 0 | 2 | = | 2 |
| | | | RS2 | 1 | 0 | 0 | 0 | 1 | 0 | 2 | = | 2 |
| | | | RS3 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| | | | Total Assigned | 1 | 1 | 1 | 0 | 2 | 0 | | | |
| | | | | <= | <= | <= | <= | <= | <= | | | |
| | | | Demand | 2 | 4 | 1 | 0 | 2 | 0 | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | Total Satisfaction | 32 | |

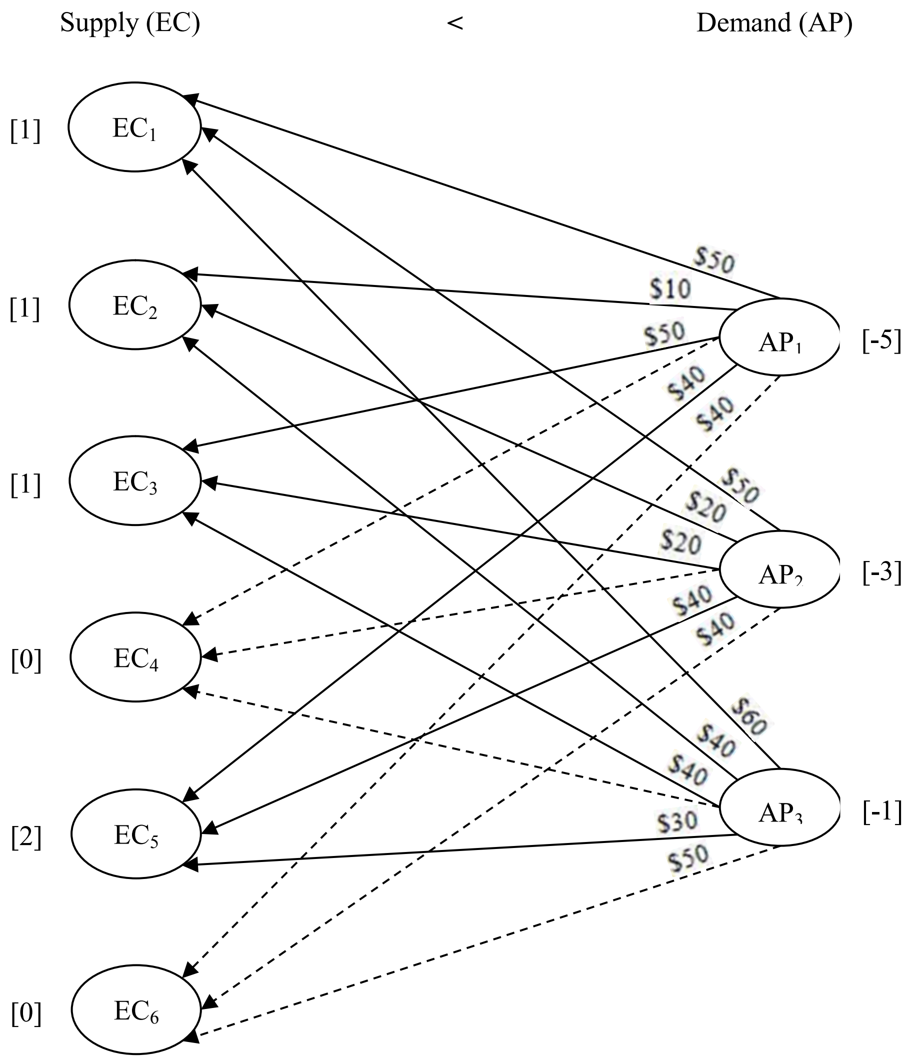
**T=5 (Phase 2):** New demand are generated after t=4. Except the demand of new opened parts in ECs, the unsatisfied demand in $EC_5$ during round 1 is added to this phase. However, the total supply of RVs is still deficient.




With the purpose of cost minimization, the results in EXCEL are: one full truckload of RCs is shipped to $EC_1$, one to $EC_2$, one to $EC_3$, and three to $EC_5$. The demands in open parts of $EC_1$, $EC_2$, and $EC_3$ are met, while the demand in $EC_5$ is still not totally satisfied which will be added to round 3.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T=5 Phase 2: Transportation Problem of Relief Commodities | | | | | | | | | | | |
| | | | | | | | | | | | |
| Unit Shipping Cost | | | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | | | |
| | | RV | $10 | $50 | $30 | - | $70 | $60 | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| Shipment Quantity | | | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | Total Shipped | | Supply |
| (truckload) | | RV | 1 | 1 | 1 | 0 | 3 | 0 | 6 | = | 6 |
| | | Total Received | 1 | 1 | 1 | 0 | 3 | 0 | | | |
| | | | <= | <= | <= | <= | <= | <= | | | |
| | | Demand | 1 | 1 | 1 | 0 | 4 | 0 | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | Total Cost | 240 | |

**T=6 (Phase 3):** More ECs are opened; therefore, more AP can be evacuated. Although the amount of RVs is a limitation, the RVs are enough during this period and the only constraint is the capacity of ECs.

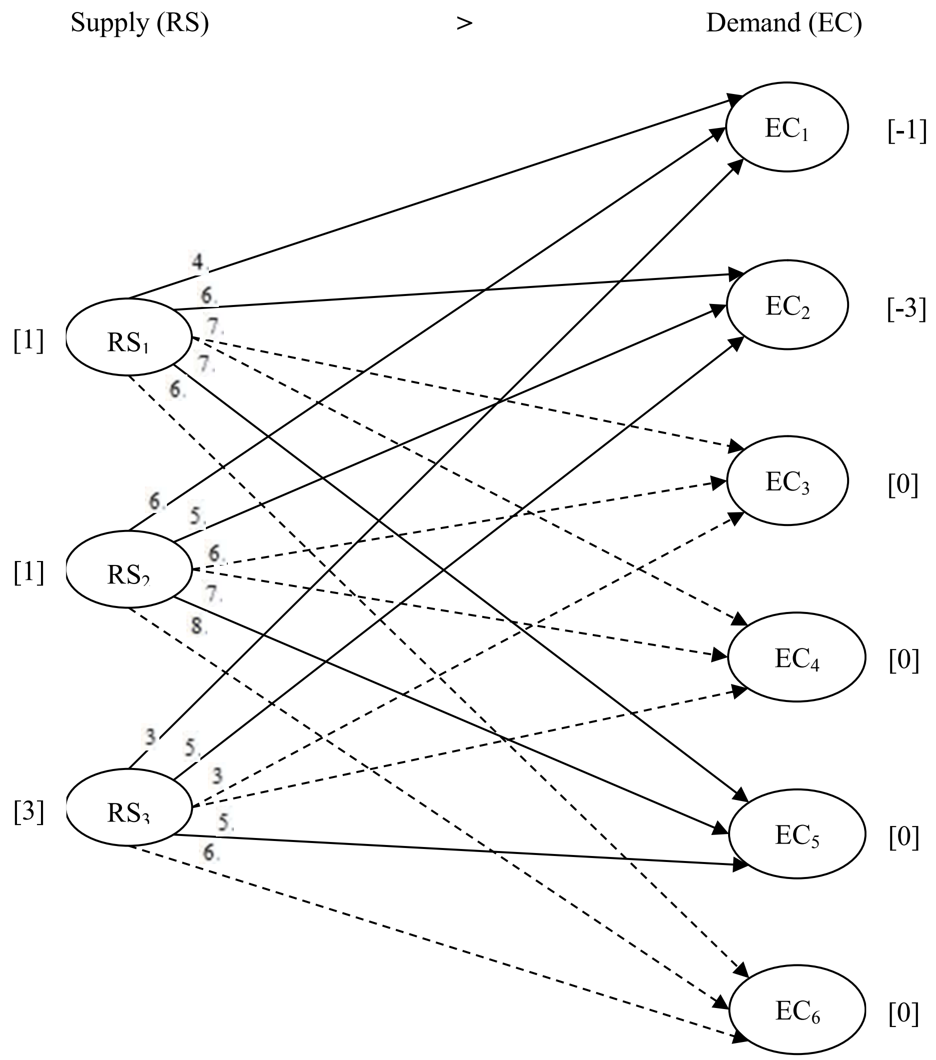



In order to minimize the total delivery cost, 30 people in $AP_1$ are evacuated (10 to $EC_1$, 10 to $EC_2$, 10 to $EC_5$); 10 people in $AP_2$ are evacuated to $EC_3$; and 10 people in $AP_3$ are evacuated to $EC_5$. Until to this moment, $EC_3$ is fully opened and the demand of it is totally satisfied.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| T=6 Phase 3: Transportation Problem of Evacuation | | | | | | | | |
| | | | | | | | | |
| Unit Delivery Cost | | | AP1 | AP2 | AP3 | | | |
| | | EC1 | \$50 | \$50 | \$60 | | | |
| | | EC2 | \$10 | \$20 | \$40 | | | |
| | | EC3 | \$50 | \$20 | \$40 | | | |
| | | EC4 | - | - | - | | | |
| | | EC5 | \$40 | \$40 | \$30 | | | |
| | | EC6 | \$40 | \$40 | \$50 | | | |
| | | | | | | | | |
| | | | | | | | | |
| Shipment Quantity | | | AP1 | AP2 | AP3 | Total Received | | Supply |
| (truckload) | | EC1 | 1 | 0 | 0 | 1 | = | 1 |
| | | EC2 | 1 | 0 | 0 | 1 | = | 1 |
| | | EC3 | 0 | 1 | 0 | 1 | = | 1 |
| | | EC4 | 0 | 0 | 0 | 0 | = | 0 |
| | | EC5 | 1 | 0 | 1 | 2 | = | 2 |
| | | EC6 | 0 | 0 | 0 | 0 | = | 0 |
| | | Total Delivered | 3 | 1 | 1 | | | |
| | | | <= | <= | <= | | | |
| | | Demand | 5 | 3 | 1 | | | |
| | | | | | | | | |
| | | RV Needed | 5 | | | | | |
| | | | <= | | | | | |
| | | RV Available | 8 | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | Total Cost | 150 | |

**Round 3:**

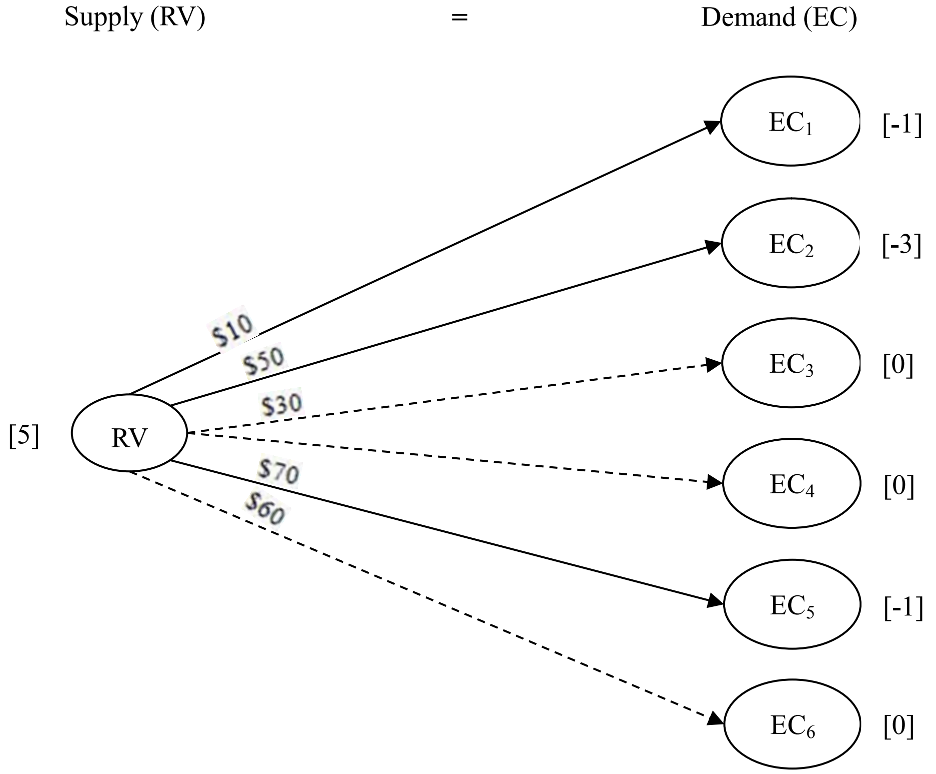
**T=7 (Phase 1):** After the response in round 2, $EC_3$ has been already fully opened and fully satisfied, it is not within the scope of consideration any more. Similar to $EC_6$, dotted arrows are used for $EC_3$. Different from the above situations, the supply of RS groups is greater than the unsatisfied demand in all ECs. Five RS groups are available: one of them is good, one is medium, and three are weak. Thus, all ECs can be fully opened after this time.




With the aim to maximize the total satisfaction score, one medium group is assigned to $EC_1$ and three groups (a good one and two weak ones) are assigned to $EC_2$. Phase 1 does not need round 4 since all the ECs are fully opened now.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| T=7 Phase 1: Assignment Problem | | | | | | | | | | |
| | | | | | | | | | | |
| Unit Satisfaction Score | | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | | | |
| | RS1 | 4 | 6 | 7 | - | 7 | 6 | | | |
| | RS2 | 6 | 5 | 6 | - | 7 | 8 | | | |
| | RS3 | 3 | 5 | 3 | - | 5 | 6 | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| Assignment | | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | Total Assignments | | Supply |
| | RS1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | <= | 1 |
| | RS2 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | <= | 1 |
| | RS3 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | <= | 3 |
| | Total Assigned | 1 | 3 | 0 | 0 | 0 | 0 | | | |
| | | = | = | = | = | = | = | | | |
| | Demand | 1 | 3 | 0 | 0 | 0 | 0 | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | Total Satisfaction | 22 | |

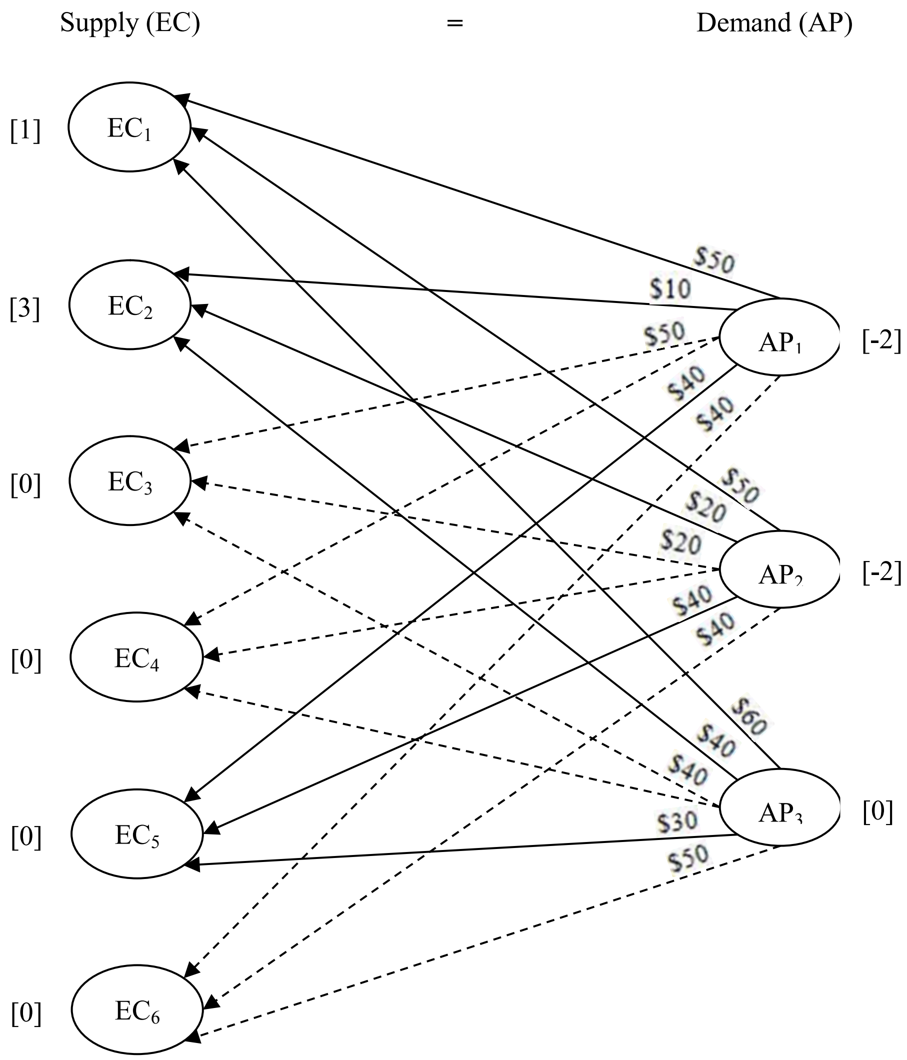
**T=8 (Phase 2):** Given that all ECs are opened now, the demand information also needs to be updated. At this period, the total demand of RVs is equal to the supply of them.




To make the total shipping cost minimum, one truckload of RCs is sent to $EC_1$, three to $EC_2$, and one to $EC_5$. At the end of this time, the demand of RCs in all ECs is satisfied and phase 2 also does not need round 4.

| T=8 Phase 2: Transportation Problem of Relief Commodities | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| Unit Shipping Cost | | | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | | | |
| | | RV | $10 | $50 | $30 | - | $70 | $60 | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| Shipment Quantity | | | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | Total Shipped | | Supply |
| (truckload) | | RV | 1 | 3 | 0 | 0 | 1 | 0 | 5 | <= | 5 |
| | | Total Received | 1 | 3 | 0 | 0 | 1 | 0 | | | |
| | | | = | = | = | = | = | = | | | |
| | | Demand | 1 | 3 | 0 | 0 | 1 | 0 | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | Total Cost | 70 | |

**T=9 (Phase 3):** At this time, all ECs are fully opened and operated. The capacity of ECs is not a constraint and all AP might be evacuated successfully. However, the amount of available RVs is not adequate. Thus, phase 3 still need round 4.



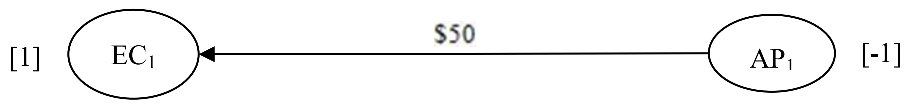

With the purpose of minimizing total delivering cost, 20 people in $AP_1$ and 10 people in $AP_2$ are evacuated to $EC_2$, making $EC_2$ achieve its full capacity.

| T=9 Phase 3: Transportation Problem of Evacuation | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Unit Delivery Cost | | | AP1 | AP2 | AP3 | | | |
| | | EC1 | $50 | $50 | $60 | | | |
| | | EC2 | $10 | $20 | $40 | | | |
| | | EC3 | $50 | $20 | $40 | | | |
| | | EC4 | - | - | - | | | |
| | | EC5 | $40 | $40 | $30 | | | |
| | | EC6 | $40 | $40 | $50 | | | |
| | | | | | | | | |
| Shipment Quantity | | | AP1 | AP2 | AP3 | Total Received | | Supply |
| (truckload) | | EC1 | 0 | 0 | 0 | 0 | <= | 1 |
| | | EC2 | 2 | 1 | 0 | 3 | <= | 3 |
| | | EC3 | 0 | 0 | 0 | 0 | <= | 0 |
| | | EC4 | 0 | 0 | 0 | 0 | <= | 0 |
| | | EC5 | 0 | 0 | 0 | 0 | <= | 0 |
| | | EC6 | 0 | 0 | 0 | 0 | <= | 0 |
| | | Total Delivered | 2 | 1 | 0 | | | |
| | | | <= | <= | <= | | | |
| | | Demand | 2 | 2 | 0 | | | |
| | | | | | | | | |
| | | RV Needed | 3 | | | | | |
| | | | = | | | | | |
| | | RV Available | 3 | | | | | |
| | | | | | | | | |
| | | | | | | Total Cost | 40 | |

**Round 4**

**T=10 (Phase 3):** Finally, just 10 people in $AP_1$ need to be delivered to $EC_1$, only one solution exists.

Supply (EC) = Demand (AP)



| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| T=10 Phase 3: Transportation Problem of Evacuation | | | | | | | | |
| Unit Delivery Cost | | | AP1 | AP2 | AP3 | | | |
| | | EC1 | $50 | $50 | $60 | | | |
| | | EC2 | $10 | $20 | $40 | | | |
| | | EC3 | $50 | $20 | $40 | | | |
| | | EC4 | - | - | - | | | |
| | | EC5 | $40 | $40 | $30 | | | |
| | | EC6 | $40 | $40 | $50 | | | |
| Shipment Quantity | | | AP1 | AP2 | AP3 | Total Received | | Supply |
| (truckload) | | EC1 | 0 | 1 | 0 | 1 | <= | 1 |
| | | EC2 | 0 | 0 | 0 | 0 | <= | 0 |
| | | EC3 | 0 | 0 | 0 | 0 | <= | 0 |
| | | EC4 | 0 | 0 | 0 | 0 | <= | 0 |
| | | EC5 | 0 | 0 | 0 | 0 | <= | 0 |
| | | EC6 | 0 | 0 | 0 | 0 | <= | 0 |
| | | Total Delivered | 0 | 1 | 0 | | | |
| | | | = | = | = | | | |
| | | Demand | 0 | 1 | 0 | | | |
| | | RV Needed | 1 | | | | | |
| | | | <= | | | | | |
| | | RV Available | 2 | | | | | |
| | | | | | | Total Cost | 50 | |

## Appendix B: Automated EXCEL Spreadsheet Algorithm for Successive RV van Schedule in Phase 1

In the first phase, Relief Staff and Relief Commodities are sent to set up Evacuation Centres (ECs) by limited available vans in Emergency Base (EB). The automated EXCEL sheet algorithm is used to determine the successive van schedules. The appendix includes the progressive calculation results showed in EXCEL for four strategies in six scenarios.

**Scenario I: Two vans in Prince Street EB (The yellow cell in each strategy spreadsheet is the EC set up time in Phase 1)**

*Strategy 1: Use ranked ECs (distance between EB and EC) and van deployment strategy "together" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC8 | 300 | 6 | 2 | 3 | 1.1 | 6.6 | 6.6 | 90 | 96.6 | 0 | 96.6 | 0 | 96.6 |
| 2 | EC7 | 300 | 6 | 2 | 3 | 1.8 | 10.8 | 10.8 | 90 | 100.8 | 96.6 | 197.4 | 96.6 | 197.4 |
| 3 | EC4 | 100 | 2 | 2 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 197.4 | 230.6 | 197.4 | 230.6 |
| 4 | EC9 | 300 | 6 | 2 | 3 | 2.4 | 14.4 | 14.4 | 90 | 104.4 | 230.6 | 335 | 230.6 | 335 |
| 5 | EC6 | 300 | 6 | 2 | 3 | 4.3 | 25.8 | 25.8 | 90 | 115.8 | 335 | 450.8 | 335 | 450.8 |
| 6 | ECQ | 300 | 6 | 2 | 3 | 5.1 | 30.6 | 30.6 | 90 | 120.6 | 450.8 | 571.4 | 450.8 | 571.4 |
| 7 | EC1 | 100 | 2 | 2 | 1 | 5.3 | 10.6 | 10.6 | 30 | 40.6 | 571.4 | 612 | 571.4 | 612 |
| 8 | EC5 | 50 | 1 | 1 | 1 | 3.9 | 7.8 | 7.8 | 30 | 37.8 | 612 | 649.8 | 612 | 612 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.8 | 9.6 | 9.6 | 30 | 39.6 | 649.8 | 649.8 | 612 | 651.6 |
| 10 | EC3 | 50 | 1 | 1 | 1 | 6.6 | 6.6 | 6.6 | 30 | 36.6 | 649.8 | 686.4 | 651.6 | 651.6 |

*Strategy 2: Use ranked ECs (distance between EB and EC) and van deployment strategy "unique" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC8 | 300 | 6 | 1 | 6 | 1.1 | 13.2 | 13.2 | 180 | 193.2 | 0 | 193.2 | 0 | 0 |
| 2 | EC7 | 300 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 193.2 | 193.2 | 0 | 201.6 |
| 3 | EC4 | 100 | 2 | 1 | 2 | 1.6 | 6.4 | 6.4 | 60 | 66.4 | 193.2 | 259.6 | 201.6 | 201.6 |
| 4 | EC9 | 300 | 6 | 1 | 6 | 2.4 | 28.8 | 28.8 | 180 | 208.8 | 259.6 | 259.6 | 201.6 | 410.4 |
| 5 | EC6 | 300 | 6 | 1 | 6 | 4.3 | 51.6 | 51.6 | 180 | 231.6 | 259.6 | 491.2 | 410.4 | 410.4 |
| 6 | ECQ | 300 | 6 | 1 | 6 | 5.1 | 61.2 | 61.2 | 180 | 241.2 | 491.2 | 491.2 | 410.4 | 651.6 |
| 7 | EC1 | 100 | 2 | 1 | 2 | 5.3 | 21.2 | 21.2 | 60 | 81.2 | 491.2 | 572.4 | 651.6 | 651.6 |
| 8 | EC5 | 50 | 1 | 1 | 1 | 3.9 | 7.8 | 7.8 | 30 | 37.8 | 572.4 | 610.2 | 651.6 | 651.6 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.8 | 9.6 | 9.6 | 30 | 39.6 | 610.2 | 649.8 | 651.6 | 651.6 |
| 10 | EC3 | 50 | 1 | 1 | 1 | 6.6 | 6.6 | 6.6 | 30 | 36.6 | 649.8 | 686.4 | 651.6 | 651.6 |

*Strategy 3: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "together" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC6 | 300 | 6 | 2 | 3 | 4.3 | 25.8 | 25.8 | 90 | 115.8 | 0 | 115.8 | 0 | 115.8 |
| 2 | EC1 | 100 | 2 | 2 | 1 | 5.3 | 10.6 | 10.6 | 30 | 40.6 | 115.8 | 156.4 | 115.8 | 156.4 |
| 3 | EC8 | 300 | 6 | 2 | 3 | 1.1 | 6.6 | 6.6 | 90 | 96.6 | 156.4 | 253 | 156.4 | 253 |
| 4 | EC7 | 300 | 6 | 2 | 3 | 1.8 | 10.8 | 10.8 | 90 | 100.8 | 253 | 353.8 | 253 | 353.8 |
| 5 | EC4 | 100 | 2 | 2 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 353.8 | 387 | 353.8 | 387 |
| 6 | EC9 | 300 | 6 | 2 | 3 | 2.4 | 14.4 | 14.4 | 90 | 104.4 | 387 | 491.4 | 387 | 491.4 |
| 7 | ECQ | 300 | 6 | 2 | 3 | 5.1 | 30.6 | 30.6 | 90 | 120.6 | 491.4 | 612 | 491.4 | 612 |
| 8 | EC3 | 50 | 1 | 1 | 1 | 6.6 | 13.2 | 13.2 | 30 | 43.2 | 612 | 655.2 | 612 | 612 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.8 | 9.6 | 9.6 | 30 | 39.6 | 655.2 | 655.2 | 612 | 651.6 |
| 10 | EC5 | 50 | 1 | 1 | 1 | 3.9 | 3.9 | 3.9 | 30 | 33.9 | 655.2 | 655.2 | 651.6 | 685.5 |

*Strategy 4: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "unique" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC6 | 300 | 6 | 1 | 6 | 4.3 | 51.6 | 51.6 | 180 | 231.6 | 0 | 231.6 | 0 | 0 |
| 2 | EC1 | 100 | 2 | 2 | 2 | 5.3 | 21.2 | 21.2 | 60 | 81.2 | 231.6 | 231.6 | 0 | 81.2 |
| 3 | EC8 | 300 | 6 | 2 | 6 | 1.1 | 13.2 | 13.2 | 180 | 193.2 | 231.6 | 231.6 | 81.2 | 274.4 |
| 4 | EC7 | 300 | 6 | 2 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 231.6 | 433.2 | 274.4 | 274.4 |
| 5 | EC4 | 100 | 2 | 1 | 2 | 1.6 | 6.4 | 6.4 | 60 | 66.4 | 433.2 | 433.2 | 274.4 | 340.8 |
| 6 | EC9 | 300 | 6 | 1 | 6 | 2.4 | 28.8 | 28.8 | 180 | 208.8 | 433.2 | 433.2 | 340.8 | 549.6 |
| 7 | ECQ | 300 | 6 | 2 | 6 | 5.1 | 61.2 | 61.2 | 180 | 241.2 | 433.2 | 674.4 | 549.6 | 549.6 |
| 8 | EC3 | 50 | 1 | 1 | 1 | 6.6 | 13.2 | 13.2 | 30 | 43.2 | 674.4 | 674.4 | 549.6 | 592.8 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.8 | 9.6 | 9.6 | 30 | 39.6 | 674.4 | 674.4 | 592.8 | 632.4 |
| 10 | EC5 | 50 | 1 | 1 | 1 | 3.9 | 3.9 | 3.9 | 30 | 33.9 | 674.4 | 674.4 | 632.4 | 666.3 |

**Scenario II: Two vans in Paramount Drive EB (The yellow cell in each strategy spreadsheet is the EC set up time in Phase 1)**

*Strategy 1: Use ranked ECs (distance between EB and EC) and van deployment strategy "together" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ECQ | 300 | 6 | 2 | 3 | 2.6 | 15.6 | 15.6 | 90 | 105.6 | 0 | 105.6 | 0 | 105.6 |
| 2 | EC6 | 300 | 6 | 2 | 3 | 3.9 | 23.4 | 23.4 | 90 | 113.4 | 105.6 | 219 | 105.6 | 219 |
| 3 | EC8 | 300 | 6 | 2 | 3 | 4.7 | 28.2 | 28.2 | 90 | 118.2 | 219 | 337.2 | 219 | 337.2 |
| 4 | EC1 | 100 | 2 | 2 | 1 | 3.4 | 6.8 | 6.8 | 30 | 36.8 | 337.2 | 374 | 337.2 | 374 |
| 5 | EC7 | 300 | 6 | 2 | 3 | 5.6 | 33.6 | 33.6 | 90 | 123.6 | 374 | 497.6 | 374 | 497.6 |
| 6 | EC9 | 300 | 6 | 2 | 3 | 6.2 | 37.2 | 37.2 | 90 | 127.2 | 497.6 | 624.8 | 497.6 | 624.8 |
| 7 | EC4 | 100 | 2 | 2 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 624.8 | 665.6 | 624.8 | 665.6 |
| 8 | EC5 | 50 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 665.6 | 701.4 | 665.6 | 665.6 |
| 9 | EC3 | 50 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 701.4 | 701.4 | 665.6 | 703.8 |
| 10 | EC2 | 50 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 701.4 | 735.6 | 703.8 | 703.8 |

*Strategy 2: Use ranked ECs (distance between EB and EC) and van deployment strategy "unique" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ECQ | 300 | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 0 | 211.2 | 0 | 0 |
| 2 | EC6 | 300 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 211.2 | 211.2 | 0 | 226.8 |
| 3 | EC8 | 300 | 6 | 1 | 6 | 4.7 | 56.4 | 56.4 | 180 | 236.4 | 211.2 | 447.6 | 226.8 | 226.8 |
| 4 | EC1 | 100 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 447.6 | 447.6 | 226.8 | 300.4 |
| 5 | EC7 | 300 | 6 | 1 | 6 | 5.6 | 67.2 | 67.2 | 180 | 247.2 | 447.6 | 447.6 | 300.4 | 547.6 |
| 6 | EC9 | 300 | 6 | 1 | 6 | 6.2 | 74.4 | 74.4 | 180 | 254.4 | 447.6 | 702 | 547.6 | 547.6 |
| 7 | EC4 | 100 | 2 | 1 | 2 | 5.4 | 21.6 | 21.6 | 60 | 81.6 | 702 | 702 | 547.6 | 629.2 |
| 8 | EC5 | 50 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 702 | 702 | 629.2 | 665 |
| 9 | EC3 | 50 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 702 | 702 | 665 | 703.2 |
| 10 | EC2 | 50 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 702 | 736.2 | 703.2 | 703.2 |

*Strategy 3: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "together" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC6 | 300 | 6 | 2 | 3 | 3.9 | 23.4 | 23.4 | 90 | 113.4 | 0 | 113.4 | 0 | 113.4 |
| 2 | EC1 | 100 | 2 | 2 | 1 | 3.4 | 6.8 | 6.8 | 30 | 36.8 | 113.4 | 150.2 | 113.4 | 150.2 |
| 3 | EC8 | 300 | 6 | 2 | 3 | 4.7 | 28.2 | 28.2 | 90 | 118.2 | 150.2 | 268.4 | 150.2 | 268.4 |
| 4 | EC7 | 300 | 6 | 2 | 3 | 5.6 | 33.6 | 33.6 | 90 | 123.6 | 268.4 | 392 | 268.4 | 392 |
| 5 | EC4 | 100 | 2 | 2 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 392 | 432.8 | 392 | 432.8 |
| 6 | EC9 | 300 | 6 | 2 | 3 | 6.2 | 37.2 | 37.2 | 90 | 127.2 | 432.8 | 560 | 432.8 | 560 |
| 7 | ECQ | 300 | 6 | 2 | 3 | 2.6 | 15.6 | 15.6 | 90 | 105.6 | 560 | 665.6 | 560 | 665.6 |
| 8 | EC3 | 50 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 665.6 | 703.8 | 665.6 | 665.6 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 703.8 | 703.8 | 665.6 | 704 |
| 10 | EC5 | 50 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 703.8 | 736.7 | 704 | 704 |

*Strategy 4: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "unique" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC6 | 300 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 0 | 226.8 | 0 | 0 |
| 2 | EC1 | 100 | 2 | 2 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 226.8 | 226.8 | 0 | 73.6 |
| 3 | EC8 | 300 | 6 | 2 | 6 | 4.7 | 56.4 | 56.4 | 180 | 236.4 | 226.8 | 226.8 | 73.6 | 310 |
| 4 | EC7 | 300 | 6 | 2 | 6 | 5.6 | 67.2 | 67.2 | 180 | 247.2 | 226.8 | 474 | 310 | 310 |
| 5 | EC4 | 100 | 2 | 1 | 2 | 5.4 | 21.6 | 21.6 | 60 | 81.6 | 474 | 474 | 310 | 391.6 |
| 6 | EC9 | 300 | 6 | 1 | 6 | 6.2 | 74.4 | 74.4 | 180 | 254.4 | 474 | 474 | 391.6 | 646 |
| 7 | ECQ | 300 | 6 | 2 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 474 | 685.2 | 646 | 646 |
| 8 | EC3 | 50 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 685.2 | 685.2 | 646 | 684.2 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 685.2 | 685.2 | 684.2 | 722.6 |
| 10 | EC5 | 50 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 685.2 | 718.1 | 722.6 | 722.6 |

**Scenario III: Three vans in Prince Street EB (The yellow cell in each strategy spreadsheet is the EC set up time in Phase 1 with an exception of Strategy 4)**

*Strategy 1: Use ranked ECs (distance between EB and EC) and van deployment strategy "together" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC8 | 300 | 6 | 3 | 2 | 1.1 | 4.4 | 4.4 | 60 | 64.4 | 0 | 64.4 | 0 | 64.4 | 0 | 64.4 |
| 2 | EC7 | 300 | 6 | 3 | 2 | 1.8 | 7.2 | 7.2 | 60 | 67.2 | 64.4 | 131.6 | 64.4 | 131.6 | 64.4 | 131.6 |
| 3 | EC4 | 100 | 2 | 2 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 131.6 | 164.8 | 131.6 | 164.8 | 131.6 | 131.6 |
| 4 | EC9 | 300 | 6 | 3 | 2 | 2.4 | 9.6 | 9.6 | 60 | 69.6 | 164.8 | 234.4 | 164.8 | 234.4 | 131.6 | 201.2 |
| 5 | EC6 | 300 | 6 | 3 | 2 | 4.3 | 17.2 | 17.2 | 60 | 77.2 | 234.4 | 311.6 | 234.4 | 311.6 | 201.2 | 278.4 |
| 6 | ECQ | 300 | 6 | 3 | 2 | 5.1 | 20.4 | 20.4 | 60 | 80.4 | 311.6 | 392 | 311.6 | 392 | 278.4 | 358.8 |
| 7 | EC1 | 100 | 2 | 2 | 1 | 5.3 | 10.6 | 10.6 | 30 | 40.6 | 392 | 432.6 | 392 | 392 | 358.8 | 399.4 |
| 8 | EC5 | 50 | 1 | 1 | 1 | 3.9 | 7.8 | 7.8 | 30 | 37.8 | 432.6 | 432.6 | 392 | 429.8 | 399.4 | 399.4 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.8 | 9.6 | 9.6 | 30 | 39.6 | 432.6 | 432.6 | 429.8 | 429.8 | 399.4 | 439 |
| 10 | EC3 | 50 | 1 | 1 | 1 | 6.6 | 6.6 | 6.6 | 30 | 36.6 | 432.6 | 432.6 | 429.8 | 466.4 | 439 | 439 |

*Strategy 2: Use ranked ECs (distance between EB and EC) and van deployment strategy "unique" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC8 | 300 | 6 | 1 | 6 | 1.1 | 13.2 | 13.2 | 180 | 193.2 | 0 | 193.2 | 0 | 0 | 0 | 0 |
| 2 | EC7 | 300 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 193.2 | 193.2 | 0 | 201.6 | 0 | 0 |
| 3 | EC4 | 100 | 2 | 1 | 2 | 1.6 | 6.4 | 6.4 | 60 | 66.4 | 193.2 | 193.2 | 201.6 | 201.6 | 0 | 66.4 |
| 4 | EC9 | 300 | 6 | 1 | 6 | 2.4 | 28.8 | 28.8 | 180 | 208.8 | 193.2 | 193.2 | 201.6 | 201.6 | 66.4 | 275.2 |
| 5 | EC6 | 300 | 6 | 1 | 6 | 4.3 | 51.6 | 51.6 | 180 | 231.6 | 193.2 | 424.8 | 201.6 | 201.6 | 275.2 | 275.2 |
| 6 | ECQ | 300 | 6 | 1 | 6 | 5.1 | 61.2 | 61.2 | 180 | 241.2 | 424.8 | 424.8 | 201.6 | 442.8 | 275.2 | 275.2 |
| 7 | EC1 | 100 | 2 | 1 | 2 | 5.3 | 21.2 | 21.2 | 60 | 81.2 | 424.8 | 424.8 | 442.8 | 442.8 | 275.2 | 356.4 |
| 8 | EC5 | 50 | 1 | 1 | 1 | 3.9 | 7.8 | 7.8 | 30 | 37.8 | 424.8 | 424.8 | 442.8 | 442.8 | 356.4 | 394.2 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.8 | 9.6 | 9.6 | 30 | 39.6 | 424.8 | 424.8 | 442.8 | 442.8 | 394.2 | 433.8 |
| 10 | EC3 | 50 | 1 | 1 | 1 | 6.6 | 6.6 | 6.6 | 30 | 36.6 | 424.8 | 461.4 | 442.8 | 442.8 | 433.8 | 433.8 |

*Strategy 3: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "together" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC6 | 300 | 6 | 3 | 2 | 4.3 | 17.2 | 17.2 | 60 | 77.2 | 0 | 77.2 | 0 | 77.2 | 0 | 77.2 |
| 2 | EC1 | 100 | 2 | 2 | 1 | 5.3 | 10.6 | 10.6 | 30 | 40.6 | 77.2 | 117.8 | 77.2 | 117.8 | 77.2 | 77.2 |
| 3 | EC8 | 300 | 6 | 3 | 2 | 1.1 | 4.4 | 4.4 | 60 | 64.4 | 117.8 | 182.2 | 117.8 | 182.2 | 77.2 | 141.6 |
| 4 | EC7 | 300 | 6 | 3 | 2 | 1.8 | 7.2 | 7.2 | 60 | 67.2 | 182.2 | 249.4 | 182.2 | 249.4 | 141.6 | 208.8 |
| 5 | EC4 | 100 | 2 | 2 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 249.4 | 282.6 | 249.4 | 249.4 | 208.8 | 242 |
| 6 | EC9 | 300 | 6 | 3 | 2 | 2.4 | 9.6 | 9.6 | 60 | 69.6 | 282.6 | 352.2 | 249.4 | 319 | 242 | 311.6 |
| 7 | ECQ | 300 | 6 | 3 | 2 | 5.1 | 20.4 | 20.4 | 60 | 80.4 | 352.2 | 432.6 | 319 | 399.4 | 311.6 | 392 |
| 8 | EC3 | 50 | 1 | 1 | 1 | 6.6 | 13.2 | 13.2 | 30 | 43.2 | 432.6 | 432.6 | 399.4 | 399.4 | 392 | 435.2 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.8 | 9.6 | 9.6 | 30 | 39.6 | 432.6 | 432.6 | 399.4 | 439 | 435.2 | 435.2 |
| 10 | EC5 | 50 | 1 | 1 | 1 | 3.9 | 3.9 | 3.9 | 30 | 33.9 | 432.6 | 466.5 | 439 | 439 | 435.2 | 435.2 |

*Strategy 4: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "unique" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC6 | 300 | 6 | 1 | 6 | 4.3 | 51.6 | 51.6 | 180 | 231.6 | 0 | 231.6 | 0 | 0 | 0 | 0 |
| 2 | EC1 | 100 | 2 | 1 | 2 | 5.3 | 21.2 | 21.2 | 60 | 81.2 | 231.6 | 231.6 | 0 | 81.2 | 0 | 0 |
| 3 | EC8 | 300 | 6 | 1 | 6 | 1.1 | 13.2 | 13.2 | 180 | 193.2 | 231.6 | 231.6 | 81.2 | 81.2 | 0 | 193.2 |
| 4 | EC7 | 300 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 231.6 | 231.6 | 81.2 | 282.8 | 193.2 | 193.2 |
| 5 | EC4 | 100 | 2 | 1 | 2 | 1.6 | 6.4 | 6.4 | 60 | 66.4 | 231.6 | 231.6 | 282.8 | 282.8 | 193.2 | 259.6 |
| 6 | EC9 | 300 | 6 | 1 | 6 | 2.4 | 28.8 | 28.8 | 180 | 208.8 | 231.6 | 440.4 | 282.8 | 282.8 | 259.6 | 259.6 |
| 7 | ECQ | 300 | 6 | 1 | 6 | 5.1 | 61.2 | 61.2 | 180 | 241.2 | 440.4 | 440.4 | 282.8 | 282.8 | 259.6 | 500.8 |
| 8 | EC3 | 50 | 1 | 1 | 1 | 6.6 | 13.2 | 13.2 | 30 | 43.2 | 440.4 | 440.4 | 282.8 | 326 | 500.8 | 500.8 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.8 | 9.6 | 9.6 | 30 | 39.6 | 440.4 | 440.4 | 326 | 365.6 | 500.8 | 500.8 |
| 10 | EC5 | 50 | 1 | 1 | 1 | 3.9 | 3.9 | 3.9 | 30 | 33.9 | 440.4 | 440.4 | 365.6 | 399.5 | 500.8 | 500.8 |

Similar to the exceptional circumstance illustrated in section 5.4, there is a big gap of time among the three vans in this table. In the automated spreadsheet, Van 2 does not return to the EB after sending enough RS and RC to $EC_5$. Consequently, Van 2 needs to return to the EB first, and then deploy one more time to $EC_{10}$ so as to reduce the time used by Van 3. The one-way distance between $EC_5$ and Prince Street EB is 3.9 km. In addition, the round-trip distance between Prince Street EB and $EC_{10}$ is 10.2 km and 30 minutes need to be used to load and unload all materials. As a result, one more deployment occupies 40.2 minutes. After applying this modification, Van 2 needs 399.5 + 3.9 + 40.2 = 443.6 minutes and Van 3 needs 500.8 – 40.2 = 460.6 minutes. Since Van 3 still needs 460.6 minutes, the longest time used among three vans, Van 3 does not need to go back to EB; therefore, the time used by Van 3 is 460.6 – 5.1 = 455.5 minutes. In the end, the maximum deployment time becomes 455.5 minutes.

**Scenario IV: Three vans in Paramount Drive EB (The yellow cell in each strategy spreadsheet is the EC set up time in Phase 1 with an exception of Strategy 4)**

*Strategy 1: Use ranked ECs (distance between EB and EC) and van deployment strategy "together" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ECQ | 300 | 6 | 3 | 2 | 2.6 | 10.4 | 10.4 | 60 | 70.4 | 0 | 70.4 | 0 | 70.4 | 0 | 70.4 |
| 2 | EC6 | 300 | 6 | 3 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 70.4 | 146 | 70.4 | 146 | 70.4 | 146 |
| 3 | EC8 | 300 | 6 | 3 | 2 | 4.7 | 18.8 | 18.8 | 60 | 78.8 | 146 | 224.8 | 146 | 224.8 | 146 | 224.8 |
| 4 | EC1 | 100 | 2 | 2 | 1 | 3.4 | 6.8 | 6.8 | 30 | 36.8 | 224.8 | 261.6 | 224.8 | 261.6 | 224.8 | 224.8 |
| 5 | EC7 | 300 | 6 | 3 | 2 | 5.6 | 22.4 | 22.4 | 60 | 82.4 | 261.6 | 344 | 261.6 | 344 | 224.8 | 307.2 |
| 6 | EC9 | 300 | 6 | 3 | 2 | 6.2 | 24.8 | 24.8 | 60 | 84.8 | 344 | 428.8 | 344 | 428.8 | 307.2 | 392 |
| 7 | EC4 | 100 | 2 | 2 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 428.8 | 469.6 | 428.8 | 428.8 | 392 | 432.8 |
| 8 | EC5 | 50 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 469.6 | 469.6 | 428.8 | 464.6 | 432.8 | 432.8 |
| 9 | EC3 | 50 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 469.6 | 469.6 | 464.6 | 464.6 | 432.8 | 471 |
| 10 | EC2 | 50 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 469.6 | 469.6 | 464.6 | 498.8 | 471 | 471 |

*Strategy 2: Use ranked ECs (distance between EB and EC) and van deployment strategy "unique" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ECQ | 300 | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 0 | 211.2 | 0 | 0 | 0 | 0 |
| 2 | EC6 | 300 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 211.2 | 211.2 | 0 | 226.8 | 0 | 0 |
| 3 | EC8 | 300 | 6 | 1 | 6 | 4.7 | 56.4 | 56.4 | 180 | 236.4 | 211.2 | 211.2 | 226.8 | 226.8 | 0 | 236.4 |
| 4 | EC1 | 100 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 211.2 | 284.8 | 226.8 | 226.8 | 236.4 | 236.4 |
| 5 | EC7 | 300 | 6 | 1 | 6 | 5.6 | 67.2 | 67.2 | 180 | 247.2 | 284.8 | 284.8 | 226.8 | 474 | 236.4 | 236.4 |
| 6 | EC9 | 300 | 6 | 1 | 6 | 6.2 | 74.4 | 74.4 | 180 | 254.4 | 284.8 | 284.8 | 474 | 474 | 236.4 | 490.8 |
| 7 | EC4 | 100 | 2 | 1 | 2 | 5.4 | 21.6 | 21.6 | 60 | 81.6 | 284.8 | 366.4 | 474 | 474 | 490.8 | 490.8 |
| 8 | EC5 | 50 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 366.4 | 402.2 | 474 | 474 | 490.8 | 490.8 |
| 9 | EC3 | 50 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 402.2 | 440.4 | 474 | 474 | 490.8 | 490.8 |
| 10 | EC2 | 50 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 440.4 | 474.6 | 474 | 474 | 490.8 | 490.8 |

*Strategy 3: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "together" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC6 | 300 | 6 | 3 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 0 | 75.6 | 0 | 75.6 | 0 | 75.6 |
| 2 | EC1 | 100 | 2 | 2 | 1 | 3.4 | 6.8 | 6.8 | 30 | 36.8 | 75.6 | 112.4 | 75.6 | 112.4 | 75.6 | 75.6 |
| 3 | EC8 | 300 | 6 | 3 | 2 | 4.7 | 18.8 | 18.8 | 60 | 78.8 | 112.4 | 191.2 | 112.4 | 191.2 | 75.6 | 154.4 |
| 4 | EC7 | 300 | 6 | 3 | 2 | 5.6 | 22.4 | 22.4 | 60 | 82.4 | 191.2 | 273.6 | 191.2 | 273.6 | 154.4 | 236.8 |
| 5 | EC4 | 100 | 2 | 2 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 273.6 | 314.4 | 273.6 | 273.6 | 236.8 | 277.6 |
| 6 | EC9 | 300 | 6 | 3 | 2 | 6.2 | 24.8 | 24.8 | 60 | 84.8 | 314.4 | 399.2 | 273.6 | 358.4 | 277.6 | 362.4 |
| 7 | ECQ | 300 | 6 | 3 | 2 | 2.6 | 10.4 | 10.4 | 60 | 70.4 | 399.2 | 469.6 | 358.4 | 428.8 | 362.4 | 432.8 |
| 8 | EC3 | 50 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 469.6 | 469.6 | 428.8 | 467 | 432.8 | 432.8 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 469.6 | 469.6 | 467 | 467 | 432.8 | 471.2 |
| 10 | EC5 | 50 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 469.6 | 469.6 | 467 | 499.9 | 471.2 | 471.2 |

*Strategy 4: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "unique" to EC*

| Rank | EC | Capacity | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | EC6 | 300 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 0 | 226.8 | 0 | 0 | 0 | 0 |
| 2 | EC1 | 100 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 226.8 | 226.8 | 0 | 73.6 | 0 | 0 |
| 3 | EC8 | 300 | 6 | 1 | 6 | 4.7 | 56.4 | 56.4 | 180 | 236.4 | 226.8 | 226.8 | 73.6 | 73.6 | 0 | 236.4 |
| 4 | EC7 | 300 | 6 | 1 | 6 | 5.6 | 67.2 | 67.2 | 180 | 247.2 | 226.8 | 226.8 | 73.6 | 320.8 | 236.4 | 236.4 |
| 5 | EC4 | 100 | 2 | 1 | 2 | 5.4 | 21.6 | 21.6 | 60 | 81.6 | 226.8 | 308.4 | 320.8 | 320.8 | 236.4 | 236.4 |
| 6 | EC9 | 300 | 6 | 1 | 6 | 6.2 | 74.4 | 74.4 | 180 | 254.4 | 308.4 | 308.4 | 320.8 | 320.8 | 236.4 | 490.8 |
| 7 | ECQ | 300 | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 308.4 | 519.6 | 320.8 | 320.8 | 490.8 | 490.8 |
| 8 | EC3 | 50 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 519.6 | 519.6 | 320.8 | 359 | 490.8 | 490.8 |
| 9 | EC2 | 50 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 519.6 | 519.6 | 359 | 397.4 | 490.8 | 490.8 |
| 10 | EC5 | 50 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 519.6 | 519.6 | 397.4 | 430.3 | 490.8 | 490.8 |

This table is the exceptional circumstance illustrated in section 5.4, there is a big gap of time among the three vans in this table. In the automated spreadsheet, Van 2 does not return to the EB after sending enough RS and RC to $EC_5$. Consequently, Van 2 needs to return to the EB first, and then deploy one more time to $EC_{10}$ so as to reduce the time used by Van 1. The one-way distance between $EC_5$ and Paramount Drive EB is 2.9 km. In addition, the round-trip distance between Paramount Drive EB and $EC_{10}$ is 5.2 km and 30 minutes need to be used to load and unload all materials. As a result, one more deployment occupies 35.2 minutes. After applying this modification, Van 2 needs 430.3 + 2.9 + 35.2 = 468.4 minutes and Van 1 needs 519.6 – 35.2 = 484.6 minutes. Since Van 3 still needs 490.8 minutes, the longest time used among three vans, Van 3 does not need to go back to EB; therefore, the time used by Van 3 is 490.8 – 6.2 = 484.6 minutes. In the end, the maximum deployment time becomes 484.6 minutes.

**Scenario V: Two vans in Prince Street EB and one van in Paramount Drive EB (The yellow cell in each strategy spreadsheet is the EC set up time in Phase 1 with an exception of Strategy 4 in Scenario Va)**

The total demands in ten ECs are 37 full truckloads of RS and RC. There is an assumption that Prince Street EB provides 24 truckloads and Paramount Drive EB offers 12 truckloads. The 37th truckload demand can be supplied by either Prince Street EB or Paramount Drive EB.

**Step 1**: Introduce a dummy EB to determine where the first 36 truckloads of RS and RC come from

| Km | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 5.3 | 4.8 | 6.6 | 1.6 | 3.9 | 4.3 | 1.8 | 1.1 | 2.4 | 5.1 |
| EB2 | 3.4 | 4.2 | 4.1 | 5.4 | 2.9 | 3.9 | 5.6 | 4.7 | 6.2 | 2.6 |
| EBD | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Km | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from EB | | Supply in EB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 0 | 0 | 0 | 2 | 0 | 4 | 6 | 6 | 6 | 0 | 24 | = | 24 |
| EB2 | 2 | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 6 | 12 | = | 12 |
| EBD | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| Total to EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| | = | = | = | = | = | = | = | = | = | = | | | |
| Demand in EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| | | | | | | | | | | | Total travel distance | = | 89.4 |

**Step 2**: Apply the four deployment strategies twice to Scenario V (Character "a" means the $37^{th}$ truckload of demand is supplied by Prince Street EB, and "b" entails Paramount Drive EB)

**Scenario Va: Prince Street EB is responsible for EC2, EC4, EC6, EC7, EC8, EC9, and Paramount Drive EB is responsible for EC1, EC3, EC5, EC6, EC10**

| Full truckload | EC2 | EC4 | EC6 | EC7 | EC8 | EC9 |
|---|---|---|---|---|---|---|
| EB1 | 1 | 2 | 4 | 6 | 6 | 6 |
| Full truckload | EC1 | EC3 | EC5 | EC6 | EC10 | |
| EB2 | 2 | 1 | 1 | 2 | 6 | |

*Strategy 1: Use ranked ECs (distance between EB and EC) and van deployment strategy "together" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC8 | 6 | 2 | 3 | 1.1 | 6.6 | 6.6 | 90 | 96.6 | 0 | 96.6 | 0 | 96.6 |
| | 2 | EC7 | 6 | 2 | 3 | 1.8 | 10.8 | 10.8 | 90 | 100.8 | 96.6 | 197.4 | 96.6 | 197.4 |
| | 3 | EC4 | 2 | 2 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 197.4 | 230.6 | 197.4 | 230.6 |
| | 4 | EC9 | 6 | 2 | 3 | 2.4 | 14.4 | 14.4 | 90 | 104.4 | 230.6 | 335 | 230.6 | 335 |
| | 5 | EC6 | 4 | 2 | 2 | 4.3 | 17.2 | 17.2 | 60 | 77.2 | 335 | 412.2 | 335 | 412.2 |
| | 6 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 412.2 | 447 | 412.2 | 412.2 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 0 | 211.2 | | |
| | 2 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 211.2 | 286.8 | | |
| | 3 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 286.8 | 360.4 | | |
| | 4 | EC5 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 360.4 | 396.2 | | |
| | 5 | EC3 | 1 | 1 | 1 | 4.1 | 4.1 | 4.1 | 30 | 34.1 | 396.2 | 430.3 | | |

*Strategy 2: Use ranked ECs (distance between EB and EC) and van deployment strategy "unique" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC8 | 6 | 1 | 6 | 1.1 | 13.2 | 13.2 | 180 | 193.2 | 0 | 193.2 | 0 | 0 |
| | 2 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 193.2 | 193.2 | 0 | 201.6 |
| | 3 | EC4 | 2 | 1 | 2 | 1.6 | 6.4 | 6.4 | 60 | 66.4 | 193.2 | 259.6 | 201.6 | 201.6 |
| | 4 | EC9 | 6 | 1 | 6 | 2.4 | 28.8 | 28.8 | 180 | 208.8 | 259.6 | 259.6 | 201.6 | 410.4 |
| | 5 | EC6 | 4 | 1 | 4 | 4.3 | 34.4 | 34.4 | 120 | 154.4 | 259.6 | 414 | 410.4 | 410.4 |
| | 6 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 414 | 414 | 410.4 | 445.2 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 0 | 211.2 | | |
| | 2 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 211.2 | 286.8 | | |
| | 3 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 286.8 | 360.4 | | |
| | 4 | EC5 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 360.4 | 396.2 | | |
| | 5 | EC3 | 1 | 1 | 1 | 4.1 | 4.1 | 4.1 | 30 | 34.1 | 396.2 | 430.3 | | |

*Strategy 3: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "together" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC6 | 4 | 2 | 2 | 4.3 | 17.2 | 17.2 | 60 | 77.2 | 0 | 77.2 | 0 | 77.2 |
| | 2 | EC8 | 6 | 2 | 3 | 1.1 | 6.6 | 6.6 | 90 | 96.6 | 77.2 | 173.8 | 77.2 | 173.8 |
| | 3 | EC7 | 6 | 2 | 3 | 1.8 | 10.8 | 10.8 | 90 | 100.8 | 173.8 | 274.6 | 173.8 | 274.6 |
| | 4 | EC4 | 2 | 2 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 274.6 | 307.8 | 274.6 | 307.8 |
| | 5 | EC9 | 6 | 2 | 3 | 2.4 | 14.4 | 14.4 | 90 | 104.4 | 307.8 | 412.2 | 307.8 | 412.2 |
| | 6 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 412.2 | 447 | 412.2 | 412.2 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 0 | 75.6 | | |
| | 2 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 75.6 | 149.2 | | |
| | 3 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 149.2 | 360.4 | | |
| | 4 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 360.4 | 398.6 | | |
| | 5 | EC5 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 398.6 | 431.5 | | |

*Strategy 4: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "unique" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC6 | 4 | 1 | 4 | 4.3 | 34.4 | 34.4 | 120 | 154.4 | 0 | 154.4 | 0 | 0 |
| | 2 | EC8 | 6 | 1 | 6 | 1.1 | 13.2 | 13.2 | 180 | 193.2 | 154.4 | 154.4 | 0 | 193.2 |
| | 3 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 154.4 | 356 | 193.2 | 193.2 |
| | 4 | EC4 | 2 | 1 | 2 | 1.6 | 6.4 | 6.4 | 60 | 66.4 | 356 | 356 | 193.2 | 259.6 |
| | 5 | EC9 | 6 | 1 | 6 | 2.4 | 28.8 | 28.8 | 180 | 208.8 | 356 | 356 | 259.6 | 468.4 |
| | 6 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 356 | 390.8 | 468.4 | 468.4 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 0 | 75.6 | | |
| | 2 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 75.6 | 149.2 | | |
| | 3 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 149.2 | 360.4 | | |
| | 4 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 360.4 | 398.6 | | |
| | 5 | EC5 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 398.6 | 431.5 | | |

Similar to the exceptional circumstance illustrated in section 5.4, there is a big gap of time between the two vans in Prince Street EB (EB1). In the automated spreadsheet, Van 1 does not return to the EB1 after sending enough RS and RC to $EC_2$. Consequently, Van 1 needs to return to the EB1 first, and then deploy one more time to $EC_9$ so as to reduce the time used by Van 2. The one-way distance between $EC_2$ and EB1 is 4.8 km. In addition, the round-trip distance between EB1 and $EC_9$ is 4.8 km and 30 minutes need to be used to load and unload all materials. As a result, one more deployment occupies 34.8 minutes. After applying this modification, Van 1 needs 390.8 + 4.8 + 34.8 = 430.4 minutes and Van 2 needs 468.4 – 34.8 = 433.6 minutes. Since Van 2 uses more time than Van 1, Van 2 does not need to go back to EB; therefore, the time used by Van 2 is 433.6 – 2.4 = 431.2 minutes. In the end, the maximum deployment time becomes 431.2 minutes.

**Scenario Vb: Prince Street EB is responsible for EC4, EC6, EC7, EC8, EC9, and Paramount Drive EB is responsible for EC1, EC2, EC3, EC5, EC6, EC10**

| Full truckload | EC4 | EC6 | EC7 | EC8 | EC9 | |
|---|---|---|---|---|---|---|
| EB1 | 2 | 4 | 6 | 6 | 6 | |
| Full truckload | EC1 | EC2 | EC3 | EC5 | EC6 | EC10 |
| EB2 | 2 | 1 | 1 | 1 | 2 | 6 |

*Strategy 1: Use ranked ECs (distance between EB and EC) and van deployment strategy "together" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC8 | 6 | 2 | 3 | 1.1 | 6.6 | 6.6 | 90 | 96.6 | 0 | 96.6 | 0 | 96.6 |
| | 2 | EC7 | 6 | 2 | 3 | 1.8 | 10.8 | 10.8 | 90 | 100.8 | 96.6 | 197.4 | 96.6 | 197.4 |
| | 3 | EC4 | 2 | 2 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 197.4 | 230.6 | 197.4 | 230.6 |
| | 4 | EC9 | 6 | 2 | 3 | 2.4 | 14.4 | 14.4 | 90 | 104.4 | 230.6 | 335 | 230.6 | 335 |
| | 5 | EC6 | 4 | 2 | 2 | 4.3 | 12.9 | 12.9 | 60 | 72.9 | 335 | 407.9 | 335 | 407.9 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 0 | 211.2 | | |
| | 2 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 211.2 | 286.8 | | |
| | 3 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 286.8 | 360.4 | | |
| | 4 | EC5 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 360.4 | 396.2 | | |
| | 5 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 396.2 | 434.4 | | |
| | 6 | EC2 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 434.4 | 468.6 | | |

*Strategy 2: Use ranked ECs (distance between EB and EC) and van deployment strategy "unique" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC8 | 6 | 1 | 6 | 1.1 | 13.2 | 13.2 | 180 | 193.2 | 0 | 193.2 | 0 | 0 |
| | 2 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 193.2 | 193.2 | 0 | 201.6 |
| | 3 | EC4 | 2 | 1 | 2 | 1.6 | 6.4 | 6.4 | 60 | 66.4 | 193.2 | 259.6 | 201.6 | 201.6 |
| | 4 | EC9 | 6 | 1 | 6 | 2.4 | 28.8 | 28.8 | 180 | 208.8 | 259.6 | 259.6 | 201.6 | 410.4 |
| | 5 | EC6 | 4 | 1 | 4 | 4.3 | 30.1 | 30.1 | 120 | 150.1 | 259.6 | 409.7 | 410.4 | 410.4 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 0 | 211.2 | | |
| | 2 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 211.2 | 286.8 | | |
| | 3 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 286.8 | 360.4 | | |
| | 4 | EC5 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 360.4 | 396.2 | | |
| | 5 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 396.2 | 434.4 | | |
| | 6 | EC2 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 434.4 | 468.6 | | |

*Strategy 3: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "together" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC6 | 4 | 2 | 2 | 4.3 | 17.2 | 17.2 | 60 | 77.2 | 0 | 77.2 | 0 | 77.2 |
| | 2 | EC8 | 6 | 2 | 3 | 1.1 | 6.6 | 6.6 | 90 | 96.6 | 77.2 | 173.8 | 77.2 | 173.8 |
| | 3 | EC7 | 6 | 2 | 3 | 1.8 | 10.8 | 10.8 | 90 | 100.8 | 173.8 | 274.6 | 173.8 | 274.6 |
| | 4 | EC4 | 2 | 2 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 274.6 | 307.8 | 274.6 | 307.8 |
| | 5 | EC9 | 6 | 2 | 3 | 2.4 | 12 | 12 | 90 | 102 | 307.8 | 409.8 | 307.8 | 409.8 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 0 | 75.6 | | |
| | 2 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 75.6 | 149.2 | | |
| | 3 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 149.2 | 360.4 | | |
| | 4 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 360.4 | 398.6 | | |
| | 5 | EC2 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 398.6 | 437 | | |
| | 6 | EC5 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 437 | 469.9 | | |

*Strategy 4: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "unique" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC6 | 4 | 1 | 4 | 4.3 | 34.4 | 34.4 | 120 | 154.4 | 0 | 154.4 | 0 | 0 |
| | 2 | EC8 | 6 | 1 | 6 | 1.1 | 13.2 | 13.2 | 180 | 193.2 | 154.4 | 154.4 | 0 | 193.2 |
| | 3 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 154.4 | 356 | 193.2 | 193.2 |
| | 4 | EC4 | 2 | 1 | 2 | 1.6 | 6.4 | 6.4 | 60 | 66.4 | 356 | 356 | 193.2 | 259.6 |
| | 5 | EC9 | 6 | 1 | 6 | 2.4 | 26.4 | 26.4 | 180 | 206.4 | 356 | 356 | 259.6 | 466 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 0 | 75.6 | | |
| | 2 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 75.6 | 149.2 | | |
| | 3 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 149.2 | 360.4 | | |
| | 4 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 360.4 | 398.6 | | |
| | 5 | EC2 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 398.6 | 437 | | |
| | 6 | EC5 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 437 | 469.9 | | |

Similar to the exceptional circumstance illustrated in section 5.4, there is a big gap of time between the two vans in Prince Street EB (EB1). In the automated spreadsheet, Van 1 returns to the EB1 after sending enough RS and RC to $EC_7$. Consequently, Van 1 can deploy one more time directly from EB1 to $EC_9$ so as to reduce the time used by Van 2. The round-trip distance between EB1 and $EC_9$ is 4.8 km and 30 minutes need to be used to load and unload all materials. As a result, one more deployment occupies 34.8 minutes. After applying this modification, Van 1 needs 356 + 34.8 = 390.8 minutes and Van 2 needs 466 – 34.8 = 431.2 minutes. Although the gap between Van 1 and Van 2 is reduced, the maximum deployment time is still caused by Van 3, 469.9 minutes.

**Scenario VI: One van in Prince Street EB and two vans in Paramount Drive EB (The yellow cell in each strategy spreadsheet is the EC set up time in Phase 1 with an exception of Strategy 4)**

The total demands in ten ECs are 37 full truckloads of RS and RC. There is an assumption that Prince Street EB provides 12 truckloads and Paramount Drive EB offers 24 truckloads. The 37th truckload demand can be supplied by either Prince Street EB or Paramount Drive EB.

**Step 1**: Introduce a dummy EB to determine where the first 36 truckloads of RS and RC come from

| Km | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 5.3 | 4.8 | 6.6 | 1.6 | 3.9 | 4.3 | 1.8 | 1.1 | 2.4 | 5.1 |
| EB2 | 3.4 | 4.2 | 4.1 | 5.4 | 2.9 | 3.9 | 5.6 | 4.7 | 6.2 | 2.6 |
| EBD | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Km | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from EB | | Supply in EB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 0 | 0 | 0 | 1 | 0 | 0 | 6 | 0 | 5 | 0 | 12 | = | 12 |
| EB2 | 2 | 1 | 1 | 1 | 1 | 6 | 0 | 6 | 0 | 6 | 24 | = | 24 |
| EBD | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| Total to EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| | = | = | = | = | = | = | = | = | = | = | | | |
| Demand in EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| | | | | | | | | | | | Total travel distance | = | 115 |

**Step 2**: Apply the four deployment strategies twice to Scenario VI (Character "a" means the 37$^{th}$ truckload of demand is supplied by Prince Street EB, and "b" entails Paramount Drive EB)

**Scenario VIa: Prince Street EB is responsible for EC4, EC7, EC9, and Paramount Drive EB is responsible for EC1,EC2, EC3, EC4, EC5, EC6, EC8, EC10**

| Full truckload | EC4 | EC7 | EC9 | | | | | |
|---|---|---|---|---|---|---|---|---|
| EB1 | 1 | 6 | 6 | | | | | |
| Full truckload | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC8 | EC10 |
| EB2 | 2 | 1 | 1 | 1 | 1 | 6 | 6 | 6 |

*Strategy 1: Use ranked ECs (distance between EB and EC) and van deployment strategy "together" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 0 | 201.6 | | |
| | 2 | EC4 | 1 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 201.6 | 234.8 | | |
| | 3 | EC9 | 6 | 1 | 6 | 2.4 | 26.4 | 26.4 | 180 | 206.4 | 234.8 | 441.2 | | |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
| | 1 | ECQ | 6 | 2 | 3 | 2.6 | 15.6 | 15.6 | 90 | 105.6 | 0 | 105.6 | 0 | 105.6 |
| | 2 | EC6 | 6 | 2 | 3 | 3.9 | 23.4 | 23.4 | 90 | 113.4 | 105.6 | 219 | 105.6 | 219 |
| | 3 | EC8 | 6 | 2 | 3 | 4.7 | 28.2 | 28.2 | 90 | 118.2 | 219 | 337.2 | 219 | 337.2 |
| | 4 | EC1 | 2 | 2 | 1 | 3.4 | 6.8 | 6.8 | 30 | 36.8 | 337.2 | 374 | 337.2 | 374 |
| | 5 | EC4 | 1 | 1 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 374 | 414.8 | 374 | 374 |
| | 6 | EC5 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 414.8 | 414.8 | 374 | 409.8 |
| | 7 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 414.8 | 414.8 | 409.8 | 448 |
| | 8 | EC2 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 414.8 | 449 | 448 | 448 |

*Strategy 2: Use ranked ECs (distance between EB and EC) and van deployment strategy "unique" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 0 | 201.6 | | |
| | 2 | EC4 | 1 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 201.6 | 234.8 | | |
| | 3 | EC9 | 6 | 1 | 6 | 2.4 | 26.4 | 26.4 | 180 | 206.4 | 234.8 | 441.2 | | |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
| | 1 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 0 | 211.2 | 0 | 0 |
| | 2 | EC6 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 211.2 | 211.2 | 0 | 226.8 |
| | 3 | EC8 | 6 | 1 | 6 | 4.7 | 56.4 | 56.4 | 180 | 236.4 | 211.2 | 447.6 | 226.8 | 226.8 |
| | 4 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 447.6 | 447.6 | 226.8 | 300.4 |
| | 5 | EC4 | 1 | 1 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 447.6 | 447.6 | 300.4 | 341.2 |
| | 6 | EC5 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 447.6 | 447.6 | 341.2 | 377 |
| | 7 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 447.6 | 447.6 | 377 | 415.2 |
| | 8 | EC2 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 447.6 | 447.6 | 415.2 | 449.4 |

*Strategy 3: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "together" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 0 | 201.6 | | |
| | 2 | EC4 | 1 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 201.6 | 234.8 | | |
| | 3 | EC9 | 6 | 1 | 6 | 2.4 | 26.4 | 26.4 | 180 | 206.4 | 234.8 | 441.2 | | |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
| | 1 | EC6 | 6 | 2 | 3 | 3.9 | 23.4 | 23.4 | 90 | 113.4 | 0 | 113.4 | 0 | 113.4 |
| | 2 | EC1 | 2 | 2 | 1 | 3.4 | 6.8 | 6.8 | 30 | 36.8 | 113.4 | 150.2 | 113.4 | 150.2 |
| | 3 | EC8 | 6 | 2 | 3 | 4.7 | 28.2 | 28.2 | 90 | 118.2 | 150.2 | 268.4 | 150.2 | 268.4 |
| | 4 | EC4 | 1 | 1 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 268.4 | 309.2 | 268.4 | 268.4 |
| | 5 | ECQ | 6 | 2 | 3 | 2.6 | 15.6 | 15.6 | 90 | 105.6 | 309.2 | 414.8 | 268.4 | 374 |
| | 6 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 414.8 | 414.8 | 374 | 412.2 |
| | 7 | EC2 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 414.8 | 414.8 | 412.2 | 450.6 |
| | 8 | EC5 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 414.8 | 447.7 | 450.6 | 450.6 |

*Strategy 4: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "unique" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 0 | 201.6 | | |
| | 2 | EC4 | 1 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 201.6 | 234.8 | | |
| | 3 | EC9 | 6 | 1 | 6 | 2.4 | 26.4 | 26.4 | 180 | 206.4 | 234.8 | 441.2 | | |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
| | 1 | EC6 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 0 | 226.8 | 0 | 0 |
| | 2 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 226.8 | 226.8 | 0 | 73.6 |
| | 3 | EC8 | 6 | 1 | 6 | 4.7 | 56.4 | 56.4 | 180 | 236.4 | 226.8 | 226.8 | 73.6 | 310 |
| | 4 | EC4 | 1 | 1 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 226.8 | 267.6 | 310 | 310 |
| | 5 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 267.6 | 478.8 | 310 | 310 |
| | 6 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 478.8 | 478.8 | 310 | 348.2 |
| | 7 | EC2 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 478.8 | 478.8 | 348.2 | 386.6 |
| | 8 | EC5 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 478.8 | 478.8 | 386.6 | 419.5 |

Similar to the exceptional circumstance illustrated in section 5.4, there is a big gap of time between the two vans in Paramount Drive EB (EB2). In the automated spreadsheet, Van 3 does not return to the EB2 after sending enough RS and RC to $EC_5$. Consequently, Van 3 needs to return to the EB2 first, and then deploy one more time to $EC_{10}$ so as to reduce the time used by Van 2. The one-way distance between $EC_5$ and EB2 is 2.9 km. In addition, the round-trip distance between EB2 and $EC_{10}$ is 5.2 km and 30 minutes need to be used to load and unload all materials. As a result, one more deployment occupies 35.2 minutes. After applying this modification, Van 3 needs 419.5 + 2.9 + 35.2 = 457.6 minutes and Van 2 needs 478.8 – 35.2 = 443.6 minutes. Since Van 3 uses more time than Van 2, Van 3 does not need to go back to EB; therefore, the time used by Van 3 is 457.6 – 2.6 = 455 minutes. In the end, the maximum deployment time becomes 455 minutes.

**Scenario VIb: Prince Street EB is responsible for EC4, EC7, EC9, and Paramount Drive EB is responsible for EC1,EC2, EC3, EC4, EC5, EC6, EC8, EC9, EC10**

| Full truckload | EC4 | EC7 | EC9 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| EB1 | 1 | 6 | 5 | | | | | | |
| Full truckload | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC8 | EC9 | EC10 |
| EB2 | 2 | 1 | 1 | 1 | 1 | 6 | 6 | 1 | 6 |

*Strategy 1: Use ranked ECs (distance between EB and EC) and van deployment strategy "together" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 0 | 201.6 | | |
| | 2 | EC4 | 1 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 201.6 | 234.8 | | |
| | 3 | EC9 | 5 | 1 | 5 | 2.4 | 21.6 | 21.6 | 150 | 171.6 | 234.8 | 406.4 | | |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
| | 1 | ECQ | 6 | 2 | 3 | 2.6 | 15.6 | 15.6 | 90 | 105.6 | 0 | 105.6 | 0 | 105.6 |
| | 2 | EC6 | 6 | 2 | 3 | 3.9 | 23.4 | 23.4 | 90 | 113.4 | 105.6 | 219 | 105.6 | 219 |
| | 3 | EC8 | 6 | 2 | 3 | 4.7 | 28.2 | 28.2 | 90 | 118.2 | 219 | 337.2 | 219 | 337.2 |
| | 4 | EC1 | 2 | 2 | 1 | 3.4 | 6.8 | 6.8 | 30 | 36.8 | 337.2 | 374 | 337.2 | 374 |
| | 5 | EC9 | 1 | 1 | 1 | 6.2 | 12.4 | 12.4 | 30 | 42.4 | 374 | 416.4 | 374 | 374 |
| | 6 | EC4 | 1 | 1 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 416.4 | 416.4 | 374 | 414.8 |
| | 7 | EC5 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 416.4 | 416.4 | 414.8 | 450.6 |
| | 8 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 416.4 | 454.6 | 450.6 | 450.6 |
| | 9 | EC2 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 454.6 | 454.6 | 450.6 | 484.8 |

*Strategy 2: Use ranked ECs (distance between EB and EC) and van deployment strategy "unique" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 0 | 201.6 | | |
| | 2 | EC4 | 1 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 201.6 | 234.8 | | |
| | 3 | EC9 | 5 | 1 | 5 | 2.4 | 21.6 | 21.6 | 150 | 171.6 | 234.8 | 406.4 | | |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
| | 1 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 0 | 211.2 | 0 | 0 |
| | 2 | EC6 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 211.2 | 211.2 | 0 | 226.8 |
| | 3 | EC8 | 6 | 1 | 6 | 4.7 | 56.4 | 56.4 | 180 | 236.4 | 211.2 | 447.6 | 226.8 | 226.8 |
| | 4 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 447.6 | 447.6 | 226.8 | 300.4 |
| | 5 | EC9 | 1 | 1 | 1 | 6.2 | 12.4 | 12.4 | 30 | 42.4 | 447.6 | 447.6 | 300.4 | 342.8 |
| | 6 | EC4 | 1 | 1 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 447.6 | 447.6 | 342.8 | 383.6 |
| | 7 | EC5 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 447.6 | 447.6 | 383.6 | 419.4 |
| | 8 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 447.6 | 447.6 | 419.4 | 457.6 |
| | 9 | EC2 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 447.6 | 481.8 | 457.6 | 457.6 |

*Strategy 3: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "together" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 0 | 201.6 | | |
| | 2 | EC4 | 1 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 201.6 | 234.8 | | |
| | 3 | EC9 | 5 | 1 | 5 | 2.4 | 21.6 | 21.6 | 150 | 171.6 | 234.8 | 406.4 | | |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
| | 1 | EC6 | 6 | 2 | 3 | 3.9 | 23.4 | 23.4 | 90 | 113.4 | 0 | 113.4 | 0 | 113.4 |
| | 2 | EC1 | 2 | 2 | 1 | 3.4 | 6.8 | 6.8 | 30 | 36.8 | 113.4 | 150.2 | 113.4 | 150.2 |
| | 3 | EC8 | 6 | 2 | 3 | 4.7 | 28.2 | 28.2 | 90 | 118.2 | 150.2 | 268.4 | 150.2 | 268.4 |
| | 4 | EC4 | 1 | 1 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 268.4 | 309.2 | 268.4 | 268.4 |
| | 5 | EC9 | 1 | 1 | 1 | 6.2 | 12.4 | 12.4 | 30 | 42.4 | 309.2 | 309.2 | 268.4 | 310.8 |
| | 6 | ECQ | 6 | 2 | 3 | 2.6 | 15.6 | 15.6 | 90 | 105.6 | 309.2 | 414.8 | 310.8 | 416.4 |
| | 7 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 414.8 | 453 | 416.4 | 416.4 |
| | 8 | EC2 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 453 | 453 | 416.4 | 454.8 |
| | 9 | EC5 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 453 | 485.9 | 454.8 | 454.8 |

*Strategy 4: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "unique" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 0 | 201.6 | | |
| | 2 | EC4 | 1 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 201.6 | 234.8 | | |
| | 3 | EC9 | 5 | 1 | 5 | 2.4 | 21.6 | 21.6 | 150 | 171.6 | 234.8 | 406.4 | | |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van2 (min) | Van2 deployment time (min) | Start time Van3 (min) | Van3 deployment time (min) |
| | 1 | EC6 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 0 | 226.8 | 0 | 0 |
| | 2 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 226.8 | 226.8 | 0 | 73.6 |
| | 3 | EC8 | 6 | 1 | 6 | 4.7 | 56.4 | 56.4 | 180 | 236.4 | 226.8 | 226.8 | 73.6 | 310 |
| | 4 | EC4 | 1 | 1 | 1 | 5.4 | 10.8 | 10.8 | 30 | 40.8 | 226.8 | 267.6 | 310 | 310 |
| | 5 | EC9 | 1 | 1 | 1 | 6.2 | 12.4 | 12.4 | 30 | 42.4 | 267.6 | 310 | 310 | 310 |
| | 6 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 310 | 521.2 | 310 | 310 |
| | 7 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 521.2 | 521.2 | 310 | 348.2 |
| | 8 | EC2 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 521.2 | 521.2 | 348.2 | 386.6 |
| | 9 | EC5 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 521.2 | 521.2 | 386.6 | 419.5 |

Similar to the exceptional circumstance illustrated in section 5.4, there is a big gap of time between the two vans in Paramount Drive EB (EB2). In the automated spreadsheet, Van 3 does not return to the EB2 after sending enough RS and RC to $EC_5$. Consequently, Van 3 needs to return to the EB2 first, and then deploy one more time to $EC_{10}$ so as to reduce the time used by Van 2. The one-way distance between $EC_5$ and EB2 is 2.9 km. In addition, the round-trip distance between EB2 and $EC_{10}$ is 5.2 km and 30 minutes need to be used to load and unload all materials. As a result, one more deployment occupies 35.2 minutes. After applying this modification, Van 3 needs 419.5 + 2.9 + 35.2 = 457.6 minutes and Van 2 needs 521.2 – 35.2 = 486 minutes. Since Van 2 uses more time than Van 3, Van 2 does not need to go back to EB; therefore, the time used by Van 2 is 486 – 2.6 = 483.4 minutes. In the end, the maximum deployment time becomes 483.4 minutes.

# Appendix C: General Phase 2 EXCEL Solver Results

**Step 1**: Send RV buses from the Bus Centres (BCs) to the Affected Areas (AAs)

| Number of buses | BC1 | BC2 | Total to AA | | Demand in AA |
|---|---|---|---|---|---|
| AA1 | 0 | 1 | 1 | = | 1 |
| AA2 | 2 | 0 | 2 | = | 2 |
| AA3 | 1 | 0 | 1 | = | 1 |
| AA4 | 2 | 0 | 2 | = | 2 |
| AA5 | 0 | 2 | 2 | = | 2 |
| AA6 | 1 | 8 | 9 | = | 9 |
| AA7 | 0 | 1 | 1 | = | 1 |
| AA8 | 0 | 2 | 2 | = | 2 |
| AA9 | 0 | 3 | 3 | = | 3 |
| AA10 | 0 | 2 | 2 | = | 2 |
| AA11 | 0 | 2 | 2 | = | 2 |
| AA12 | 0 | 2 | 2 | = | 2 |
| AA13 | 0 | 2 | 2 | = | 2 |
| AA14 | 4 | 0 | 4 | = | 4 |
| AA15 | 1 | 0 | 1 | = | 1 |
| AA16 | 2 | 0 | 2 | = | 2 |
| AA17 | 0 | 2 | 2 | = | 2 |
| AA18 | 2 | 0 | 2 | = | 2 |
| AA19 | 0 | 2 | 2 | = | 2 |
| AA20 | 0 | 1 | 1 | = | 1 |
| Total from BC | 15 | 30 | | | |
| | = | = | | | |
| Supply in BC | 15 | 30 | | | |
| Total travel distance (km) | | | | = | 151.4 |

**Step 2**: Transport full buses from Affected Areas (AAs) to Evacuation Centres (ECs)

| Number of full buses | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA6 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 6 | 0 | 0 | 8 | = | 8 |
| AA7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | = | 2 |
| AA10 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA13 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA14 | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 0 | 0 | 0 | 3 | = | 3 |
| AA15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA17 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA18 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| Total to EC | 1 | 1 | 1 | 2 | 0 | 2 | 6 | 6 | 5 | 1 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | | |
| Supply in EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| Total travel distance (km) | | | | | | | | | | | | = | 37.27 |

**Step 3**: Transport remainders on partially full buses from Affected Areas (AAs) to Evacuation Centres (ECs)

| Partially full buses | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA7 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA9 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA13 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA14 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA20 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| Total to EC | 50 | 0 | 0 | 0 | 49 | 195 | 0 | 0 | 48 | 250 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | |
| Supply in EC | 50 | 0 | 0 | 0 | 50 | 200 | 0 | 0 | 50 | 250 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 64.52 |

# Appendix D: What-if Analysis Results

## D1: Results of Assumption I – What if the flood prevents certain routes to be used

**Phase 1 – Deliver Relief Staff (RS) and Relief Commodities (RCs) via Relief Vehicle (RV) vans to set up Evacuation Centres (ECs)**
As the characteristics of Scenario V described in section 4.3.5, the assumption is Prince Street EB provide 24 truckloads and Paramount Drive EB offer 12 truckloads (the total demand is 37 full truckloads of RS and RC).

**Step 1**: Introduce a dummy EB (EBD) to determine where the 37th truckload demand comes from

| Km | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 5.3 | 4.8 | 6.6 | 2.4 | 3.9 | 4.3 | 1.8 | 1.4 | 2.4 | 5.1 |
| EB2 | 3.4 | 4.2 | 4.1 | 5.4 | 2.9 | 3.9 | 5.6 | 4.7 | 6.2 | 2.6 |
| EBD | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Km | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from EB | | Supply in EB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 0 | 0 | 0 | 2 | 0 | 4 | 6 | 6 | 6 | 0 | 24 | = | 24 |
| EB2 | 2 | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 6 | 12 | = | 12 |
| EBD | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| Total to EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| | = | = | = | = | = | = | = | = | = | = | | | |
| Demand in EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 92.8 |

According to the illustration in section 5.9, the 37th truckload demand in EC2 is supplied by Prince Street EB (EB1). Prince Street EB (EB1) is responsible for EC2, EC4, EC6, EC7, EC8, EC9, and Paramount Drive EB (EB2) is responsible for EC1, EC3, EC5, EC6, EC10.

| Full truckload | EC2 | EC4 | EC6 | EC7 | EC8 | EC9 |
|---|---|---|---|---|---|---|
| EB1 | 1 | 2 | 4 | 6 | 6 | 6 |
| Full truckload | EC1 | EC3 | EC5 | EC6 | EC10 | |
| EB2 | 2 | 1 | 1 | 2 | 6 | |

**Step 2**: Apply four different strategies to deploy RS and RC according to the EC separation (The yellow cell in each strategy spreadsheet is the EC set up time in Phase 1)

*Strategy 1: Use ranked ECs (distance between EB and EC) and van deployment strategy "together" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC8 | 6 | 2 | 3 | 1.4 | 8.4 | 8.4 | 90 | 98.4 | 0 | 98.4 | 0 | 98.4 |
| | 2 | EC7 | 6 | 2 | 3 | 1.8 | 10.8 | 10.8 | 90 | 100.8 | 98.4 | 199.2 | 98.4 | 199.2 |
| | 3 | EC9 | 6 | 2 | 3 | 2.4 | 14.4 | 14.4 | 90 | 104.4 | 199.2 | 303.6 | 199.2 | 303.6 |
| | 4 | EC4 | 2 | 2 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 303.6 | 338.4 | 303.6 | 338.4 |
| | 5 | EC6 | 4 | 2 | 2 | 4.3 | 17.2 | 17.2 | 60 | 77.2 | 338.4 | 415.6 | 338.4 | 415.6 |
| | 6 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 415.6 | 450.4 | 415.6 | 415.6 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 0 | 211.2 | | |
| | 2 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 211.2 | 286.8 | | |
| | 3 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 286.8 | 360.4 | | |
| | 4 | EC5 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 360.4 | 396.2 | | |
| | 5 | EC3 | 1 | 1 | 1 | 4.1 | 4.1 | 4.1 | 30 | 34.1 | 396.2 | 430.3 | | |

*Strategy 2: Use ranked ECs (distance between EB and EC) and van deployment strategy "unique" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC8 | 6 | 1 | 6 | 1.4 | 16.8 | 16.8 | 180 | 196.8 | 0 | 196.8 | 0 | 0 |
| | 2 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 196.8 | 196.8 | 0 | 201.6 |
| | 3 | EC9 | 6 | 1 | 6 | 2.4 | 28.8 | 28.8 | 180 | 208.8 | 196.8 | 405.6 | 201.6 | 201.6 |
| | 4 | EC4 | 2 | 1 | 2 | 2.4 | 9.6 | 9.6 | 60 | 69.6 | 405.6 | 405.6 | 201.6 | 271.2 |
| | 5 | EC6 | 4 | 1 | 4 | 4.3 | 34.4 | 34.4 | 120 | 154.4 | 405.6 | 405.6 | 271.2 | 425.6 |
| | 6 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 405.6 | 440.4 | 425.6 | 425.6 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 0 | 211.2 | | |
| | 2 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 211.2 | 286.8 | | |
| | 3 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 286.8 | 360.4 | | |
| | 4 | EC5 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 360.4 | 396.2 | | |
| | 5 | EC3 | 1 | 1 | 1 | 4.1 | 4.1 | 4.1 | 30 | 34.1 | 396.2 | 430.3 | | |

*Strategy 3: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "together" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC6 | 4 | 2 | 2 | 4.3 | 17.2 | 17.2 | 60 | 77.2 | 0 | 77.2 | 0 | 77.2 |
| | 2 | EC7 | 6 | 2 | 3 | 1.8 | 10.8 | 10.8 | 90 | 100.8 | 77.2 | 178 | 77.2 | 178 |
| | 3 | EC4 | 2 | 2 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 178 | 212.8 | 178 | 212.8 |
| | 4 | EC8 | 6 | 2 | 3 | 1.4 | 8.4 | 8.4 | 90 | 98.4 | 212.8 | 311.2 | 212.8 | 311.2 |
| | 5 | EC9 | 6 | 2 | 3 | 2.4 | 14.4 | 14.4 | 90 | 104.4 | 311.2 | 415.6 | 311.2 | 415.6 |
| | 6 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 415.6 | 450.4 | 415.6 | 415.6 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 0 | 75.6 | | |
| | 2 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 75.6 | 149.2 | | |
| | 3 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 149.2 | 360.4 | | |
| | 4 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 360.4 | 398.6 | | |
| | 5 | EC5 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 398.6 | 431.5 | | |

*Strategy 4: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "unique" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC6 | 4 | 1 | 4 | 4.3 | 34.4 | 34.4 | 120 | 154.4 | 0 | 154.4 | 0 | 0 |
| | 2 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 154.4 | 154.4 | 0 | 201.6 |
| | 3 | EC4 | 2 | 1 | 2 | 2.4 | 9.6 | 9.6 | 60 | 69.6 | 154.4 | 224 | 201.6 | 201.6 |
| | 4 | EC8 | 6 | 1 | 6 | 1.4 | 16.8 | 16.8 | 180 | 196.8 | 224 | 224 | 201.6 | 398.4 |
| | 5 | EC9 | 6 | 1 | 6 | 2.4 | 28.8 | 28.8 | 180 | 208.8 | 224 | 432.8 | 398.4 | 398.4 |
| | 6 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 432.8 | 432.8 | 398.4 | 433.2 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | EC6 | 2 | 1 | 2 | 3.9 | 15.6 | 15.6 | 60 | 75.6 | 0 | 75.6 | | |
| | 2 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 75.6 | 149.2 | | |
| | 3 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 149.2 | 360.4 | | |
| | 4 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 360.4 | 398.6 | | |
| | 5 | EC5 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 398.6 | 431.5 | | |

**Phase 2 – Send RV buses to Affected Areas (AAs) and evacuate Affected People (AP) to open ECs**

Parameters for transportation and assignment problems in Phase 2 are as follows:

| Distance (km) | BC1 | BC2 | BC3 |
|---|---|---|---|
| AA1 | 1.8 | 5.1 | 0.95 |
| AA2 | 1.2 | 5.8 | 0.18 |
| AA3 | 0.8 | 4.6 | 0.75 |
| AA4 | 1.1 | 4.7 | 0.85 |
| AA5 | 1.4 | 4.8 | 1.2 |
| AA6 | 1.4 | 4.9 | 1.1 |
| AA7 | 2 | 4.5 | 1.7 |
| AA8 | 1.9 | 4.2 | 2.4 |
| AA9 | 1.7 | 4 | 2.5 |
| AA10 | 1.7 | 4 | 2.5 |
| AA11 | 3.6 | 0.2 | 5.4 |
| AA12 | 5 | 2.1 | 7.1 |
| AA13 | 4.6 | 1.1 | 8.6 |
| AA14 | 1.2 | 5.4 | 0.18 |
| AA15 | 4.4 | 8.7 | 3.6 |
| AA16 | 2.5 | 7.9 | 1.5 |
| AA17 | 4.6 | 7.6 | 5.6 |
| AA18 | 4.4 | 8.7 | 3.6 |
| AA19 | 2.7 | 4.3 | 3.4 |
| AA20 | 2.6 | 4.2 | 3.3 |

| Distance (km) | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 8.2 | 2.6 | 4.4 | 1.2 | 2.8 | 8.7 | 3.2 | 2.2 | 3.6 | 2.6 |
| AA2 | 8.6 | 2.9 | 4.8 | 0.95 | 3.5 | 4.8 | 3.2 | 1.5 | 3.8 | 3.3 |
| AA3 | 5.6 | 3.5 | 4.4 | 0.5 | 3.2 | 4.5 | 2.3 | 1.5 | 2.8 | 3.4 |
| AA4 | 5.6 | 4 | 5.8 | 2.7 | 3.6 | 4.6 | 2.2 | 1.7 | 2.7 | 4.3 |
| AA5 | 6.2 | 4.5 | 6.4 | 3 | 4.1 | 4.7 | 2.7 | 1.2 | 2.9 | 4.9 |
| AA6 | 6.2 | 4.2 | 6.1 | 1.8 | 3.9 | 6 | 2.8 | 1 | 3 | 4.6 |
| AA7 | 5.5 | 4.8 | 6.7 | 2.4 | 4.4 | 5.3 | 1.6 | 1.5 | 2.2 | 5.2 |
| AA8 | 4.6 | 5.9 | 7.7 | 2.2 | 4.3 | 4.3 | 1.3 | 1.5 | 1.3 | 4.5 |
| AA9 | 4.4 | 5.6 | 7.4 | 2.2 | 4.3 | 4.1 | 0.9 | 1.2 | 1.1 | 4.3 |
| AA10 | 4.4 | 5.6 | 7.4 | 2.2 | 4.2 | 4.1 | 0.7 | 1.2 | 1.1 | 4.2 |
| AA11 | 1.4 | 6.7 | 6.6 | 4.2 | 3.8 | 0.12 | 3.4 | 4 | 3.1 | 5 |
| AA12 | 2.4 | 9.6 | 9.6 | 5.7 | 5.2 | 2.1 | 3.6 | 5.5 | 3.5 | 6 |
| AA13 | 0.4 | 6.2 | 6.2 | 7.5 | 4.9 | 1.2 | 3.3 | 5 | 3.1 | 4.6 |
| AA14 | 8.9 | 3.3 | 5.1 | 0.85 | 3.8 | 5.3 | 2.9 | 1.2 | 3.4 | 3.6 |
| AA15 | 8 | 1.7 | 4.2 | 4 | 6.1 | 8.5 | 6 | 5.1 | 6.4 | 4.3 |
| AA16 | 7.3 | 1.6 | 3.4 | 1.8 | 5.3 | 7.7 | 3.8 | 2.8 | 4.2 | 1.7 |
| AA17 | 6.9 | 3.2 | 1.4 | 4.5 | 4.9 | 7.4 | 6.1 | 4.9 | 6.4 | 3.2 |
| AA18 | 8 | 1.7 | 4.2 | 4 | 6.1 | 8.5 | 6 | 5.1 | 6.4 | 4.3 |
| AA19 | 4.7 | 6.6 | 8.4 | 2.9 | 5.4 | 4.4 | 1.9 | 2.3 | 1.4 | 5.2 |
| AA20 | 4.6 | 6.5 | 6.4 | 3.1 | 5.4 | 4.3 | 1.9 | 2.1 | 1.3 | 5.1 |

| | No. full buses | Remainders on partially full bus |
|---|---|---|
| AA1 | 0 | 30 |
| AA2 | 1 | 23 |
| AA3 | 0 | 40 |
| AA4 | 1 | 48 |
| AA5 | 1 | 15 |
| AA6 | 8 | 46 |
| AA7 | 0 | 22 |
| AA8 | 1 | 5 |
| AA9 | 2 | 28 |
| AA10 | 1 | 3 |
| AA11 | 1 | 46 |
| AA12 | 1 | 29 |
| AA13 | 1 | 11 |
| AA14 | 3 | 49 |
| AA15 | 0 | 47 |
| AA16 | 1 | 39 |
| AA17 | 1 | 19 |
| AA18 | 1 | 31 |
| AA19 | 1 | 30 |
| AA20 | 0 | 31 |

**Step 1**: Deploy buses to AAs

| Number of buses | BC1 | BC2 | Total to AA | | Demand in AA |
|---|---|---|---|---|---|
| AA1 | 0 | 1 | 1 | = | 1 |
| AA2 | 2 | 0 | 2 | = | 2 |
| AA3 | 1 | 0 | 1 | = | 1 |
| AA4 | 2 | 0 | 2 | = | 2 |
| AA5 | 0 | 2 | 2 | = | 2 |
| AA6 | 1 | 8 | 9 | = | 9 |
| AA7 | 0 | 1 | 1 | = | 1 |
| AA8 | 0 | 2 | 2 | = | 2 |
| AA9 | 0 | 3 | 3 | = | 3 |
| AA10 | 0 | 2 | 2 | = | 2 |
| AA11 | 0 | 2 | 2 | = | 2 |
| AA12 | 0 | 2 | 2 | = | 2 |
| AA13 | 0 | 2 | 2 | = | 2 |
| AA14 | 4 | 0 | 4 | = | 4 |
| AA15 | 1 | 0 | 1 | = | 1 |
| AA16 | 2 | 0 | 2 | = | 2 |
| AA17 | 0 | 2 | 2 | = | 2 |
| AA18 | 2 | 0 | 2 | = | 2 |
| AA19 | 0 | 2 | 2 | = | 2 |
| AA20 | 0 | 1 | 1 | = | 1 |
| Total from BC | 15 | 30 | | | |
| | = | = | | | |
| Supply in BC | 15 | 30 | | | |
| | | | Total travel | = | 151.4 |
| | | | distance (km) | | |

**Step 2**: Transport full buses from AA to EC

| Number of full buses | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA6 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 6 | 0 | 0 | 8 | = | 8 |
| AA7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | = | 2 |
| AA10 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA13 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA14 | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 0 | 0 | 0 | 3 | = | 3 |
| AA15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA17 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA18 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| Total to EC | 1 | 1 | 1 | 2 | 0 | 2 | 6 | 6 | 5 | 1 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | | |
| Supply in EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 37.27 |

**Step 3**: Transport remainders from AA to EC

| Partially full buses | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA7 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA9 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA13 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA14 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA20 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| Total to EC | 50 | 0 | 0 | 0 | 49 | 195 | 0 | 0 | 48 | 250 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | |
| Supply in EC | 50 | 0 | 0 | 0 | 50 | 200 | 0 | 0 | 50 | 250 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 64.52 |

## D2: Results of Assumption II – What if van1 in Prince Street EB is out of use

**Phase 1 – Deliver Relief Staff (RS) and Relief Commodities (RCs) via Relief Vehicle (RV) vans to set up Evacuation Centres (ECs)**
As the characteristics of Scenario V described in section 4.3.5, the assumption is Prince Street EB provide 18 truckloads and Paramount Drive EB offer 18 truckloads (the total demand is 37 full truckloads of RS and RC).

**Step 1**: Introduce a dummy EB (EBD) to determine where the 37th truckload demand comes from

| Km | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 5.3 | 4.8 | 6.6 | 1.6 | 3.9 | 4.3 | 1.8 | 1.1 | 2.4 | 5.1 |
| EB2 | 3.4 | 4.2 | 4.1 | 5.4 | 2.9 | 3.9 | 5.6 | 4.7 | 6.2 | 2.6 |
| EBD | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Km | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from EB | | Supply in EB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 0 | 0 | 0 | 2 | 0 | 0 | 6 | 5 | 5 | 0 | 18 | = | 18 |
| EB2 | 2 | 1 | 1 | 0 | 1 | 6 | 0 | 1 | 0 | 6 | 18 | = | 18 |
| EBD | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| Total to EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| | = | = | = | = | = | = | = | = | = | = | | | |
| Demand in EC | 2 | 1 | 1 | 2 | 1 | 6 | 6 | 6 | 6 | 6 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 93.2 |

The 37th truckload demand is in EC9 that is supplied by EB1, so Prince Street EB (EB1) provide 19 truckloads and Paramount Drive EB (EB2) offer 18 truckloads. EB1 is responsible for EC4, EC7, EC8, EC9, and EB2 is responsible for EC1, EC2, EC3, EC5, EC6, EB8, EC10.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Full truckload | EC4 | EC7 | EC8 | EC9 | | | |
| EB1 | 2 | 6 | 5 | 6 | | | |
| Full truckload | EC1 | EC2 | EC3 | EC5 | EC6 | EC8 | EC10 |
| EB2 | 2 | 1 | 1 | 1 | 6 | 1 | 6 |

**Step 2**: Apply four different strategies to deploy RS and RC according to the EC separation (The yellow cell in each strategy spreadsheet is the EC set up time in Phase 1)

*Strategy 1&2: Use ranked ECs (distance between EB and EC)*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC8 | 5 | 1 | 5 | 1.1 | 11 | 11 | 150 | 161 | 0 | 161 |
| | 2 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 161 | 362.6 |
| | 3 | EC4 | 2 | 1 | 2 | 1.6 | 6.4 | 6.4 | 60 | 66.4 | 362.6 | 429 |
| | 4 | EC9 | 6 | 1 | 6 | 2.4 | 26.4 | 26.4 | 180 | 206.4 | 429 | 635.4 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) |
| | 1 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 0 | 211.2 |
| | 2 | EC6 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 211.2 | 438 |
| | 3 | EC8 | 1 | 1 | 1 | 4.7 | 9.4 | 9.4 | 30 | 39.4 | 438 | 477.4 |
| | 4 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 477.4 | 551 |
| | 5 | EC5 | 1 | 1 | 1 | 2.9 | 5.8 | 5.8 | 30 | 35.8 | 551 | 586.8 |
| | 6 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 586.8 | 625 |
| | 7 | EC2 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 625 | 659.2 |

*Strategy 3&4: Use ranked ECs (shortest distance between EC and AA)*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC8 | 5 | 1 | 5 | 1.1 | 11 | 11 | 150 | 161 | 0 | 161 |
| | 2 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 161 | 362.6 |
| | 3 | EC4 | 2 | 1 | 2 | 1.6 | 6.4 | 6.4 | 60 | 66.4 | 362.6 | 429 |
| | 4 | EC9 | 6 | 1 | 6 | 2.4 | 26.4 | 26.4 | 180 | 206.4 | 429 | 635.4 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) |
| | 1 | EC6 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 0 | 226.8 |
| | 2 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 226.8 | 300.4 |
| | 3 | EC8 | 1 | 1 | 1 | 4.7 | 9.4 | 9.4 | 30 | 39.4 | 300.4 | 339.8 |
| | 4 | ECQ | 6 | 1 | 6 | 2.6 | 31.2 | 31.2 | 180 | 211.2 | 339.8 | 551 |
| | 5 | EC3 | 1 | 1 | 1 | 4.1 | 8.2 | 8.2 | 30 | 38.2 | 551 | 589.2 |
| | 6 | EC2 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 589.2 | 627.6 |
| | 7 | EC5 | 1 | 1 | 1 | 2.9 | 2.9 | 2.9 | 30 | 32.9 | 627.6 | 660.5 |

**Phase 2 – Send RV buses to Affected Areas (AAs) and evacuate Affected People (AP) to open ECs**
Parameters for transportation and assignment problems do not change. Details for Phase 2 see Appendix C.

## D3: Results of Assumption III – What if three ECs ($EC_1$, $EC_6$, $EC_{11}$) are flooded and unavailable

**Phase 1 – Deliver Relief Staff (RS) and Relief Commodities (RCs) via Relief Vehicle (RV) vans to set up Evacuation Centres (ECs)**
As the characteristics of Scenario V described in section 4.3.5, the assumption is Prince Street EB provide 24 truckloads and Paramount Drive EB offer 12 truckloads (the total demand is 37 full truckloads of RS and RC).

**Step 1**: Introduce a dummy EB (EBD) to determine where the 37th truckload demand comes from

| Km | EC2 | EC3 | EC4 | EC5 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|
| EB1 | 4.8 | 6.6 | 1.6 | 3.9 | 1.8 | 1.1 | 2.4 | 5.1 |
| EB2 | 4.2 | 4.1 | 5.4 | 2.9 | 5.6 | 4.7 | 6.2 | 2.6 |
| EBD | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Km | EC2 | EC3 | EC4 | EC5 | EC7 | EC8 | EC9 | EC10 | Total from EB | | Supply in EB |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 0 | 0 | 3 | 0 | 7 | 7 | 7 | 0 | 24 | = | 24 |
| EB2 | 1 | 2 | 0 | 2 | 0 | 0 | 0 | 7 | 12 | = | 12 |
| EBD | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| Total to EC | 2 | 2 | 3 | 2 | 7 | 7 | 7 | 7 | | | |
| | = | = | = | = | = | = | = | = | | | |
| Demand in EC | 2 | 2 | 3 | 2 | 7 | 7 | 7 | 7 | | | |
| | | | | | | | | | Total travel distance (km) | = | 78.3 |

According to the illustration in section 5.9, the 37th truckload demand in EC2 is supplied by Prince Street EB (EB1). Prince Street EB is responsible for EC2, EC4, EC7, EC8, EC9, and Paramount Drive EB is responsible for EC2, EC3, EC5, EC10.

| Full truckload | EC2 | EC4 | EC7 | EC8 | EC9 |
|---|---|---|---|---|---|
| EB1 | 1 | 3 | 7 | 7 | 7 |
| Full truckload | EC2 | EC3 | EC5 | EC10 | |
| EB2 | 1 | 2 | 2 | 7 | |

**Step 2**: Apply four different strategies to deploy RS and RC according to the EC separation (The yellow cell in each strategy spreadsheet is the EC set up time in Phase 1)

*Strategy 1: Use ranked ECs (distance between EB and EC) and van deployment strategy "together" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC8 | 7 | 2 | 3 | 1.1 | 6.6 | 6.6 | 90 | 96.6 | 0 | 96.6 | 0 | 96.6 |
| | | EC8 | 1 | 1 | 1 | 1.1 | 2.2 | 2.2 | 30 | 32.2 | 96.6 | 128.8 | 96.6 | 96.6 |
| | 2 | EC7 | 7 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 128.8 | 128.8 | 96.6 | 130.2 |
| | | EC7 | 6 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 128.8 | 162.4 | 130.2 | 130.2 |
| | | EC7 | 5 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 162.4 | 162.4 | 130.2 | 163.8 |
| | | EC7 | 4 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 162.4 | 196 | 163.8 | 163.8 |
| | | EC7 | 3 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 196 | 196 | 163.8 | 197.4 |
| | | EC7 | 2 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 196 | 229.6 | 197.4 | 197.4 |
| | | EC7 | 1 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 229.6 | 229.6 | 197.4 | 231 |
| | 3 | EC4 | 3 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 229.6 | 262.8 | 231 | 231 |
| | | EC4 | 2 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 262.8 | 262.8 | 231 | 264.2 |
| | | EC4 | 1 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 262.8 | 296 | 264.2 | 264.2 |
| | 4 | EC9 | 7 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 296 | 296 | 264.2 | 299 |
| | | EC9 | 6 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 296 | 330.8 | 299 | 299 |
| | | EC9 | 5 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 330.8 | 330.8 | 299 | 333.8 |
| | | EC9 | 4 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 330.8 | 365.6 | 333.8 | 333.8 |
| | | EC9 | 3 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 365.6 | 365.6 | 333.8 | 368.6 |
| | | EC9 | 2 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 365.6 | 400.4 | 368.6 | 368.6 |
| | | EC9 | 1 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 400.4 | 400.4 | 368.6 | 403.4 |
| | 5 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 400.4 | 435.2 | 403.4 | 403.4 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | ECQ | 7 | 1 | 7 | 2.6 | 36.4 | 36.4 | 210 | 246.4 | 0 | 246.4 | | |
| | 2 | EC5 | 2 | 1 | 2 | 2.9 | 11.6 | 11.6 | 60 | 71.6 | 246.4 | 318 | | |
| | 3 | EC3 | 2 | 1 | 2 | 4.1 | 16.4 | 16.4 | 60 | 76.4 | 318 | 394.4 | | |
| | 4 | EC2 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 394.4 | 428.6 | | |

*Strategy 2: Use ranked ECs (distance between EB and EC) and van deployment strategy "unique" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC8 | 7 | 1 | 7 | 1.1 | 15.4 | 15.4 | 210 | 225.4 | 0 | 225.4 | 0 | 0 |
| | 2 | EC7 | 7 | 1 | 7 | 1.8 | 25.2 | 25.2 | 210 | 235.2 | 225.4 | 225.4 | 0 | 235.2 |
| | 3 | EC4 | 3 | 1 | 3 | 1.6 | 9.6 | 9.6 | 90 | 99.6 | 225.4 | 325 | 235.2 | 235.2 |
| | 4 | EC9 | 7 | 1 | 7 | 2.4 | 33.6 | 33.6 | 210 | 243.6 | 325 | 325 | 235.2 | 478.8 |
| | 6 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 325 | 359.8 | 478.8 | 478.8 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | ECQ | 7 | 1 | 7 | 2.6 | 36.4 | 36.4 | 210 | 246.4 | 0 | 246.4 | | |
| | 2 | EC5 | 2 | 1 | 2 | 2.9 | 11.6 | 11.6 | 60 | 71.6 | 246.4 | 318 | | |
| | 3 | EC3 | 2 | 1 | 2 | 4.1 | 16.4 | 16.4 | 60 | 76.4 | 318 | 394.4 | | |
| | 4 | EC2 | 1 | 1 | 1 | 4.2 | 4.2 | 4.2 | 30 | 34.2 | 394.4 | 428.6 | | |

Similar to the exceptional circumstance illustrated in section 5.4, there is a big gap of time between the two vans in EB1. In the automated spreadsheet, Van 1 does not return to the EB1 after sending enough RS and RC to $EC_2$. Consequently, Van 1 needs to return to the EB1 first, and then deploy two more time to $EC_9$ so as to reduce the time used by Van 2. The one-way distance between $EC_2$ and Prince Street EB is 4.8 km. In addition, the round-trip distance between Prince Street EB and $EC_9$ is 4.8 km and 30 minutes need to be used to load and unload all materials. As a result, two more deployment occupies 34.8 * 2 = 69.6 minutes. After applying this modification, Van 1 needs 359.8 + 4.8 + 69.6 = 434.2 minutes and Van 2 needs 478.8 – 69.9 = 408.9 minutes. Since Van 1 uses more time than Van 2, the last van truckload demand is delivered by Van 1 and Van 1 does not need to go back to EB; therefore, the time used by Van 1 is 434.2 – 2.4 = 431.8 minutes. In the end, the maximum deployment time becomes 431.8 minutes.

*Strategy 3: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "together" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC4 | 3 | 2 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 0 | 33.2 | 0 | 33.2 |
| | | EC4 | 1 | 1 | 1 | 1.6 | 3.2 | 3.2 | 30 | 33.2 | 33.2 | 66.4 | 33.2 | 33.2 |
| | 2 | EC8 | 7 | 1 | 1 | 1.1 | 2.2 | 2.2 | 30 | 32.2 | 66.4 | 66.4 | 33.2 | 65.4 |
| | | EC8 | 6 | 1 | 1 | 1.1 | 2.2 | 2.2 | 30 | 32.2 | 66.4 | 66.4 | 65.4 | 97.6 |
| | | EC8 | 5 | 1 | 1 | 1.1 | 2.2 | 2.2 | 30 | 32.2 | 66.4 | 98.6 | 97.6 | 97.6 |
| | | EC8 | 4 | 1 | 1 | 1.1 | 2.2 | 2.2 | 30 | 32.2 | 98.6 | 98.6 | 97.6 | 129.8 |
| | | EC8 | 3 | 1 | 1 | 1.1 | 2.2 | 2.2 | 30 | 32.2 | 98.6 | 130.8 | 129.8 | 129.8 |
| | | EC8 | 2 | 1 | 1 | 1.1 | 2.2 | 2.2 | 30 | 32.2 | 130.8 | 130.8 | 129.8 | 162 |
| | | EC8 | 1 | 1 | 1 | 1.1 | 2.2 | 2.2 | 30 | 32.2 | 130.8 | 163 | 162 | 162 |
| | 3 | EC7 | 7 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 163 | 163 | 162 | 195.6 |
| | | EC7 | 6 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 163 | 196.6 | 195.6 | 195.6 |
| | | EC7 | 5 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 196.6 | 196.6 | 195.6 | 229.2 |
| | | EC7 | 4 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 196.6 | 230.2 | 229.2 | 229.2 |
| | | EC7 | 3 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 230.2 | 230.2 | 229.2 | 262.8 |
| | | EC7 | 2 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 230.2 | 263.8 | 262.8 | 262.8 |
| | | EC7 | 1 | 1 | 1 | 1.8 | 3.6 | 3.6 | 30 | 33.6 | 263.8 | 263.8 | 262.8 | 296.4 |
| | 4 | EC9 | 7 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 263.8 | 298.6 | 296.4 | 296.4 |
| | | EC9 | 6 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 298.6 | 298.6 | 296.4 | 331.2 |
| | | EC9 | 5 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 298.6 | 333.4 | 331.2 | 331.2 |
| | | EC9 | 4 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 333.4 | 333.4 | 331.2 | 366 |
| | | EC9 | 3 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 333.4 | 368.2 | 366 | 366 |
| | | EC9 | 2 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 368.2 | 368.2 | 366 | 400.8 |
| | | EC9 | 1 | 1 | 1 | 2.4 | 4.8 | 4.8 | 30 | 34.8 | 368.2 | 403 | 400.8 | 400.8 |
| | 5 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 403 | 403 | 400.8 | 435.6 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | ECQ | 7 | 1 | 7 | 2.6 | 36.4 | 36.4 | 210 | 246.4 | 0 | 246.4 | | |
| | 2 | EC3 | 2 | 1 | 2 | 4.1 | 16.4 | 16.4 | 60 | 76.4 | 246.4 | 322.8 | | |
| | 3 | EC2 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 322.8 | 361.2 | | |
| | 4 | EC5 | 2 | 1 | 2 | 2.9 | 8.7 | 8.7 | 60 | 68.7 | 361.2 | 429.9 | | |

*Strategy 4: Use ranked ECs (shortest distance between EC and AA) and van deployment strategy "unique" to EC*

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC4 | 3 | 1 | 3 | 1.6 | 9.6 | 9.6 | 90 | 99.6 | 0 | 99.6 | 0 | 0 |
| | 2 | EC8 | 7 | 1 | 7 | 1.1 | 15.4 | 15.4 | 210 | 225.4 | 99.6 | 99.6 | 0 | 225.4 |
| | 3 | EC7 | 7 | 1 | 7 | 1.8 | 25.2 | 25.2 | 210 | 235.2 | 99.6 | 334.8 | 225.4 | 225.4 |
| | 4 | EC9 | 7 | 1 | 7 | 2.4 | 33.6 | 33.6 | 210 | 243.6 | 334.8 | 334.8 | 225.4 | 469 |
| | 5 | EC2 | 1 | 1 | 1 | 4.8 | 4.8 | 4.8 | 30 | 34.8 | 334.8 | 369.6 | 469 | 469 |

| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | ECQ | 7 | 1 | 7 | 2.6 | 36.4 | 36.4 | 210 | 246.4 | 0 | 246.4 |
| | 2 | EC3 | 2 | 1 | 2 | 4.1 | 16.4 | 16.4 | 60 | 76.4 | 246.4 | 322.8 |
| | 3 | EC2 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 322.8 | 361.2 |
| | 4 | EC5 | 2 | 1 | 2 | 2.9 | 8.7 | 8.7 | 60 | 68.7 | 361.2 | 429.9 |

Similar to the exceptional circumstance illustrated in section 5.4, there is a big gap of time between the two vans in EB1. In the automated spreadsheet, Van 1 does not return to the EB1 after sending enough RS and RC to $EC_2$. Consequently, Van 1 needs to return to the EB1 first, and then deploy two more time to $EC_9$ so as to reduce the time used by Van 2. The one-way distance between $EC_2$ and Prince Street EB is 4.8 km. In addition, the round-trip distance between Prince Street EB and $EC_9$ is 4.8 km and 30 minutes need to be used to load and unload all materials. As a result, two more deployment occupies 34.8 * 2 = 69.6 minutes. After applying this modification, Van 1 needs 369.6 + 4.8 + 34.8 = 409.2 minutes and Van 2 needs 469 – 34.8 = 432.2 minutes. Since Van 2 uses more time than Van 1, the last van truckload demand is delivered by Van 2 and Van 2 does not need to go back to EB; therefore, the time used by Van 2 is 432.2 – 2.4 = 431.8 minutes. In the end, the maximum deployment time becomes 431.8 minutes.

**Phase 2 – Send RV buses to Affected Areas (AAs) and evacuate Affected People (AP) to open ECs**

Parameters for transportation and assignment problems in Phase 2 are as follows:

| Distance (km) | BC1 | BC2 | BC3 |
|---|---|---|---|
| AA1 | 1.8 | 5.1 | 0.95 |
| AA2 | 1.2 | 5.8 | 0.18 |
| AA3 | 0.8 | 4.6 | 0.75 |
| AA4 | 1.1 | 4.7 | 0.85 |
| AA5 | 1.4 | 4.8 | 1.2 |
| AA6 | 1.4 | 4.9 | 1.1 |
| AA7 | 2 | 4.5 | 1.7 |
| AA8 | 1.9 | 4.2 | 2.4 |
| AA9 | 1.7 | 4 | 2.5 |
| AA10 | 1.7 | 4 | 2.5 |
| AA11 | 3.6 | 0.2 | 5.4 |
| AA12 | 5 | 2.1 | 7.1 |
| AA13 | 4.6 | 1.1 | 8.6 |
| AA14 | 1.2 | 5.4 | 0.18 |
| AA15 | 4.4 | 8.7 | 3.6 |
| AA16 | 2.5 | 7.9 | 1.5 |
| AA17 | 4.6 | 7.6 | 5.6 |
| AA18 | 4.4 | 8.7 | 3.6 |
| AA19 | 2.7 | 4.3 | 3.4 |
| AA20 | 2.6 | 4.2 | 3.3 |

| Distance (km) | EC2 | EC3 | EC4 | EC5 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|
| AA1 | 2.6 | 4.4 | 1.2 | 2.8 | 3.2 | 2.2 | 3.6 | 2.6 |
| AA2 | 2.9 | 4.8 | 0.95 | 3.5 | 3.2 | 1.5 | 3.8 | 3.3 |
| AA3 | 3.5 | 4.4 | 0.5 | 3.2 | 2.3 | 0.65 | 2.8 | 3.4 |
| AA4 | 4 | 5.8 | 0.85 | 3.6 | 2.2 | 0.8 | 2.7 | 4.3 |
| AA5 | 4.5 | 6.4 | 1.6 | 4.1 | 2.7 | 1.2 | 2.9 | 4.9 |
| AA6 | 4.2 | 6.1 | 1.8 | 3.9 | 2.8 | 1 | 3 | 4.6 |
| AA7 | 4.8 | 6.7 | 2.4 | 4.4 | 1.6 | 1.5 | 2.2 | 5.2 |
| AA8 | 5.9 | 7.7 | 2.2 | 4.3 | 1.3 | 1.5 | 1.3 | 4.5 |
| AA9 | 5.6 | 7.4 | 2.2 | 4.3 | 0.9 | 1.2 | 1.1 | 4.3 |
| AA10 | 5.6 | 7.4 | 2.2 | 4.2 | 0.7 | 1.2 | 1.1 | 4.2 |
| AA11 | 6.7 | 6.6 | 4.2 | 3.8 | 3.4 | 4 | 3.1 | 5 |
| AA12 | 9.6 | 9.6 | 5.7 | 5.2 | 3.6 | 5.5 | 3.5 | 6 |
| AA13 | 6.2 | 6.2 | 7.5 | 4.9 | 3.3 | 5 | 3.1 | 4.6 |
| AA14 | 3.3 | 5.1 | 0.85 | 3.8 | 2.9 | 1.2 | 3.4 | 3.6 |
| AA15 | 1.7 | 4.2 | 4 | 6.1 | 6 | 5.1 | 6.4 | 4.3 |
| AA16 | 1.6 | 3.4 | 1.8 | 5.3 | 3.8 | 2.8 | 4.2 | 1.7 |
| AA17 | 3.2 | 1.4 | 4.5 | 4.9 | 6.1 | 4.9 | 6.4 | 3.2 |
| AA18 | 1.7 | 4.2 | 4 | 6.1 | 6 | 5.1 | 6.4 | 4.3 |
| AA19 | 6.6 | 8.4 | 2.9 | 5.4 | 1.9 | 2.3 | 1.4 | 5.2 |
| AA20 | 6.5 | 6.4 | 3.1 | 5.4 | 1.9 | 2.1 | 1.3 | 5.1 |

| | No. full buses | Remainders on partially full bus |
|---|---|---|
| AA1 | 0 | 30 |
| AA2 | 1 | 23 |
| AA3 | 0 | 40 |
| AA4 | 1 | 48 |
| AA5 | 1 | 15 |
| AA6 | 8 | 46 |
| AA7 | 0 | 22 |
| AA8 | 1 | 5 |
| AA9 | 2 | 28 |
| AA10 | 1 | 3 |
| AA11 | 1 | 46 |
| AA12 | 1 | 29 |
| AA13 | 1 | 11 |
| AA14 | 3 | 49 |
| AA15 | 0 | 47 |
| AA16 | 1 | 39 |
| AA17 | 1 | 19 |
| AA18 | 1 | 31 |
| AA19 | 1 | 30 |
| AA20 | 0 | 31 |

**Step 1**: Deploy buses to AAs

| Number of buses | BC1 | BC2 | Total to AA | | Demand in AA |
|---|---|---|---|---|---|
| AA1 | 0 | 1 | 1 | = | 1 |
| AA2 | 2 | 0 | 2 | = | 2 |
| AA3 | 1 | 0 | 1 | = | 1 |
| AA4 | 2 | 0 | 2 | = | 2 |
| AA5 | 0 | 2 | 2 | = | 2 |
| AA6 | 1 | 8 | 9 | = | 9 |
| AA7 | 0 | 1 | 1 | = | 1 |
| AA8 | 0 | 2 | 2 | = | 2 |
| AA9 | 0 | 3 | 3 | = | 3 |
| AA10 | 0 | 2 | 2 | = | 2 |
| AA11 | 0 | 2 | 2 | = | 2 |
| AA12 | 0 | 2 | 2 | = | 2 |
| AA13 | 0 | 2 | 2 | = | 2 |
| AA14 | 4 | 0 | 4 | = | 4 |
| AA15 | 1 | 0 | 1 | = | 1 |
| AA16 | 2 | 0 | 2 | = | 2 |
| AA17 | 0 | 2 | 2 | = | 2 |
| AA18 | 2 | 0 | 2 | = | 2 |
| AA19 | 0 | 2 | 2 | = | 2 |
| AA20 | 0 | 1 | 1 | = | 1 |
| Total from BC | 15 | 30 | | | |
| | = | = | | | |
| Supply in BC | 15 | 30 | | | |
| | | | Total travel distance (km) | = | 151.4 |

**Step 2**: Transport full buses from AA to EC

| Number of full buses | EC2 | EC3 | EC4 | EC5 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA4 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA5 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA6 | 0 | 0 | 0 | 0 | 1 | 7 | 0 | 0 | 8 | = | 8 |
| AA7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA8 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA9 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | = | 2 |
| AA10 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA13 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA14 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 3 | = | 3 |
| AA15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA17 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA18 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| Total to EC | 2 | 1 | 3 | 0 | 7 | 7 | 4 | 1 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | | | |
| Supply in EC | 2 | 2 | 3 | 2 | 7 | 7 | 7 | 7 | | | |
| | | | | | | | | | Total travel distance (km) | = | 39.85 |

**Step 3**: Transport remainders from AA to EC

| Partially full buses | EC2 | EC3 | EC4 | EC5 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA5 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA7 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA8 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA9 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA10 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA11 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA12 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA13 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA17 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA18 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA20 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| Total to EC | 0 | 50 | 0 | 98 | 0 | 0 | 145 | 299 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | | |
| Supply in EC | 0 | 50 | 0 | ## | 0 | 0 | 150 | 300 | | | |
| | | | | | | | | | Total travel distance (km) | = | 57 |

## D4: Results of Assumption IV – What if the number of Affected People decreases or increases

### D4.1: Assumption of 2342 Affected People

**Situation:** Increase each EC's full capacity by 1 vans (50 Affected People), the total number of Affect People becomes 2342.

**Phase 1 – Deliver Relief Staff (RS) and Relief Commodities (RCs) via Relief Vehicle (RV) vans to set up Evacuation Centres (ECs)**
Since the total demand is 47 full truckloads of RS and RC, the assumption is Prince Street EB provide 30 truckloads and Paramount Drive EB offer 15 truckloads.

**Step 1**: Introduce a dummy EB to determine where the last 2 truckload demand comes from

| Km | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 5.3 | 4.8 | 6.6 | 1.6 | 3.9 | 4.3 | 1.8 | 1.1 | 2.4 | 5.1 |
| EB2 | 3.4 | 4.2 | 4.1 | 5.4 | 2.9 | 3.9 | 5.6 | 4.7 | 6.2 | 2.6 |
| EBD* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Km | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from EB | | Supply in EB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 0 | 0 | 0 | 3 | 0 | 6 | 7 | 7 | 7 | 0 | 30 | = | 30 |
| EB2 | 3 | 0 | 2 | 0 | 2 | 1 | 0 | 0 | 0 | 7 | 15 | = | 15 |
| EBD* | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | = | 2 |
| Total to EC | 3 | 2 | 2 | 3 | 2 | 7 | 7 | 7 | 7 | 7 | | | |
| | = | = | = | = | = | = | = | = | = | = | | | |
| Demand in EC | 3 | 2 | 2 | 3 | 2 | 7 | 7 | 7 | 7 | 7 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 114 |

There is an assumption: extra demands are always supplied by the EB with 2 vans, the results will be as follows. Prince Street EB is responsible for EC2, EC4, EC6, EC7, EC8, EC9, and Paramount Drive EB is responsible for EC1, EC3, EC5, EC6, EC10.

| Full truckload | EC2 | EC4 | EC6 | EC7 | EC8 | EC9 |
|---|---|---|---|---|---|---|
| EB1 | 2 | 3 | 6 | 7 | 7 | 7 |
| Full truckload | EC1 | EC3 | EC5 | EC6 | EC10 | |
| EB2 | 3 | 2 | 2 | 1 | 7 | |

**Step 2**: Use Strategy 4 to deploy RS and RC according to the segment

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC6 | 6 | 1 | 6 | 4.3 | 51.6 | 51.6 | 180 | 231.6 | 0 | 231.6 | 0 | 0 |
| | 2 | EC4 | 3 | 1 | 3 | 1.6 | 9.6 | 9.6 | 90 | 99.6 | 231.6 | 231.6 | 0 | 99.6 |
| | 3 | EC8 | 7 | 1 | 7 | 1.1 | 15.4 | 15.4 | 210 | 225.4 | 231.6 | 231.6 | 99.6 | 325 |
| | 4 | EC7 | 7 | 1 | 7 | 1.8 | 25.2 | 25.2 | 210 | 235.2 | 231.6 | 466.8 | 325 | 325 |
| | 5 | EC9 | 7 | 1 | 7 | 2.4 | 33.6 | 33.6 | 210 | 243.6 | 466.8 | 466.8 | 325 | 568.6 |
| | 6 | EC2 | 2 | 1 | 2 | 4.8 | 14.4 | 14.4 | 60 | 74.4 | 466.8 | 541.2 | 568.6 | 568.6 |
| **For EB2** | **Rank** | **EC** | **Total demand (van)** | **No. Vans** | **No. Round trips** | **Trip distance (km)** | **Total distance (km)** | **Travel time (min)** | **Total setup time (min)** | **Total time (min)** | **Start time Van3 (min)** | **Van3 deployment time (min)** | | |
| | 1 | EC6 | 1 | 1 | 1 | 3.9 | 7.8 | 7.8 | 30 | 37.8 | 0 | 37.8 | | |
| | 2 | EC1 | 3 | 1 | 3 | 3.4 | 20.4 | 20.4 | 90 | 110.4 | 37.8 | 148.2 | | |
| | 3 | ECQ | 7 | 1 | 7 | 2.6 | 36.4 | 36.4 | 210 | 246.4 | 148.2 | 394.6 | | |
| | 4 | EC3 | 2 | 1 | 2 | 4.1 | 16.4 | 16.4 | 60 | 76.4 | 394.6 | 471 | | |
| | 5 | EC5 | 2 | 1 | 2 | 2.9 | 8.7 | 8.7 | 60 | 68.7 | 471 | 539.7 | | |

**Phase 2 – Send RV buses to Affected Areas (AAs) and evacuate Affected People (AP) to open ECs**

**Step 1**: Deploy buses to AAs

| Number of buses | BC1 | BC2 | Total to AA | | Demand in AA |
|---|---|---|---|---|---|
| AA1 | 0 | 2 | 2 | = | 2 |
| AA2 | 2 | 0 | 2 | = | 2 |
| AA3 | 2 | 0 | 2 | = | 2 |
| AA4 | 3 | 0 | 3 | = | 3 |
| AA5 | 0 | 2 | 2 | = | 2 |
| AA6 | 2 | 8 | 10 | = | 10 |
| AA7 | 0 | 1 | 1 | = | 1 |
| AA8 | 0 | 2 | 2 | = | 2 |
| AA9 | 0 | 4 | 4 | = | 4 |
| AA10 | 0 | 2 | 2 | = | 2 |
| AA11 | 0 | 3 | 3 | = | 3 |
| AA12 | 0 | 3 | 3 | = | 3 |
| AA13 | 0 | 2 | 2 | = | 2 |
| AA14 | 5 | 0 | 5 | = | 5 |
| AA15 | 2 | 0 | 2 | = | 2 |
| AA16 | 3 | 0 | 3 | = | 3 |
| AA17 | 0 | 2 | 2 | = | 2 |
| AA18 | 3 | 0 | 3 | = | 3 |
| AA19 | 0 | 3 | 3 | = | 3 |
| AA20 | 0 | 2 | 2 | = | 2 |
| Total from BC | 22 | 36 | | | |
| | = | = | | | |
| Supply in BC | 22 | 36 | | | |
| | | | Total travel distance (km) | = | 187.1 |

**Step 2**: Transport full buses from AA to EC

| Number of full buses | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA3 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | = | 2 |
| AA5 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA6 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 7 | 0 | 0 | 9 | = | 9 |
| AA7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 3 | = | 3 |
| AA10 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | = | 2 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | = | 2 |
| AA13 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA14 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 1 | 4 | = | 4 |
| AA15 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | = | 2 |
| AA17 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA18 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | = | 2 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | = | 2 |
| AA20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| Total to EC | 1 | 2 | 2 | 3 | 0 | 4 | 7 | 7 | 7 | 5 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | | |
| Supply in EC | 3 | 2 | 2 | 3 | 2 | 7 | 7 | 7 | 7 | 7 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 60.64 |

**Step 3**: Transport remainders from AA to EC

| Partially full buses | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA3 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA5 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA6 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA7 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA8 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA10 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA13 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA14 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA20 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| Total to EC | 100 | 0 | 0 | 0 | 100 | 148 | 0 | 0 | 0 | 94 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | | |
| Supply in EC | 100 | 0 | 0 | 0 | 100 | 150 | 0 | 0 | 0 | 100 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 70.67 |

The longest route is from $AA_7$ to $EC_6$, that is, 5.3 km.

**D4.2: Assumption of 2842 Affected People**

**Situation**: Increase each EC’s full capacity by 2 vans (100 Affected People), the total number of Affect People becomes 2842.

**Phase 1 – Deliver Relief Staff (RS) and Relief Commodities (RCs) via Relief Vehicle (RV) vans to set up Evacuation Centres (ECs)**
Since the total demand is 57 full truckloads of RS and RC, the assumption is Prince Street EB provide 38 truckloads and Paramount Drive EB offer 19 truckloads.

**Step 1**: Make a separation among ten ECs

| Km | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 5.3 | 4.8 | 6.6 | 1.6 | 3.9 | 4.3 | 1.8 | 1.1 | 2.4 | 5.1 |
| EB2 | 3.4 | 4.2 | 4.1 | 5.4 | 2.9 | 3.9 | 5.6 | 4.7 | 6.2 | 2.6 |

| Km | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from EB | | Supply in EB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EB1 | 0 | 2 | 0 | 4 | 0 | 8 | 8 | 8 | 8 | 0 | 38 | = | 38 |
| EB2 | 4 | 1 | 3 | 0 | 3 | 0 | 0 | 0 | 0 | 8 | 19 | = | 19 |
| Total to EC | 4 | 3 | 3 | 4 | 3 | 8 | 8 | 8 | 8 | 8 | | | |
| | = | = | = | = | = | = | = | = | = | = | | | |
| Demand in EC | 4 | 3 | 3 | 4 | 3 | 8 | 8 | 8 | 8 | 8 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 152.4 |

Prince Street EB is responsible for EC2, EC4, EC6, EC7, EC8, EC9, and Paramount Drive EB is responsible for EC1, EC2, EC3, EC5, EC10.

| | | | | | | |
|---|---|---|---|---|---|---|
| Full truckload | EC2 | EC4 | EC6 | EC7 | EC8 | EC9 |
| EB1 | 2 | 4 | 8 | 8 | 8 | 8 |
| Full truckload | EC1 | EC2 | EC3 | EC5 | EC10 | |
| EB2 | 4 | 1 | 3 | 3 | 8 | |

**Step 2**: Use Strategy 4 to deploy RS and RC according to the segment

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC6 | 8 | 1 | 8 | 4.3 | 68.8 | 68.8 | 240 | 308.8 | 0 | 308.8 | 0 | 0 |
| | 2 | EC4 | 4 | 1 | 4 | 1.6 | 12.8 | 12.8 | 120 | 132.8 | 308.8 | 308.8 | 0 | 132.8 |
| | 3 | EC8 | 8 | 1 | 8 | 1.1 | 17.6 | 17.6 | 240 | 257.6 | 308.8 | 308.8 | 132.8 | 390.4 |
| | 4 | EC7 | 8 | 1 | 8 | 1.8 | 28.8 | 28.8 | 240 | 268.8 | 308.8 | 577.6 | 390.4 | 390.4 |
| | 5 | EC9 | 8 | 1 | 8 | 2.4 | 38.4 | 38.4 | 240 | 278.4 | 577.6 | 577.6 | 390.4 | 668.8 |
| | 6 | EC2 | 2 | 1 | 2 | 4.8 | 14.4 | 14.4 | 60 | 74.4 | 577.6 | 652 | 668.8 | 668.8 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | EC1 | 4 | 1 | 4 | 3.4 | 27.2 | 27.2 | 120 | 147.2 | 0 | 147.2 | | |
| | 2 | ECQ | 8 | 1 | 8 | 2.6 | 41.6 | 41.6 | 240 | 281.6 | 147.2 | 428.8 | | |
| | 3 | EC3 | 3 | 1 | 3 | 4.1 | 24.6 | 24.6 | 90 | 114.6 | 428.8 | 543.4 | | |
| | 4 | EC2 | 1 | 1 | 1 | 4.2 | 8.4 | 8.4 | 30 | 38.4 | 543.4 | 581.8 | | |
| | 5 | EC5 | 3 | 1 | 3 | 2.9 | 14.5 | 14.5 | 90 | 104.5 | 581.8 | 686.3 | | |

**Phase 2 – Send RV buses to Affected Areas (AAs) and evacuate Affected People (AP) to open ECs**

**Step 1**: Deploy buses to AAs

| Number of buses | BC1 | BC2 | Total to AA | | Demand in AA |
|---|---|---|---|---|---|
| AA1 | 0 | 2 | 2 | = | 2 |
| AA2 | 3 | 0 | 3 | = | 3 |
| AA3 | 2 | 0 | 2 | = | 2 |
| AA4 | 3 | 0 | 3 | = | 3 |
| AA5 | 0 | 3 | 3 | = | 3 |
| AA6 | 4 | 6 | 10 | = | 10 |
| AA7 | 0 | 2 | 2 | = | 2 |
| AA8 | 0 | 3 | 3 | = | 3 |
| AA9 | 0 | 4 | 4 | = | 4 |
| AA10 | 0 | 3 | 3 | = | 3 |
| AA11 | 0 | 3 | 3 | = | 3 |
| AA12 | 0 | 3 | 3 | = | 3 |
| AA13 | 0 | 3 | 3 | = | 3 |
| AA14 | 5 | 0 | 5 | = | 5 |
| AA15 | 2 | 0 | 2 | = | 2 |
| AA16 | 3 | 0 | 3 | = | 3 |
| AA17 | 0 | 3 | 3 | = | 3 |
| AA18 | 3 | 0 | 3 | = | 3 |
| AA19 | 0 | 3 | 3 | = | 3 |
| AA20 | 0 | 2 | 2 | = | 2 |
| Total from BC | 25 | 40 | | | |
| | = | = | | | |
| Supply in BC | 25 | 40 | | | |
| | | | Total travel distance (km) | = | 208 |

**Step 2**: Transport full buses from AA to EC

| Number of full buses | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | = | 2 |
| AA3 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | = | 2 |
| AA5 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | = | 2 |
| AA6 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 8 | 0 | 0 | 9 | = | 9 |
| AA7 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | = | 2 |
| AA9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 3 | = | 3 |
| AA10 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | = | 2 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | = | 2 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | = | 2 |
| AA13 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | = | 2 |
| AA14 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | = | 4 |
| AA15 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | = | 2 |
| AA17 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | = | 2 |
| AA18 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | = | 2 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | = | 2 |
| AA20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| Total to EC | 2 | 3 | 2 | 4 | 1 | 4 | 8 | 8 | 8 | 5 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | | |
| Supply in EC | 4 | 3 | 3 | 4 | 3 | 8 | 8 | 8 | 8 | 8 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 65.84 |

**Step 3**: Transport remainders from AA to EC

| Partially full buses | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA5 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA6 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA7 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA8 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA9 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA10 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA13 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA14 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | = | 1 |
| AA17 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA18 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA19 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA20 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| Total to EC | 100 | 0 | 50 | 0 | 98 | 195 | 0 | 0 | 0 | 149 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | | |
| Supply in EC | 100 | 0 | 50 | 0 | 100 | 200 | 0 | 0 | 0 | 150 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 68.67 |

The longest route is from $AA_{14}$ to $EC_6$, that is, 5.3 km.

**D4.3: Assumption of 1342 Affected People**

**Situation**: Decrease each EC's full capacity by 1 vans (50 Affected People), the total number of Affect People becomes 1342.

**Phase 1 – Deliver Relief Staff (RS) and Relief Commodities (RCs) via Relief Vehicle (RV) vans to set up Evacuation Centres (ECs)**
Since the total demand is 27 full truckloads of RS and RC, the assumption is Prince Street EB provide 18 truckloads and Paramount Drive EB offer 9 truckloads.

**Step 1**: Make a segment among the first six ECs (according to the ranking list: open EC6, EC1, EC8, EC7, EC4, EC9)

| Km | EC1 | EC4 | EC6 | EC7 | EC8 | EC9 |
|---|---|---|---|---|---|---|
| EB1 | 5.3 | 1.6 | 4.3 | 1.8 | 1.1 | 2.4 |
| EB2 | 3.4 | 5.4 | 3.9 | 5.6 | 4.7 | 6.2 |

| Km | EC1 | EC4 | EC6 | EC7 | EC8 | EC9 | Total from EB | | Supply in EB |
|---|---|---|---|---|---|---|---|---|---|
| EB1 | 0 | 2 | 0 | 6 | 5 | 5 | 18 | = | 18 |
| EB2 | 2 | 0 | 6 | 0 | 1 | 0 | 9 | = | 9 |
| Total to EC | 2 | 2 | 6 | 6 | 6 | 5 | | | |
| | = | = | = | = | = | = | | | |
| Demand in EC | 2 | 2 | 6 | 6 | 6 | 5 | | | |
| | | | | | | | Total travel distance (km) | = | 66.4 |

Prince Street EB is responsible for EC4, EC7, EC8, EC9, and Paramount Drive EB is responsible for EC1, EC6, EC8.

| Full truckload | EC4 | EC7 | EC8 | EC9 |
|---|---|---|---|---|
| EB1 | 2 | 6 | 5 | 5 |
| Full truckload | EC1 | EC6 | EC8 | |
| EB2 | 2 | 6 | 1 | |

**Step 2**: Use Strategy 4 to deploy RS and RC according to the segment

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC8 | 5 | 1 | 5 | 1.1 | 11 | 11 | 150 | 161 | 0 | 161 | 0 | 0 |
| | 2 | EC7 | 6 | 1 | 6 | 1.8 | 21.6 | 21.6 | 180 | 201.6 | 161 | 161 | 0 | 201.6 |
| | 3 | EC4 | 2 | 1 | 2 | 1.6 | 6.4 | 6.4 | 60 | 66.4 | 161 | 227.4 | 201.6 | 201.6 |
| | 4 | EC9 | 5 | 1 | 5 | 2.4 | 21.6 | 21.6 | 150 | 171.6 | 227.4 | 227.4 | 201.6 | 373.2 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | EC6 | 6 | 1 | 6 | 3.9 | 46.8 | 46.8 | 180 | 226.8 | 0 | 226.8 | | |
| | 2 | EC1 | 2 | 1 | 2 | 3.4 | 13.6 | 13.6 | 60 | 73.6 | 226.8 | 300.4 | | |
| | 3 | EC8 | 1 | 1 | 1 | 4.7 | 4.7 | 4.7 | 30 | 34.7 | 300.4 | 335.1 | | |

Similar to the exceptional circumstance illustrated in section 5.4, there is a big gap of time between the two vans in EB1. In the automated spreadsheet, Van 1 returns to the EB1 after sending enough RS and RC to $EC_4$. Consequently, Van 1 can directly deploy two more truckloads of materials from EB1 to $EC_9$ so as to reduce the time used by Van 2. The round-trip distance between Prince Street EB1 and $EC_9$ is 4.8 km and 30 minutes need to be used to load and unload all materials. As a result, two more deployment occupies 34.8 * 2 = 69.6 minutes. After applying this modification, Van 1 needs 227.4 + 69.6 = 297 minutes and Van 2 needs 373.2 – 69.6 = 303.6 minutes. Since Van 3 uses 335.1 minutes, the longest time among the three vans; therefore, the maximum deployment time becomes 335.1 minutes.

**Phase 2 – Send RV buses to Affected Areas (AAs) and evacuate Affected People (AP) to open ECs**

**Step 1**: Deploy buses to AAs

| Number of buses | BC1 | BC2 | Total to AA | | Demand in AA |
|---|---|---|---|---|---|
| AA1 | 0 | 1 | 1 | = | 1 |
| AA2 | 1 | 0 | 1 | = | 1 |
| AA3 | 1 | 0 | 1 | = | 1 |
| AA4 | 2 | 0 | 2 | = | 2 |
| AA5 | 0 | 1 | 1 | = | 1 |
| AA6 | 2 | 7 | 9 | = | 9 |
| AA7 | 0 | 0 | 0 | = | 0 |
| AA8 | 0 | 1 | 1 | = | 1 |
| AA9 | 0 | 3 | 3 | = | 3 |
| AA10 | 0 | 1 | 1 | = | 1 |
| AA11 | 0 | 2 | 2 | = | 2 |
| AA12 | 0 | 2 | 2 | = | 2 |
| AA13 | 0 | 1 | 1 | = | 1 |
| AA14 | 4 | 0 | 4 | = | 4 |
| AA15 | 1 | 0 | 1 | = | 1 |
| AA16 | 2 | 0 | 2 | = | 2 |
| AA17 | 0 | 1 | 1 | = | 1 |
| AA18 | 2 | 0 | 2 | = | 2 |
| AA19 | 0 | 2 | 2 | = | 2 |
| AA20 | 0 | 1 | 1 | = | 1 |
| Total from BC | 15 | 23 | | | |
| | <= | <= | | | |
| Supply in BC | 15 | 30 | | | |
| | | | Total travel distance (km) | = | 121 |

**Step 2**: Transport full buses from AA to EC

| Number of full buses | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 2 | 0 | 8 | = | 8 |
| AA7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA9 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | = | 2 |
| AA10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA14 | 0 | 0 | 0 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 3 | = | 3 |
| AA15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA18 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| Total to EC | 0 | 0 | 0 | 2 | 0 | 2 | 6 | 6 | 3 | 0 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | | |
| Supply in EC | 2 | 0 | 0 | 2 | 0 | 6 | 6 | 6 | 5 | 0 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 34.02 |

**Step 3**: Transport remainders from AA to EC

| Partially full buses | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA5 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA8 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA13 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA14 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA15 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA17 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| AA20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | = | 1 |
| Total to EC | 96 | 0 | 0 | 0 | 0 | 196 | 0 | 0 | 100 | 0 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | | |
| Supply in EC | 100 | 0 | 0 | 0 | 0 | 200 | 0 | 0 | 100 | 0 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 67.22 |

The longest route is from $AA_{15}$ to $EC_1$, that is, 8 km.

**D4.4: Assumption of 842 Affected People**

**Situation:** Decrease each EC's full capacity by 2 vans (100 Affected People), the total number of Affect People becomes 842.

**Phase 1 – Deliver Relief Staff (RS) and Relief Commodities (RCs) via Relief Vehicle (RV) vans to set up Evacuation Centres (ECs)**
Since the total demand is 17 full truckloads of RS and RC, the assumption is Prince Street EB provide 10 truckloads and Paramount Drive EB offer 5 truckloads.

**Step 1**: Introduce a dummy EB to determine where the last 2 truckloads demand come from

| Km | EC1 | EC6 | EC7 | EC8 | | | |
|---|---|---|---|---|---|---|---|
| EB1 | 5.3 | 4.3 | 1.8 | 1.1 | | | |
| EB2 | 3.4 | 3.9 | 5.6 | 4.7 | | | |
| EBD* | 0 | 0 | 0 | 0 | | | |
| | | | | | | | |
| Km | EC1 | EC6 | EC7 | EC8 | Total from EB | | Supply in EB |
| EB1 | 0 | 1 | 3 | 6 | 10 | = | 10 |
| EB2 | 2 | 3 | 0 | 0 | 5 | = | 5 |
| EBD* | 0 | 2 | 0 | 0 | 2 | = | 2 |
| Total to EC | 2 | 6 | 3 | 6 | | | |
| | = | = | = | = | | | |
| Demand in EC | 2 | 6 | 3 | 6 | | | |
| | | | | | Total travel distance (km) | = | 34.8 |

There is an assumption: extra demands are always supplied by the EB with 2 vans, the results will be as follows. Prince Street EB is responsible for EC6, EC7, EC8, and Paramount Drive EB is responsible for EC1, EC6.

| Full truckload | EC6 | EC7 | EC8 |
|---|---|---|---|
| EB1 | 3 | 3 | 6 |
| Full truckload | EC1 | EC6 | |
| EB2 | 2 | 3 | |

**Step 2**: Use Strategy 4 to deploy RS and RC according to the segment

| For EB1 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van1 (min) | Van1 deployment time (min) | Start time Van2 (min) | Van2 deployment time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | EC6 | 3 | 1 | 3 | 4.3 | 25.8 | 25.8 | 90 | 115.8 | 0 | 115.8 | 0 | 0 |
| | 2 | EC8 | 6 | 1 | 6 | 1.1 | 13.2 | 13.2 | 180 | 193.2 | 115.8 | 115.8 | 0 | 193.2 |
| | 3 | EC7 | 3 | 1 | 3 | 1.8 | 9 | 9 | 90 | 99 | 115.8 | 214.8 | 193.2 | 193.2 |
| For EB2 | Rank | EC | Total demand (van) | No. Vans | No. Round trips | Trip distance (km) | Total distance (km) | Travel time (min) | Total setup time (min) | Total time (min) | Start time Van3 (min) | Van3 deployment time (min) | | |
| | 1 | EC6 | 3 | 1 | 3 | 3.9 | 23.4 | 23.4 | 90 | 113.4 | 0 | 113.4 | | |
| | 2 | EC1 | 2 | 1 | 2 | 3.4 | 10.2 | 10.2 | 60 | 70.2 | 113.4 | 183.6 | | |

**Phase 2 – Send RV buses to Affected Areas (AAs) and evacuate Affected People (AP) to open ECs**

**Step 1**: Deploy buses to AAs

| Number of buses | BC1 | BC2 | Total to AA | | Demand in AA |
|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | = | 0 |
| AA2 | 1 | 0 | 1 | = | 1 |
| AA3 | 0 | 0 | 0 | = | 0 |
| AA4 | 1 | 0 | 1 | = | 1 |
| AA5 | 1 | 0 | 1 | = | 1 |
| AA6 | 7 | 0 | 7 | = | 7 |
| AA7 | 0 | 0 | 0 | = | 0 |
| AA8 | 0 | 1 | 1 | = | 1 |
| AA9 | 0 | 2 | 2 | = | 2 |
| AA10 | 0 | 1 | 1 | = | 1 |
| AA11 | 0 | 1 | 1 | = | 1 |
| AA12 | 0 | 1 | 1 | = | 1 |
| AA13 | 0 | 1 | 1 | = | 1 |
| AA14 | 3 | 0 | 3 | = | 3 |
| AA15 | 0 | 0 | 0 | = | 0 |
| AA16 | 1 | 0 | 1 | = | 1 |
| AA17 | 0 | 1 | 1 | = | 1 |
| AA18 | 1 | 0 | 1 | = | 1 |
| AA19 | 0 | 1 | 1 | = | 1 |
| AA20 | 0 | 0 | 0 | = | 0 |
| Total from BC | 15 | 9 | | | |
| | <= | <= | | | |
| Supply in BC | 15 | 30 | | | |
| | | | Total travel distance (km) | = | 55.5 |

**Step 2**: Transport full buses from AA to EC

| Number of full buses | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 6 | = | 6 |
| AA7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA9 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | = | 1 |
| AA10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA14 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | = | 2 |
| AA15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| Total to EC | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 6 | 0 | 0 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | | |
| Supply in EC | 2 | 0 | 0 | 0 | 0 | 6 | 3 | 6 | 0 | 0 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 12.7 |

**Step 3**: Transport remainders from AA to EC

| Partially full buses | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 | Total from AA | | Demand in AA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA4 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA5 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA6 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA8 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA9 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA10 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA11 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA12 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA13 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA14 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| AA16 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA17 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA18 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA19 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | = | 1 |
| AA20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | = | 0 |
| Total to EC | 100 | 0 | 0 | 0 | 0 | 292 | 0 | 0 | 0 | 0 | | | |
| | <= | <= | <= | <= | <= | <= | <= | <= | <= | <= | | | |
| Supply in EC | 100 | 0 | 0 | 0 | 0 | 300 | 0 | 0 | 0 | 0 | | | |
| | | | | | | | | | | | Total travel distance (km) | = | 67.07 |

The longest route is from $AA_{18}$ to $EC_1$, that is, 8 km.