Disaster Relief Network Design: Investigating the Effects of Physical Barriers and Information Sharing

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ABSTRACT

Disaster Relief Network Design: Investigating the Effects of Physical Barriers and Information Sharing

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Concordia University, 2013

Planning, organizing, and managing logistics activities by humanitarian organizations before and after a disaster like a flood, plays an important role in the minimization of public suffering. This thesis investigates two crucial issues that define disaster relief network designs; these are the presence of physical barriers, such as flooded regions of different impacts, and the effect or lack of information sharing. It is common that natural and/or man-made disasters cause major disruptions in critical infrastructure. The availability and proper dissemination of information amongst key players provides efficient operations which are reflected in minimizing suffering. The integrated model analyzes six barrier - information sharing scenarios using modern decision support tools, such as geographic information systems and optimization tools. Montreal districts' populations and road network map are used for the investigation. First, Demand is forecasted based on flood damage estimates, locating central warehouses follows, then allocating regional warehouses, and finally routing solutions are computed. Both location-allocation and routing integrated models take capacity into consideration. The findings are, the lack of information sharing and the presence of barriers cause increase in travel distance as opposed to having full information disclosure and no barriers. Total distance traveled in the presence of scaled-cost-barriers were more than that of having forbidden-zone-barriers or no-barriers.

Dedications and Acknowledgments

This research is dedicated to my biological and spiritual family for their unconditional support, effort, and guidance. I am forever in debt.

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List of Acronyms

3PL	Third Party Logistics
CAD	Canadian Dollar currency
CRED	Centre for Research on the Epidemiology of Disasters
EM-DAT	Emergency Database, a CRED initiative
EMS	Emergency Medical Station
GA	Genetic Algorithm
GB	Giga Bytes
GHz	Giga Hertz
GIS	Geographic Information System
GPS	Global Positioning System
HL	Humanitarian Logistics
IFRC	International Federation of Red Cross Red Crescent
IP	Integer Programming
LAP	Location Allocation Problem
MIP	Mixed Integer Programming
NGO	Non-governmental organization
OD	Origin Destination
OECD	Organization for Economic Co-Operation and Development
RAM	Random Access Memory
SC	Supply Chain
SCM	Supply Chain Management
USD	United States of America Dollar currency
VRP	Vehicle Routing Problem
WFP	World Food Program

WHO	World Health Organization
WVI	World Vision International

Chapter 1

Introduction

The World Health Organization (WHO) defines a disaster as an unforeseen situation or event that causes damage, ecological disruption, human suffering, loss of human life, deterioration of health and health services on a scale sufficient to warrant an extraordinary response from outside the affected community or area. Though often caused by nature, disasters can have human origins. Causes of disasters can be: blizzard, ice storm, drought, epidemic, earthquake, explosion, fire, flood, hurricane, nuclear incident, tornado, volcano, hazardous material or transportation incident (such as a chemical spill). Disaster can be categorized in many ways: (1) those that can be predicted and those that are spontaneous, (2) those that happen for a period of time, and those that are sudden, (3) natural disasters, and man-made disasters (Wassenhove, 2006). Examples of sudden-onset disasters include earthquakes, hurricanes, tornadoes, as well as terrorist attacks, and chemical leaks, whereas famine, drought, and poverty as well as political and refugee crisis are categorized as slow-onset occurring disasters (Kovacs & Spens, 2009).

Hundreds of millions of people are affected by disasters each year. The numbers of natural disasters and the people affected by disasters have increased over recent years. According to the World Disasters Report published by the International Federation of Red Cross and Red Crescent Societies (IFRC), the average annual number of disasters during 2000-2004 was 55% higher than during 1995-1999, and disasters affected 33% more people during 2000-2004 than during 1995-1999 (Balcik & Beamon, 2008). The

International Disaster Database (EM-DAT), maintained by the WHO Collaborating Center for Research on the Epidemiology of the Disasters (CRED), and the United Nations' International Strategy for Disaster Reduction Program show that between 1974 and 2003, there were 6,637 natural disasters resulting in more than 5.1 billion affected people, 182 million homeless, 2 million deaths, and with a reported damage of $1.38 trillion USD. In 2008 alone, between 150 and 220 million people were affected by disasters, resulting in over 240,000 deaths; and financial loss of $190 - $270 billion were incurred. In Canada, The Great ice storm of 1998 that hit Eastern Ontario, Southern Quebec and New Brunswick resulted in more than 4 million people displaced, 3 million households without electricity; and property damage over CAD $5.5 billion. It has been predicted that, over the next 50 years, both natural and man-made disasters will increase fivefold and that worldwide costs caused by these events will amount to $64 trillion over this period (Blecken, 2010). This increasing trend in the number and impact of large-scale disasters, along with growing media coverage, has drawn growing attention from various relief organizations to manage the logistics of relief supplies efficiently by making strategic design and operational decisions in an integrated and rigorous manner.

The logistics of a disaster relief operation is the most costly part of disaster relief. It accounts for 40% up to 80% of total relief operations cost (McClintock, 2009; Balcik et al, 2010). Large disaster relief agencies are starting to realize the importance of investing in their supply chains. However, logistics are generally seen as an expense rather than a strategic advancement (Balcik and Beamon, 2008). Yet only 20% of all humanitarian organizations consistently and thoroughly measure the performance of their supply chain operations. Lack of planning, use of inefficient routes like airborne shipments, failure to pre-plan stocks, and congestion are evident in humanitarian logistics (Oloruntoba and Gray, 2006). Humanitarian organizations are in competition on resources, and donors (Balcik et al, 2010; Oloruntoba and Gray, 2009). Lack of coordination between players are noted (Blacik et al. 2010) although there is a notable formation of ad-hoc networks and the presences of swift-trust (Tatham & Kovacs, 2010). Despite the alarming figures, the strategic importance of effective SCM in the humanitarian domain is not yet recognized on a large scale (Blacken, 2010).

After the disaster has taken place, one of the major challenges is to distribute relief supplies (emergency food, water, medicine, shelter, and other supplies) from central storage locations to affected regions in need (usually within few hours of the disaster) amidst the potential damage of logistics infrastructure in place. The objective of disaster relief supply chain is to deliver the relief supplies to the right people, at the right place (areas affected by large-scale emergencies), at the right time, so as to minimize the human sufferings and loss of lives. This is achieved though the design and operation of a distribution system that facilitates the dispatching of different types of supplies from multiple storage facilities such as central warehouses to regional distribution centers where they can be picked up or further delivered to affected regions. Transportation accessibility and availability varies from one disaster's occurrence to another. Unpredictability of exact demand forecasts is another dominating characteristic that brings additional complexity and unique challenges to the design and operation of relief supply chains (in terms of timing, location, type, and size); sudden-occurrence of demand in large quantities and short lead times for a wide variety of supplies; high stakes associated with adequate and timely deliveries; and the lack of resources (supplies, people, technology, and transportation capacity). These characteristics arise a number of challenge in designing an effective and efficient distribution network of supplies' stocking facilities, planning stocking levels, and dispatching the required supplies from the stocking facility to geographically dispersed regions in need.

The contribution of this research study to the body of knowledge that is available in the disaster relief network design domain is the following:

- Analysis of the disaster relief network design problem by disaster type.
- Developed two integrated models that take capacity into consideration and tested them with a real case study. The models used are:
  - Location-Allocation Model (Yin and Mu, (2012), Pirkul and Schilling (1991)).
  - Vehicle Routing Problem (Matai et al. (2010), Toth and Vigo (2002)).
- Investigated barrier effects on disaster relief network designing (3 barrier scenarios).
- Investigated information sharing effects on disaster relief network designing (2 information sharing scenarios).
- Analyzed the modeled, 2 information sharing – 3 barrier, scenario matrix.

This thesis highlights the above aforementioned topics by using state-of-the art decision support tools under hypothetical scenarios of supply network barriers which constrain the locating central facilities decision and routing to the regional warehouses from the central ones. The next section, the literature review, more detail as to what are the definition and characteristics of disasters, what is disaster relief and what is significant about their operations as opposed to regular non-disaster related logistics are discussed. Mathematical models related to disaster relief network design, and specific network design considerations to be taken by the planners for different disasters are highlighted. Chapter 3 of the thesis will state the problem to be investigated, and the scenarios' details to be tackled. Chapter 4 will discuss the proposed solution methodology and the models that will be used. The numerical application will follow in Chapter 5, followed by conclusions and further works in Chapter 6.

Chapter 2

Literature Review

The topic of logistics for disasters is not a new one, however it has not received much coverage as other matured domains. Before investigating disaster relief network design, it is important to stop and define certain key topics. First define what disasters are, what is disaster relief and what characterizes it? What is special about disaster relief logistics as opposed to common commercial logistic operations? Is there a difference between preparing for a flood, an earthquake, or an explosion? What special characteristics there are for specific disaster relief supply networks? What about hurdles that obstruct the flow of goods in a relief network, i.e. barriers? Are they the same? What types of barriers are there and how to deal with them? Does the special characteristics of relief operations helps or hinders the efficiency of the operation? How is information handled between major stakeholders? Are there major collaborations?

All the above questions will be handled in this literature review section. Section 2.1 defines disasters, whereas section 2.2 defines and describes disaster relief, section 2.3 explores the characteristics of relief supply networks, section 2.4 highlights the uniqueness of relief operations as opposed to commercial operations and specifically from a holistic supply chain point of view, section 2.5 discusses network design models found in literatures by disaster category, and model's technical characteristics. Section 2.6 categorizes barrier types and their characteristics, finally section 2.7 discusses the topic of collaboration and information sharing.

2.1 Disasters

Disasters increased more than 50% after 2000 than before as reported by The International Federation of Red Cross Red Crescent. IFRC reported that disasters increased from 400 natural disasters in 1998 to an average of 707 per year from 1999 to 2003. (Beamon and Kotleba, 2006; Balcik and Beamon, 2008)). Disasters are increasing exponentially, Figure 1. It is expected that disasters will increase five folds in the next 50 years (Blecken, 2010). 150 - 220 million people were affected by disasters in 2008, resulting in over 240,000 deaths; and incurred financial loss within \$190 - \$270 billion range (Blacken, 2010). Disaster figures show that the overall trend is increasing; Haiti's 2010 earthquake is just a taste of what to come (Whybark et al. 2010). Whybark et al. (2010) point out that more than half of the planet's 20 costliest catastrophes, see white dashes in Figure 2, have occurred since 1970, due to (1) a world population that is

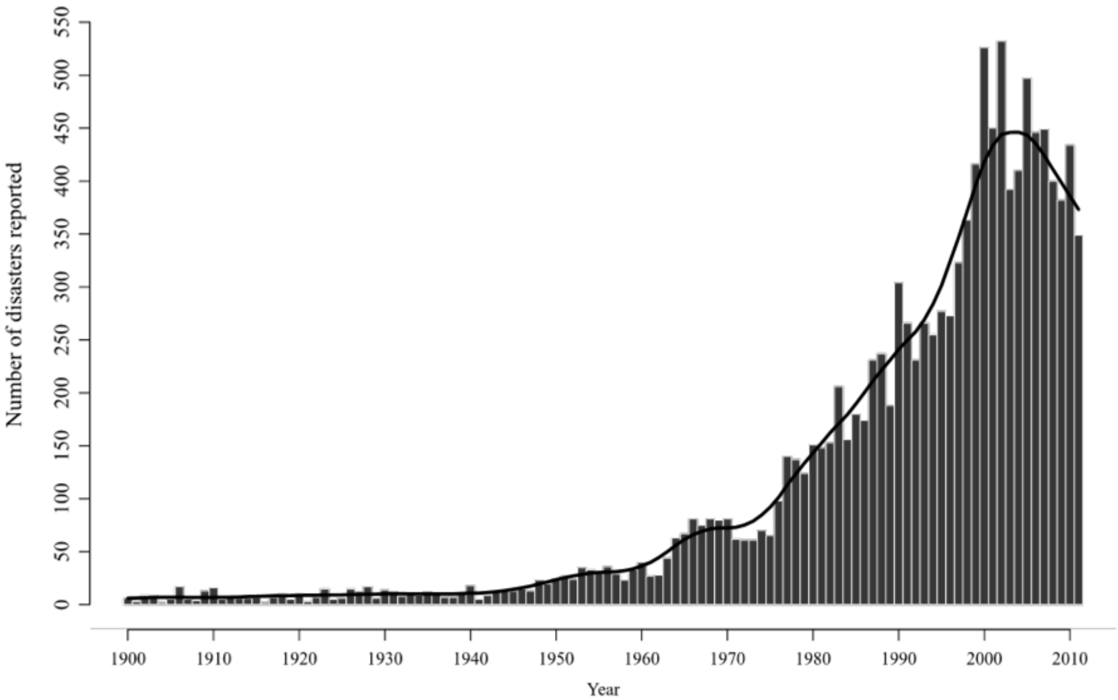


Figure 1 Natural Disasters Frequency, 1900 – 2011. (Source: EM-DAT, 2012)

quickly growing; (2) a larger concentration of assets (and people) in high-risk areas; and, (3) increasing social and economic interdependency.

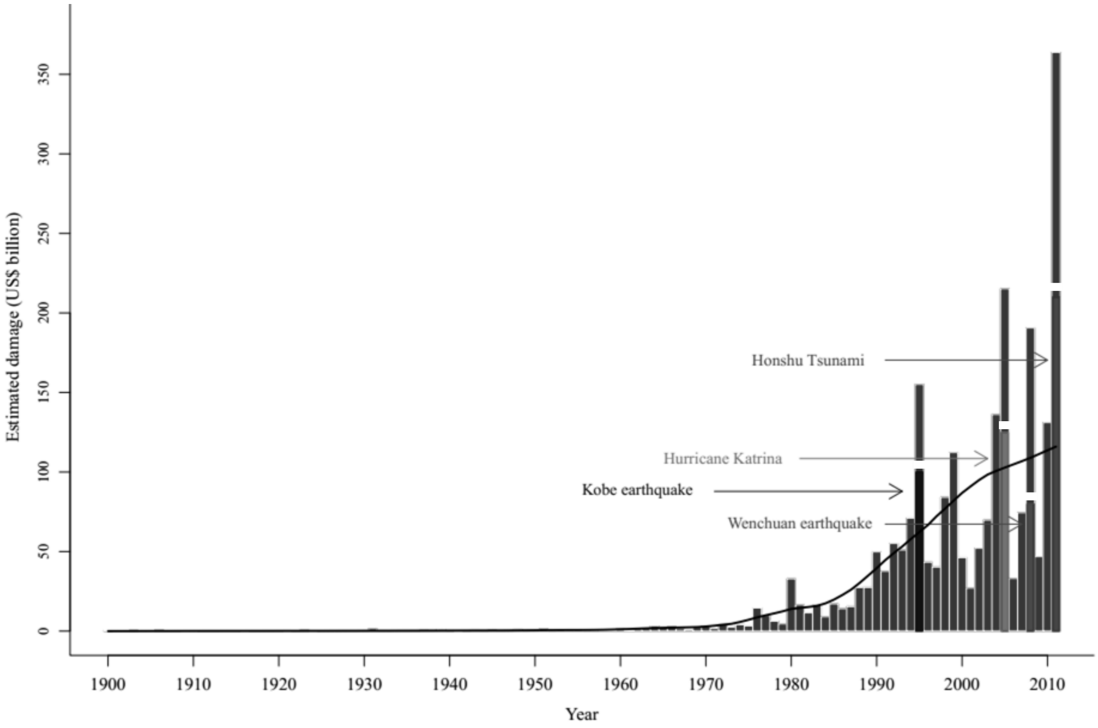


Figure 2 Annual disaster's damage estimates (US$ billion), 1900 – 2009. (Source: EM-DAT, 2012).

White dash reflects estimates of major disasters.

The definition of a disaster is relative. It can be both functional and quantitative. Disaster can be seen from different angles. There are those that can be predicted and those that are spontaneous. Another is natural disasters, and man-made disasters. All of which can be broken further into many subsets. Those that happen for a period of time, and those that are sudden and don't continue over time. For example under sudden-onset there can be earthquakes, hurricanes, tornadoes, as well as terrorist attacks, and chemical leaks. An example for slow-onset would be famine, drought, and poverty as well as political and refugee crisis. (Kovacs and Spens, 2009)

The International Disaster Database (EM-DAT) defines a disaster as, situation or event, which overwhelms local capacity, necessitating a request to national or international level for external assistance, typically an unforeseen and often sudden event that causes great damage, destruction and human suffering. Though often caused by nature, disasters can have human origins. Wars and civil disturbances that destroy homelands and displace people are included among disasters. Other causes can be: blizzard, drought, epidemic, earthquake, explosion, fire, flood, hazardous material or transportation incident (such as a chemical spill), hurricane, nuclear incident, tornado, or volcano. Altay, and Green (2006) have a supporting definition which states that "operationally, the transition to a higher category of emergency occurs when resources become stressed, when non-standard procedures must be implemented to save life or when special authorities must be invoked to manage the event. "

2.2 Disaster Relief

Disaster relief efforts have been increasing in quantity and quality. It is noted by the EM-DAT's 2010 report, that casualties figures have remained relatively the same, which indicates more disaster relief efforts. Disaster relief happens prior to the event, as well as after the event. A good disaster relief plan should integrate both stages, pre-event and post-event, in its strategy (Altay, and Green, 2006). A commonly used breakdown of disaster relief is preparation, response, and recovery (Pettit, and Beresford, 2005). Other authors such as Kovacs and Spens (2007) emphasize that relief operations are optimally a closed loop cycle, where lessons' learned are mitigated into preparation for the next disaster resulting in continuous improvement of operations. Figure 3, illustrates a micro and macro process view of relief operations. Note how the response and recovery phase intersect as it is critical to have synergy in these processes for increased disaster relief operational efficiency.

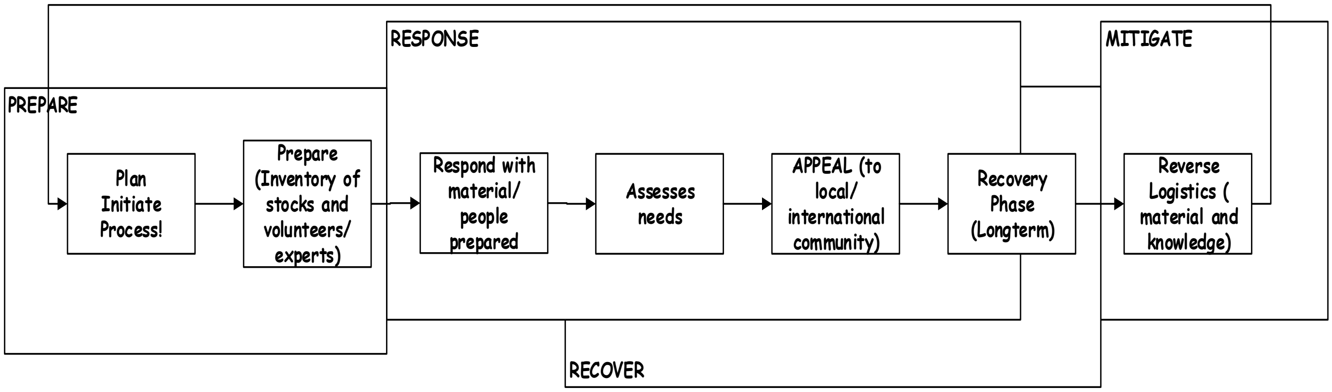


Figure 3 Disaster Relief Operations

Typically before a disaster strikes, the local authorities will have stocks of essentials at specific locations. The stocks as well as the prepared response plan differ by disaster type. From a logistics point of view, disaster relief can be broken into two levels, inbound logistics and outbound logistics (Wohlgemuth et al., 2012). Evacuation plans are an example of outbound logistics where inbound logistics would be bringing in material after a disaster strike. Stocking-up on essential life supporting goods, like canned food, blankets, and water sanitation kits, when done in preparation for a disaster would be inbound logistics where as when victims would be seeking out the shelters and the goods post a disaster it is outbound logistics. Earthquakes for example require a lot of outbound logistics in moving debris from damaged sites. A medical emergency would require people to be transported to hospitals which would be inbound logistics to the hospitals.

Section 2.5 dwells into the details of disaster relief network design issues related to different disaster types, a less developed research domain.

Beamon, and Balcik (2008) define relief activities as those short term activities that aim at minimizing immediate risks. Famine relief counted for about $5 billion worth of food in 1991 (Long, and Wood, 1995). The research domain has just begun to grow. Although the end goal of relief operations is to elevate suffering of victims, which might seem all coordinated and synchronized never the less the humanitarian space is very complex. "While operations and actors are intertwined, different groups of actors and different phases of disaster relief operations can be distinguished." (Beamon, and Balcik, 2008).

2.3 Characteristics of Disaster Relief Logistics

Logistics of disaster relief, is a sub branch of emergency logistics. Emergency logistics is defined as ‘‘A process of planning, managing and controlling the efficient flows of relief, information, and services from the points of origin to the points of destination to meet the urgent needs of the affected people under emergency conditions’’ (Balcik et al. 2010). Disaster relief is also a subset of the humanitarian operations. Unlike some humanitarian operations, sudden-disaster relief occurs without much warning they are a surprise to the system, and surpass current capacities, as opposed to ongoing operations like the case of a famine. "The objective of disaster response in the humanitarian relief chain is to rapidly provide relief (emergency food, water, medicine, shelter, and supplies) to areas affected by large-scale emergencies, so as to minimize human suffering and death" (Balcik and Beamon, 2008).

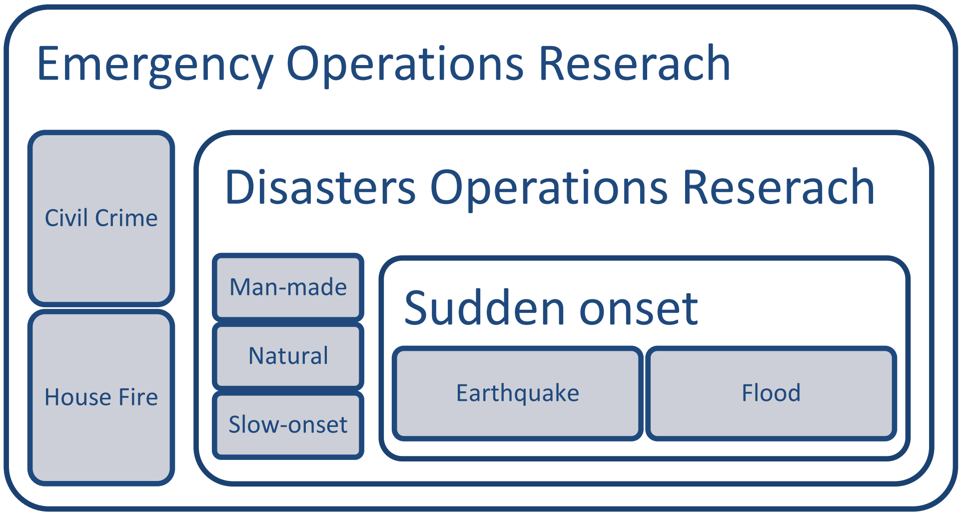


Figure 4 Thesis position within literature

Humanitarian aid has economic implications as well as social ones. Unlike common perspectives that disaster events drag the economy down, it helps stimulates the economy. "What is more, humanitarian aid has a significant economic importance" (Thomas and Fritz, 2006). Official expenditures on developing assistance programs alone counted for USI$ 103.7 billion in 2007 (OECD, 2008), not including private donors. This money goes into creating job for so many people, as well as buy merchandise from companies, governments and donors also pay for their transportation. This increase in the trafficking of people, money, merchandise, and related information stimulates the market.

Relief logistics operations, also known as humanitarian logistics, has similar managerial hierarchy to that of its commercial counterpart: strategic, tactical and operational, further they share similar functional processes of assessment, demand forecasts, procurement, warehousing, and transportation. Operational support takes place between the various functional levels while reporting would be done at the different managerial level. Blecken (2010) provides detailed example of how relief operations breakdown into these categories. Figure 5 shows Blecken's (2010) hierarchy, task’s breakdown, and relationships between both functional and operational levels.

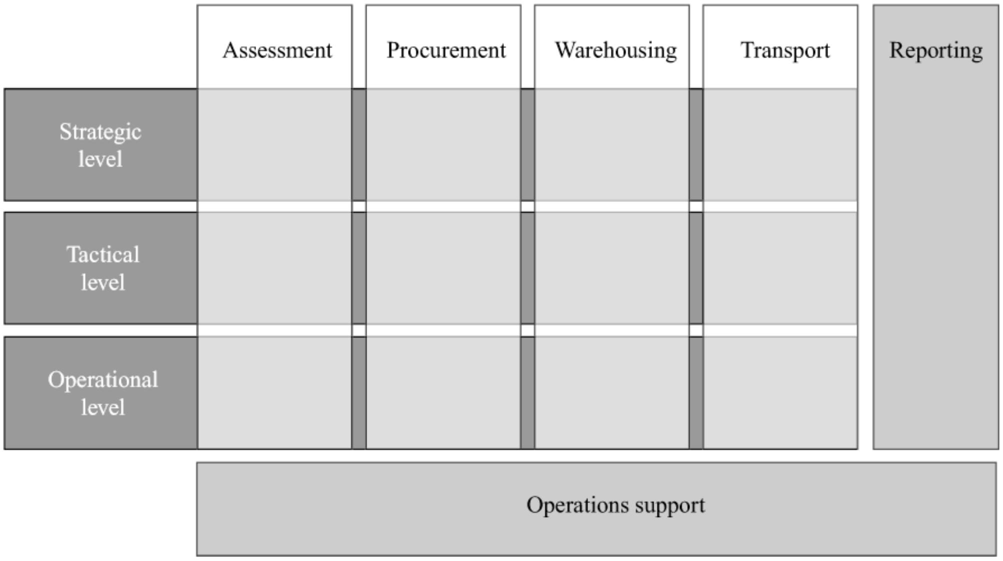


Figure 5 Disaster Relief Processes Reference Task Model. (Source: Blecken, 2010)

Humanitarian logistics, however, require special enablers to its processes. Expecting the unexpected, flexibility to demand changes, agile to resource availabilities, while maintaining speed, and efficiencies. The more money per relief operations, the bigger the relief capacity is, and the smaller the suffering of victims becomes. Disaster relief agencies face the complexity of planning at a strategic level while meeting donor's tight short term funding requirements. This means that funds come in to support a current relief operation made public in the media, however the task is to plan long term, where to place facilities, how much to stock, how many trucks to own, etc. Typically a call of appeal goes out to the donors after a disaster strikes to gather donations, typically after the first and second assessment another appeal is sent out to meet the gap between the preplanned response resources and the actual disaster’s impact. Unlike what most people perceive, customers of disaster relief organization are the donors, and beneficiaries providers (Oloruntoba and Grey, 2009; Beamon and Balcik, 2008); they provide the money needed to stimulate the “humanitarian” supply chain, i.e. it pays and funds the money all the way back to the raw material supplier. Never the less from a logistical point of view beneficiaries, disaster victims, are the end-user and final customers of humanitarian logistics.

Disaster relief supply chains are the most agile supply chains out there (Oloruntoba and Gray, 2006). This agility requirement is a double edge sword, it leads to competition amongst stakeholder on the few resources that are available, which increases the challenges of a disaster relief operations. For example, one observation is that as a disaster strike many self-initiated, smaller, less experienced groups form, these smaller initiatives create bottlenecks in the flow of good to the final beneficiaries. This occurs typically when there is no formal and transparent relationship between the small and large donors (See section 2.7 for more details on collaboration in relief supply chains). When proper collaboration occurs between stakeholders, these groups provide vital feedback and support to operations; they become specialists in their regions while working at a low overhead (Long and Wood, 1995). See Figure 6 to get a feeling of the humanitarian space and the variety of stakeholders involved. In another scenario they can be disruptive to operations, if not integrated properly, as they would also be fighting to secure some of the scarce resources, and are seen as a liability rather than an asset (Whybark et al. 2010).

Figure 6 explains the eminent collaboration (good or bad) that occurs amongst almost all types of organizations out there: government is one of them, local and international non-government organizations, military forces, also government and military forces from other countries coming in to the rescue complicating the space further.

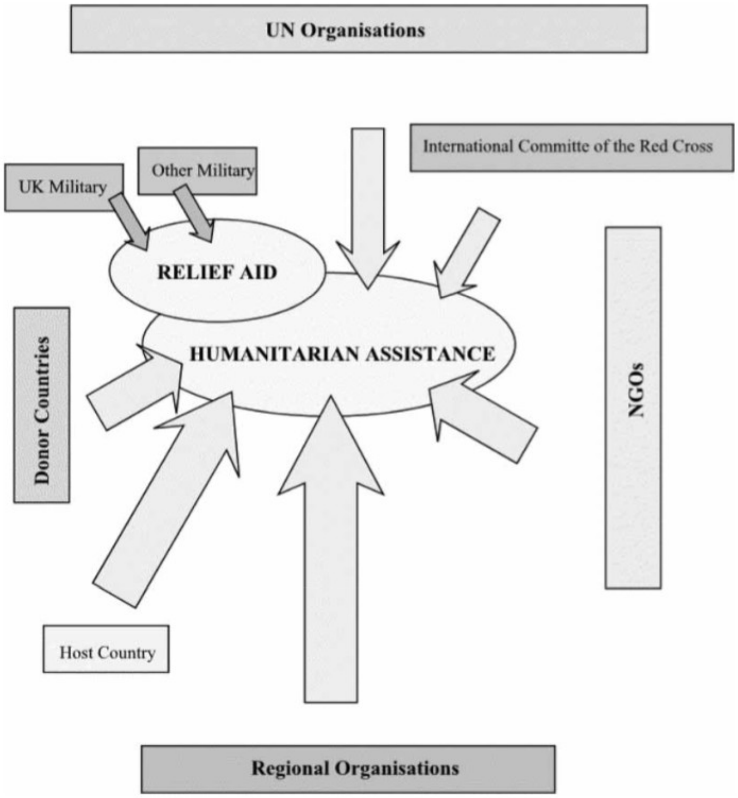


Figure 6 Humanitarian Relief Space. (Source: Pettit & Beresford, 2005)

Disaster relief supply chains have come a long way in recent years. For example, International Federation for Red Cross Red Crescent has won the 2006 Supply Chain Excellence Award of Europe. Further standardization initiatives have took place via dedicated organizations, for example The Sphere Project and LogCluster, alliances which were formed between academic, commercial, and humanitarian agencies. Organizations like WFP and IFRC as well as others who have identified their strategic advantage have retained their position in the market as 3PL, and excelled in that domain, as to ensure their continuity and efficiency.

Figure 7 Typical Humanitarian Supply Chain. (Source: Oloruntoba & Gray, 2006)

Relief chains of international organizations can be seen as two interlinked supply chains, one which is dormant, passive, and long term focused, i.e. strategic, and one which is active, current and more responsive, tactical and operational (Kovacs and Spens 2007, Jahre et al. 2009). Another view of relief supply chains is the resource view. The resource view sees the relief supply chain, in its entire complexity, as a set of resources which are available for multiple relief operations. Some resources are shared and others are unique. The combination of which determine the relief operation. Also it can be seen from a project management approach (Jahre et al, 2009). Viewing one's operations as part of a solo relief operation is critical in understanding one's role and function in the overall relief efforts. This mode would also enable sharing of resources between the project members as well as the synergy of operations and sharing of information. This organizational structure can help better visualize the complexity of a relief learnt from the more experienced organization, it also leads to establish most of best-in-class processes and frameworks. This type of complex process modeling have been explored further in literature (Chandana, and Leung, 2010; Blecken, 2010; Pettit, and Beresford, 2005).

Challenges faced by a humanitarian logistician vary according to their organization's mandate, the type of disaster, and the current stakeholder’s environment (Kovacs and Spens, 2009). The availability or lack of one key player can reduce challenges or add one (Whybark et al. 2010). The need for collaboration amongst stakeholders has been resonating in the academic domain. (Kovacs and Spens, 2011); although critical to relief operations this need have not until recently been identified (Balcik and Beamon, 2008). Section 2.6 will look more into details as to what collaboration types are there and the importance of sharing a resource such as information.

Managing large scale distribution networks further complexities of dealing with international exchange rates, tariffs, and cost of shipping which can include excessive air-freight costs. Identifying suppliers (local and/or international), conducting the procurement process, and identifying and renting potential warehouse sites are the most important activities in the design of networks (Duran et al., 2011).

For dealing with disasters efficiently and effectively, an agile supply chain is required (Oloruntoba and Gray, 2006). Prepositioning of relief supply can increase the ability to mobilize relief supplies and deliver aids quickly, however it can be financially prohibitive. As such, few relief organizations such as World Vision International (WVI) and United Nations' World Food Program are able to take on the expense of operating and coordinating international scale disaster relief supply chains. Transportation operations are outsourced to such large organizations for operational convenience, and economies of scale due to their specialization. Direct shipments to warehouses from suppliers are utilized, which can be costly at times. Storing in proximity eliminates the procurement process from the relief supply chain, leading to faster response, and reduction in human suffering. Key factors to a successful propositioning strategy are having an upfront capital investment for inventory and warehouse setup, operating costs of relief items, transportation, and warehouse running costs. Finally average response time is critical to monitor. Other topics such as Reverse Logistics are sighted in international organization's logistical reports. For example in an operational assessment report of Turkey's Earthquake of IFRC tents were gathered from the disaster site and stored at the warehouse again. Also after an earthquake there is logistics operations relating to the removal of debris. The topic of reverse logistics in disaster relief supply chains has received no attention from an academic point of view (Kovacs and Spens, 2011). The following section will explore the sited differences between disaster relief supply chains and commercial supply chains. The terms logistics, supply chain are used interchangeably in this study.

2.4 Disaster Relief Logistics versus Commercial Logistics

Table 1 Disaster Relief Logistics Versus Commercial Logistics

Type	**Disaster Relief Logistics**	**Commercial Logistics**	**Sources**
Commodity Type	Supply depends on what the donors have and want to provide	Order has to meet demand to make sales	Whybark et al. (2010)
Customers	End-users not customers of supplier, transport-carrier, or donor, the NGO is.	End-users are the main customers / and money source	Oloruntoba and Gray (2006); Long and Wood (1995)
Demand	Uncertain location, scale, scope	Relatively predictable	Beamon and Balcik (2008)
Distribution channels	Hard to predict due to demand location uncertainty, infrastructure status, in addition transportation might be unreliable due to political conflicts	Available, established, reliable, and static. Able to plan capacities prior to events.	Beamon and Balcik (2008)
Distribution model	Quick reaction and flexibility model based on real time communication	many distribution models are suited for repetitious actions	Long and Wood (1995)
End-users Complaints	End-user has no formal complaint mechanism, end-user has no power (monopoly)	End-users feedback is critical, customer have purchasing power	Long and Wood (1995); Oloruntoba and Gray (2006); Oloruntoba, and Gray (2009); Beamon and Balcik (2008)
Focus	NGOs have two major bottom lines: mission effectiveness and financial sustainability	focus on a single bottom line	Beamon and Balcik (2008)
Infrastructure	Destabilized	Stable	Beamon, and Balcik (2008)
Lead time	Zero lead time (no warning) between even and need	Accepted lead time, especially for customized products	Beamon and Balcik (2008)

Type	**Disaster Relief Logistics**	**Commercial Logistics**	**Sources**
Long term planning	Meeting short term objectives more important than building long term infrastructure due to donors funding demands … leads to short term ad hoc inefficient supply chains	For profits abide for long term strategic planning.	Beamon and Balcik (2008)
Management / Command and Control	Conflict of authority leading to delay in decision making due to distance, communication impediments	Conflicts of authority very unusual even across great distances	Whybark et al. (2010), Oloruntoba and Gray (2006)
Money Perception	"Money is the means to a desired social end." / money is a constraint	Money is an objective/ "the products and services delivered are the means to the end of making money"	Beamon and Balcik (2008)
Money Source	Money source at the upper end of the supply chain	End-user is money source	Beamon and Balcik (2008)
Overall Priority	Priority on real time communications and transportation assets	Commercial operations put more priority on procedures and capital investments.	Long and Wood (1995)
Performance Measures	No clear tangible indicators, variety of interests and standards of stakeholders	Clear indicators, financial statements are good performance indicator	Beamon and Balcik (2008)
Post-Activities	Planning post-disaster relief is explicitly critical for example materials use in reducing disaster can have a negative or positive effect on soil, or water availability after disaster response	Reverse logistics for end-of-life products is fairly new (especially in Europe)	Whybark et al. (2010)
Price	Suppliers often increase prices of commodities as disaster strikes. Price gauging is Exacerbated reoccurring bid request after disasters"	Pricing is relatively static over a reasonable time horizon	Beamon and Balcik (2008)
Publicity	Heavy press coverage on operations, creating coordination disincentives, competition for publicity, negative propagation	Not as much press coverage on operations - providing more "efficiency" or "sparing them scrutiny and management time"	Whybark et al. (2010)

Type	**Disaster Relief Logistics**	**Commercial Logistics**	**Sources**
SC formation	Supply Chain formation dependent on unprecedented events, and constraints. Key players might be absent, roads blocked, heightened security, etc.	Supply chains formation occurs given anticipated changing needs of customers.	Whybark et al. (2010); Beamon and Balcik (2008)
Self-Initiated Participants	Increased number of self-initiated participants	It would be odd to see large number of players integrate so quickly with an existing SC	Whybark et al. (2010)
Shifting Operational Needs	Changing processes (operational needs), skipping procedures, prioritizing operations over others	Not as dynamic, more stable	Whybark et al. (2010)
Shifting Overall Priorities	Shifting priorities from fast push response at high cost to more efficient network designs later on,	Rarely so quickly and radically as HL	Whybark et al. (2010)
Stakeholder's Interests	There might be trade-offs and Constraints by donors and benefit providers	Generally does not conflict with for-profit's long term goals	Beamon and Balcik (2008)
Supply Chain Evolution	Shifting in design as relief operation matures	Evolve as customer taste change but not as rapid	Whybark et al. (2010)
Supply Chain Roles	Donner is for the most part the supplier and is the customer who wants a good relief service!	The supplier is separate from the customer	Oloruntoba, and Gray (2009)
Time Pressure	Delay leads to Loss in life, increase in suffering,	Delay leads to Loss of market shares, loss in sales	Van Wassenhove (2006), Thomas and Kopczak (2005), Beamon and Balcik (2008)
Training	Staff is untrained / volunteers	Highly trained professionals	Oloruntoba, and Gray (2009)
Uncertainty and Information	High levels of uncertainty, if there is information might not be where needed in most cases	Significantly less than HL	Whybark et al. (2010)

2.5 Disaster Relief Network Design by Disaster Category

It is now evident that disaster relief supply chains are fundamentally different from commercial supply chains in many ways. After a major sudden-onset disaster strikes, a timely response is critical to saving human lives and mitigating affected population sufferings. In fact, the first few hours after a disaster strikes are critical as the chances for survival beyond that time window without water or food decreases drastically. The challenge is to deliver the right relief supplies (emergency food, water, medicine, shelter, and other supplies) to areas affected by large-scale emergencies, at the right time, and in the right quantities so as to minimize the human sufferings and loss of lives. However, in practice, the lack of planning, failure to pre-position emergency supplies, use of inefficient routes like airborne shipments, and congestion are evident in humanitarian relief supply chains (Oloruntoba and Gray, 2006). For example, Haiti earthquake left more than 2 million people homeless lacking basic necessities such as water and urgent medical care. Many of the needed supplies were present on site, however packed at the entry ports waiting to be processed for distribution. As a result of delayed relief, an increase in crime resulted. Victims desperately tried to loot the premise where the material resided (Ichoua, 2010). This problem could be overcome by the pre design of appropriate disaster relief supply chain that facilitates dispatching different types of supplies from multiple sources.

Disaster-specific characteristics should be taken into account when designing distribution networks, however only the most common disasters, such as hurricanes, epidemic, floods and earthquakes, have received attention in the literature. Reasons include large scale of a disaster, regional importance of a disaster, increased media attention, government's intervention, and increased data availability, among others. In this section, disaster relative network design characteristics are discussed. Specifically those disaster that received attention in the literature, namely man-made disasters, epidemics, large scale medical emergencies, oil spills, evacuation, hurricanes, earthquakes, floods, tsunamis, and military operations. The models are analyzed first with regards to their disaster focus, then by model's characteristics of coverage of logistics aspects of demand forecasting, facility location, demand allocation, inventory, and routing. The models are also analyzed with regards to their stochasticity, dynamism, single or multiple commodities, and objective functions, as well as the number of stages covered. Interestingly there is no straight correlation between the model type and the disasters. The following sections break down disaster relief network design into disaster categories. This is a unique view of the subject matter, which would provide for specific development in the literature disaster relief network designs specific to disaster types.

2.5.1 Network Designs for Manmade Disasters

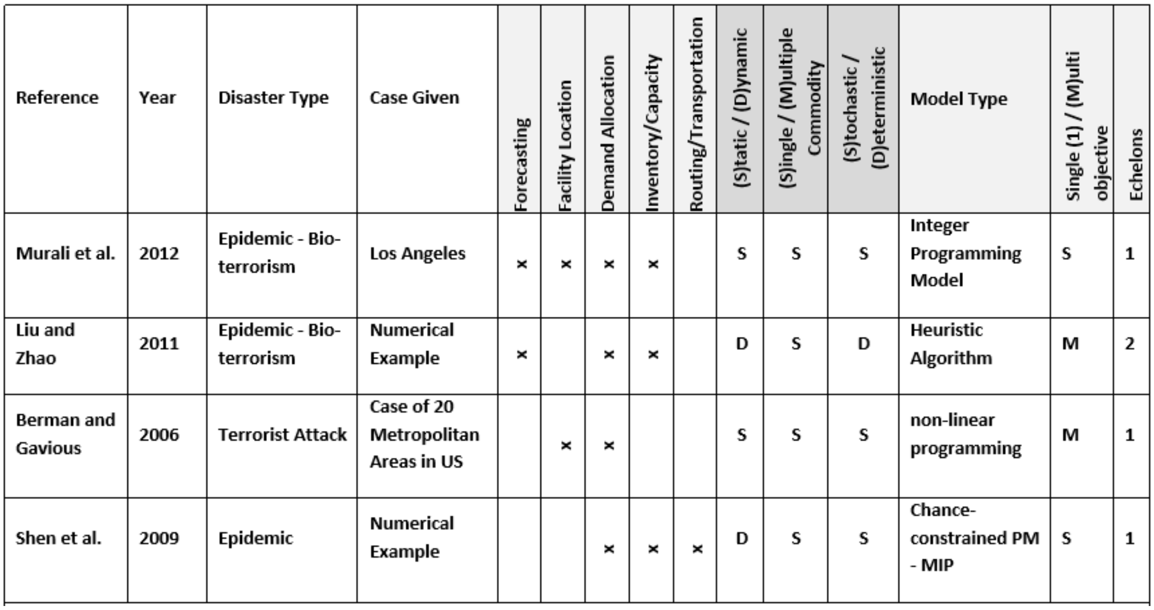
Man-made disasters, commonly referred to as terrorism, occurrences have been the same over the past millennia, and thus received attention just as natural disasters do. Institutionalizing mechanism to prevent or reduce disasters' impacts and deal with their consequences should be taken into consideration in any national emergency management network. The aforementioned strategic characteristics of emergency management have come to shape the agenda of the new command-and-control oriented Homeland Security System. The time to return to "business as usual" demonstrates the stability and resiliency of society. The definition of the man-made disaster at its initial stages is critical, it determines which response agencies have principal or lead responsibilities for addressing it and it largely determines the means employed to prevent or punish acts of terrorist violence (Waugh, 2003). Unlike natural disasters which utilize remote sensing tools for prediction, Waugh, (2003) indicated that man-made disasters are predicted using socioeconomic precipitants. This means that in some cases man-made disasters can be stopped with a significant amount of investment spent on prevention. Wright et al. (2006) identified several planning portfolios to countermeasure biological, chemical, radiological, explosive; and other component-support portfolios such as border and transportation security, critical infrastructure protection, cyber security, emergency preparedness and response, and threat analysis.

2.5.1.1 Epidemics Network Design

Liu and Zhao (2011) indicate that relief logistics for bio-terrorism disasters are complex due to the fact that it happens suddenly and is unpredictable; once the attack takes place the demand for particular medicine takes place. Relief/antidote has to be supplied in a specific time frame as to maximize the effectiveness, minimize delays, and stop further escalation of the disaster situation. Another characteristic that signifies this particular type of disaster is that it is between two players, namely the state and its relief resources and the terrorist which in many cases has more knowledge of the state’s resources, while the state is unaware of when, where, how, or what type of attack the terrorist will initiate (Berman and Gavious, 2006). Most of the literature reviewed covers Anthrax attacks as those are the ones that have been a recent threat in global affairs. Liu and Zhao (2011) also broke down the relief of a bio-terrorist attack into 3 stages. At stage 1, pre-diffusion of the bio-virus into the population, where facilities and pre-positioned supplies are sufficient to contain the casualties. At stage 2, the bio-virus has been diffused and more resources are required dynamically to contain the disaster and save lives. At stage 3, the decision is on how to replenish emergency resource to the local health departments, and allocate emergency resources to the epidemic areas.

Another interesting aspect of bio-terrorist attacks is that the area which is hit with the bio-virus has to be isolated from other areas. Logistical strategies as to accessing and leaving these areas have to be taken into consideration. Demand forecast has to be dynamic, quick, and precise to efficiently allocate the limited and precious supply of antidotes.

Table 2 Epidemic Related Network Design Models

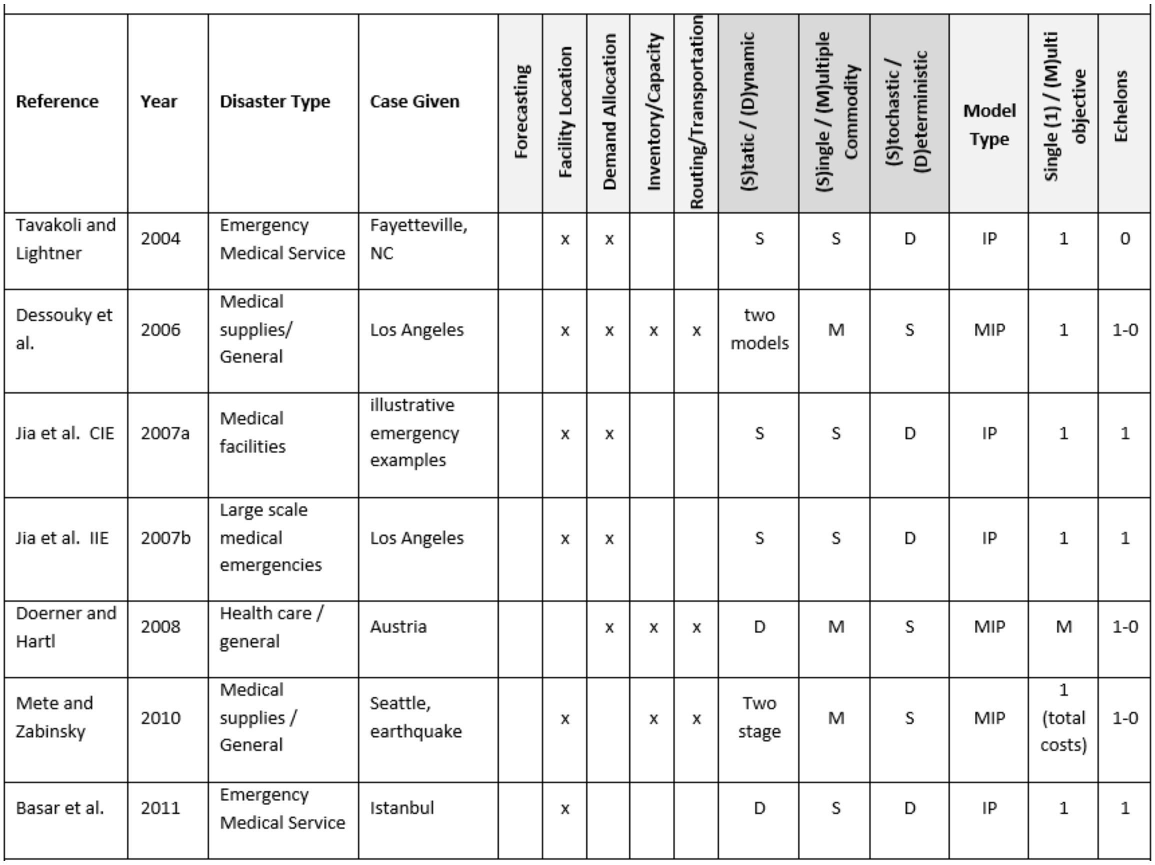


Reference	Year	Disaster Type	Case Given	Forecasting	Facility Location	Demand Allocation	Inventory/Capacity	Routing/Transportation	(S)tatic / (D)ynamic	(S)ingle / (M)ultiple Commodity	(S)tochastic / (D)eterministic	Model Type	Single (1) / (M)ulti objective	Echelons
Murali et al.	2012	Epidemic - Bio-terrorism	Los Angeles	×	×	×	×		S	S	S	Integer Programming Model	S	1
Liu and Zhao	2011	Epidemic - Bio-terrorism	Numerical Example	×		×	×		D	S	D	Heuristic Algorithm	M	2
Berman and Gavious	2006	Terrorist Attack	Case of 20 Metropolitan Areas in US		×	×			S	S	S	non-linear programming	M	1
Shen et al.	2009	Epidemic	Numerical Example			×	×	×	D	S	S	Chance-constrained PM - MIP	S	1

2.5.1.2 Large-scale Medical Emergency Service Network Design

When designing large-scale medical emergency service networks, one should take into consideration that local first responders are resources that will be overwhelmed, and false medical calls will increase due to public panic resulting in a huge demand appearing in a short period of time requiring logistical agility. Countries maintain a stockpile of medical supplies ready to be dispatched as needed; these stockpiles should be safe and easily accessible from multiple routes. Pharmaceutical supply chains are normally special in their complexity compared to regular supply chains (Jia et al., 2007a, and Jia et al., 2007b).

Table 3 Medical and Healthcare Related Network Design Models



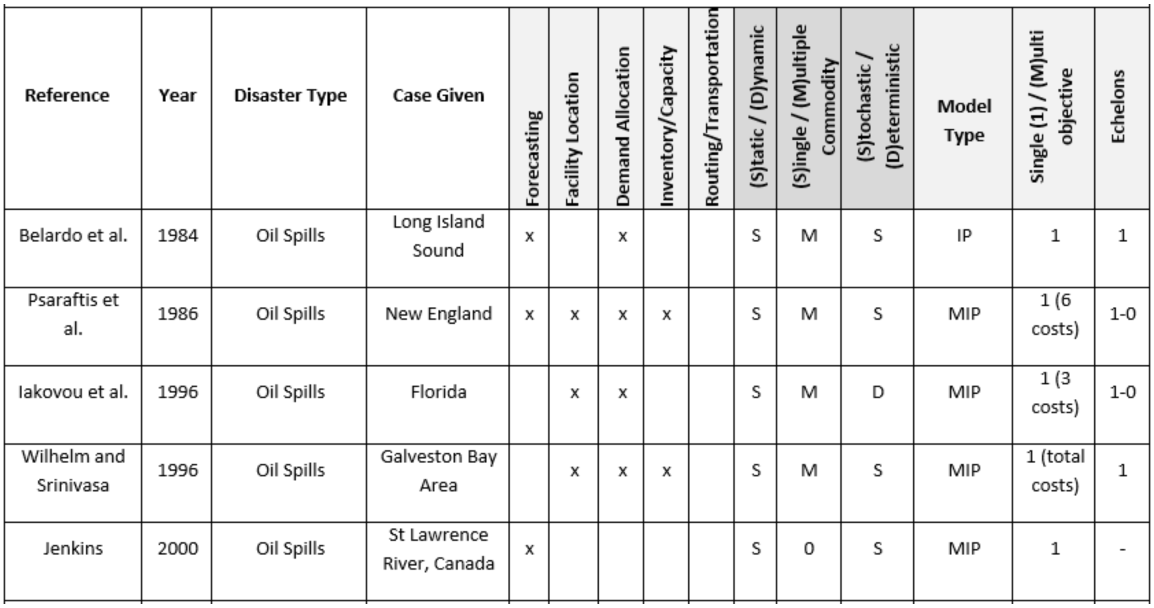
Reference	Year	Disaster Type	Case Given	Forecasting	Facility Location	Demand Allocation	Inventory/Capacity	Routing/Transportation	(S)tatic / (D)ynamic	(S)ingle / (M)ultiple Commodity	(S)tochastic / (D)eterministic	Model Type	Single (1) / (M)ulti objective	Echelons
Tavakoli and Lightner	2004	Emergency Medical Service	Fayetteville, NC		x	x			S	S	D	IP	1	0
Dessouky et al.	2006	Medical supplies/ General	Los Angeles		x	x	x	x	two models	M	S	MIP	1	1-0
Jia et al. CIE	2007a	Medical facilities	illustrative emergency examples		x	x			S	S	D	IP	1	1
Jia et al. IIE	2007b	Large scale medical emergencies	Los Angeles		x	x			S	S	D	IP	1	1
Doerner and Hartl	2008	Health care / general	Austria			x	x	x	D	M	S	MIP	M	1-0
Mete and Zabinsky	2010	Medical supplies / General	Seattle, earthquake		x		x	x	Two stage	M	S	MIP	1 (total costs)	1-0
Basar et al.	2011	Emergency Medical Service	Istanbul		x				D	S	D	IP	1	1

The availability of medical products varies in importance, where basic life support services are needed on site immediately, while medical transport service comes after (Yang and Hamedi, 2004). The total number of Emergency Medical Stations (EMS) should reflect the desired service quality and budget as well as other constraints (Basar et al., 2011). Having dispersed and redundant facility location patterns improves survivability of infrastructure and serviceability to demand points. It is important to also note that large-scale medical emergencies are distinct in nature; close attention should be brought to case-specific deployment strategies (Jia et al., 2007a, and Jia et al.2007b). For example blood related logistics; time is very critical and can mean losing donated blood if the tight time windows are not met in a matter of minutes (Doerner and Hartl, 2008). As in most emergency response designs, medical emergency facilities should be accessible from more than one major road, and should be safe from the emergencies expected (Dessouky et al. 2006). "The objective is typically to maximize a certain type of coverage with respect to constraints that restrict the total number of EMS stations and ensure a certain level of service quality" (Basar, 2011).

2.5.1.3 Oil Spill Recovery Network Design

Oil spills can take various forms, and made up from various oil types. It's response scope is location and weather relevant. Different types of oil (crude, gasoline, etc.) behave differently when spilled on the water, and hence different strategies and resources must be used to clean them up. Similarly, the weather, sea, and current conditions dramatically affect spill behavior and so the equipments used capability. A potential spill event is defined by geographical area, oil type, and weather-current-sea condition (Belardo et al., 1984). Removing different oil spills requires different combinations of tools jointly and/or sequentially. The objective of offshore oil spill containment, removal, and amelioration activities are, therefore, to minimize the magnitude of the shoreline cleaning operation. Many of the models are static, custom-made to given scenarios (Belardo et al., 1984). Iakovou et al. (1996) states that the most important performance measure in the oil spill clean-up effort is the response time since the success and efficiency of all subsequent clean-up efforts rely heavily on it. Wilhelm and Srinivasa (1996) note the importance of considering various factors such as history, and proximity to pipelines. As technological solutions are not easy, the investment is small-scale clean up technology would be more cost efficient accompanied by multiple facility service to any spill (Psaraftis et al., 1986). In network designs for oil spills response and recovery, all literature used the assumption that simultaneous oil spills occurrence is negligible, and very unlikely (Psaraftis et al., 1986). Another interesting observation that all models are single stage models, which indicates that oil spills response does not necessarily require dynamic models.

Table 4 Oil Spill Related Network Design Models

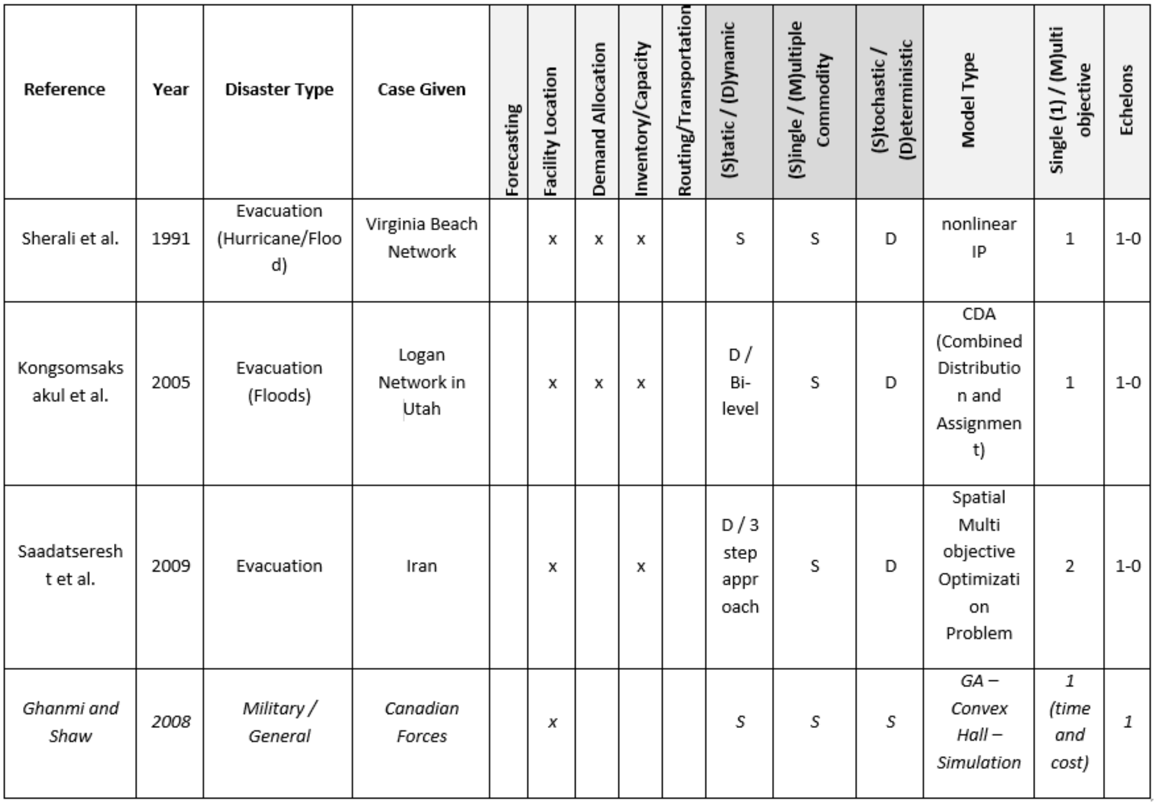


Reference	Year	Disaster Type	Case Given	Forecasting	Facility Location	Demand Allocation	Inventory/Capacity	Routing/Transportation	(S)tatic / (D)ynamic	(S)ingle / (M)ultiple Commodity	(S)tochastic / (D)eterministic	Model Type	Single (1) / (M)ulti objective	Echelons
Belardo et al.	1984	Oil Spills	Long Island Sound	x		x			S	M	S	IP	1	1
Psaraftis et al.	1986	Oil Spills	New England	x	x	x	x		S	M	S	MIP	1 (6 costs)	1-0
Iakovou et al.	1996	Oil Spills	Florida		x	x			S	M	D	MIP	1 (3 costs)	1-0
Wilhelm and Srinivasa	1996	Oil Spills	Galveston Bay Area		x	x	x		S	M	S	MIP	1 (total costs)	1
Jenkins	2000	Oil Spills	St Lawrence River, Canada	x					S	0	S	MIP	1	-

2.5.1.4 Evacuation Network Design

In evacuation planning, decision makers have to identify where each evacuee will go and from which route. Identifying safe areas, their capacities, and proximity from potential disaster location are important decisions (Saadatseresht et al, 2009). The smaller the shelter capacity the more shelters must be selected, thus increasing total evacuation time (Kongsomsakakul and Yang, 2005). Evacuation models take on the form of p-median problems. One of the main challenges is congestion and the overall flow of the system. Some models give priority to larger population zones, while other model uses multi-stage models to provide space for evacuees to choose their routes. The models reviewed assume single commodity, i.e. evacuees, and deterministic demand settings. Determining the capacity of the critical facility is another important challenge, and can affect the network design (Saadatseresh et al., 2009).

Table 5 Evacuation and Military Related Network Design Models



Reference	**Year**	**Disaster Type**	**Case Given**	**Forecasting**	**Facility Location**	**Demand Allocation**	**Inventory/Capacity**	**Routing/Transportation**	**(S)tatic / (D)ynamic**	**(S)ingle / (M)ultiple Commodity**	**(S)tochastic / (D)eterministic**	**Model Type**	**Single (1) / (M)ulti objective**	**Echelons**
Sherali et al.	1991	Evacuation (Hurricane/Flood)	Virginia Beach Network		x	x	x		S	S	D	nonlinear IP	1	1-0
Kongsomsakakul et al.	2005	Evacuation (Floods)	Logan Network in Utah		x	x	x		D / Bi-level	S	D	CDA (Combined Distribution and Assignment)	1	1-0
Saadatseresht et al.	2009	Evacuation	Iran		x		x		D / 3 step approach	S	D	Spatial Multi objective Optimization Problem	2	1-0
Ghanmi and Shaw	*2008*	*Military / General*	*Canadian Forces*		*x*				*S*	*S*	*S*	*GA – Convex Hall – Simulation*	*1 (time and cost)*	*1*

2.5.1.5 Military Operations Network Design

In military operations, when time is not a constraint, sea lift is the most economical. Regular predictably consumed parts such as spare parts, medical supplies, fuel, and lubricants should be kept in strategic locations replenished by sea to the maximum extent possible is suggested as a good mitigation strategy (Ghanmi and Shaw, 2008). Ghanmi and Shaw (2008) and Lambert (2004) are both example of military operation optimization using simulation.

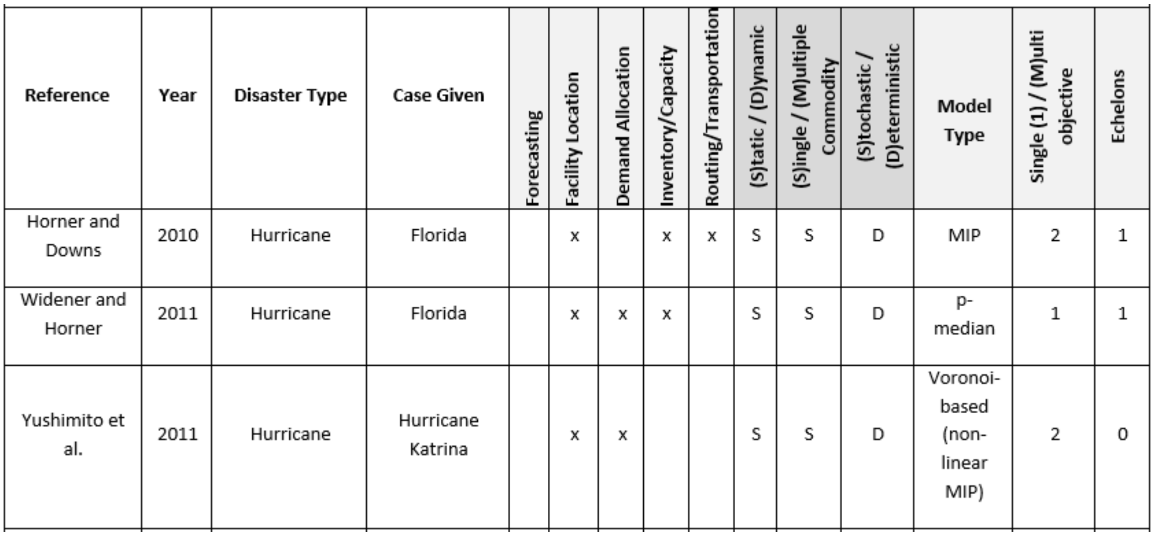
2.5.2 Network Designs characteristics for Natural Disasters

Natural disasters are the oldest type of disaster known to mankind. Although there is a wide variety of natural disasters that exists in the world, such as volcanoes, tsunamis, earthquakes, floods, wild fires, tornados, hurricanes, blizzards, heat waves, and so on, only four types were found in the literature review. Hurricanes, earthquakes, floods, and tsunamis are discussed in the following sections as found in network designs for disaster relief literature.

2.5.2.1 Hurricane Relief Network Design

Unlike oil spill, hurricane relief has other dimensions, the key difference is that clients are expected to reach the relief station, i.e. the direction of flow is going towards the facilities not towards the demand region. It is protocol to have pre-positioned stations in hurricane prone areas (Horner & Downs, 2010). Hurricanes by-products vary. They can be accompanied by floods and cause relative damage to nature, households, public facilities, and transportation infrastructure. A Hurricane's path and damage can be predicated. It is common that some residents will choose not to evacuate, a concept that is still treated as marginal to evacuation research. Finally, an important inquiry relates to how the distribution will be done given a particular evacuation profile.

Table 6 Hurricane Related Network Design Models



Reference	Year	Disaster Type	Case Given	Forecasting	Facility Location	Demand Allocation	Inventory/Capacity	Routing/Transportation	(S)tatic / (D)ynamic	(S)ingle / (M)ultiple Commodity	(S)tochastic / (D)eterministic	Model Type	Single (1) / (M)ulti objective	Echelons
Horner and Downs	2010	Hurricane	Florida		x		x	x	S	S	D	MIP	2	1
Widener and Horner	2011	Hurricane	Florida		x	x	x		S	S	D	p-median	1	1
Yushimito et al.	2011	Hurricane	Hurricane Katrina		x	x			S	S	D	Voronoi-based (non-linear MIP)	2	0

Models for hurricane relief networks try to locate facilities near hurricane prone zones, in order to assure a shelter near by hurricane victims. This can be done in different ways using a p-median location model; capacity constraints can be added as in Widener and Horner (2011), or one can solve the facility location problem with special social benefits/costs considerations (Yushimito et al., 2010). Since hurricanes' path and damage can be predicted, it would be advisable to add temporary, mobile facilities, and to have a dynamic model that is case specific to each hurricane's occurance. Although the reviewed models mention the need for multiple commodities, the models were of single commodity type. Also deterministic demand was assumed.

2.5.2.2 Earthquake and Flood Relief Network Design

In the case of earthquakes (similar to hurricanes), stockpiles of supplies such as tents, water, food, etc. is pre stocked to meet demand after an earthquake. These facilities should be earthquake resistant. Public facilities can be utilized temporary to meet demand. Demand can be characterized as 100% from highly damaged buildings, 50% from moderately damaged buildings and 10% from partially damaged buildings; facilities should have multi-access (Gormez et al., 2010). It is also important to dynamically identify feasible routes, and optimize the network accordingly as information inflows. Origin-Destination pairs (O-D pairs) should be connected in the minimum time and distance possible, subject to resource constraints (Viswanath & Peeta, 2003). Changing daily tours requires significant organizations and administrative efforts (Nolz et al., 2011). Compared to earthquakes, floods are more frequent and more easily predicted and prevented, providing a greater chance of a more comprehensive contingency measures. Demand points are also more random (Chang et al., 2007).

Table 7 Earthquake, Flood, and Tsunami Network Design Models

Reference	Year	Disaster Type	Case Given	Forecasting	Facility Location	Demand Allocation	Inventory/Capacity	Routing/Transportation	(S)tatic / (D)ynamic	(S)ingle / (M)ultiple Commodity	(S)tochastic / (D)eterministic	Model Type	Single (1) / (M)ulti objective	Echelons
Viswanath and Peeta	2003	Earthquake	Indiana			x		x	S	M	D	IP	2	1-0
Gormez et al.	2010	Earthquake	Istanbul	x	x	x			D	S	D	IP	M	0
Nolz et al.	2011	Earthquake and Flood	Ecuador			x		x	D	S	D	MIP	M	0
Chang et al.	2007	Flood	Taipei, Taiwan		x	x	x	x	D	M	S	MIP	1 (many costs)	m
Doerner et al.	2009	Tsunami	Southern Sri Lanka		x	x			D	S	D	MIP	3	1

2.5.2.3 Tsunami Relief Network Design

Although tsunami's have frequent occurrence in developing countries, especially around the Indian Ocean, warning and information systems are still insufficient (Doerner et al., 2009). For location decisions, possible locations are evaluated according to three criteria: (i) a combination of the min-sum facility location criterion, which minimizes the sum of distances between all members of a population and their nearest facility, and the maximal covering location criterion, which minimizes the number of the population members unable to reach a facility within a predefined maximum distance, (ii) a tsunami risk criterion, based on estimates of probability and effect of future tsunami occurrences, and (iii) a cost criterion, related to specific construction methods influencing the safety of a building. It is important to note that in the case of Tsunami relief network design, the farther one is from the coast the more preferable the location is, i.e. the farther away it is from public facilities. (Doerner et al., 2009)

2.6 Physical Barriers in Disaster Relief Logistics' Planning

When discussing logistics during disaster scenarios, one has to stop and reflect upon having barriers in a supply network. Barriers have not been discussed in any of the researched disaster logistics network design models. It has been emphasized as a state of operations, where infrastructure is damaged. The literature nevertheless lacked a direct tackle of this subject matter specifically when planning for disaster relief logistics operations.

In disaster relief there can exit several types of barriers for both locating facilities and routing. Floods for example can cause a total obstruction to a road network. In another flood scenario of a medium impact, military trucks, specially equipped ones, can travel through the flooded regions. Locating disaster relief facilities is also an important decision that is highly affected by the barriers that should be present in the network design of disaster relief. First the barrier type has to be identified based on the impact of the disaster at hand. The regions affected and demand of the disaster relief network design will depend on the type of the disasters that are prone to happen. Typically different region have historical data that can predict the barrier types, also geographic studies can indicate the type of barrier that might or is present. For example is an earthquake, buildings that are resistant to earthquakes have a high potential to become disaster relief operation facilities; similarly when it comes to traveling during an earthquake some routes might be unavailable for traveling. Hurricanes also require special arrangements with regards to facilities and traveling; facilities are typically located below ground level equipped with various supplies, and traveling is forbidden in the predicted hurricane region. Military preparedness for national security instances would not have forbidden regions, as they would be granted access to forbidden locations. They would create imaginary restriction zones to civilian traveling.

Butt & Cavalier (1996) were amongst the first to shed light of locating facilities in the presence of forbidden. They proposed polygon barriers, where traveling and locating facilities are forbidden. The convex hull of such a network design optimization problem would look something like that of Figure 8. Polygon barrier are not the only center of attention when it comes to barriers. Canbolat and Wesolowsky (2010) highlighted a list of barrier types discussed in literature, including circles, lines, and rectangles. They also

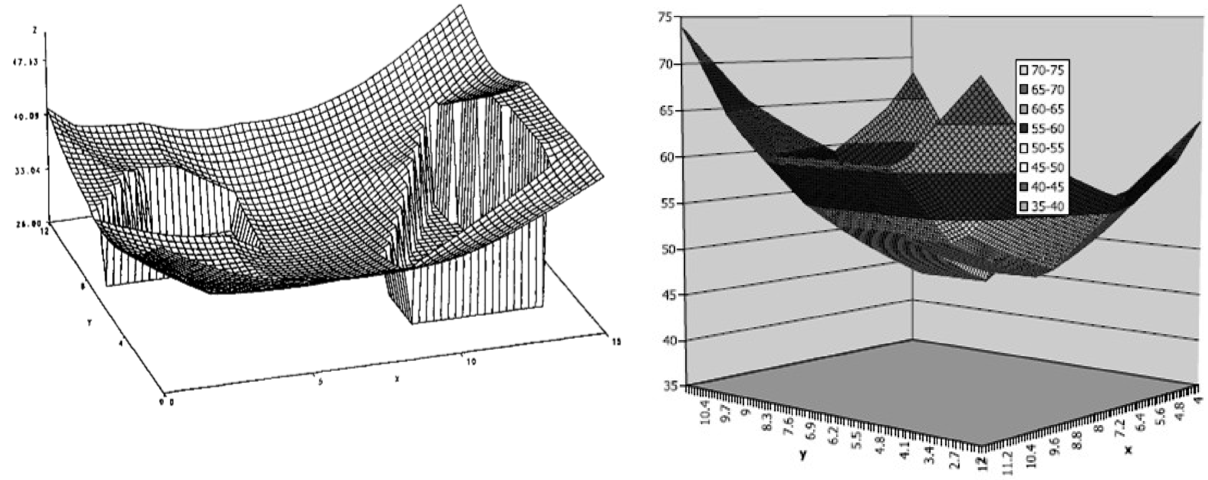


Figure 8 - Objective function curve in the presence of barriers, (Source: Left: Butt & Cavalier, 1996. Right: Canbolat & Wesolowsky, 2010)

identified three categories of barriers, a) forbidden location but not traveling, b) forbidden location with penalty traveling, c) forbidden location and traveling.

This thesis will focus on the latter two. Two basic forms of barriers that can obstruct the normal flow of a supply network are discussed in this thesis. The first type is barriers as forbidden regions. This means that nothing can be placed in or go through this forbidden zone, this would be the case of a toxic epidemic, or fast current zone of a flood for example. The second type are scaled-cost barriers where nothing can be placed in but traveling can occur at extra cost, see Figure 9 for illustrative solution example of a location-allocation problem given those scenarios. Literature has discussed the former type with regards to weber problem with different barrier shapes (Canbolat and Wesolowsky, 2010).

When seeing things from a network design perspective, a forbidden zone barrier assumes that no facilities can be located within the barrier zone as well as no routes or traveling is allowed within the barrier region. This is majorly to ensure the safety of the stakeholders. When solving for particular network design related outcomes, a new set of

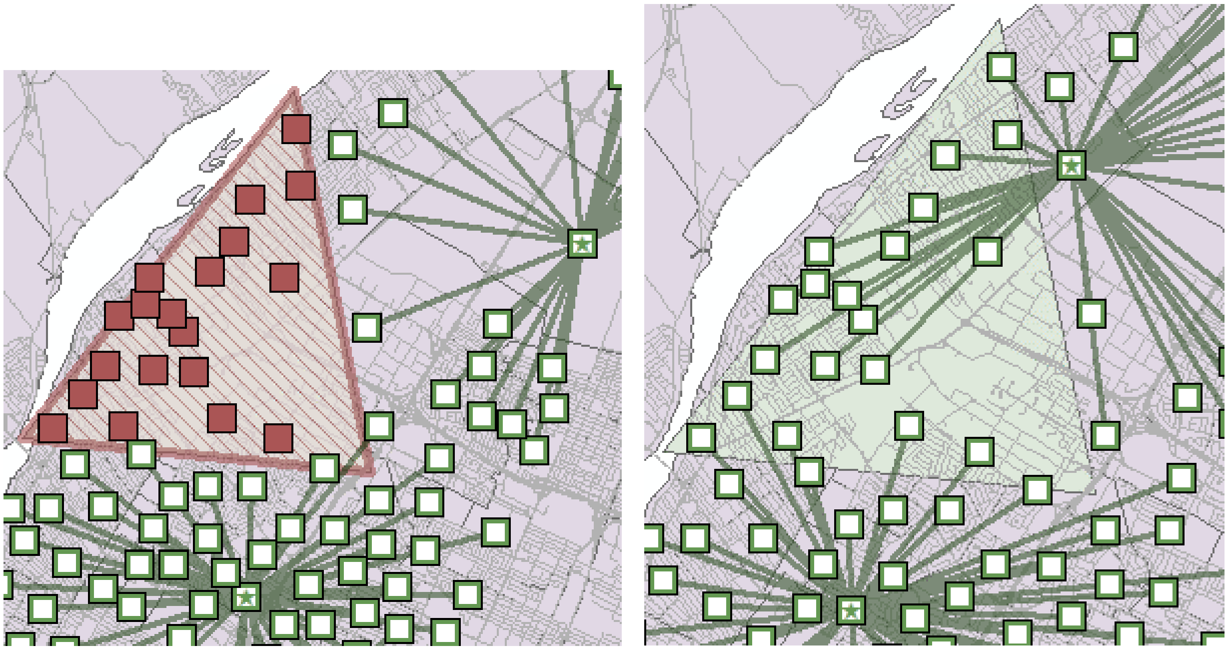


Figure 9 (left) Forbidden-zone Barrier, (right) Scaled Cost Barrier (right)

possible facility locations as well as a new set of available arcs are generated when there is a change in the barrier size or location. The new feasibility region, which includes all possible sets solutions would be defined. Dynamic communication is essential when defining this parameter so that redundancy in operations is avoided, and accurate zones defined.

Barrier zones basically redefine the feasibility region, this means that any chosen route (x_{ij}) or facility (y_j) has to belong to $\mathbb{F}$, where $\mathbb{F}$ is a feasible solution region. $\mathbb{F}$ is the set of feasible points and vector sets, and it changes based on the barrier type. If the barrier does not allow for locating facilities or traveling then all points and vectors passing through the barrier zones would be excluded from the feasibility region. If traveling and facility locating are allowed at extra costs then all nodes and vectors belonging in the barrier would be included in the final solution. Once the barrier zones are identified (whether through prediction using historical data or through actual observation), the feasibility region can be identified. Thus in the case of forbidden-zone barriers, $\mathbb{F} = \mathbb{R}^2 \setminus \bigcup_{l=1}^{L}$ interior (B_l); i.e. the feasible region is all values in the solution space less the interior of the union of the barriers in the space (Bischoff et al., 2009). A commonly used concept used to understand the barrier region's effects is a visibility graphs (Butt & Cavalier, 1996). Two points are said to be visible of each other if they are not obstructed by a forbidden-zone barrier. The visibility graph, Figure 10, all lines (visible lines) are connecting either possible facilities, a_1 … a_5, or connecting possible facility locations to other facility locations via barriers' extreme points. Barrier extreme points define the polygon barrier regions, and are either predicated or observed as previously mentioned.

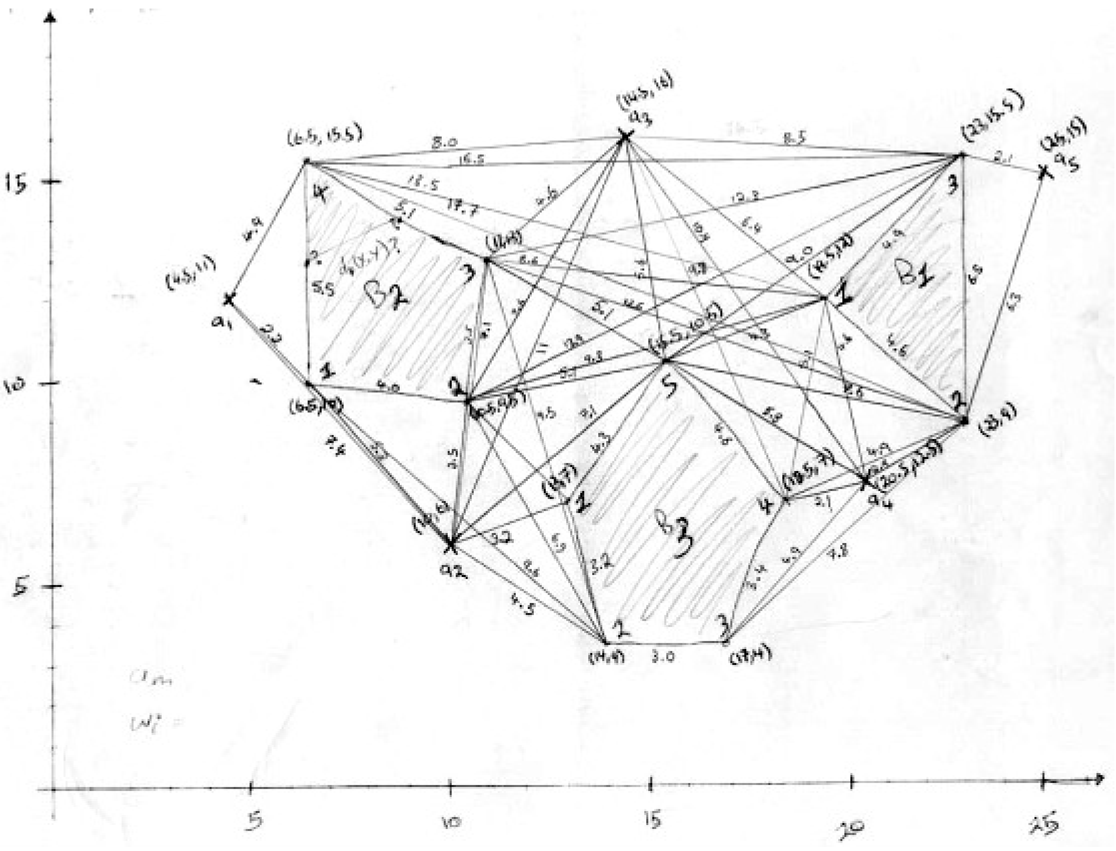


Figure 10 Visibility Graph

When barriers are not forbidden-zones, i.e traveling and facility locations are allowed within the barriers, a visibility graph would not be needed. The resulting network would be regular, and the feasibility region would be all the available nodes, and links. When the barrier is of scaled-cost type, third barrier type investigated in this research, these type of barriers allow for traveling within barrier at a higher weight increment than usual. Locating facilities is allowed in the scaled-cost barrier region, however it may be avoided for the high associated costs.

Before moving further, it is important to touch upon the logic behind scaled-cost barriers. Identifying the partial length of the route traveled through the barrier region can be understood through basic line geometry. The length of a horizontal line is found by the difference between its two x-axis equivalents, and if it is vertical then the difference between its two y-axis equivalents is found. Earth has several coordinate systems most commonly geographic which is circular and thus made of curves not straight lines, and the projected which is the straightened up coordinates of a particular region and not for the whole earth. These coordinate systems makes it easy to find geometric characteristics in networks and are available by local organizations. For example a link which starts at points (1,2) and ends at (1,8), and is intersected by a barrier region from point (1,3.25) to points (1,5.25), this means that 5.25-3.25= 2 length units of the line fall in the barrier zone and would have extra weights as opposed to the other 4 units of the line ((8-2)-2) that are in the regular no barrier zone. Thus the exact line segment of a route that incurs extra scaled-cost can be identified and taken into consideration when planning network designs for disaster relief response. In the case of a line with a slope, Pythagoras Theorem would be useful to find the line's length.

Pythagoras Theorem helps find the distance between any two given points in a coordinate system. In case the point is unknown, the intersection between the barrier line and the link between two nodes can be solved for using simple coordinate geometry; this is done by first finding the equation of the line that connects the barrier extreme points, and the equation of the line that links the two nodes, then the intersection point can be found. The intersection point is the start of where the scaled weight (or cost) will start on any link that passes through the barrier zone.

Planning for possible barrier location will help reinforce the disaster relief plan. Stakeholder must have a clear vision of their available resources and whether or not they can respond to different barrier restrictions in their disaster relief network. Will they need to seek other capable organizations before disaster strikes? Pre-preparedness is essential to mitigate and respond realistically to upcoming disasters which is exactly where this research comes in. Next, sharing information and collaboration aspects are discussed.

2.7 The Information Sharing Effect in Disaster Relief Logistics

A supply chain manager's job is all about coordinating, and efficient use of resources. Information availability and sharing helps facilitate and optimize decision making in any supply chains. This section will discuss the elements of coordination, collaboration, and use of information with regards to relief supply chains. It is noted that when implementing a distribution plan, managers have to take into consideration many factors that affect their supply network's efficiency and effectiveness. Internal factors such as organizational mandate, background, structure, and decision making hierarchy; external factors such as overall operating conditions which includes physical network infrastructure capabilities, security, taxes, exchange rate, resulting/expected demand, time of disaster, frequency and duration uncertainty, and amount of donations available. On the fleet level (aka last mile distribution) there are other important factors that affect the strategic planning of relief distribution network design; number, type, and allocation of vehicles and warehouses, life-cycle management with regards to maintenance, fuel management, disposal, replacement, and procurement of extra requirements; Security and insurance of facilities and staff, monitoring and evaluation, and data collection (Besiou et al., 2011). It is also important to take into consideration the recovery of communities after the response phase. Response phase is more time critical and efficiency is measured mainly in the speed delivery of supplies as opposed to cost efficiency. In the recovery phase focus is also/more specialized on access to and coverage of post disaster development supplies (Martinez et al., 2011).

The disaster relief space is filled with stakeholders from different origins, objectives, capacities, and connections. Large international NGOs have a defined system of standard operating procedures, unlike other small to medium sized faith-based or national NGOs. Having preset connections in disaster prone countries facilitates disaster relief operations. This is where the role of information sharing is critical. The capacity of information shared would dictate the quality of disaster relief operations. Information is categorized is many ways, for example current information, past information, and future forecasts are important in their own ways. Technological advances such as the internet has enabled another dimension of coordinating supply chain efforts and creating end customer value (Kara et al., 2004). Information is one of the many flows in a supply network (the 5 B's, bodies, brains, bucks, boxes, and bytes). This section will highlight the importance of information sharing followed by a brief discussion of information sharing role in disaster relief operations and the efficiencies and importance of having coordination and collaboration. It is presumed by the authors that information sharing is a prerequisite and enabler for stakeholders’ collaboration. Collaboration is one of the enablers of supply chain excellence. In a supply chain made of multiple stakeholders, a common shared platform is important to exchange information. A body of literature supports the idea that external integration is predecessor of internal integration which requires information sharing (Cao and Zheng, 2013).

2.7.1 Information sharing and relief distribution

Information sharing is described as the ‘‘heart’’, ‘‘lifeblood’’, ‘‘nerve center’’, ‘‘essential ingredient’’, ‘‘key requirement’’, and ‘‘foundation’’, of supply chain collaboration (Cao & Zhang, 2013). All models reviewed needed some form of information inputs. The wide availability of information systems, cheap hardware, open-source software, relational database, and telecommunication advances must have improved the disaster relief operations and preparedness. Manipulative visuals, interactive maps, user-friendly interfaces make for easier decision making. Information sharing, and planning synchronization in the humanitarian context leads to improvements in operational capabilities and improvements of relief distribution efforts. Information comes in many forms in disaster relief, supply information, logistics, and cooperation. “Speed, accuracy, and completeness of information can help save lives” (Zhang et al., 2002). Information sharing can be done via interactive GIS, or manually over the phone, teleconferences, and/or physical meetings.

The use of information technology in disaster's relief distribution is not straight cut, many challenges are identified that can hindrance the use of such tools. Simple language barriers, lack of technical proficiency at the operational level by first responders such as police, fire, medical emergency personnel, and preference of paper maps and human gathered data rather than remote sensing (Cutter, 2003). Lack of funding or IT infrastructure, limited information technology infrastructure, other challenges relate to identifying the relationships amongst the logistics parameters that are needed for the optimization models and their representation on the interface that is used by multiple end users on various portals, and whether the interface is stationary or mobile. Information is not typically shared or kept in a central accessible location by stakeholders, which leads to redundancy in operations. The following table, for example, summarizes the operations stated in the mission of International Federation of Red Cross/Crescent, United Nations, Oxfam and Habitat for Humanity taken from their websites. It can be seen that these four organizations amongst many others present in the humanitarian space have redundant operations and similar relief items are being distributed by them. If they are not sharing demand information then they are performing redundant tasks which would be leading to increase in total travel distances, inventory levels, and leading to bottle neck processes.

Table 8 Mission of four humanitarian organizations

Major Organizations	Mission regarding Emergency such as earthquake
IFRC	Emergency Response Unites (ERUs) provide health and water and sanitation services and support major disaster operations with logistics, IT, and telecommunications and relief using standardized equipment and pre-trained personnel.
United Nations	Shelter equipment, water purification, and distribution equipment, blankets, tools, kitchen sets, electric generators, and other basic survival items. WHO- provides medical needs; World Food Program- provides food items.
Oxfam	Clean water, sanitation, shelter, seeds, and running cash for work programs, support recovery and reconstruction.
Habitat for Humanity	To develop innovative housing and shelter assistance models that generate sustainable interventions for people vulnerable to or affected by disasters or conflicts.

There are major benefits from information sharing starting off with lower costs and shorter order cycles result from higher levels of information sharing (Lin et al., 2002). This means faster, more efficient response. Organization to organization transactions are increasingly dependent on information exchange (Kara et al. 2004). Although the use of information systems is on the rise, such that of Oracle and SAP, their focus remains on modular view of individual companies and not a process oriented one (Cao & Zhang, 2013).

One of the widely used information systems that can enhance information sharing are Geographic Information Systems. After Haiti earthquake of 2010, Google dedicated a free web site to help spread post and share disaster logistical information via Google Maps, which later developed into the Google Crisis Response Project (www.google.org/crisisresponse). Geographical Information Systems (GIS) is a multi-functional and cross science information system based on geographical or spatial data. GIS are fully capable of viewing, storing, and analyzing large spatial data sets. Spatial data have coordinates to them, which makes data more relevant and easier to manipulate with modern graphical user interface and web tools. Another major breakthrough in network designs and information sharing is open-source map network resources such as OpenStreetMap, which is a collaborative platform of transportation networks, accessible and editable by the public world-wide. It can easily be viewed on a GIS to determine real distances and network characteristics, structure, and existing post disaster barriers.

2.7.2 Coordination and Collaboration

Organizations typically have their own decision making styles, they gather and use information differently, as well as have different orientation towards hierarchy and authority. (Waugh, 2003). Coordination is more complex when there are multiple agencies trying to work together as one unit. Collaboration is beneficial for small NGO who do not have enough resources to manage large, disperse staff and resources. Naslund et al. (2012) indicate that no clear distinction has been made in literature between coordination and collaboration. Coordination can happen within one organization or unit and collaboration typically involves more than one player. In the relief context there are many forms of collaboration. McLachlin and Larson (2011) break collaboration into four types; "humanitarian" - between two or more NGOs, "humalitarian" - between NGOs and military forces, "humanitaiUN" - between NGOs and a United Nation's agency; and "humoneytarian" - between NGOs and commercial firms, as service provider or donor. In this form, the humanitarian space is a complex network. Waugh (2003) regarded a network as "structures of interdependence involving multiple organizations or part thereof, where one unit is not merely the formal subordinate of the others in some larger hierarchical arrangement". This means that the disaster relief supply chain is a complex network of multiple and a various base of players which collaborate together in many different ways in order to meet a common final objective which is the aid of disaster victims subject to circumstantial and strategic constraints. Collaboration can be done on different aspects, donations are a form of collaboration, sharing resources such as information is a form of collaboration, providing services such information related like GIS Crisis Response or expertise wise is a third form of possible collaboration, and sharing demand statistics, inventory stocks, etc are all forms of collaboration in disaster relief supply chains for better coordination. Given the availability of historical data international NGO with large resources, and experience are moving towards speculative prepositioning of supplies and early on supplier relationships management. All of which is based on the sharing of information, first and foremost, then followed by space, material, and/or service collaboration.

None of the network design models analyzed investigated the topic of information sharing from an empirical view point, although the topic did receive substantial coverage in the literature domain of disaster relief network designs. The following section illustrates in more details the problem statement which will investigate information sharing aspects in disaster relief network design as well as barriers effects discussed in previous sections.

Chapter 3

Problem Statement

As per the title of the thesis, the intent behind this research work is to explore disaster relief network design. As thoroughly analyzed in the literature review section, disaster relief is the operations that taken place in response to a disaster in order to elevate suffering and save lives. This happens before and after the disaster. A logistics network design should take into consideration all of the following questions:

- How many pre-positioned relief supply facilities are needed to support the relief chain and meet population requirements?
- Where facilities should be located in order to minimize travel distances?
- How much relief supplies will be needed at these facilities? What are the optimal inventory ordering policies for the various stocking points?
- Which demand nodes should be allocated to which facility?
- How will the supplies be dispatched from the stocking facility to the regions in need?

The above questions however are typical for any network design problem. The extra emphasis this paper achieves is answering such question under several hypothetical scenarios specifically shaping the disaster relief network design, these are:

- What is the effect of different barrier types on the network design?
- What is the effect of sharing information on the network design?

Significant effort have been dedicated on the available network design problems related to disaster relief, and two of the major hurdles for disaster relief logistics which are the presence of physical barriers and the information sharing between different players, such as government and local and/or international disaster relief agencies. It is assumed from studying collaboration and information sharing that the presence of information sharing in disaster relief would lead to smoother operations. The availability of shared information and the lack of it thereof would have an impact on the design of disaster relief distribution networks. Investigating the presence of information sharing and barriers is important for the grasps of the volatile factors under which disaster relief occurs. Investigating these aspects would help in the better preparedness to potential disasters. In the light of this the definition of our problem arises. Three barrier scenarios, and two information sharing scenarios are identified, Table 9 and Table 10, and integrated into a holistic disaster relief network design approach. So that not only are we solving for facility and routing problems but as well taking into consideration different planning scenarios.

Barriers in a disaster relief can take various forms depending on disaster type. For example, in a war, international regulations can impose a no fly zone over particular regions, obstructing air-borne relief distribution, this is an example of a forbidden zone barrier. Similarly in the case of tsunami road networks can be totally destroyed causing many regions to be non-accessible by road networks due to high water levels and/or damage to infrastructure. When it comes to locating disaster relief facilities, the type and intensity of a disaster affects the set of possible facility locations available to choose from. For example in a case of low impact flood or earthquake, disaster relief material

Table 9 Barrier Scenarios Definition

No Barrier

- Facilities can be located anywhere
- Demand nodes can exist anywhere
- Routes exist between all nodes

Barrier (Scaled-Cost)

- Facilities can only be located outside barrier
- Demand nodes can exist anywhere
- Routes exist between all nodes, with extra weights associated if traveling is in the barrier zone

Barrier (Forbidden-Zone)

- Facilities can only be located outside barrier
- Demand nodes only exist outside of barrier
- Routes can not travel within barrier zone

can be located at any regular facility, like the nearest hospital, which is equipped to meet low demand capacities and is made to withstand a small flood. Once the disaster relief planning takes into consideration a higher impact disaster the possible facility locations become limited to the set of structures that can withstand harsh conditions. In some instances, for example a high impact flood where neither facilities nor traveling is feasible within the highly flooded region, the best way to respond to the disaster is to shift demand from the flooded region to the nearest region that is not affected by the disaster. There are three barrier types that are considered in this investigation. First in the presence of forbidden zone barrier, where traveling and locating facilities is either ridiculously expensive or infeasible such as high impact tsunami or floods, in the cunt type of barrier scenario traveling is feasible at extra cost or weights, for example specially equipped trucks or the same distance is traveled at a longer duration due to being slowed down by low to medium impact floods. Locating facilities is considered infeasible in this cunt scenario. A third scenario is when both routing and locating facilities is allowed when there is low impact disaster such as a low impact earthquake.

The other dimension of our problem is regarding information sharing. The default assumption of this model is that for a disaster relief scenario, there is full sharing of information, there is total collaboration on the use of resources, and that there is no competition over resources or insufficient capacities. The second scenario of investigation is where there is collaboration on coordination aspects such as facility location and transportation but lack of information sharing with regards to demand estimates only. This means that any non-profit organization can send disaster relief material to the disaster zones using common trucks and facilities; however the thing that differentiates this scenario is that the demand estimates are not shared between players, for example the government agency which runs the resources and the material sent in from local or international NGOs. This results in inflated total demand estimates. The model assumes that demand increases, inflated, by %50 of the original demand at that node. For example if demand at node one is 100 then in the no information sharing scenario the demand at node one is 150 (100+100*0.5). Table 10 summarizes the information sharing scenarios.

Disaster relief logistics is a network design issue as well as a routing and transportation issue. As noticed in the literature review, many of the models out there cover a variety of aspect from forecasting, facility location, demand allocation, inventory/capacity planning, vehicle routing and transportation. A problem will be created to study network design under these scenarios. The holistic proposed solution approach will cover most common network design characteristics found in literature. First, demand will be forecasted based

Table 10 Information Sharing Scenarios Definition

Information Sharing

- Default Scenario
- Visibility of demand estimates to all stakeholders
- Sharing Resources is given (no competition for resources)

No Information sharing

- Demand Nodes Doubles with %50 of original demand forecast
- Facility capacities increase to meet increased estimation
- Route Capacities Increase by Minimum Amount

on widely available data as will be highlighted in Chapter 4, Solution Approach. Second, facilities will be located based on parameters, demand and distance, and demand will be allocated to the respective facilities based on maximizing coverage (to relieve suffering) and minimize travel distances or relative weights. These scenarios would also have an effect on last mile distribution so routing is analyzed. This would create a comprehensive logistics response plan, i.e. includes locating disaster relief facilities and the distribution of those goods to their final destinations in the supply network. Once a disaster occurs, the new actual demand parameters can replace the predicated demand estimations.

The parameters and results of this investigation will be recorded, analyzed, and a conclusion will be drawn from the analysis. The following chapter describes the parameters involved, models, softwares, and technical aspects behind the models' assumptions. This is followed by the numerical application chapter which will use produce results for analysis, and finally the conclusion and future work chapter follows.

Chapter 4

Solution Approach

It can be clear to the reader at this stage that this is an operation research problem. The proposed solution approach consists of different optimization models. These models are solved using optimization softwares. As previously highlighted in the literature review, modern technology facilitates the use of information to enhance operations. One of the critical tools for disaster relief is GIS. In order to make the best out of modern network design and optimization tools, this paper uses two popular softwares, those are AIMMS 3.13 and ArcGIS 10.1, to solve the problem statement, i.e. the effect of barriers and information sharing on network designing for disaster relief logistics,. The following sections explores and clarifies the holistic view of this solution approach, what optimization models and assumptions made to solve the network design problems. Section 4.2 goes into the software and technology specifications needed and used in this type of study. Section 4.3 suggests a methodology to forecasting disaster relief demand. Section 4.4 and 4.5 will elaborate and define the Location Allocation Problem, and the Vehicle Routing Problem, both problems take into consideration capacity constraints. The aforementioned 6 scenarios will be mathematically reflected upon and defined in Section 4.6. First the sequence of our solution methodology and technological aspects are discussed:

4.1 Solution Methodology

To start, the past decade witnessed a great advancement from technological point of view, so will future decades to come based on Moore’s Law. Digital mapping has become a competitive market for end customers and enterprises. Major internet communities compete in that domain. GPS is widely used for traffic navigation. Solving network problems is constantly taking place by the average person, worldwide, using popular websites like Google. When paired with GPS device, which is widely available on any smartphone, accuracy of “current location” and travel routes are within less than 10 meters! Network databases are open-sourced online using service provider such as OpenStreetMap. Definitely these resources have to be part of any network design problem of this century. Section 4.2 dwells on the use of different decision support tools in this study, which are an important aspect of any network design problem.

The proposed solution methodology consists of several steps. Figure 11 looks at the solution methodology from a flow chart view. The first step is finding a demand estimate, experts inputs, real data, and assumptions are used to complete this steps (Section 4.3). Step 2 is finding the best locations to locate facilities and allocate demand to them (Section 4.4), finally step 3 will look into the best route to be taken from the facility to the demand nodes (Section 4.5). Both steps 2, and 3 take into consideration the capacity of facilities, for Step 2, and routes, for Step 3. The above 3 steps are done for 6 scenarios, which are a results of a 3 by 2 matrix: 3 barrier scenarios and 2 information sharing scenarios. Those scenarios are explored further in section 4.6. This will help investigate the effects of barriers and information sharing on disaster relief network designs.

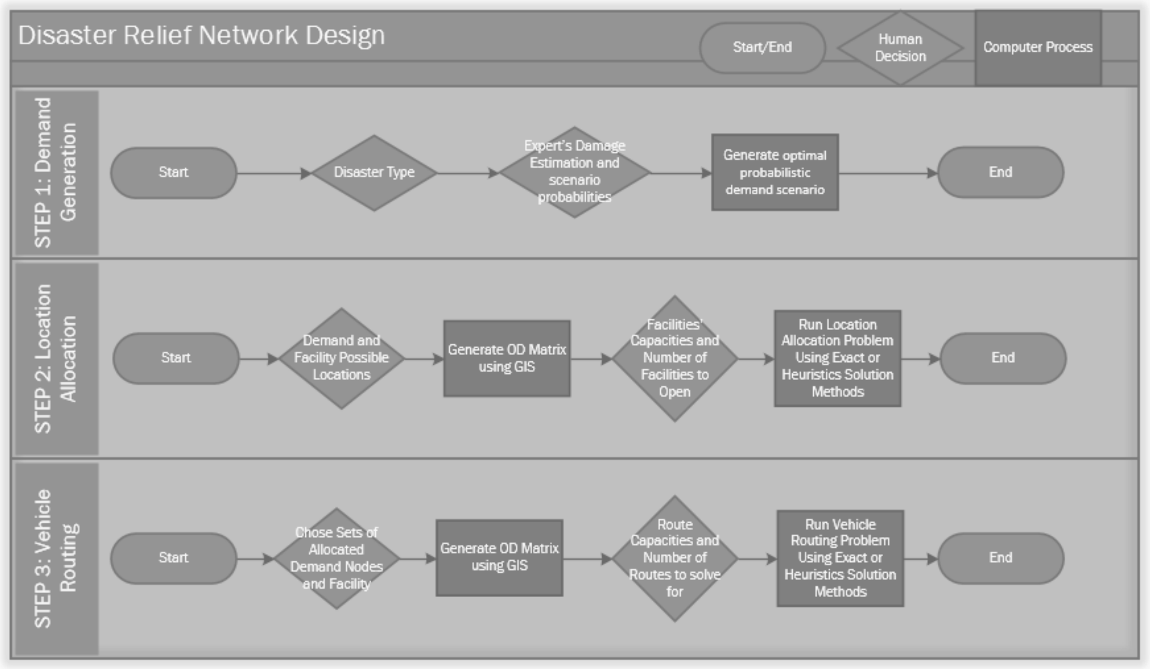


Figure 11 Solution Approach Flow Chart

4.2 Technological Aspects

Technology is a critical tool for the operations researcher. Three softwares were used in the solution and analysis of the disaster relief planning network design. The processor's power used in the research is 3.40 GHz, with 16 GB of RAM. The three main softwares are AIMMS 3.13, ArcGIS 10.1, and Microsoft Excel 2013.

Previous to using AIMMS 3.13, the models described in the following section were tested on smaller instances on Excel 2013 Solver and Lingo was also tested but stopped after reaching the 500 variables problems. As the problem instance got larger Solver gave the error that it has a limit of up to 200 decision variables. AIMMS was recommended and indeed solved a larger network where model's variables where up to 58303 variable with 58426 constraints. AIMMS 3.13 was tried and successfully was able to solve both location allocation model and vehicle routing model. All models were solved using CPLEX solver.

AIMMS 3.13 was not the only software used in testing this solution approach. In fact all data used in the study was generated specifically for the study. It is important to highlight that all the distances between the nodes of the Montreal network, the road network used for investigation, are generated using the Origin-Destination Matrix Layer of ArcGIS 10.1. OD Matrix Layer in ArcGIS 10.1 solves for distances of all the possible links between the nodes provided on a plane, in this case road map of Montreal. ArcGIS 10.1 also consists of a Network Analyst Extension which solves various problems including location-allocation and vehicle routing problem. It is however unknown to the user how these calculations are exactly being made. Although, ArcGIS does solve for the LAP and VRP, the heuristics algorithm behind ArcGIS are not 100% available, some description of the heuristic is given but not all of it. The author feels the need to use this exact solution algorithm software, AIMMS, to document the models' results and analyze it. ArcGIS 10.1's documentation, ArcGIS Help 10.1, explains a multiple step heuristic for solving location-allocation problem which includes meta-heuristics within, and another for solving vehicle routing problems (ESRI, 2012). The second dataset produced for the study in GIS software such as ArcGIS are regarding the pairing of census data to the district map of Montreal, as both districts map and districts census data share similar codes which a GIS software such as ArcGIS acts as a database management system and pairs information together from different data layers. It is very beneficial for an operations research to have such a tool in his toolkit. ArcGIS 10.1 is also programmable which means you can connect a mathematical algorithm in computer language to the map interface to easy manipulate data and have a visual representation of the model's results.

It is worthwhile noting that most of the reviewed articles illustrated or discussed the use of GIS tools. GIS can be used on various operational scales. Delen et al., (2011) states that by using GIS at regional level users can analyze the status of their operations, identify imbalances in the inventory positions of different distribution points, and detect changes in trends in inventory, consumptions and expirations. At facility level, users can analyze the inventory status of their individual facilities, identify shortages (overages), and develop a plan to coordinate with other facilities to address the shortages or overages. GIS can facilitate the operation of disaster relief supply chains. Users at different cross sections find it easy to understand and manipulate cross data. This enriches and unites the strategic decision making process. Also visualizing data on common maps has the by-product of identifying spatial errors. One of GIS's main functions is to query relevant data and find relationships between them (Camm et al., 1997). It was used in the rescue and relief operations in the World Trade Center disaster (Cutter, 2003). These ranged from micro-level risk assessments (shifts in the debris pile and temperature hot spots at the site) to the spatial status of lifelines (electric, water, telephone, transportation networks), all of which changed almost daily. In this light, the authors wanted to use a tool such as ArcGIS for the analysis.

The appendix section includes screen shots of both AIMMS and ArcGIS, for reference of the reader, with some parameters, and constraints.

4.3 Demand Forecast Methodology

The damage forecasts of Gormez et al. (2010) for earthquake and flood disasters are used to create the demand in the solution approach and numerical application along with real population figures previously discussed. The three damage probabilities to affect a population are: 100% from heavily damaged buildings, 50% from moderately damaged buildings and 10% from partially damaged buildings. Gormez et al. (2010) identified population damage based on building damage. The total population damage which depends on the building damage in each scenario depends on the strength of the disaster. This means that the higher the disaster damage the more 100% damage buildings will occur and vice versa, the lower the disaster impact the more 10% damaged buildings result. Demand forecast depends on the disaster's impact probability. Estimating different impact probabilities, high, medium, and low impacts, enables the predication of an average scenario which can be used to plan to minimize suffering. The following figure and table, Figure 12 and Table 11, explains how this optimal average probabilistic demand scenario is reached. The impact probabilities used are estimation based on historical of the region in question. The main assumptions here are the disaster impact probabilities. The damage estimates are taken from Gormez et al. (2010); 100% of building damage equals 100% affected population, and so on for 50% and 10%..

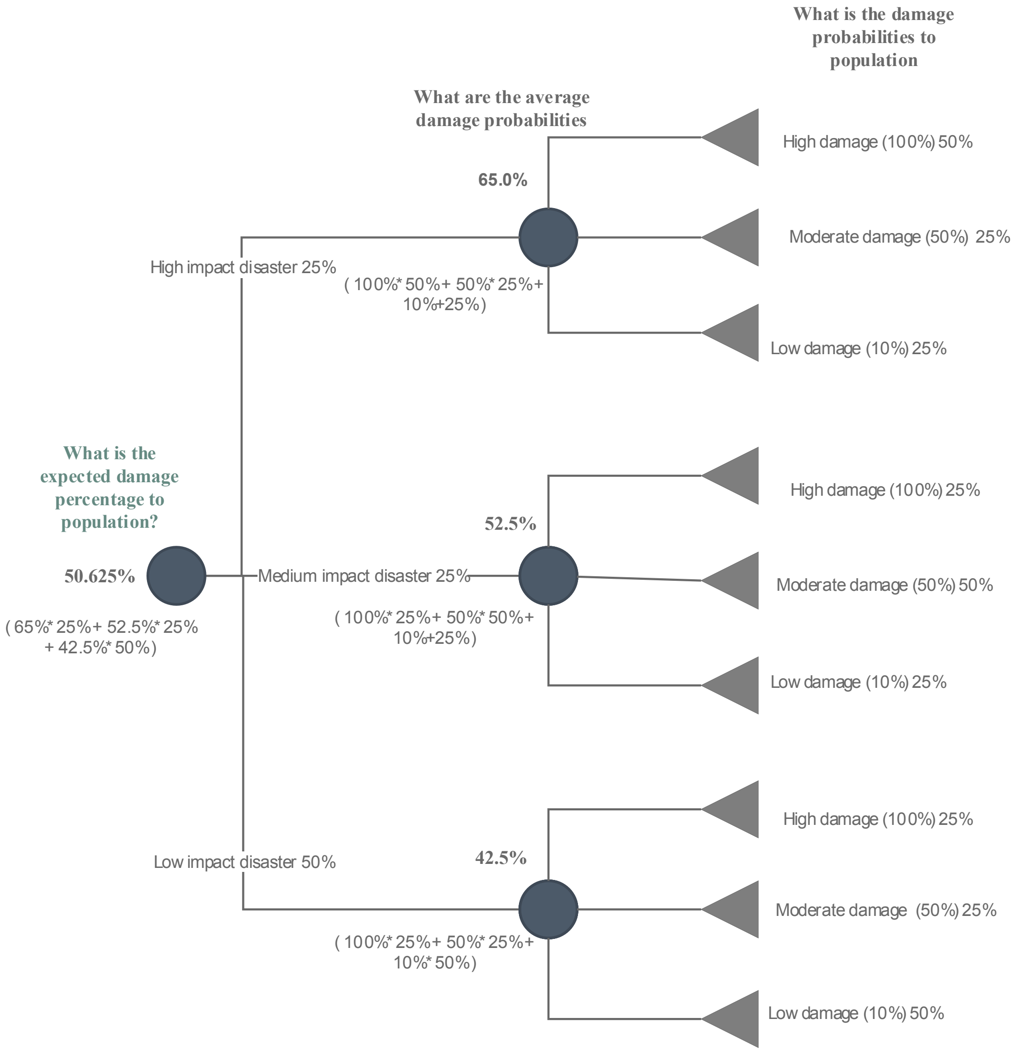
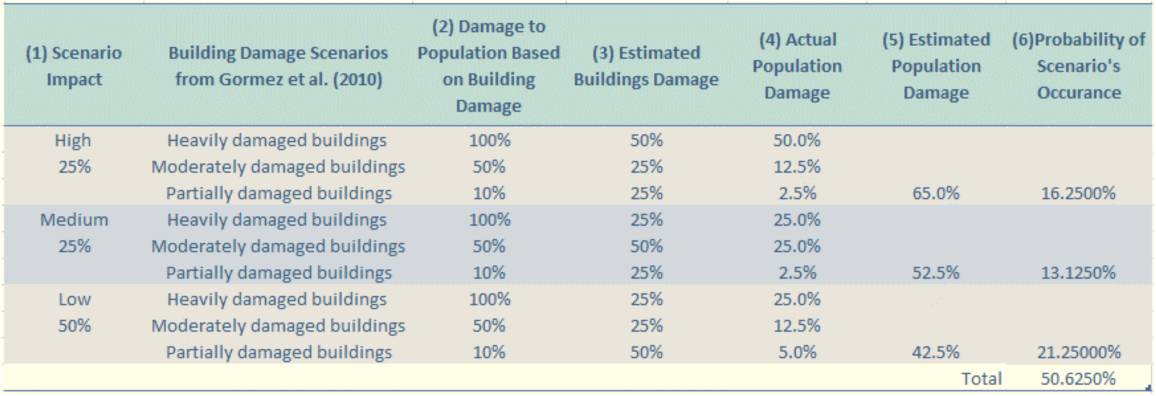


Figure 12 Creating a demand forecast using assigned probabilities

Table 11 Optimal Demand Scenario Calculation



(1) Scenario Impact	Building Damage Scenarios from Gormez et al. (2010)	(2) Damage to Population Based on Building Damage	(3) Estimated Buildings Damage	(4) Actual Population Damage	(5) Estimated Population Damage	(6)Probability of Scenario's Occurance
High	Heavily damaged buildings	100%	50%	50.0%		
25%	Moderately damaged buildings	50%	25%	12.5%		
	Partially damaged buildings	10%	25%	2.5%	65.0%	16.2500%
Medium	Heavily damaged buildings	100%	25%	25.0%		
25%	Moderately damaged buildings	50%	50%	25.0%		
	Partially damaged buildings	10%	25%	2.5%	52.5%	13.1250%
Low	Heavily damaged buildings	100%	25%	25.0%		
50%	Moderately damaged buildings	50%	25%	12.5%		
	Partially damaged buildings	10%	50%	5.0%	42.5%	21.25000%
					Total	50.6250%

First the three probable disaster scenarios, high impact, medium impact, and low impact are defined, column 1. If the disaster impact is high, then there will be more 100% damaged buildings, and if the impact is low, there will be more 10% damaged buildings, column 3. If 25% of the buildings will have 50% damage, then the total damage will be, (2)*(3) = (4), 0.25*0.50 = 0.125 percent of the original population. The sum of damage from each impact scenario is then summed in column (5), and the probability of that individual occurrence, (1)*(5)=(6), is recorded in column (6). The probabilistic equivalence of our three impact scenarios and predicated damage estimations can be summarized in one percentage value which is 50.625%, the summation of the values in column (6). This value, 0.50625, is multiplied by the population of the where the disaster might occur to give us the demand forecast for disaster response plan.

4.4 The Location Allocation Model

When locating facilities in preparation of a disaster, certain elements have to be considered. Depending on the disaster type that is being prepared for, certain characteristics has to be emphasized than others (See section 2.5 for details on network design consideration by disaster type). The common goal of any disaster relief operation is to maximize the number of people who are served; therefore one of the objects of the model is to maximize the number of people being allocated to the chosen facility locations. Choosing this objective alone to solve the problem, might result in ridiculous travel distances or costs associated with traveling. In order to meet these two objectives of maximizing the number of people served, as well as, minimizing the other side of the objective function, time, cost, or distance. This multi-objective function has been adopted from Yin and Mu (2012) and joined with constraints from Pirkul and Schilling (1991), resulting in the following LAP. The model's constraints below define the number of facilities to open (1), the capacity limits of each facility (4), the constraint that only a demand location is served from the facility if the facility is opened (3), and finally each and every demand node has to be served (2).

$$\text{Max} \quad \sum_{j=1}^{n} \sum_{i=1}^{n} a_i x_{ij} - w \sum_{j=1}^{n} \sum_{i=1}^{n} d_{ij} x_{ij}$$

$$\text{S.t} \qquad \sum_{j=1}^{n} y_j \leq k \qquad\qquad (1)$$

$$\sum_{j=1}^{n} x_{ij} = 1 \qquad \forall\ i \qquad (2)$$

$$x_{ij} \leq y_j \qquad\qquad (3)$$

$$\sum_{i=1}^{n} a_i x_{ij} \leq s y_j \qquad \forall\ j \qquad (4)$$

Here is the list of indexes, parameters of the model:

Sets:

j = the *j* set of possible facility location

i = the *i* set of demand nodes

Variables:

x_{ij} = binary variable which equals 1 if demand i is allocated to facility j, else 0

y_j = binary variable which equals 1 if facility j is opened at location j, else 0

Parameters:

d_{ij} = the distance between facility *j* to demand node *i*

a_i = forecasted demand at demand node *i*

k = maximum number of facilities to be opened

s = maximum capacity of facilities

w = weight factor

Most of the model is not complex. The key thing to explain in the above model is the w factor. The w factor gives importance to the second objective in the objective function. If $w = 0$ then the only thing that will be maximized is the allocation of demand. As w increase the weight shifts to the other objective function which in our case is distance. Yin and Mu (2012) proposed that the weight factor should be between: $0 \leq w \leq \frac{1}{A\,(d_{max} - d_{min})}$, this equation was first used and proved in 1996 by Ali Haghani.

The complexity however lies in the implementation of the proposed set of scenarios to the problem, i.e. the effect the presence of different type of barriers and information sharing would have on the model. As mentioned in section 2.6, barrier region will redefine the feasible region of the objective function's solution. The main change will be in the size of the sets I and J, also the barriers will influence the distance parameter, d_{ij}, and the information sharing will influence the demand parameter, a_i. Section 4.6 will be dedicated to explain the different scenarios affect on the model.

The output of this model will be a set of chosen facilities and the set of allocated demand nodes to each facility. These multiple sets are entered into the vehicle routing problem in order to investigate the effects of physical barriers and information sharing in the case of disaster relief routing.

4.5 The Vehicle Routing Model

Choosing a set of facilities to open and the set of demand nodes allocated to each node is not enough for us to design and study a full logistics network for disaster relief. The second essential step needed is creating a hypothetical optimal route that will deliver the relief material to the allocated demand nodes. Solving the location allocation model is a pre-requisite to this stage of the model. It is important to mention that demand nodes represent regional facilities. The delivery from the central warehouses, facilities chosen from the first stage, to the regional facilities, set of demand nodes allocated to the chosen facilities, can be done again once a disaster strikes with actual barrier and information sharing details. It is important for the reader, and the logistician, to understand the effect of different scenarios on this step of planning for disaster relief.

The model used in this stage is adapted from Matai et al. (2010) and Toth and Vigo (2002). The inputs of this model consist of an OD matrix of distances between the set of demand nodes and their allocated facility, d_{ij}. Note that this model solves for routing decisions for one facility only. The OD matrix is generated using ArcGIS 10.1. The objective function solves for the shortest travel route of one or more trucks. Note that since the location-allocation model solved for location and allocation with the consideration of barrier regions and information sharing effects, at this stage the problem is purely a routing problem, where the inputs are a set of vector nodes, with distance parameters (adopted based on the barrier-specific OD Matrix), and the model will solve for the shortest route(s) between the nodes while taking into consideration the origin node and number of trucks and their capacities. Following is the model's sets, variables , and parameters:

Sets:

i and *j* are the set of origin and destination nodes they are subsets of *n* total nodes

Variables:

x_{ij} = binary variable which equals 1 if origin *i* is linked to destination *j*, else 0

Parameters:

d_{ij} = the distance between origin *i* and destination *j*

k = maximum number routes needed

s = maximum capacity of routes

a_i = demand forecasted at node *i* ; a_j = respective demand at destination *j*

u_i, u_j = are additional continuous variables associated with demand at node *i* and *j*

The model:

$$\text{Min} \quad \sum_{j=1}^{n} \sum_{i=1}^{n} d_{ij} x_{ij}$$

$$\text{S.t} \quad \sum_{j=2}^{n} x_{1j} = k \qquad (1)$$

$$\sum_{i=2}^{n} x_{i1} = k \qquad (2)$$

$$\sum_{i=1}^{n} x_{ij} = 1 \quad \forall\, j > 1 \qquad (3)$$

$$\sum_{j=1}^{n} x_{ij} = 1 \quad \forall\, i > 1 \qquad (4)$$

$$u_i - u_j + s x_{ij} \le s - a_j \qquad \forall\, i, j \,;\, i \ne j; i > 1; j > 1 \qquad (5)$$

$$\left.\begin{matrix} a_i \le u_i \le s \\ a_j \le u_j \le s \end{matrix}\right\} \forall\, i, j \,;\, i > 1; j > 1 \qquad (6)$$

$$x_{ij} \in \{0,1\};\ u_i, u_j \in R_{>0} \qquad (7)$$

Following the objective functions which minimizes travel distance, constraint (1) and (2) control the number of routes that will leave the origin node, the facility located at *i*=1.

Constraint (3) and (4) then conserve the route integrity meaning that each node is only served once and the driver would leave it once, therefore conserving the integrity of the route. This means that not more than two drivers will visit the same node. The following constraints (5) and (6), are known as the sub-tour constraints, they are adopted from Toth and Vigo, (2002). They ensure that a truck does not go back to the origin destination without being used optimally. The s is the maximum route/truck capacity allowed, and a_j is the demand at each next node j. When $x_{ij} = 0$, constraint (5) is non-binding. When $x_{ij} = 1$, it is imposed that $u_j \geq u_i + a_j$, which in turn imposes that the maximum capacity assigned is not violated (Toth and Vigo, 2002). The origin destination does not have to be 1, it can be any n value. If that is the case then modification have to be done in the constraints to make sure that any point relating to the origin would reflect the order of the node in the node set (and OD matrix). Also any other node that does not refer to the origin, for example in the conservation constraints (3) the $i > 1$ would be $i \neq$ origin's order, and similarly for constraint (4) the $j \neq$ the origin's order. This concept is more elaborated on in the next section.

4.6 Scenarios' Modeling

Referring to the scenario Tables 9 and 10 in Problem Statement Chapter, it is now time to translate these in mathematical terms. Given are three scenarios related to barriers and two related to information sharing, this means that in total 6 (2x3=6) scenarios to be investigated. The proposed solution methodology, step 1 to 3, can be solved under any of the scenarios proposed. This is because depending on the barrier types the variable sets of the problem is modified to match that barrier type, as well as the distance parameter. The information sharing scenario is also accommodated by changing the demand parameter.

Assuming that the feasible solution set is $\digamma$ and the barriers are B_l, where L is the set of barriers in the problem, then the following table, Table 12, illustrates the differences in the input variables of the three barrier scenarios. Where x_{ij} is the link joining any two nodes and y_j is the possible facility location, both of which are decision variables.

Table 12 Barrier Scenarios in mathematical terms

Scenario	**Feasible Solution Set**
No Barrier	$x_{ij}, y_j \in \{0,1\} \qquad \forall\, i, j \in \digamma$
Scaled Barrier	$x_{ij} \in \{0,1\} \qquad \forall\, i, j \in \digamma$ $y_j \in \{0,1\} \qquad \forall\, j \in F \setminus \bigcup_{l=1}^{L} interior\ (B_l)$
Forbidden Barrier	$x_{ij}, y_j \in \{0,1\} \qquad \forall\, i, j \in F \setminus \bigcup_{l=1}^{L} interior\ (B_l)$

When it comes to barriers effect on planning, the main change to a model would be with regards to the number of facility locations available to choose from. In both barrier types, other than no barrier scenario, a facility location inside of the barrier region is not a feasible location, as opposed to not having barrier scenario. It is different for the routes. The distance and number of routes that are available for the final solution differ based on the barrier type. When there is no barriers all links x_{ij} that connect demand location i and location j are available to the final solution and their distances are not affected by barriers. When the barrier type is of a forbidden zone, then all links x_{ij} that intersect in the barrier zone are re-routed around the barrier zone, which results in new distance parameter, d_{ij}. Finally if the barrier type is of a scaled-cost barrier, the links x_{ij} that intersect the barrier zone are increased in weight (in this study, weight is distance, d_{ij}) by the length of segment which falls within the barrier zone and by multiple times of the measure unit's increments (in the numerical application, 5 times the length in meters of the barrier intersecting segment). In summary, depending on the type of scenario the set of variables available for the objective function change. The barriers also affects the distance parameter, d_{ij}.

The information sharing scenario affects the demand forecast parameter, a_i. The definition of the no-information-sharing scenario is that demand forecasts increase by %50. This means if demand forecast is 100 unit, then due to the lack of collaboration, the total demand forecast would be 150 (100+100*0.5). This reflects the redundancy in assessment done by a local or international NGO in addition to that of the military for example. The %50 increase results from This is a generalized methodology that can be applied to any disaster relief network design. In the no-information-sharing.

The following chapter generates a specific case which will be introduced and the above methodology will be applied. The case of Montreal and rising river levels, aka floods, is generated for the testing of the different effects of the six generated disaster relief scenarios.

Chapter 5

Numerical Application

This section is dedicated towards presenting a numerical example that would act as an illustration to how key stakeholders would investigate and plan for different network design planning aspects as well as will help investigate the effect of different disaster relief scenarios to designers. The case provided is based on real data that are acquired from different sources and brought together using GIS. There are several components that are needed in the creation of a similar study those are, a) elevation map, b) district's map and populations, and c) road network map. Typically upon the striking of a disaster this type of data is circulated on the internet to facilitate planning. In this case we assume the role of the municipality or government. The numerical application is made for the city of Montreal. The data acquired is gathered from academic as well as government resources. Montreal’s road network was acquired from the Concordia’s Department of Geography, Planning, and Environment. This network was paired with census data from Statistics Canada, providing us with a reflection of Montreal’s road network and population of 2006. This section will prepare Montreal Island for one of its most probable disaster scenarios, i.e. that of a flood and/or rising sea levels. The flooded regions are chosen by visually placing polygon barriers on top of the lowest elevation location of the city of Montreal. The elevation maps used in the study was taken from GeoBase a free online service (www.geobase.ca). Once the barrier regions are identified the rest of the case following the solution approach provided, i.e. demand forecast generation, location allocation model, and finally vehicle routing problem for the six scenarios in question.

5.1 Scenarios' Generation and Modeling

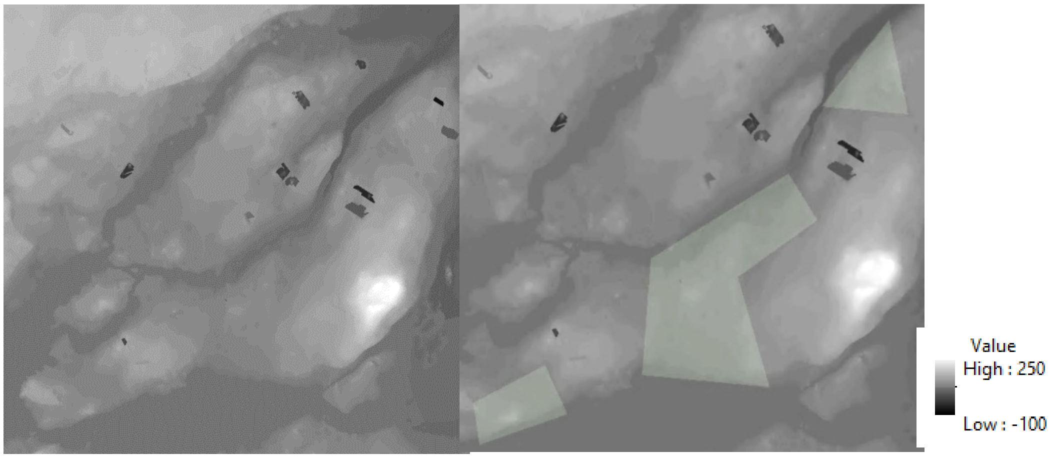


Figure 13 - Montreal Elevation Map (left), and Barrier Locations (right)

Figure 13 is the elevation map of Montreal and surrounding regions (www.geobase.ca). The lowest elevation areas of Montreal were chosen as the barrier zones. It is assumed that the lowest elevations on the island of Montreal are the one's marked by the polygon barriers, Figure 13 (right). The middle barrier, the largest, cuts through the whole island. This will be interesting to investigate. Next these barrier are applied to Montreal's districts map layer, a layer is a set of information presented on a data frame which ends up being a digital map. Figure 14, left, shows the districts that are included in our case study, all the districts of Montreal Island. The right of Figure 14 is the barrier regions as reflected on the districts. This figure is important because it defines which districts fall within the barriers and which do not. Here the districts centroids, the middle point of the polygon which is at equal distance from its extreme points, are the nodes of our model.

There are 475 district in Montreal. One is excluded because it not connected via the road network, see Figure 15. The model only covers road networks. Each centroid is assigned a population figure through joining it with a census table from Statistic Canada, 2006 Census Data.

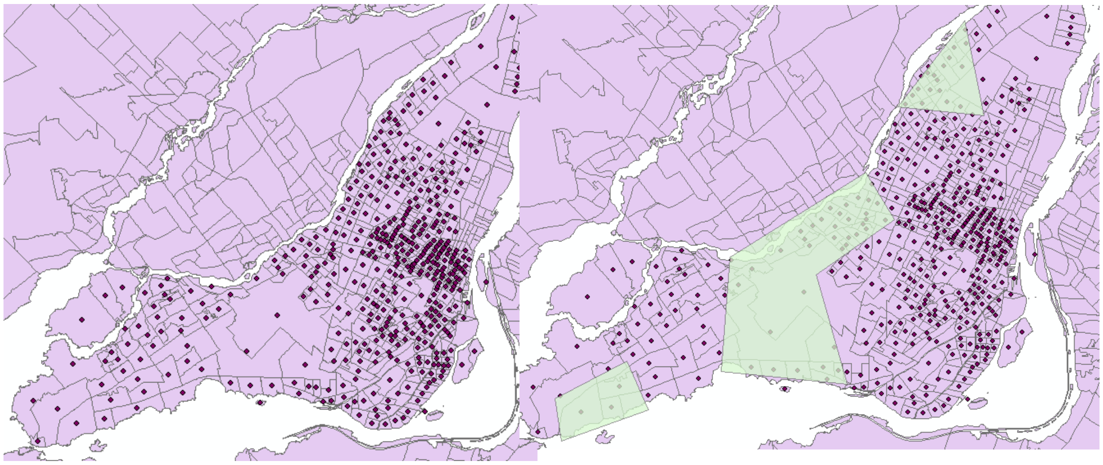


Figure 14 Montreal Districts Map (left), Within barrier districts (right)

Based on the scenario that is being investigated the model inputs vary. When the barrier zones, polygons in the right map in Figure 14, are forbidden regions, all the population of the 61 districts that fall within the barrier region are allocated to the nearest surrounding 47 districts. A scaled cost barrier would include all districts, however the change applies to traveling within the barrier zone. The following table, Table 13, is a summary of the 3 by 2 matrix that results from the investigation of barrier scenarios and information sharing.

Obviously the below table needs some more elaboration. First the difference between no information sharing scenario and information scenario is that 50% of the original forecasted demand is duplicated at the same demand points. For instance for scenario 2, no-barrier & no-information-sharing, the demand nodes double from 61 to 122. The extra 61 nodes are located in the same location as their duplicates and have half their demand. That is the difference between no-information sharing and information sharing levels.

Table 13 The 6 scenarios details

	Information Sharing	*No Information Sharing*
No Barrier	**<u>Scenario 1:</u>** Facilities, *J* = 474 Demand Nodes, *I* = 61 No Extra Distance No Extra Demand	**<u>Scenario 2:</u>** Facilities, *J* = 474 Demand Nodes, *I* = 122 No Extra Distance Extra Demand
Barrier (Scaled-Cost)	**<u>Scenario 3:</u>** Facilities, *J* = 413 Demand Nodes, *I* = 61 Extra Scaled Distance No Extra Demand	**<u>Scenario 4:</u>** Facilities, *J* = 413 Demand Nodes, *I* = 122 Extra Scaled Distance Extra Demand
Barrier (Forbidden-Zone)	**<u>Scenario 5:</u>** Facilities, *J* = 413 Demand Nodes, *I* = 47 Extra Distance No Extra Demand	**<u>Scenario 6:</u>** Facilities, *J* = 413 Demand Nodes, *I* = 94 Extra Distance Extra Demand

When looking at the differences between the scenarios from the barrier levels. No-barrier level is the same as an ordinary or commercial supply chain, a barrier level would incur more cost for the links that travel through the barrier region. Also the set of facilities decreases because it is assumed that facilities cannot be located within the barrier region, however traveling is allowed. Notice the decrease from 474 possible facility location to 413, see Figure 15 (right).

Finally for the barrier as forbidden zone level, there are no extra scaled distance, however traveling and locating facilities are forbidden. This may result in some routes might ending up being longer because it has to go all around the barrier. Demand forecasts in this level are allocated equally to the nearest nodes outside of the barrier region; this is where the number 47 comes up. i.e. 47 demand nodes outside of the barriers, see Figure 15 (left).

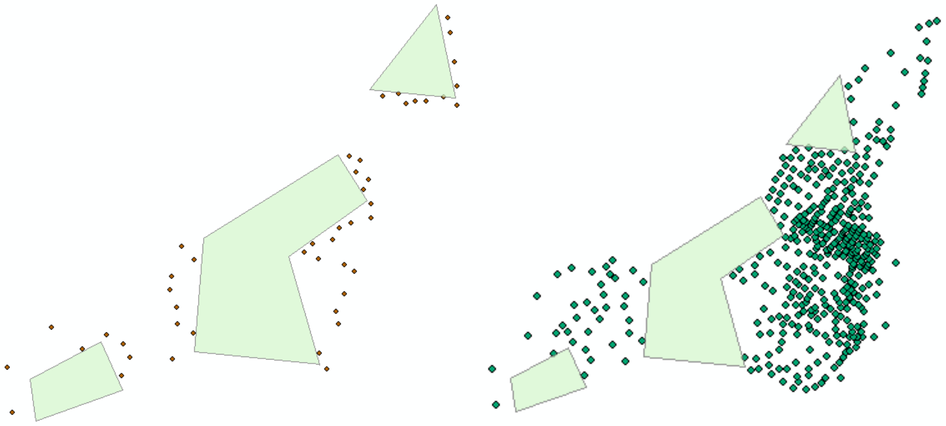


Figure 15 - 47 Districts surrounding barrier region (left); 413 Possible facility locations outside barrier (right)

The information sharing scenario basically means that the demand forecast in the same districts is doubled by an second assessment that is not done by the original play. The example being that the military does the initial assessment and when there is no information sharing then a local NGO will have its own assessment for the same locations. The NGO in essence will be operating on the same location as the military. Collaboration over other aspects such as facility space and transportation resources still remains. The only thing affected here is the forecasting of demand.

Figure 16 Montreal Road Network

Notice by simply adding the barrier layer to the Montreal road network, Figure 16, the network will be capable of providing different solutions as per the barrier type. Also notice that the road network extends beyond Montreal, so technically if a barrier blocks Montreal from North to South of the Island, as does the largest barrier, demand can still be covered from a longer route around and outside of the island. In the literature review section 2.6 it was indicated how a straight line would react to the different type of barriers analyzed. ArcGIS does these algorithms on a wider scale. Thus it is capable of providing OD Matrixes of distance, time, or costs, as per defined by the user. The focus of analysis in this paper is distance. Time and cost parameters are not taken into consideration. Also it is worth mentioning that the hierarchy option was disabled in the Network Analyst. Hierarchies are typically set in road network to differentiate a highway from a normal road which would indicate different traveling speeds.This gives analyst the opportunity to measure travel distance with different speed restrictions.

5.2 Demand Generation

Looking back at section 4.3. The resulting average demand probability generated from Table 11 and Figure 12 is 50.6125% which is basically 0.506125 of each of the districts that fall within the inflected region, i.e. within the barrier region. The other factor affecting the demand parameter, a_i, is the information sharing scenario being investigated. Under information sharing the demand forecast is shared amongst the player in the disaster relief operation. Ideally government officials such as government would run their own assessments on scale of the disaster and its impact on the population and precisely the inflected districts. This information is disseminated to a public website and made available for all players that contribute to that disaster. Other information that is assumed to be shared are inventory at chosen facility sites, number of trucks and truck capacities available for each site. When there is no information sharing, the main change from the information sharing scenario is that demand is inflated due to shared objectives, but no communication. The redundancy of %50 of the disaster demand forecasts or assessments is added to the disaster inflected zones. This reflects the assessments done by a NGO, local or international, that the government agency does not share information with. This will help shed light on the effects of no information sharing in disaster relief network design.

5.3 Location Allocation Model's Parameters and Results

Prior to solving the location allocation problem, variables and parameters have to be properly set as illustrated in previous sections on scenario modeling and demand generation. Based on that body of variables, possible facility locations, y_j, and demand, x_{ij}, nodes, the distances, d_{ij}, are generated using OD matrixes which differ based on the barrier scenario used. Demand parameter, are defined by the information sharing rule. Another parameter, *w,* that is used to emphasize on the optimization of distance as well as demand coverage, as this is a multiple objective LAP, needs to be identified. The weight variable is changed based on the equation of the best value for the weight factor. See Table 14 for the weights used in the model. The largest value in the ranges were used in order to ensure the importance of optimizing this second part of the objective function of the LAP. This means that for each scenario we can chose between the computed value in Table 14 and down to zero.

Table 14 Weights associated with LAP using AIMMS

Scenario	**Weight factor** $\mathbf{0 \leq w \leq \frac{1}{A\,(d_{max} - d_{min})}}$
No Barrier	0.402108
Scaled Barrier	0.759239
Forbidden Barrier	0.870464

The number of facilities, k, to open and the capacity, s, of each has to be determined prior to the model. This is based on the demand forecast and the chosen location capacity, i.e.

the larger the capacity the less facilities would need to be opened. The number of facilities to open was chosen to be 11 based on dividing the total forecasted demand by the desired warehouse capacity or the desired number of facilities to open, which led to the capacity being 12000 for the information sharing scenarios and 17000 for the no information sharing scenarios, which accommodates for the %50 increase in total demand.

The scenarios specific variables (number of nodes, and possible facilities), parameters, were inputted in AIMMS and ArcGIS. Both exact, AIMMS, and heuristic, ArcGIS, approaches did fully cover the forecasted demand as well provided a good distance solution based on the given weights. Figures 17 and 18 illustrate the objective function results. Note that this LAP model is multi-objective model, the first part, Figure 17, solves for maximum coverage, and the second part is regarding the distance traveled, Figure 18. The conservation constraint along with the maximize coverage objective function worked perfectly. Total demand covered by all models on both softwares matched exactly total forecasted demand.

It is important to notice that in both instances when solving the particular case of forbidden barriers scenario with information sharing, both sofwares had an error. There was a capacity violation with the model in both solutions, however it was mitigated. ArcGIS was able to visualize the location of the uncovered demand nodes. However it was visually identified and using Excel to validate scenario's solution. For AIMMS, the model did not provide any solutions and pin-pointed that the solution is infeasible.

After tracking the uncovered demand nodes, they were found to be demand nodes number 457,462, and 35 where left out in the ArcGIS solution. Demand nodes 457 and 462 were allocated to the nearest open facility 422, and demand node 35 was allocated to the open facility 91. This is reflected in the increase in capacity of facility 422 to 18000 and facility 91 to 1500 from the 12000 default capacity. There are several observation to be made about this, first the software did not indicate any errors in the model; all the demand nodes where marked as covered. There was however three missing links. This violates the constraint that each demand node has to be allocated to one facility (constraint 2 in LAP, section 4.4). The important thing to note here is that the visual capability of a GIS enabled us to locate the nearest facility and make the added capacity decision specifically to these nearest already chosen facilities.

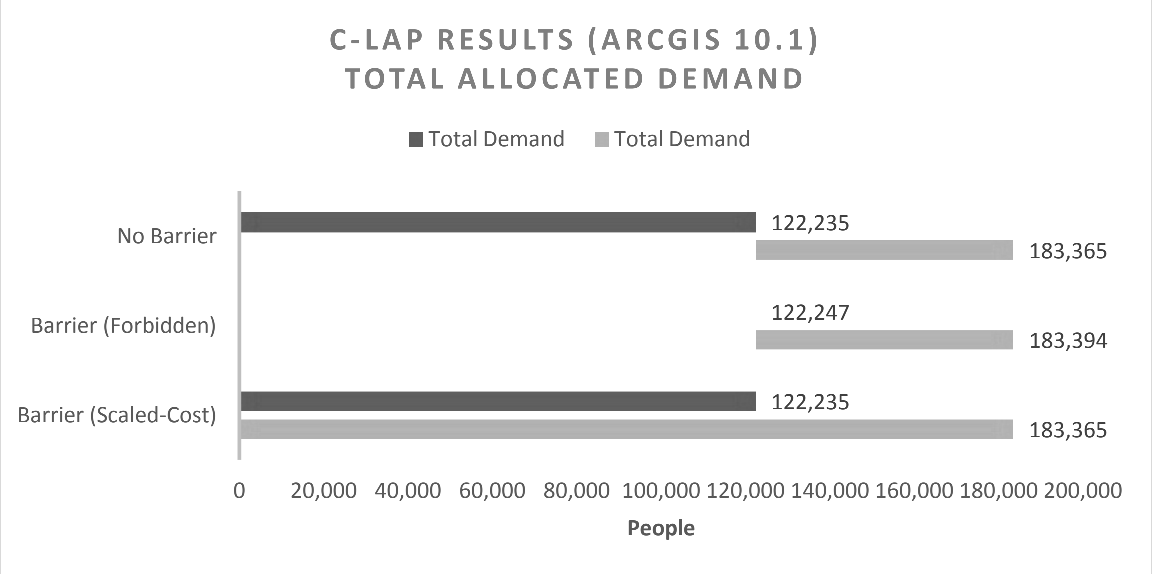


Figure 17 Demand Coverage in LAP for the 6 Scenarios Using ArcGIS

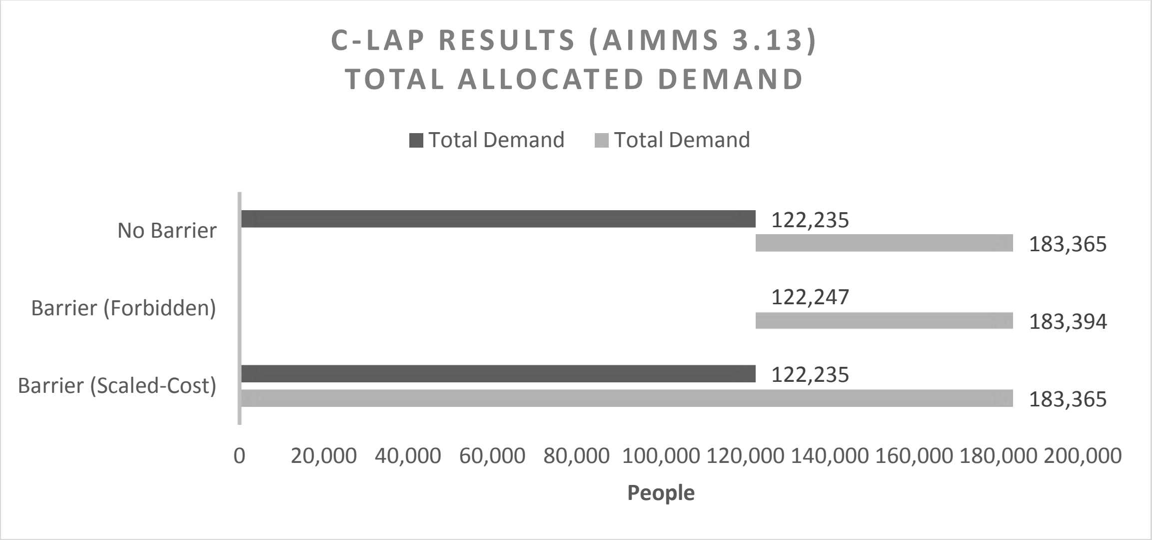


Figure 18 Demand Coverage in LAP for the 6 Scenarios Using AIMMS

In the case of forbidden barriers-information sharing scenario in AIMMS, what was observed is that AIMMS did not solve any of the problem, in fact it declared the problem as infeasible solution. The way to come about around this is to increase the default capacity of all facilities or add more facility options to be opened. The decision was made for the latter as it was more consistent with the investigation results. These results of the modification can be seen in the striped bars in Figure 17 and 18.

The following graphs (Figure 19 and 20) summarize the second part of the objective function, i.e. minimize distance. It is notable that exact solutions from AIMMS are always better than ArcGIS's heuristic. The other thing to note is that scaled barrier regions have the longest travel distance regardless of the information scenario investigated. There was not that much difference between the forbidden-zone barrier solution and the no barrier solutions. Also with information sharing the results are about %50 less than the no information sharing scenario. For example, the total distance traveled for the information sharing-no barrier scenario is 235,168.32 for AIMMS and

258,898.37 for ArcGIS, where when there is no information sharing and no barrier the numbers decrease to 94,669.69 (AIMMS) and to 120,202,22 (ArcGIS) respectively. It can also be noted that the lowest and best solution in the 12 problems (6 scenarios for AIMMS and 6 for ArcGIS) is the AIMMS solution for 94,699.69 meters which is in the presence of no barrier and information sharing, which is what is expected. Since having no barriers and full information disclosure would facilitate decision making. In Figure 19, the striped bars represent the scenario solution that needed to be revisited, i.e. information sharing - forbidden barrier scenario, that needed to be revised to cover the basic need of our model, i.e. cover all the demand.

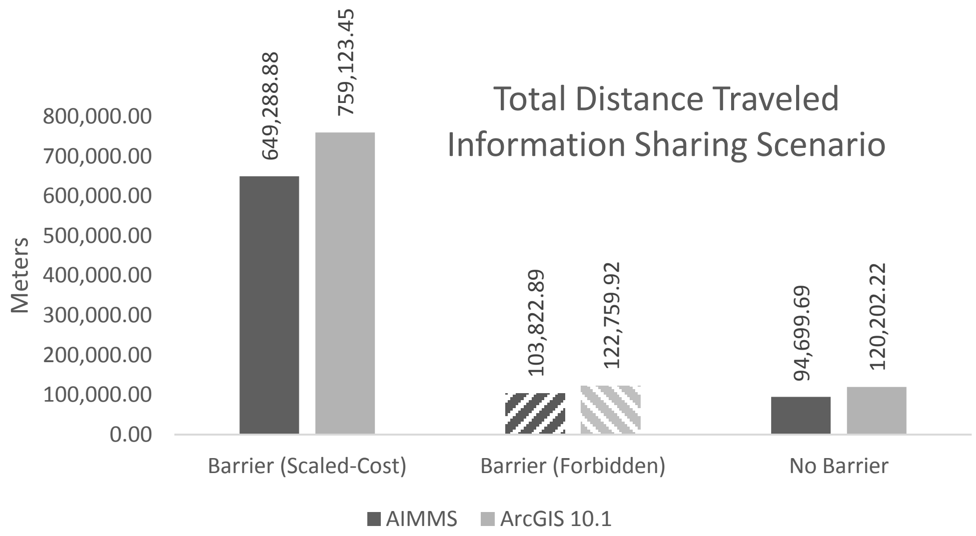


Figure 19 Total Distance Traveled in LAP model with Information Sharing

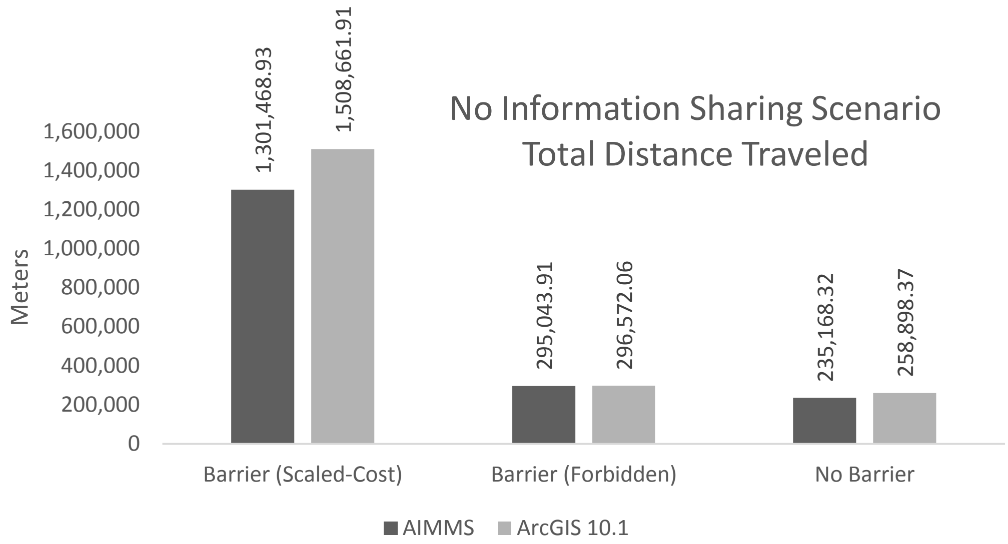


Figure 20 Total Distance Traveled in LAP model with No Information Sharing

Another observation to note is that when solving the problem with ArcGIS heuristic, the solution did not take so long of a time to solve. It is also important to note that ArcGIS heuristic algorithm solution did not take over 5 minutes to reach any solution, whereas AIMMS took from 20 seconds to 12.5 hours to reach a solution. Table 15 illustrates the time taken to solve each of the 6 models on AIMMS. The increase in solving time is a function of number of variables solved and the parameters range. The no-information scenario and no barrier or forbidden-zone barrier solution time were significantly higher than the other 4 scenarios, however looking at figure 19 it can be seen that there was no major difference between the AIMMS solution and that of ArcGIS. This means that a lot of time could be saved by using ArcGIS for such large.

Table 15 The AIMMS's computational time of the 6 scenarios of LAP

	Information Sharing	**No Information Sharing**
No barrier	1 hours 40 minutes 29389 Variable 29451 Constraint	8 hours 35 minutes 58303 Variable 58426 Constraint
Scaled Cost Barrier	40 minutes 25607 Variable 25669 Constraint	2 hours 5 minutes 50800 Variable 50923 Constraint
Forbidden-zone Barrier	20 seconds 19825 Variable 19873 Constraint	12 hours 35 minutes 39236 Variable 39331 Constraint

The outputs of the LAP are a set of facility locations to open, each with the set of demand nodes that are allocated to it. Sample output can be seen in the appendix for both solution methods (AIMMS and ArcGIS). The outputs are then cleaned up, refined, validated, and introduced to the second level, i.e. VRP.

5.4 Vehicle Routing Model's Parameters and Results

At this stage it should be relatively simple to create a vehicle routing plan for the set of demand nodes allocated to a particular facility. Demand nodes and their allocated facility location are the main variable inputs of this VRP model. Finding the distance parameter, d_{ij}, between all the nodes and the facility included and demand forecasted at each node is the first step towards solving this problem. The OD distances matrix of the allocated demand nodes and the chosen facility location is calculated which takes into consideration barrier type. The model also takes into consideration truck capacities, that is why demand parameter, a_i, is important in this capacitated vehicle routing problem. The model can solve for either one or more routes, *k*, of same or different capacities, s,. If one route is chosen to deliver the supplies for all allocated demand nodes then the route capacity has to be at least equal to the capacity of the warehouse. If two routes are chosen then the capacity of each route would have to add up to the capacity of the facility.

The output of the model is a set of links, x_{ij}, chosen so that each demand node is covered, the truck capacity is not violated, while efficiently used. AIMMS solution always came through with the best solution, as presumed. However visualizing data on ArcGIS from different maps, as previously highlighted, is an important function of GIS. The visual representation of data on a geographic interface is powerful in itself. It is worth noting that solution from AIMMS can be migrated into ArcGIS and vice versa. This allows the end analyzer with greater flexibility depending on the scale of the problem at hand, and the time available to plan.

Routing have been solved for two facilities. Figures 21 to 24, shows the solution for the VRP problems solved for different scenarios and different softwares. Each bar represents a VRP problem's objective function solution, a minimization of distance to be traveled between the nodes. The darker bars represent single routes of a capacity equal to the facility, 12000 for information sharing scenarios and 17000 for no information scenario. While light grey bars represent the solution when the capacity of a facility is delivered over two routes, meaning facility capacity divided by 2 An important thing to highlight here is that in this study no interrelation between the two solution softwares have been tried. This means that all AIMMS solutions went into AIMMS and all ArcGIS solutions where processed again in ArcGIS.

For the information sharing scenarios, the distances are always shorter in the instances trialed for the single route. The striped bars of Figure 22 indicate the increase in route capacities. This is because previously we have increased the capacity of that particular facility, located at node 422, to 18000. Similarly when two routes were investigated for this facility location the route capacity was more than the regular to accommodate the facility capacity (18000/2=9000 units). This was not the case in AIMMS since a whole new facility of same capacity of 12000 units was opened. All one route problems had a route capacity of 12000 and two route solutions had a capacity of 6000 units.

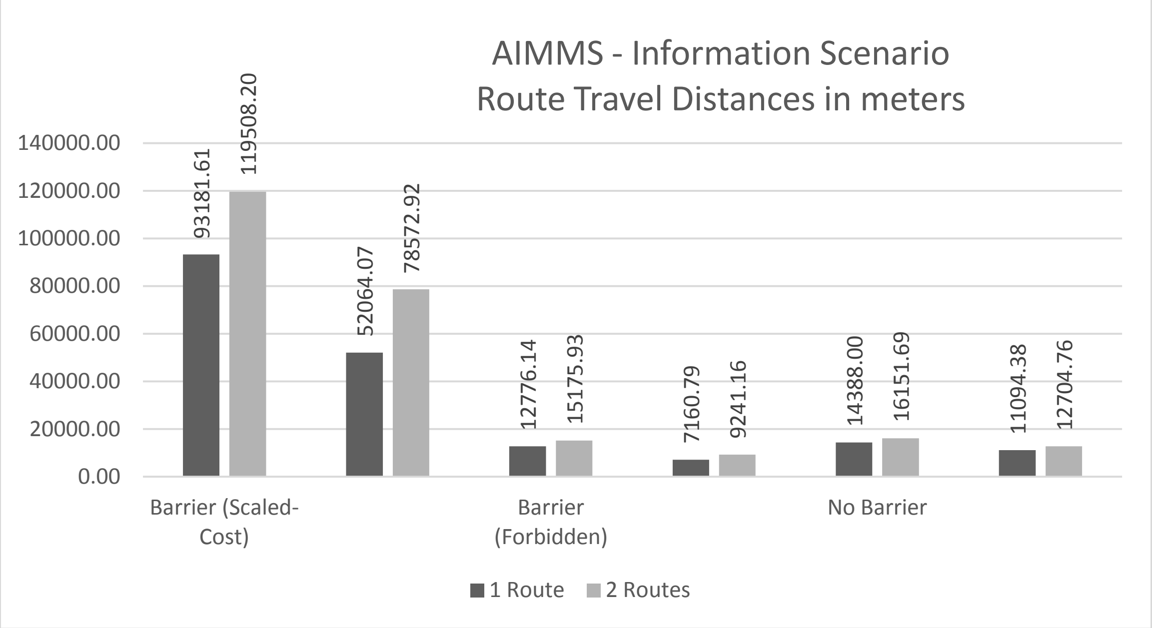


Figure 21 Optimal Routing Distance for VRP using AIMMS

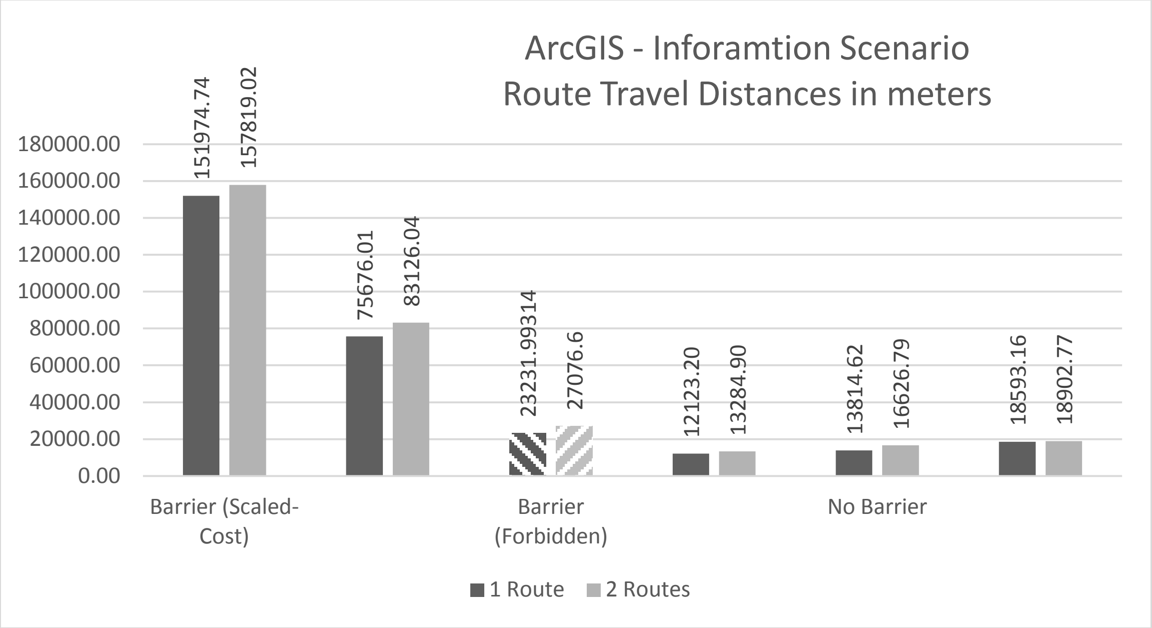


Figure 22 Optimal Routing Distanc for VRP using ArcGIS

Similarly for no-information sharing scenarios, Figure 24, and 25, the one route solution was more efficient than using multiple routes. The exception to this is in one case, the diagonal striped bar in Figure 25, where the one route was longer due to one way road restrictions. Figure 34 of the Appendix II shows the two solutions, one route vs two routes. Apparently when using one route, the trucks will have to travel more distances do to road restrictions. This is a positive aspect of using GIS, as previously mentioned, it helps visualize the problem more realistically. The other notable deviation in ArcGIS solution is for the forbidden barrier region, where the optimal solution consisted of one really long route which offset the objective function. This can be noticed in Figure 25, the dashed bars, and illustrated in Figure 23.

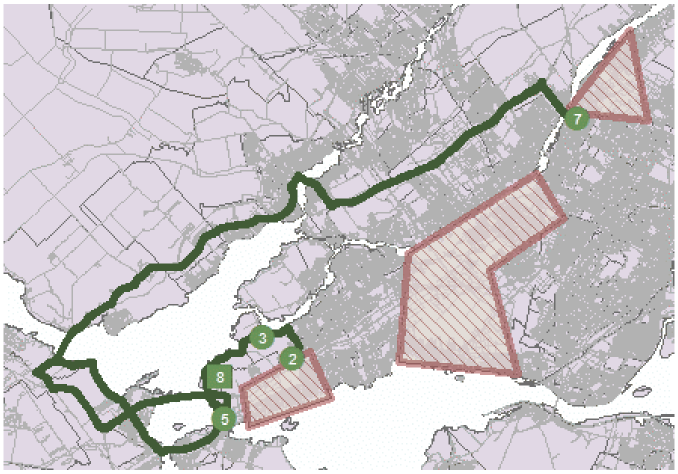


Figure 23 abnormal observation in VRP solution under forbidden barrier-no information sharing scenario

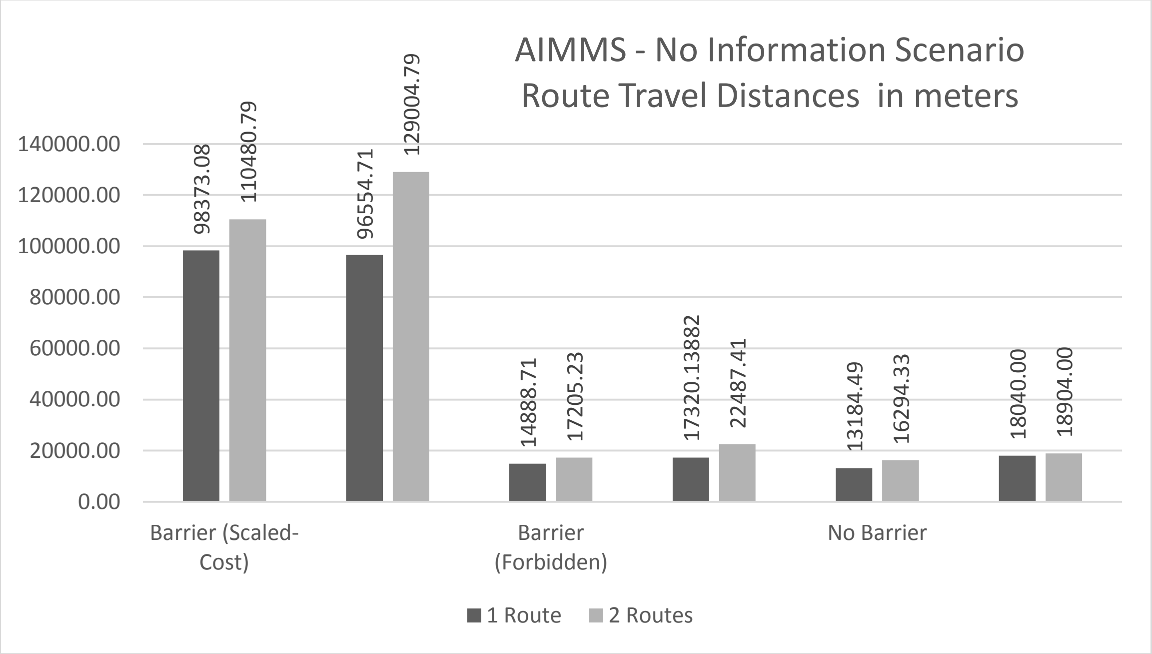


Figure 24 No-Information Sharing Scenarios VRP in AIMMS

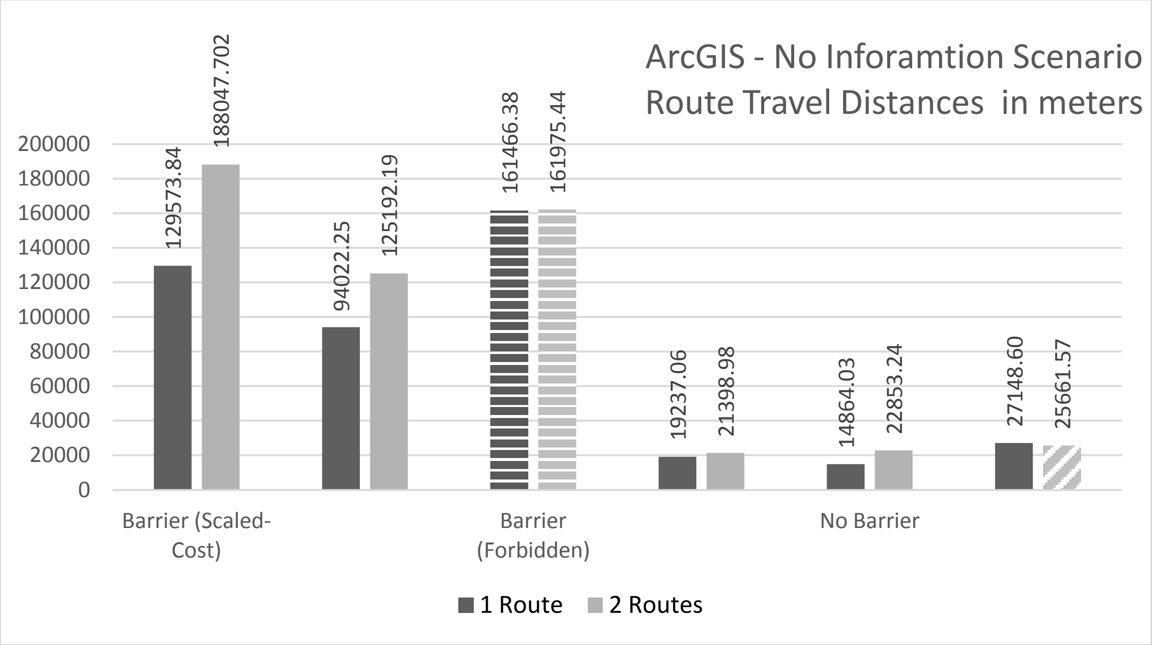


Figure 25 No-Information Sharing Scenarios VRP in ArcGIS

There are few important consideration to take into perspective when solving this type of problem using the proposed methodology. The next section will explore these consideration, followed by the final conclusion section.

5.5 Methodology Review and Validation

The above results were based on a lengthy experimentation. There are certain aspects of it that needed to be document delicately as to contain the integrity of the solution. The constraints of each of the proposed models were used to validate the solutions. Excel was intensively used to document the inputs and resulting solutions from AIMMS and ArcGIS. The results had to be matched with their original locations as running multiple models requires unique variables each time around for the integrity of the results. AIMMS produced binary tables that needed to be cleaned for analysis (see Appendix II).

ArcGIS produced numerical values (see Appendix II) which had to be transformed into binary figures using Excel's IF function.

Once the data was matched to the original set, and cleaned the validation process began based on the model type. In the LAP, the first thing was to make sure that the variables chosen satisfy the total demand. Each demand allocated had to be met only once. The summation of demand nodes allocated had to not go over the capacity requirements. The demand node can not be satisfied unless the related facility is opened.

The VRP results were similarly validated. Once the AIMMS or ArcGIS solutions were obtained they were matched to the original set of data, i.e. original variable set (variables are changed with each problem to avoid redundancy in using variables). Then the results are cleaned out, especially in ArcGIS which returns actual quantities shipped and not binary variable like AIMMS. Also very important to note that the LAP solution was for multiple facilities, and the VRP solution is for a single facility. The chosen facility and allocated demand points is then entered into ArcGIS to solve for the OD matrix of all possible links subject to barrier conditions. The results are then checked for consistency with the model requirements. First the origin has to be specified within the model inputs. If the chosen facility is the fifth of a set of 6 then the first constraint would apply to node 6 an not node 1: $\sum_{j=2}^{n} x_{1j} = k$ becomes $\sum_{j\neq 6}^{n} x_{6j} = k$. If k=2 then this constraint, constraint 1, will ensure that 2 links go out of the facility located at node 6. Validation is also done for constraint 2 to ensure that the number of links coming back to the origin is also equal to k. Constraint 3 and 4 are also validated by making sure that each node is visited only once and that no nodes is visited more than 1 time. Excel is a great support tool to operation research. Finally for each route combination the quantities allocated had to be less than the specified truck capacity s. The u variable behaved as an aggregate of the quantities allocated as the route proceeds to the next node on the route; this was also a variable to monitor to validate the model.

Another validation aspect of the study is that two different solution methodologies where used that of AIMMS, an exact solution approach, and ArcGIS, a heuristic solution approach, both of which resulted in similar results, and as predicted the exact solution approach was always better than the heuristic solution approach. The next chapter will conclude this study and put forward ways in which it can be improved.

Chapter 6

Conclusions and Future Work

Disaster relief network designing is a unique field, unlike its widely researched and developed commercial counterpart. It is in that light that this thesis was written to investigate its uniqueness. A state-of-the-art literature review was made on all disaster relief network models that are available in the disaster relief network design body of knowledge. The models were analyzed by their computational characteristics, and by their conceptual contribution to the domain. An integrative approach was adopted in order to solve for the strategic aspects found in these disaster relief network designs model, i.e. locating central warehouses, allocating regional distribution centers, and solving for routing under different scenarios. The integrated models were tested using a flood disaster affecting real population census data, Statistics Canada 2006, of Montreal's districts along with real road and real elevation maps of Montreal Island.

The decision makers can now be more confident about their strategic network design decisions, as the above model covers forecasting, facility location, allocation, inventory, and routing decisions. The models, LAP and VRP, where solved for 3 barrier types and 2 information sharing scenarios, which resulted in a 3x2 scenario matrix. The investigation accounted for effects of having barriers of different types on network design aspects. The three barrier scenarios investigated are, forbidden zone barriers, scaled cost barriers, and no barriers. The two information sharing scenarios are full information sharing, and semi information sharing between a large organizing body such as government and a smaller scale organization such as a middle sized international or local NGO.

None of the literature reviewed highlighted the criticality of barriers in their models and the affects those would have when making decision related to network designing. Mutual coordination amongst stakeholders is highlighted as an important factor for disaster relief logistics success, however lack of empirical evidence in the specific domain is evident. It is due to aforementioned reason that this research got its motivation. The 3 barrier – 2 information sharing matrix investigated for influences and implications of these special to disaster relief network design issues. The numerical case of a Montreal hypothetical flood disaster was used for the analysis.

Several conclusions that can be drawn upon from the above study. Evidently it can be concluded from the study that no-barriers and forbidden-zone-barriers scenarios surprisingly have similar outputs when compared to scaled-cost-barriers scenario. The total distance traveled was significantly less in the former as compared to the later. Travel distances under full information sharing is always more efficient than travel distances under semi information sharing regardless of the barrier's type influence.

Planners should be aware when planning disaster relief network designs. It is critical that information is shared openly with other organizations that share similar objectives in order to deliver better, more efficient operations which results in more effective relief efforts. Sharing inventory information is critical as to avoid excess supplies and bottle neck operation. At least planners should take into consideration that the lack of information sharing would change the behavior of their network design.

Planners also must take into consideration the type of barrier that is in their regions. Different barrier types require different planning efforts. It should be analyzed whether it is worth a while traveling within a scaled-cost barrier region, such as a low impact flood, as opposed to evacuating victims to non-barrier regions; results show that traveling distances for forbidden zone barrier's was significantly less than traveling within a scaled-cost barrier. When solving VRP it was noticed that using one route resulted in less travel distance than two routes. Planner should consider the efficiencies of delivering all material using one route or whether they should deliver material using two routes which always resulted in more travel distance. A key element here is whether or not time is a constraint, and another is the availability of transportation resources.

Another observation from this research is that exact solutions, i.e., building a model from scratch is better at conducting empirical research. The reason being that the methodology and/or algorithms behind a software like, ArcGIS, is not as clear. It is still unknown how the heuristics work exactly. However the visualization of the solution did have benefits in understanding several out of the ordinary observation as opposed to using AIMMS which resulted in infeasible solutions. ArcGIS heuristics was faulty at reporting the final solution of VRP, which was not the case in the AIMMS trials. See Appendix II for some insights into the structure of the two solutions and their parameters. Nevertheless, in few instances where AIMMS's took hours to compute an optimal solution, ArcGIS took minutes to find a similar solution. Solving the models via AIMMS's always resulted in better solutions (optimal) than ArcGIS; planner have to take other variable such as speed of delivery into considerations when planning a network design, or re-planning an already existing network design once more data become available.

Future Works and Weaknesses

There are several weaknesses observed while at the final stages of this research, namely:

1) The disaster impact probabilities is based on estimations.
2) Barriers are assigned manually.
3) Only covered road network, not planes, or ships.
4) Required facilities and their capacities matched forecasted demand exactly.
5) Multiple commodities and time constraints were not considered.

This research can be carried on by future master students in one of the previous or following topics:

a) Since GIS still has an advantage for being more visual and realistic than its counterpart. The future student can program an algorithm and implement it into the GIS environment for fast visualization and more controlled over model.
b) Investigate more complex information sharing scenarios than involves more than two players.
c) Add a cost, time, or monetary factor rather than only distance to give the problem more relevance to more stakeholders.

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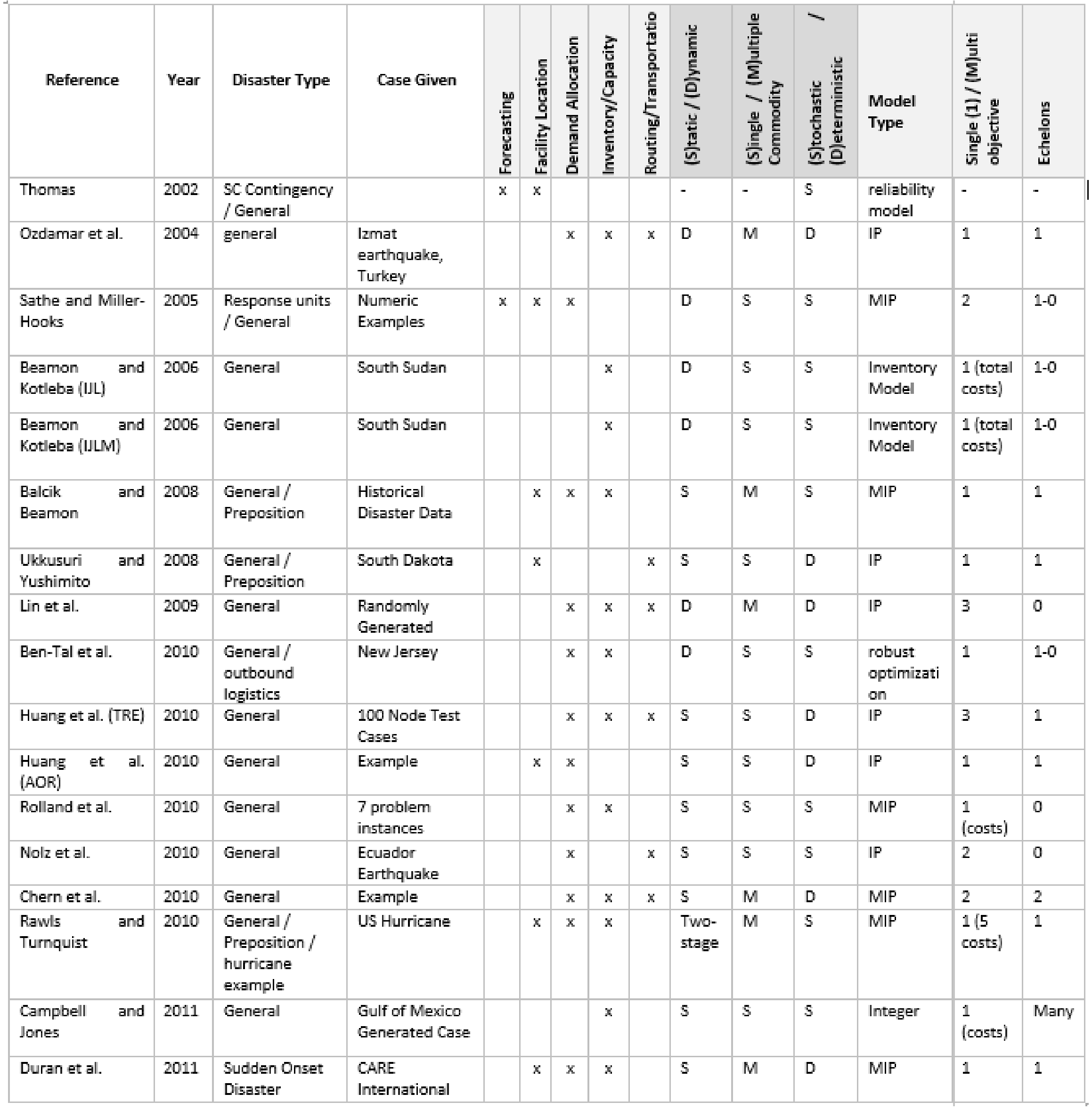
Appendix I - Literature Review Table (continued)

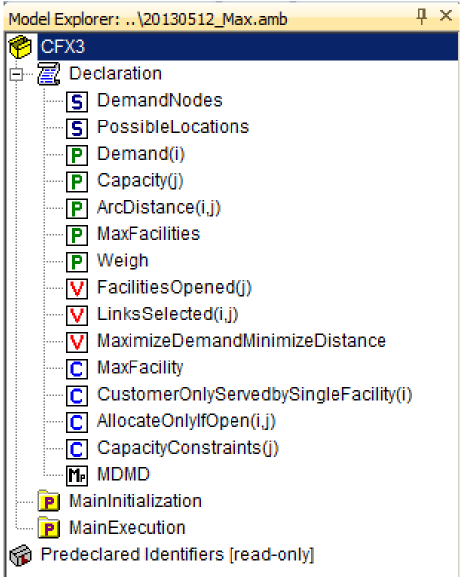
Table 16 General Disaster Network Design Models



Reference	Year	Disaster Type	Case Given	Forecasting	Facility Location	Demand Allocation	Inventory/Capacity	Routing/Transportatio	(S)tatic / (D)ynamic	(S)ingle / (M)ultiple Commodity	(S)tochastic / (D)eterministic	Model Type	Single (1) / (M)ulti objective	Echelons
Thomas	2002	SC Contingency / General		x	x				-	-	S	reliability model	-	-
Ozdamar et al.	2004	general	Izmat earthquake, Turkey			x	x	x	D	M	D	IP	1	1
Sathe and Miller-Hooks	2005	Response units / General	Numeric Examples	x	x	x			D	S	S	MIP	2	1-0
Beamon and Kotleba (IJL)	2006	General	South Sudan				x		D	S	S	Inventory Model	1 (total costs)	1-0
Beamon and Kotleba (IJLM)	2006	General	South Sudan				x		D	S	S	Inventory Model	1 (total costs)	1-0
Balcik and Beamon	2008	General / Preposition	Historical Disaster Data		x	x	x		S	M	S	MIP	1	1
Ukkusuri and Yushimito	2008	General / Preposition	South Dakota		x			x	S	S	D	IP	1	1
Lin et al.	2009	General	Randomly Generated			x	x	x	D	M	D	IP	3	0
Ben-Tal et al.	2010	General / outbound logistics	New Jersey			x	x		D	S	S	robust optimization	1	1-0
Huang et al. (TRE)	2010	General	100 Node Test Cases			x	x	x	S	S	D	IP	3	1
Huang et al. (AOR)	2010	General	Example		x	x			S	S	D	IP	1	1
Rolland et al.	2010	General	7 problem instances			x	x		S	S	S	MIP	1 (costs)	0
Nolz et al.	2010	General	Ecuador Earthquake			x		x	S	S	S	IP	2	0
Chern et al.	2010	General	Example			x	x	x	S	M	D	MIP	2	2
Rawls and Turnquist	2010	General / Preposition / hurricane example	US Hurricane		x	x	x		Two-stage	M	S	MIP	1 (5 costs)	1
Campbell and Jones	2011	General	Gulf of Mexico Generated Case				x		S	S	S	Integer	1 (costs)	Many
Duran et al.	2011	Sudden Onset Disaster	CARE International		x	x	x		S	M	D	MIP	1	1

Appendix II - Technological Aspects - Solution Approach Illustrations

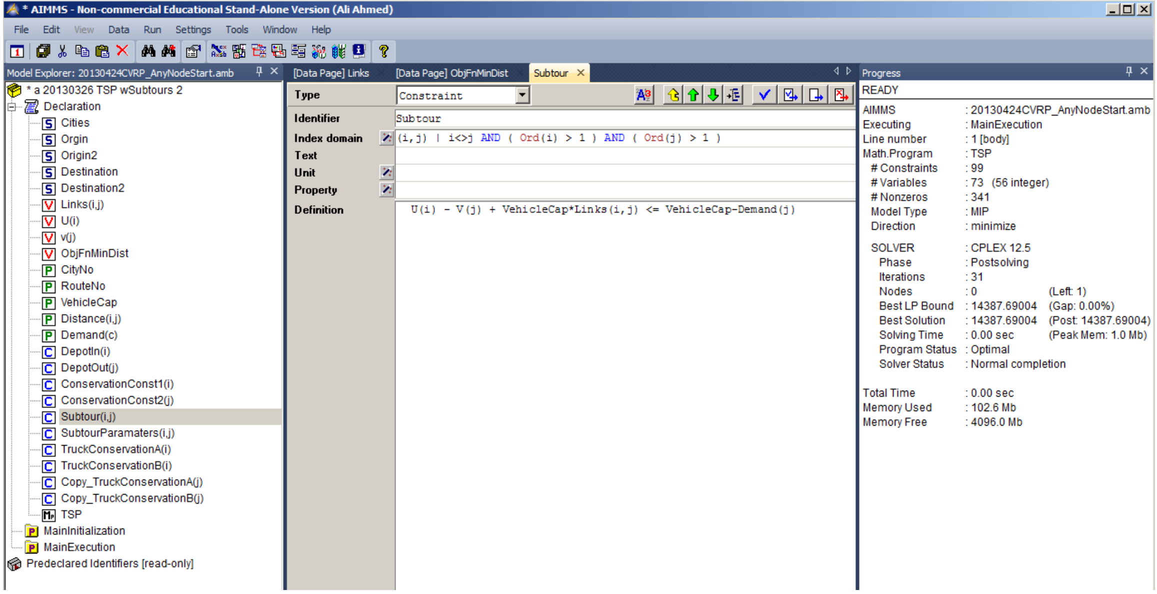
Figure 26 LAP Model in AIMMS



CFX3
- Declaration
  - DemandNodes
  - PossibleLocations
  - Demand(i)
  - Capacity(j)
  - ArcDistance(i,j)
  - MaxFacilities
  - Weigh
  - FacilitiesOpened(j)
  - LinksSelected(i,j)
  - MaximizeDemandMinimizeDistance
  - MaxFacility
  - CustomerOnlyServedbySingleFacility(i)
  - AllocateOnlyIfOpen(i,j)
  - CapacityConstraints(j)
  - MDMD
- MainInitialization
- MainExecution

Predeclared Identifiers [read-only]

Figure 27 VRP Model and Sub-Tour Constraint AIMMS



* a 20130326 TSP wSubtours 2
- Declaration
  - Cities
  - Orgin
  - Origin2
  - Destination
  - Destination2
  - Links(i,j)
  - U(i)
  - v(j)
  - ObjFnMinDist
  - CityNo
  - RouteNo
  - VehicleCap
  - Distance(i,j)
  - Demand(c)
  - DepotIn(i)
  - DepotOut(j)
  - ConservationConst1(i)
  - ConservationConst2(j)
  - Subtour(i,j)
  - SubtourParamaters(i,j)
  - TruckConservationA(i)
  - TruckConservationB(i)
  - Copy_TruckConservationA(j)
  - Copy_TruckConservationB(j)
  - TSP
- MainInitialization
- MainExecution

Predeclared Identifiers [read-only]

Type Constraint

Identifier Subtour

Index domain `(i,j) | i<>j AND ( Ord(i) > 1 ) AND ( Ord(j) > 1 )`

Text

Unit

Property

Definition

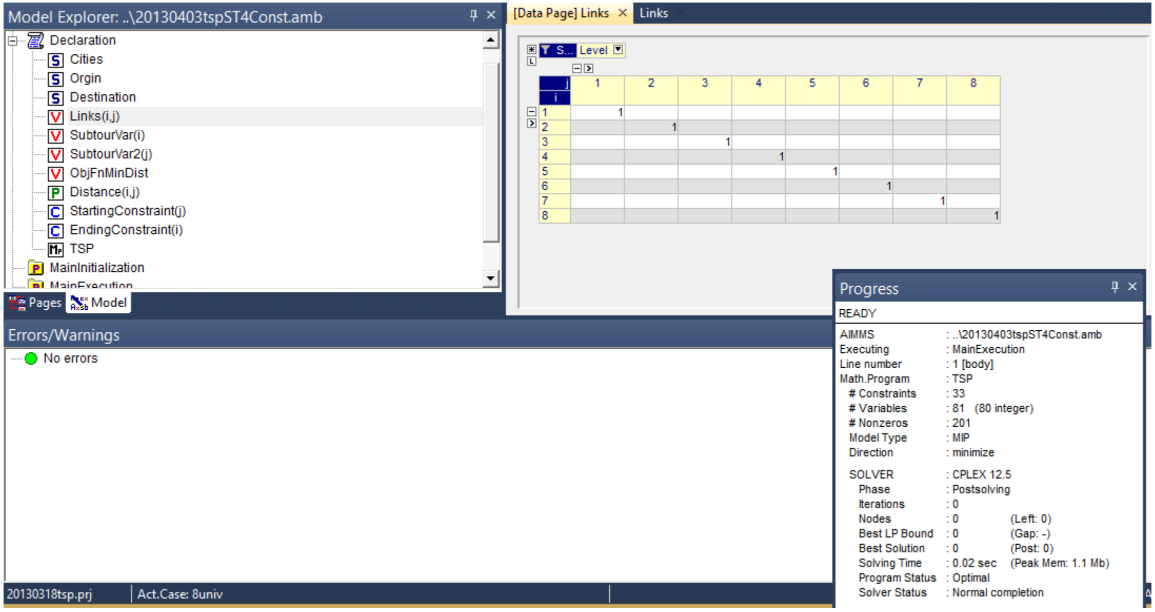
```
U(i) - V(j) + VehicleCap*Links(i,j) <= VehicleCap-Demand(j)
```

```
READY
AIMMS             : 20130424CVRP_AnyNodeStart.amb
Executing         : MainExecution
Line number       : 1 [body]
Math.Program      : TSP
  # Constraints   : 99
  # Variables     : 73  (56 integer)
  # Nonzeros      : 341
  Model Type      : MIP
  Direction       : minimize

  SOLVER          : CPLEX 12.5
    Phase         : Postsolving
    Iterations    : 31
    Nodes         : 0               (Left: 1)
    Best LP Bound : 14387.69004     (Gap: 0.00%)
    Best Solution : 14387.69004     (Post: 14387.69004)
    Solving Time  : 0.00 sec        (Peak Mem: 1.0 Mb)
    Program Status: Optimal
    Solver Status : Normal completion

Total Time        : 0.00 sec
Memory Used       : 102.6 Mb
Memory Free       : 4096.0 Mb
```

Figure 28 Sample AIMMS VRP Output (a)

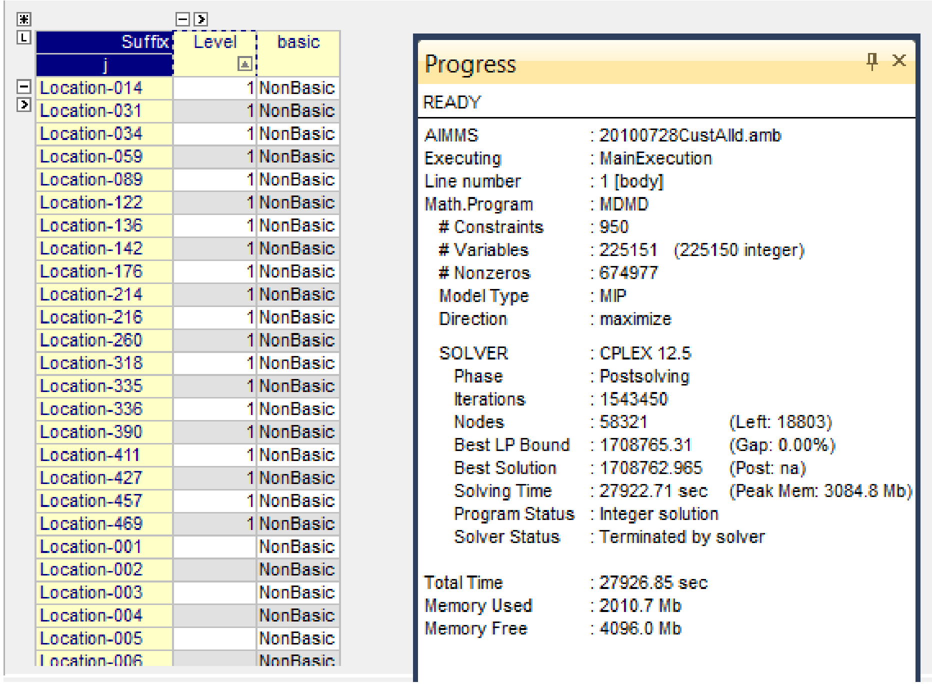


i \ j	1	2	3	4	5	6	7	8
1	1							
2		1						
3			1					
4				1				
5					1			
6						1		
7							1	
8								1

```
Progress
READY
AIMMS              : ..\20130403tspST4Const.amb
Executing          : MainExecution
Line number        : 1 [body]
Math.Program       : TSP
  # Constraints    : 33
  # Variables      : 81   (80 integer)
  # Nonzeros       : 201
  Model Type       : MIP
  Direction        : minimize

  SOLVER           : CPLEX 12.5
    Phase          : Postsolving
    Iterations     : 0
    Nodes          : 0          (Left: 0)
    Best LP Bound  : 0          (Gap: -)
    Best Solution  : 0          (Post: 0)
    Solving Time   : 0.02 sec   (Peak Mem: 1.1 Mb)
    Program Status : Optimal
    Solver Status  : Normal completion
```

Figure 29 Sample AIMMS LAP Output (b)



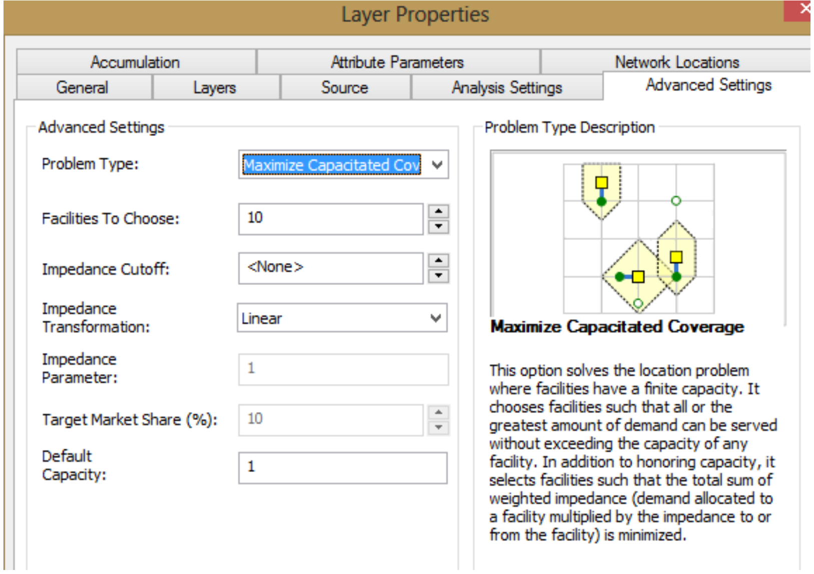
Suffix j	Level	basic
Location-014	1	NonBasic
Location-031	1	NonBasic
Location-034	1	NonBasic
Location-059	1	NonBasic
Location-089	1	NonBasic
Location-122	1	NonBasic
Location-136	1	NonBasic
Location-142	1	NonBasic
Location-176	1	NonBasic
Location-214	1	NonBasic
Location-216	1	NonBasic
Location-260	1	NonBasic
Location-318	1	NonBasic
Location-335	1	NonBasic
Location-336	1	NonBasic
Location-390	1	NonBasic
Location-411	1	NonBasic
Location-427	1	NonBasic
Location-457	1	NonBasic
Location-469	1	NonBasic
Location-001		NonBasic
Location-002		NonBasic
Location-003		NonBasic
Location-004		NonBasic
Location-005		NonBasic
Location-006		NonBasic

```
Progress
READY
AIMMS              : 20100728CustAlld.amb
Executing          : MainExecution
Line number        : 1 [body]
Math.Program       : MDMD
  # Constraints    : 950
  # Variables      : 225151   (225150 integer)
  # Nonzeros       : 674977
  Model Type       : MIP
  Direction        : maximize

  SOLVER           : CPLEX 12.5
    Phase          : Postsolving
    Iterations     : 1543450
    Nodes          : 58321          (Left: 18803)
    Best LP Bound  : 1708765.31     (Gap: 0.00%)
    Best Solution  : 1708762.965    (Post: na)
    Solving Time   : 27922.71 sec   (Peak Mem: 3084.8 Mb)
    Program Status : Integer solution
    Solver Status  : Terminated by solver

Total Time         : 27926.85 sec
Memory Used        : 2010.7 Mb
Memory Free        : 4096.0 Mb
```

Figure 30 ArcGIS LAP Model's Setting Sample



Advanced Settings

Problem Type: Maximize Capacitated Cov

Facilities To Choose: 10

Impedance Cutoff: <None>

Impedance Transformation: Linear

Impedance Parameter: 1

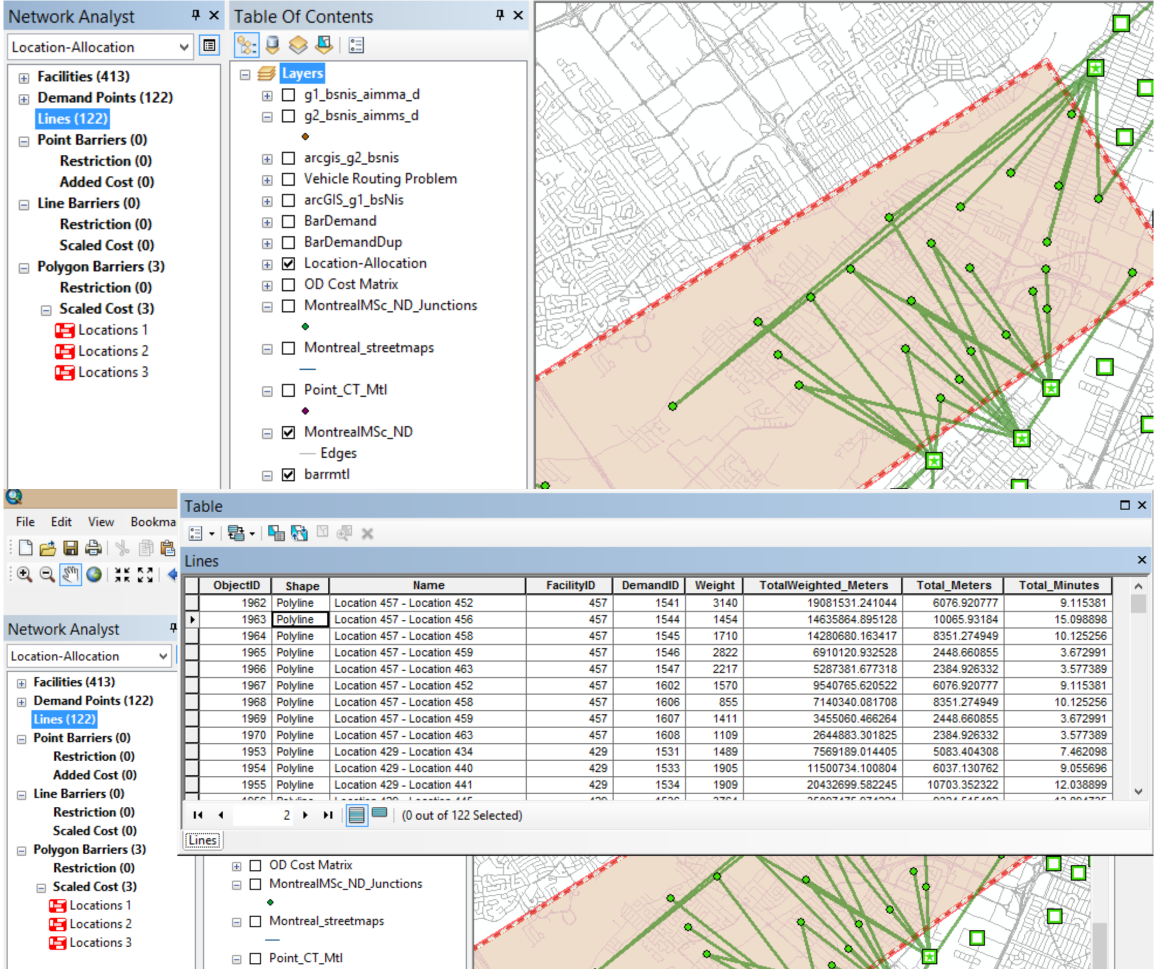
Target Market Share (%): 10

Default Capacity: 1

Maximize Capacitated Coverage

This option solves the location problem where facilities have a finite capacity. It chooses facilities such that all or the greatest amount of demand can be served without exceeding the capacity of any facility. In addition to honoring capacity, it selects facilities such that the total sum of weighted impedance (demand allocated to a facility multiplied by the impedance to or from the facility) is minimized.

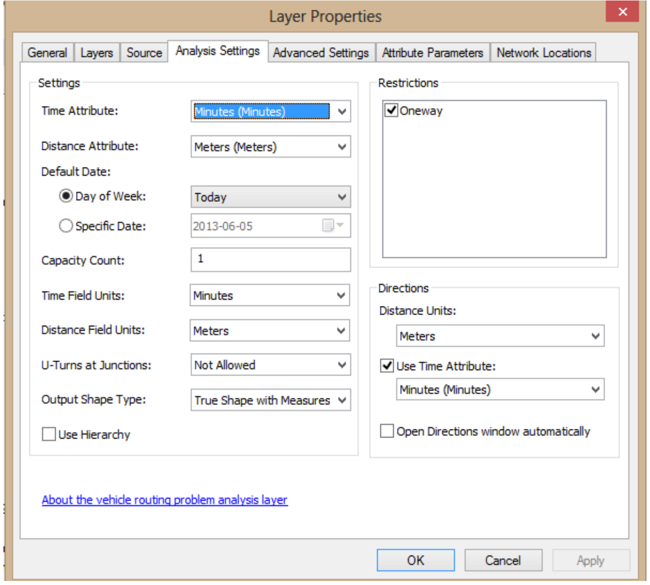
Figure 31 Sample ArcGIS LAP Solution Map (top) and Table Format (bottom)



ObjectID	Shape	Name	FacilityID	DemandID	Weight	TotalWeighted_Meters	Total_Meters	Total_Minutes
1962	Polyline	Location 457 - Location 452	457	1541	3140	19081531.241044	6076.920777	9.115381
1963	Polyline	Location 457 - Location 456	457	1544	1454	14635864.895128	10065.93184	15.098898
1964	Polyline	Location 457 - Location 458	457	1545	1710	14280680.163417	8351.274949	10.125256
1965	Polyline	Location 457 - Location 459	457	1546	2822	6910120.932528	2448.660855	3.672991
1966	Polyline	Location 457 - Location 463	457	1547	2217	5287381.677318	2384.926332	3.577389
1967	Polyline	Location 457 - Location 452	457	1602	1570	9540765.620522	6076.920777	9.115381
1968	Polyline	Location 457 - Location 458	457	1606	855	7140340.081708	8351.274949	10.125256
1969	Polyline	Location 457 - Location 459	457	1607	1411	3455060.466264	2448.660855	3.672991
1970	Polyline	Location 457 - Location 463	457	1608	1109	2644883.301825	2384.926332	3.577389
1953	Polyline	Location 429 - Location 434	429	1531	1489	7569189.014405	5083.404308	7.462098
1954	Polyline	Location 429 - Location 440	429	1533	1905	11500734.100804	6037.130762	9.055696
1955	Polyline	Location 429 - Location 441	429	1534	1909	20432699.582245	10703.352322	12.038899

2 (0 out of 122 Selected)

Figure 32 ArcGIS VRP Model's Setting Sample



Settings

Time Attribute: Minutes (Minutes)

Distance Attribute: Meters (Meters)

Default Date:

● Day of Week: Today

○ Specific Date: 2013-06-05

Capacity Count: 1

Time Field Units: Minutes

Distance Field Units: Meters

U-Turns at Junctions: Not Allowed

Output Shape Type: True Shape with Measures

☐ Use Hierarchy

Restrictions

☑ Oneway

Directions

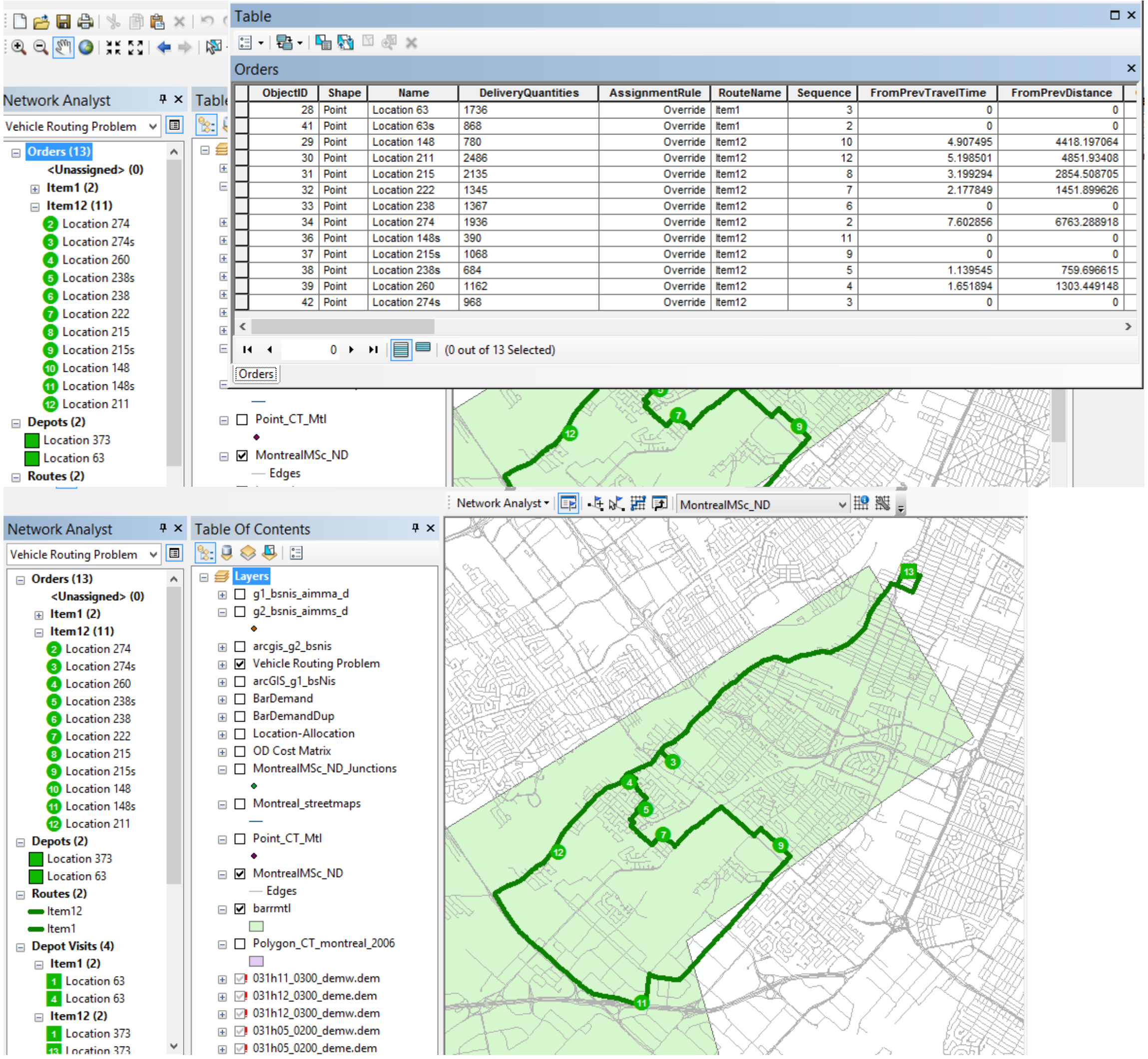
Distance Units: Meters

☑ Use Time Attribute: Minutes (Minutes)

☐ Open Directions window automatically

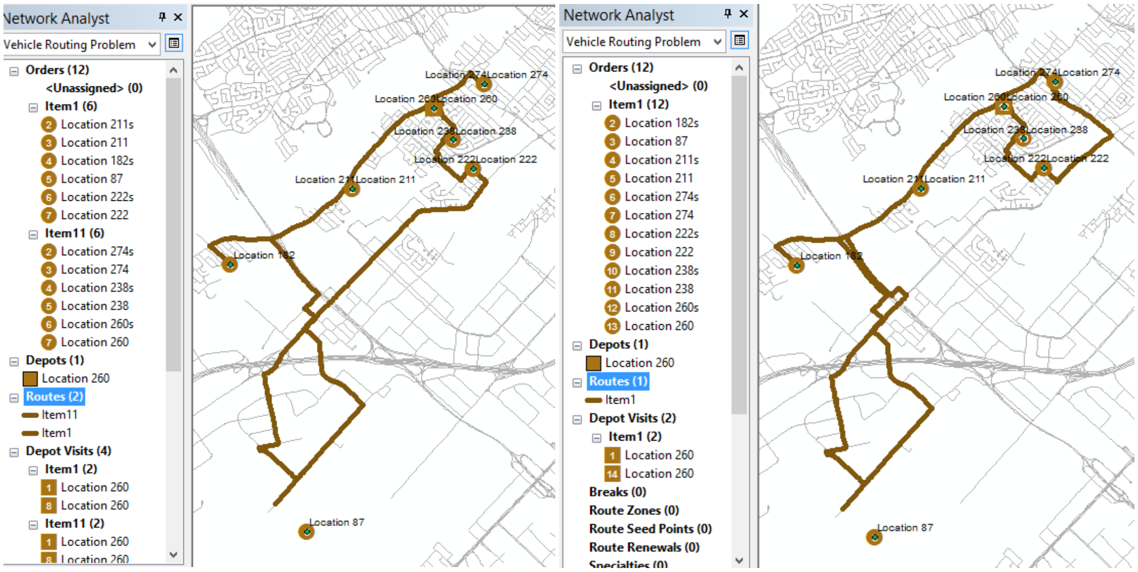
About the vehicle routing problem analysis layer

Figure 33 Sample ArcGIS VRP Solution Map (top) and Table Format (bottom)



ObjectID	Shape	Name	DeliveryQuantities	AssignmentRule	RouteName	Sequence	FromPrevTravelTime	FromPrevDistance
28	Point	Location 63	1736	Override	Item1	3	0	0
41	Point	Location 63s	868	Override	Item1	2	0	0
29	Point	Location 148	780	Override	Item12	10	4.907495	4418.197064
30	Point	Location 211	2486	Override	Item12	12	5.198501	4851.93408
31	Point	Location 215	2135	Override	Item12	8	3.199294	2854.508705
32	Point	Location 222	1345	Override	Item12	7	2.177849	1451.899626
33	Point	Location 238	1367	Override	Item12	6	0	0
34	Point	Location 274	1936	Override	Item12	2	7.602856	6763.288918
36	Point	Location 148s	390	Override	Item12	11	0	0
37	Point	Location 215s	1068	Override	Item12	9	0	0
38	Point	Location 238s	684	Override	Item12	5	1.139545	759.696615
39	Point	Location 260	1162	Override	Item12	4	1.651894	1303.449148
42	Point	Location 274s	968	Override	Item12	3	0	0

(0 out of 13 Selected)



Network Analyst

Vehicle Routing Problem

- **Orders (12)**
  - **<Unassigned> (0)**
  - **Item1 (6)**
    - 2 Location 211s
    - 3 Location 211
    - 4 Location 182s
    - 5 Location 87
    - 6 Location 222s
    - 7 Location 222
  - **Item11 (6)**
    - 2 Location 274s
    - 3 Location 274
    - 4 Location 238s
    - 5 Location 238
    - 6 Location 260s
    - 7 Location 260
- **Depots (1)**
  - Location 260
- **Routes (2)**
  - Item11
  - Item1
- **Depot Visits (4)**
  - **Item1 (2)**
    - 1 Location 260
    - 8 Location 260
  - **Item11 (2)**
    - 1 Location 260
    - 8 Location 260

Network Analyst

Vehicle Routing Problem

- **Orders (12)**
  - **<Unassigned> (0)**
  - **Item1 (12)**
    - 2 Location 182s
    - 3 Location 87
    - 4 Location 211s
    - 5 Location 211
    - 6 Location 274s
    - 7 Location 274
    - 8 Location 222s
    - 9 Location 222
    - 10 Location 238s
    - 11 Location 238
    - 12 Location 260s
    - 13 Location 260
- **Depots (1)**
  - Location 260
- **Routes (1)**
  - Item1
- **Depot Visits (2)**
  - **Item1 (2)**
    - 1 Location 260
    - 14 Location 260
- **Breaks (0)**
- **Route Zones (0)**
- **Route Seed Points (0)**
- **Route Renewals (0)**
- **Specialties (0)**

Figure 34 - Two Routes VRP Solution (left) ; One Route VRP Solution (right) - Generated in ArcGIS