Winter March 2015

Resource and Supply Allocation and Relief Center Location for Humanitarian Logistics

Guven Ince

UMASS Amherst

RESOURCE AND SUPPLY ALLOCATION AND RELIEF CENTER LOCATION FOR HUMANITARIAN LOGISTICS

A Dissertation Presented

by

GÜVEN İNCE

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

February 2015

Isenberg School of Management

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Approved as to style and content by:

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Agha Iqbal Ali, Chair

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Ahmed Ghoniem, Member

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Andrew McGregor, Member

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Senay Solak, Member

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Agha Iqbal Ali, Department Chair
Isenberg School of Management

to Ada, and Ece

ACKNOWLEDGMENTS

Over the past six years I have received support and encouragement from a great number of individuals.

I am thankful to Agha Iqbal Ali, my advisor, for believing in me and this study from the beginning and never giving up.

Senay Solak, my committee member, has been always there as a mentor, colleague and friend whenever needed, always supporting.

I hope something will prove that it was worth to make my dear wife Ece to feel so alone in a great deal of time in raising our beautiful Ada and taking care of our home during my studies.

It would be very hard to spend the past six years without Barış Hasdemir and Deniz Ertürk being around. Their comradeship has been a heaven in this new world. The hell has been the absence of Ahmet Sarıcan, Altuğ Yılmaz, Çiler Altınbilek, Erkan Bektaş, Soner Akalın, and Süreyya Algül, comrades forever.

There were times, sorrow accompanied this writing: Berkin Elvan was too young to die, in his fourteen by a tear gas canister while on his way to buy bread. Millions, crying for democracy, cried for him and for all other victims of police violence in the days of Gezi Resistance.

And, at the time this was written, people of Kobani in Syria were still waiting for humanitarian aid to be able to continue to defend their democratic freedom against the darkness.

ABSTRACT

RESOURCE AND SUPPLY ALLOCATION AND RELIEF CENTER LOCATION FOR HUMANITARIAN LOGISTICS

FEBRUARY 2015

GÜVEN İNCE

B.Sc., BOGAZICI UNIVERSITY

Ph.D., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Agha Iqbal Ali

This dissertation examines two salient issues that arise in the strategic planning of disaster management operations for providing relief to populations that are impacted by a disaster, such as an earthquake. The first issue is the alleviation of destitution faced by affected populations in the immediate aftermath of a disaster. The second is the establishment of an infrastructure for provision of relief, for a much longer period of time, until normalcy is restored. Central to the alleviation of destitution is the avoidance of critical shortages in meeting the demand for relief supplies. The literature on pro-active and strategic planning of relief operations primarily focuses on the minimization of unmet demand to address shortfalls in meeting required levels of relief. However, compromised handling capacity, which can be attributed to insufficient manpower, can deteriorate provision of supplies. The same is true for transport capacity of which there can be limited capability in the immediate

aftermath of a disaster. Better planning and management of resource and supply allocations is made possible by quantifying the destitution faced by affected populations and revealing its relationship to delays in provision of relief. The second issue is that of on-going provision of relief, whether supplies, resources, or information. Key to such relief provision is the establishment of relief centers that are easily accessible by affected populations using the available transport network. Both issues are addressed using mathematical programming in the context of strategic planning of humanitarian logistics for a catastrophic earthquake in Istanbul, of which there is a high probability of occurrence over the first thirty years of the 21st Century.

Bringing visibility to the impact of critical shortages on affected and vulnerable population segments caused by the lack of any commodity has not been addressed in the literature on relief operations. Extant research is on post-disaster reactive operations. While disasters cannot be forecasted with pinpoint accuracy, it is possible to devise pro-active contingency plans for regions of the world that are prone to natural disasters. Proactive contingency plans, proposed in this dissertation, focus on the strategic planning of the geographical and temporal staging of relief supplies with a view to minimize the impact of critical shortages. The manner in which destitution can be alleviated by revealing the impact of delays in the provision of supplies, the availability of transport units, and the deployment of manpower has not been explicitly addressed in the literature. Delays can lead to a critical shortage of one or more of the supplied commodities causing destitution which is quantified by the number of periods a population segment is without provision of supplies. The destitution levels of population segments as they are replenished with supplies that become available over time are tracked using a complex mixed-integer goal programming model which is developed. The model is used to study the impacts of delays in providing relief on destitution and criticality among affected populations for a highly probable (62$\pm$15%), catastrophic earthquake in the greater Istanbul area. Making use of the estimates for seismic hazard and damage for the districts of Istanbul that are provided in the report published by Japan International Cooperation Agency (JICA) in collaboration with the Istanbul Metropolitan Municipality, an empirical study reveals the impacts of the three sources of delay and their significance for different types of supplies and need in different segments of impacted populations.

Centers for relief operations meet the continued need for resources, supplies, and information among affected populations until the restoration of normalcy. The literature on location-allocation of centers for humanitarian logistics have employed location methodology which comprises a suite of models such as the p-median or maximal cover models. These models have not accounted for traffic networks, the travel times on links of the network, and the potential delays that can occur due to congestion on the links. The centrality of the existing traffic network and travel times on links of the network as the flow of traffic increases in locating relief centers is not accounted for in such models. In this dissertation two significant aspects of locating centers are addressed in a new mathematical programming model: First, the number of, and locations for, the centers to be established to provide a given level of access to populations in various neighborhoods of the affected region. Second, the implementation plan for the centers, detailing the identification of the specific centers that are made available over time. Further, the model also addresses the two key issues of the implied capacity of each center and of the assumed patterns of access to, and demand at, each center. These two issues are intertwined in that varying frequencies of access among different population segments dictate that populations be provided with equally, with respect to travel time, accessible alternative relief centers. The inherent stochasticity of frequency of access needs necessarily to be accounted for when determining the locations of centers. The optimization model that is developed to determine locations of supply sites and locations of centers is a two-stage stochastic mixed integer non-linear programming model over a network in which supplies move from selected supply sites to selected relief centers and subsequently acquired by affected populations accessing the relief centers over the traffic network. The travel time on each link grows exponentially with the traffic, or flow, on the link. The nonlinearity reflects the behavior of populations headed from any neighborhood, i.e. population center, to any one of centers that can be made available to them. The model identifies relief centers to locate from among a set of potential sites for centers such that the total travel time over the network is optimized. The model assumes different levels of access for populations in different neighborhoods that are defined by pre-specified distance thresholds for access to a center. The solution of the model is addressed via a piece-wise linear approximation of the objective function which is separable, convex, and monotone increasing. The model is employed in a computational study for the identification of supply sites and relief centers for stochastically varying frequencies of access by populations in the one hundred twenty-three neighborhood of Greater Istanbul. The stochastic variations examined range from fixed daily, bi-weekly, and weekly access frequencies to totally randomized access frequencies during an hour. Further, a computational study reveals an implementation plan for establishing relief centers to ensure that easy access with minimal degradation of travel times is enabled for all populations in the neighborhoods of Greater Istanbul.

> *When asked by the President of Turkey what he could get for her, a five-year old girl victim of the Van earthquake, Turkey, 2011, simply replied "A pair of socks".*

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CHAPTER 1

INTRODUCTION

Disasters have a degenerating effect on the socio-economical, political and cultural wellbeing of communities. The response quality and adequacy of a community to a disaster is restricted by its organizational ability, that is a function of efficiency in resource and time utilization. Attributed to global climate change, disasters show a dramatically increasing trend in number and also in destructiveness over the past two decades. With increasing number and impact of disasters, complications in managing response operations increase, and sometimes take an overwhelming nature having a threatening effect upon the humanitarian aid system of community. Therefore, more integrated approaches are required in defining related problems and developing solution methodologies. Although more researches have been producing in disaster management area in recent years, hundreds of thousands of deaths and hundreds of billions dollars of losses in most recent disasters suggest inadequacy of the state of the art.

This dissertation, first, takes post-disaster human suffering as an issue and suggests an optimization methodology for relief provision with the main goal of minimizing suffering caused by delays in relief provision; and second, examines the establishment of relief centers for ongoing provision of relief that are easily accessible by affected populations using the available transport network.

This chapter first discusses the issues related with disaster management, and then summarizes the research platform. Section 1.1 discusses the trend of natural disasters over the last two decades, and gives a closer look on the life-altering as well as economic impact of more recent catastrophic events. Section 1.2 summarizes the key issues of disaster management. Section 1.3 recapitulates the characteristics of humanitarian logistics. Section 1.4 surveys the relevant literature on the applications of mathematical programming techniques in the design of relief distribution operations. Finally, Section 1.5 outlines the organization of the dissertation.

1.1 A Brief History of Recent Disasters

The number of natural disasters around the world has more than doubled in the last 25 years, according to figures compiled from EM-DAT, the International Disaster Database, which is maintained by CRED, the Centre for Research on the Epidemiology of Disasters. Figure 1.1 summarizes the trend of the disasters over the period from 1975 to 2010 in terms of number of people killed, and affected, and the amount of economic losses. The figure reveals that the earth is currently experiencing approximately 400 natural disasters per year, compared with around 160 per year in the early 1980s. Another study estimates that in less than fifty years the increase will be five-fold (Thomas and Kopzack, 2005). As for the death toll caused by disasters, the increase is from around 60 up to 110 thousand deaths in the last 20 years. There are alarming figures on the increase in the number of affected people by disasters also. Over the past two decades, it has increased from an average of approximately 125 to 235 million people a year.

The more recent catastrophic events, such as 2011 Tōhoku Earthquake and Tsunami, 2010 Haiti Earthquake, 2008 Myanmar Cyclone Nargis, 2008 Sichuan Earthquake and 2005 Hurricane Katrina suggest a pattern of more frequent, more erratic, more unpredictable and more extreme events that are affecting more people. In the following subsection these events are discussed in terms of their threatening effect on human life as well as their economic effect due to their destructiveness in infrastructures and supply chain networks.

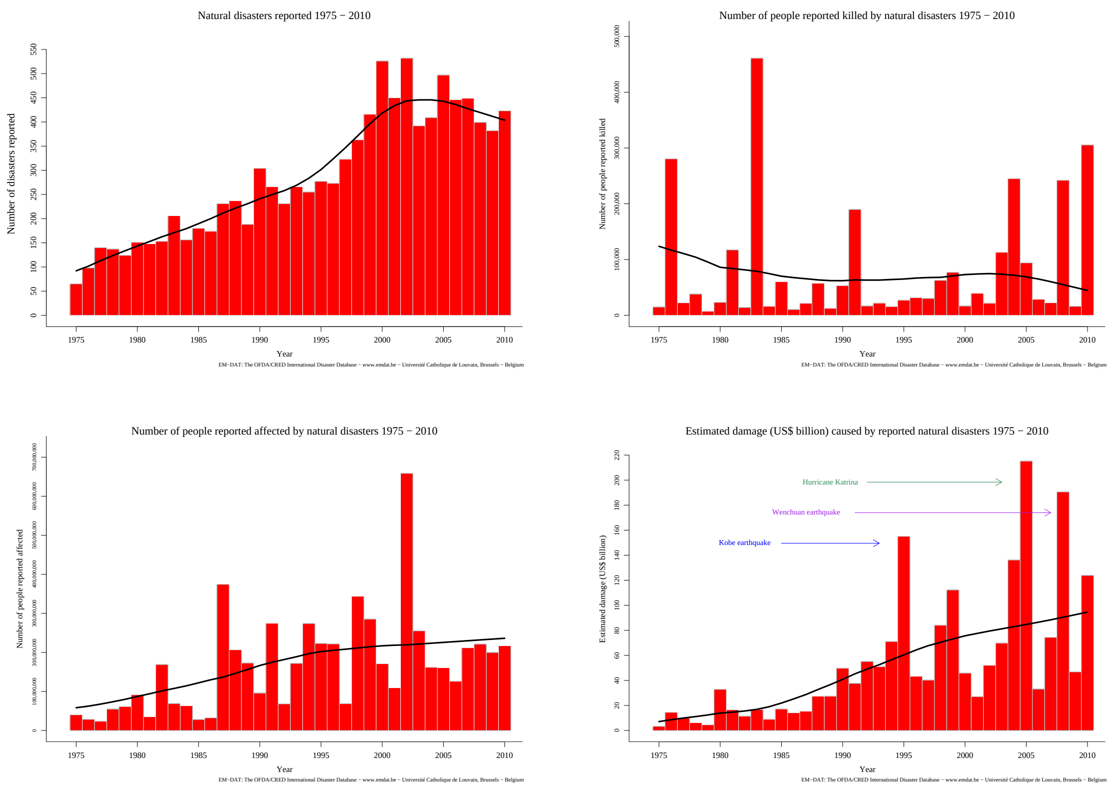


Figure 1.1: The trends of natural disasters from 1975 to 2010

1.1.1 A closer look into recent catastrophes*

In March 2011, the 9.0 magnitude earthquake and ensuing tsunami in Japan, also known as the 2011 Tōhoku earthquake, killed 19,846 people and caused 210 billions of dollars of damage. Total number of affected people has been 368,820.

As for the aftermath of the disaster, according to an online article published by Wikipedia (Wikipedia, 2011), the earthquake caused a large number of displaced people. The number of the evacuees, as of 26 January 2012, was 341,411. Some earthquake survivors died in the shelters or in the process of evacuation. Many shelters struggle to feed evacuees and were

*Unless otherwise specified, all the numbers in this section are collected from EM-DAT.

not medically sufficiently equipped. Fuel shortages hampered relief actions. In the first week after the earthquake, supplies of food, water, and medicine had been held up because of a fuel shortage and the weather condition. Food was limited for some unevacuated people, and as of late March, some were given one meal a day. There is a need for temporary housing, as the Japanese government are trying to remove evacuees from large shelters, where there have been reports of poor sanitary conditions. At the end of July 2011, the number of evacuees in Japan stood at 87,063. Of those, 12,905 were residing in public shelters and 19,918 were staying in inns or hotels. 46,081 units of temporary housing, about 88 percent of the number planned, had been built. Evacuees had moved into 73 percent of the temporary housing available.

The 2010 Haiti earthquake, hit in January, was another catastrophic magnitude earthquake. 3,700,000 people were affected by the quake; 222,570 people had died, 300,000 had been injured and 1,000,000 made homeless.

In the aftermath, slow distribution of resources resulted in sporadic violence, with looting reported. Having 250,000 residences and 30,000 commercial buildings collapsed or severely damaged, sheltering became one of the biggest issues in area. Six months after the quake the number of people in relief camps of tents and tarps was 1.6 million, and almost no transitional housing had been built. Most of the camps had no electricity, running water, or sewage disposal, and the tents were beginning to fall apart. In October, 9 months after the quake, a cholera epidemic broke out, which most often affects poor countries with limited access to clean water and proper sanitation. By the end of 2010, more than 3,333 had died at a rate of about 50 deaths a day from cholera. One year after, having only 15 percent of the required basic and temporary houses been built, more than one million people remain displaced, living in crowded camps where livelihoods, shelter and services are still hardly sufficient for children to stay healthy. Two years after, half a million Haitians remained homeless, still living under tarps and in tents (Wikipedia, 2010).

Cyclone Nargis made landfall in Myanmar (Burma) in 2008, causing catastrophic destruction of $4 billion and in total 2,420,000 people being affected. With 138,366 fatalities, Nargis is named as one of the most deadliest cyclones of all time.

The next wave of death is set to take hold as thirst, starvation, untreated injuries and infectious diseases pose an increasing threat to population health. The vast majority of survivors, more than a week after the cyclone, remain without sufficient food, water, shelter, medication or means of escape from flooded regions. The secretary general of the UN, Ban Ki-moon, expressed "deep concern" and "immense frustration" with the unacceptably slow response to the crisis by the government of Myanmar (Center for Refugee and Disaster Response, 2008).

The 2008 Sichuan earthquake was another deadly earthquake that occurred in May in Sichuan province of China, affecting 45,976,596 people, 87,476 out of which were killed. The total estimated damage became of $75 billion dollars.

The earthquake left about from 5 to 10 million people homeless. By November, 2008, it is reported by government that 200,000 homes had been rebuilt, and 685,000 were under reconstruction, but 1.94 million households were still without permanent shelter (Wikipedia, 2008).

Hurricane Katrina, 2005, has been one of the five deadliest and the costliest hurricane in the history of the United States (see Figure 1.1). 1,833 people reported to be killed in the actual hurricane and in the subsequent floods, and 500,000 people were reported to be affected by; total property damage was estimated at $125 billion.

The disaster recovery response to Hurricane Katrina included federal government agencies such as the Federal Emergency Management Agency (FEMA), state and local-level agencies, federal and National Guard soldiers, non-governmental organizations, charities, and private individuals (Wikipedia, 2005). But still, many people have suffered by the slow response, e.g., many people (particularly in New Orleans) left without water and food for three to five days after the storm. The Pentagon, among the first to express criticism of the management of the crisis, complained about some delays in response operations caused by bureaucratic red tape from the Bush' administration, which is an indication that politics may become an insurmountable barrier for relief operations.

As a last exemplary event, which is closer to the heart of the author of this dissertation, the catastrophic earthquake in Kocaeli, Turkey, with 7.6 magnitude, struck northwestern Turkey in 1999. Officially 18,000 unofficially 45,000 people died, more than 200,000 houses were damaged beyond repair and 600,000 people became homeless after the earthquake. Sheltering has become a major problem among others on the following days of the earthquake, which called an urgent need for distribution of housing units. Turkish Red Cross has led this operation. The organization managed distribution of in total around 115,000 tents (45,000 from inner sources of the organization and 70,000 from other sources), where as more than 200,000 needed (Şengün, 2007).

1.2 An overview of disaster operations

The International Federation of Red Cross and Red Crescent Societies (IFRC) defines disaster as "a sudden, calamitous event that seriously disrupts the functioning of a community or society and causes human, material, and economic or environmental losses that exceed the community's or society's ability to cope using its own resources". In a simpler form of definition, disaster can be considered as any catastrophic event that generates sufferers expecting aid from society. Table 1.2 shows a complete list of disasters[†] in a categorization by source.

[†]Wisner et al. (2004) argues against listing hazardous events as disasters by claiming, that "natural events are not disasters until a vulnerable group of people is exposed." This important argument brings *vulnerability* into attention by defining disaster as a function of hazardous events as well as vulnerability of society.

	Natural	Man-made
Sudden-onset	Earthquake Hurricane Tornadoes	Terrorist attack Coup d'Etat Chemical leak
Slow-onset	Famine Drought Poverty	Political crisis Refugee crisis

Source: Van Wassenhove (2006), p.476

Table 1.1: Categorization of disasters by the speed of onset

Natural hazards					Technological or man-made hazards
Geophysical	Hydrological	Climatological	Meteorological	Biological	
earthquakes landslides tsunamis volcanic activity	avalanches floods	extreme temperatures drought wildfires	cyclones storms/wave surges	disease epidemics insect/animal plagues	industrial accidents famine transport accidents displaced populations complex emergencies/conflicts

Source: http://www.ifrc.org/en/ what-we-do/disaster-management/about-disasters/definition-of-hazard/

Table 1.2: Categorization of disasters by source

Van Wassenhove (2006) categorizes disasters with respect to the speed of onset (Table 1.1), dividing them into two subgroups, i.e., sudden-onset and slow-onset disasters. Sudden-onset disasters, requiring more agile supply chains, where time-efficiency is more concerned than cost-efficiency (Oloruntoba and Gray, 2006), are closer to the scope of this dissertation.

The operations related to disaster management, as defined by Altay and Green (2006), are "the set of activities that are performed before, during, and after a disaster with the goal of preventing loss of human life, reducing its impact on the economy, and returning to a state of normalcy as disaster operations". FEMA, the Federal Emergency Management Agency, classifies disaster operations into four stages, which is also known as the disaster management life cycle:

1. **Mitigation** includes operations with the aim of preventing the onset of disasters, or lessening the impact of. Developing disaster scenarios and, based on those, performing risk analysis to assess the vulnerability of infrastructures; physical measures to reduce

vulnerability, e.g. constructing absorbing or deflecting barriers against destructive forces of disasters; financial measures, e.g. insurance, to lessen the financial impact of disasters are a few of activities usually to be carried in this stage.

2. **Preparedness** is the stage where the deriving actors of community is organized to act in a possible disaster scenario. The operations in this stage are directed to the goal of increasing the efficiency of post-disaster operations. Designing training activities for acting personnel as well as for community; constructing emergency operation centers if necessary; forecasting demand for relief products; planning for resource and supply allocation; planning for relief distribution operations; and, budget planning are among the activities performed in this stage.

3. **Response** is the realization stage of the plans designed in pre-disaster stages. The plans are revised, or changed, with respect to the realizations of disaster scenarios. Characteristic operations include rescue and emergency care operations; evacuation operations; sheltering; relief distribution; and management of dead bodies.

4. **Recovery** includes operations directed to the goal of recovering community life into normalcy. Debris removal; restoration of infrastructures; and (re)construction of permanent sheltering and health care units are the basic operations carried out in this stage.

The mitigation and preparedness stages of disaster management are regarded as the *strategic planning* period where possible disaster scenarios are evaluated in terms of casualties and vulnerability of infrastructures, and accordingly post-disaster operations are planned. In the response and recovery stages, which together constitute the *operational period* of the disaster management, the plans, possibly being revised and fine-tuned, are applied to disaster conditions.

There are excellent reviews of disaster management literature: Altay and Green (2006) covers the articles of up to 2005, which use OR and MS tools in disaster management. Natarajarathinam et al. (2009) extend this work by extending the timeline up to 2008 and covering additional logistics and supply chain management journals. Caunhye et al. (2011) provide a review of optimization models utilized in emergency logistics.

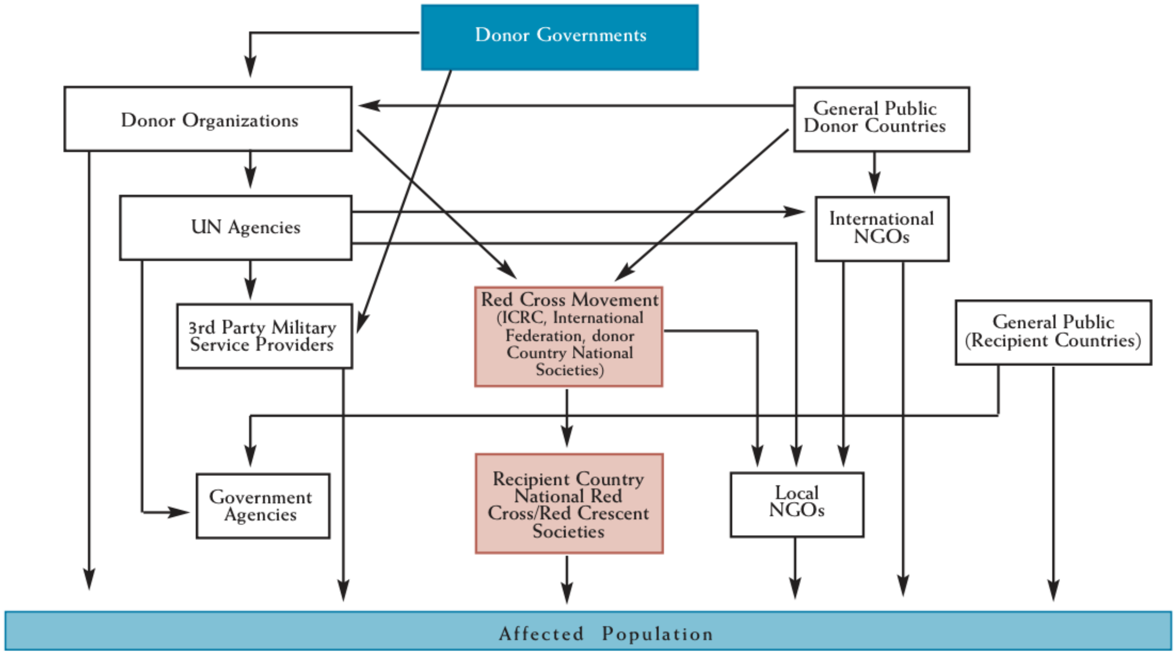
Humanitarian logistics, serves "as a bridge between disaster preparedness and response through the establishment of effective procurement procedures, supplier relationships, prepositioned stock and knowledge of local transport conditions" (Thomas, 2003) and constitutes about 80% of disaster management operations (Van Wassenhove, 2006).The following section discusses humanitarian logistics in further details.

1.3 Humanitarian Logistics

Fritz Institute[‡] defines humanitarian logistics as "the process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from the point of origin to the point of consumption for the purpose of alleviating the suffering of vulnerable people. The function encompasses a range of activities, including preparedness, planning, procurement, transport, warehousing, tracking and tracing, and customs clearance" .

As indicated by Thomas and Kopzack (2005), humanitarian logistics comprises the management of the flow of donations from global community to affected populations. As shown in Figure 1.2, flow goes through many different types of organizations before it reaches the end beneficiary. Those organizations consists of the groups that operate under the United Nations

[‡]Fritz Institute, founded in 2001 and located in California, USA, is a nonprofit organization that works in partnership with governments, nonprofit organizations and corporations around the world to innovate solutions and facilitate the adoption of best practices for rapid and effective disaster response and recovery. For further details visit http://www.fritzinstitute.org/



Source: Thomas and Kopzack (2005), p.4

Figure 1.2: Humanitarian supply network

such as the World Health Organization (WHO) and the United Nations High Commissioner for Refugees (UNHCR), international organizations such as the International Federation of Red Cross and Red Crescent Societies (IFRC), and global non-governmental organizations (NGOs) like CARE and World Vision. Some of these organizations such as IFRC maintain country offices and collaborate with local partners. In most cases, it is these partners closest to the affected populations that provide the relief services.

Before going into the details of the operations implied by the aforementioned definition of humanitarian logistics, we find it necessary to discuss some distinctive managerial goals and characteristics of humanitarian logistics that distinguish it from commercial logistics:

Logistician's success is highly proportional to the *speed* of operations, which depends "on the ability of logisticians to procure, transport and receive supplies at the site of humanitarian relief effort" (Thomas, 2003). Quick response as an objective makes humanitarian logistics a very *time-sensitive* process. In that sense, time-efficiency of a logistical plan is of a vital importance. For instance, the distribution of high priority supplies which are crucial for survival, such as water or medicals, is a process of racing against time, for it is a fact that, for instance, the survival time without the intake of water is limited to three to five days. The survival time in the deficiency of supplies is different for different products. For medical supplies it might be expressed in hours, or in minutes in some cases, whereas for food it can go as long as several weeks. That is, there is a prioritization among relief supplies per se with respect to their necessity for survival, which should be accounted for in any logistical plan.

The other obvious distinguishing characteristics of humanitarian logistics is that it deals with multiple, usually conflicting, objectives (Huang et al., 2011). In contrast to commercial operations, humanitarian operations are designed without any *profit* motive (Tomasini and Wassenhove, 2009). Since minimizing total routing costs results in solutions with longer response times (Campbell et al., 2008), *speed* beats out *cost* in the prioritization of goals. While *quick response* together with *demand satisfaction* appear to be the major objectives, design of operations might seek for a balance, or investigate the trade-offs, between such major objectives and cost.

In the aftermath, all deriving actors of community, government, army, private sector, civil initiatives, come into play. *Chaos* follows the onset of disaster, which can make assessment and realization of plans extremely hard. Besides the natural chaos originated from the disaster itself, the inadequacy or inaccuracy of forecasts and/or plans carried from planning stage, failures in the applications of those plans, incoordination between relief groups, political hostility[§] between the relief donating and receiving countries are some of the factors which might cause the impact of disaster to go beyond imagination.

As being another characteristics of humanitarian logistics, especially at the very first stages of disasters, against the enormous amount of demand, *supply shortfalls* might occur. The highly dynamic and uncertain nature of demand makes the management of prepositioned inventory very hard (Tomasini and Wassenhove, 2009, Van Wassenhove and Pedraza Martinez, 2010). Shortfalls, typically, decrease with arrivals of additional supplies over time. Resources and infrastructures, e.g., money, vehicles, equipment, personnel, transportation capacity, etc., become more and more available over time (Balcik et al., 2010). *Uncertainty* is the dominant character on the availability of resources, which requires a dynamic planning of operations.

Fairness in relief provision, that takes into account the impartiality and neutrality principles of humanitarian organizations defined by Van Wassenhove (2006), is one of the most important issues in humanitarian relief logistics. And it is the hardest, if not impossible, to evaluate. In the first days of disaster, when supplies are limited, it is obvious that some people will not get their needs immediately. Any policy in this case may lead to a discrimination among people. But is there a 'better' discrimination? For example, is it less unfair if a policy on relief distribution suggests to fully satisfy the needs of people who are closer to the epicenter of an earthquake and for whom it is possibly harder to move to a safer place? Or, when transportation capacity is limited, is it a better idea to allocate all transportation capacity to top-priority products, and let people suffer from the 'less' essential products? We can ask many similar questions, each of which corresponds to a different distribution

[§]After the Hurricane Katrina in 2005, Cuba and Venezuela (both hostile to US government themselves) were the first countries to offer assistance, pledging over $1 million, several mobile hospitals, water treatment plants, canned food, bottled water, heating oil, 1,100 doctors and 26.4 metric tons of medicine. This aid was rejected by the U.S. government (Wikipedia, "International Response to Hurricane Katrina").

policy and each policy comes with its own objective. Revelation of the trade-offs between such policies would give a better insight in the evaluation of different policies.

The following subsection elaborates on the design characteristics of relief network relevant to the studies presented in this dissertation.

1.3.1 Relief Network Design

Design of humanitarian logistics network corresponds to the strategic planning phase of disaster management, in which disaster-prone regions are assessed based on a disaster scenario, by which possible structural and financial damage is revealed. The estimations on the number of deaths and wounded people, damaged and collapsed houses and public buildings, e.g. hospitals, schools, administrative buildings, operation centers, etc., the expected degree of damage in transportation networks, e.g. ports, bridges, roads, railways, canals, public transportation lines, etc., in water and energy lines, and in sewage, wastewater, solid waste lines become crucial for the decisions on the volumetric and structural design of relief supply network. Estimations associated with casualties establish the basis for forecasting the demand for relief products. Vulnerability assessment of transportation lines makes the availability of these lines visible, and through which, potential distribution routes and shipment arrangements can be determined.

The design of relief supply network includes decisions on relief operation centers, which serve to meet the continued need for resources, supplies, and information among affected populations until the restoration of normalcy. Based on the vulnerability analysis of infrastructures, a design can come up with a plan that uses the existing centers which possibly survive the disaster, or else construction of new operation centers, whether temporary or permanent, might become necessary. Key to decisions on relief centers is the establishment of relief centers that are easily accessible by affected populations using the available transport network. Location decisions of relief operation centers and allocation of relief therein have a major impact on the performance of relief operations (Balcik and Beamon, 2008). Challenging in such decisions is the inherent complexities and uncertainties of the operation environment, a proper consideration of which would result effect effective and efficient provision of relief with the goal of saving lives and minimizing destitution among affected populations.

Relief centers should be planned in a way that they can cope with the disruption in the regular supply chain network. Location plans should take the vulnerability of the transportation network into account, and identify transportation lines and hubs to serve in relief procurement that would possibly survive an expected disaster. And, relief allocation plans should consider to meet a daily demand for essential supplies in possibly enormous amounts. As mentioned earlier, quick response is of vital importance to saving lives and maintaining welfare of populations in the aftermath of disasters. The number and locations of the relief centers play key role in timely procurement of resources and supplies. Usually, budgetary and time considerations put a limit on the number of such centers to be established. In such a case, decisions can be made on the 'level of access' for different population segments with respect to the severity of damage in the area they live in, and/or with respect to the population size. Such decisions may consider to give a 'better' access level to large affected populations that live in more severely damaged areas such that they can travel shorter distances to access relief centers. Small populations, in less damaged areas, might be compromised to travel longer distances.

As relief operation centers play key role in timely procurement of resources and supplies, their locations on the transportation network should prove easy access for affected populations. As pointed by Toregas et al. (1971), time and distance that separate a victim from a center are crucial parameters in location planning of relief operation centers. In this regard, the proximity of centers to the major transportation hubs and lines is important to maintain easy access. And, one can also consider possible degradation on arrival times to centers by

Sheltering	Tents, blankets, towels, inflatable pillows, air mattresses, sleeping bags, etc.
Medical	Aspirin, fever/pain relievers, anti-diarrhea medication, emetic, antacids, sterile gauze pads 2-3 inches, sterile roller bandages, adhesive bandages, antiseptic spray, hydrogen peroxide, rubbing alcohol, petroleum jelly, latex gloves, scissors, tweezers, safety pins, etc.
Sanitary	Soap, alcohol-based hand sanitizer, toothbrush, toothpaste, denture needs, shampoo, feminine products, wipes, bathroom tissue, facial tissue, paper towels, dust mask, garbage bags, bleach, etc.
Food	Non-perishable food which is not required to be cooked or refrigerated, e.g., canned food, ready-to-eat meals, high-energy foods, such as chocolate or emergency food bars, etc.
Water	

Table 1.3: Common relief products

congestion on transport links, which can be caused by the irregular traffic in chaotic disaster environment, as well as, the enormous demand to access relief centers. A link performance measuring framework can help in the evaluations of locations plans with respect to network traffic and possible congestion on the transport links.

Supply and resource allocation planning follows location planning in the design stage. How much of which relief commodity have to be allocated, and at which relief centers, are the questions to be answered, the answers to which also identify capacity of operation centers and load of transportation network. The needs of affected populations, depending on the type of disaster and environmental conditions, range from consumables to infrastructural supplies, such as water, sanitary products, medical products, food, sheltering units, medical consumables and devices, etc., (Table 1.3). Enormous amount of demand in the case of catastrophic disasters, together with possible budgetary restrictions and inherent uncertainties and practical difficulties makes it impossible to store all demand in relief centers. That is, total storage capacity of facilities in close distances to sufferers, is usually, if not always, limited.

It would not be wrong to define disasters as environments of supply *deficiency*, which effect welfare of affected populations. Survival time of an human in the deficiency of curtain materials is very well known. For instance, average survival time of a 70-kilogram human without intake of water is considered to be 3 days, and about 70 days without intake of food (Piantadosi, 2003). As for medical supplies, depending on the type of injury, it can be as short as a couple of hours. Varying urgency of relief supplies suggests a priority consideration in logistical plan. Depending on disaster characteristics, the commodities can be prioritized with respect to their urgency for survival, and this prioritization can be reflected in prepositioning and distribution decisions (Lin et al., 2011).

Another important aspect related to relief supplies is that one group of supplies is required for once after the onset, while another group shows a continuity in demand. Demand for infrastructural supplies, including commodities used for sheltering purposes, such as tents, heating units, stoves, blankets, etc., once met, do no recur over the planning horizon. On the other hand, demand for consumables such as water, food, toiletries, etc, recurs with respect to the consumption rate of items. This categorization of supplies has been considered by Balcik et al. (2008) who group the relief supplies into critical items, Type I, and regularly consumed items, Type II.

1.4 The Relevant Disaster Management Literature

Our examination of the literature categorizes it with respect to infrastructure, i.e. location of supply and distribution sites, operational planning for disaster management, and demand satisfaction.

The body of literature in this area has evolved over the past two decades and surveyed comprehensively by Altay and Green (2006) and Natarajarathinam et al. (2009). Further, Caunhye et al. (2011) focus on reviewing optimization models developed for addressing emergency logistics and Dessouky et al. (2006) review location and vehicle routing models used for examining disaster management related issues.

One aspect of strategic planning that has been addressed in the literature is that of the location of supply points. Mete and Zabinsky (2010) develop a two-stage stochastic programming model to address medical supply location and distribution, which recommends the best storage locations from possible warehouses and determines their inventory levels. The model incorporates the priorities of hospitals for particular medical supplies as well as specific disaster scenarios with transportation and demand estimates. During the second stage of the model, the amount of medical supplies to be delivered to hospitals is determined for each scenario at an aggregated level. This aggregated decision is converted to detailed vehicle assignments and routing for each scenario in a mixed-integer programming model which provides an emergency transportation plan with the number of vehicles to be available at each warehouse, as well as a few preplanned routes. Rawls and Turnquist (2010) propose a two-stage stochastic model for the purposes of facility location, supply pre-positioning and distribution that minimizes the total expected cost resulting from the selection of facilities, the commodity acquisition and stocking decisions, shipments, unmet demand penalties and holding costs. Demand and link-availability are considered to be stochastic. Stochasticity is modeled through the use of scenarios which are defined by the forecasted demand by commodity and location, and the availability of links. Balcik and Beamon (2008) develop a variant of maximal covering model which captures the locations of distribution regions, as well as the amount of relief supplies to be stocked in each of these distribution regions. The model, considering budgetary and capacity restrictions in a multi-commodity network, maximizes total expected demand covered by distribution regions while minimizing the cost of logistics operations. They consider a relief distribution system in which a non-governmental relief organization locates distribution regions in the global relief network to respond to disaster scenarios whose locations and impacts are known probabilistically based on data gathered from historical events. Their underlying assumptions are that in any global disaster scenario there is only one demand location, and that warehouse replenishment lead time is zero. Dessouky et al. (2006) give an extensive literature review of utilization of location and vehicle routing models in literature, and propose a facility location model and a vehicle routing model which address distribution of medical supplies in a hypothetical anthrax emergency scenario in a metropolitan area. The location model locates P facilities by minimizing total demand-weighted distance between demand points and facilities. The distribution problem is solved due to a single-period and single-objective vehicle routing model, in which, while the travel time between any two nodes on transportation network and the demand is considered to be stochastic, total unsatisfied demand is minimized. Jia et al. (2007b) also consider the distribution of medical supplies for large-scale emergencies in locating supply facilities. The possibility of lack of supplies under uncertain demand is addressed by allowing multiple deliveries to each demand point and possible shortfall in meeting demand. Ukkusiru and Yushimito (2008) model pre-positioning of relief supplies as a location routing problem that accounts for routing of vehicles and the vulnerability of existing arcs in the transportation network. An integer programming model is proposed that chooses prepositioning facilities after evaluating the most reliable paths in the network such that the probability of the inventory accessibility is maximized. They assume that the probability of failures are independent and known a priori. Horner and Downs (2010b) address hurricane disaster relief facility location and shipment using geographic information systems for a single commodity in a single period in a two echelon network with intermediate distribution facilities and demonstrate the model using spatial data for a small city in Northern Carolina. Duran et al. (2011), located three CARE International facilities in Dubai, Panama and Cambodia based on a study of warehouse locating and inventory pre-positioning of relief items on CARE's average relief-aid emergency response time. The incorporated model, while minimizing the average response time, estimates the frequency, location, and magnitude of potential demand based on historical data; it also optimizes the location of warehouses and inventory allocation, given an up-front investment in the number of warehouses to open and the amount of inventory to hold in each location.

Operational planning research typically assumes that supply and distribution sites are known, focusing on issues of delivery and prioritizing of commodities. Balcik et al. (2008) focus on "last mile" logistical inventory routing operations for the distribution of sorted commodities. The problem determines delivery schedules, vehicle routes and the amount of emergency supplies delivered to demand locations assuming that locations of local distribution regions are known and their capacities are sufficient to serve their predetermined demand locations. Lin et al. (2011) also prioritize supplies based, however, on urgency considering only regular items. The prioritization is based on the assumption, that, in the case of disasters, prescription medication (e.g., diabetic supplies) are needed most urgently, followed by water and food, respectively. Supplies, an unlimited amount of which are available, can be delivered during variable time-windows from a single depot to multiple demand points with known demand. Haghani and Oh (1996) address the aggregated minimization of vehicular flow costs, the supply and demand carry-over costs, and the transfer costs for disaster relief management over a multi-period, multi-commodity, multi-modal network with known supplies and demands. This model is extended by Barbarosoğlu and Arda (2004) by including stochasticity due to vulnerability in the transportation system and, consequently, supply for the planning transportation of vital first-aid commodities to disaster-affected areas during emergency response. Özdamar and Demir (2012) use a hierarchical cluster and route procedure for last mile delivery and pickup for a static version of the model described in Yi and Ozdamar (2007).

The reality of not satisfying demand is addressed in a variety of contexts. Özdamar et al. (2004) study a macro level planning logistics in the presence of disasters. A multi-period, multi-commodity network flow problem combined with a multi-period vehicle routing problem for distribution of commodities from supply points to distribution regions is formulated.

The associated model, while minimizing the amount of unsatisfied demand over time, determines the optimal pick-up and delivery schedules of vehicles within the considered planning time horizon as well as the optimal quantities and types of loads picked up and delivered on the routes of vehicles. Tzeng et al. (2007) Include the maximization of satisfied demand while addressing two other objectives: minimizing the total cost and minimizing the total travel time in locating facilities in a two-echelon network in which commodities are transferred from relief collection points to candidate depots and then to demand locations. Yi and Ozdamar (2007) propose a location/distribution model for dispatching medical and rescue equipment and personnel commodities to distribution regions in affected areas and evacuation and transfer of wounded people to emergency units. The objective of the model aims at minimizing the weighted sum of unsatisfied demand over all commodities and weighted sum of wounded people waiting at demand nodes and temporary and permanent emergency units. Rawls and Turnquist (2012) include the reliability of meeting specific levels of demand in distribution of supply to persons evacuated to shelters under limited storage and shipment capacities.

1.5 Organization of the Dissertation

The dissertation examines the impact of delays of relief provision on destitution in affected populations of a disaster; and, the establishment of relief centers for on-going provision of relief in the aftermath of a disaster. In Chapter 2, we study the relationship between the staging of supplies and resources and the extent of destitution among affected populations in the aftermath of a disaster using a mixed integer goal programming model. The model is applied to examine alternative supply staging strategies for potential earthquakes in Istanbul predicted to occur during the first thirty years of the 21st Century. For the purposes of clarity of exposition, before presenting the multi-commodity, multi-period, multi-vehicle model, we present the single commodity multi-period version of the model. In Chapter 3, we examine the impact of locations of relief operation centers on the travel times on a relief distribution network using a mixed integer non-linear programming model. The model is applied to identify relief center locations in Greater Istanbul area in the aftermath of the probable earthquake. In Chapter 4, we present concluding remarks and future directives associated with both studies.

CHAPTER 2

PLANNING RELIEF REPLENISHMENT WITH VISIBILITY OF THE STATE OF THE POPULATION

In the aftermath of a disaster, affected populations in one or more regions can face critical shortages of supplies and equipment to meet basic needs. The populations in these regions need a variety of supplies, products, ranging from essential infrastructural supplies such as tents, cooking equipment, heating equipment, etc. to consumables including food, water, toiletries, etc. The lack of one or more of these commodities can be critical and lead to fatality.

In this study, we address the alleviation of *destitution* and *criticality* in disaster-affected populations and the extent to which they are impacted by delays in the provision of supplies, the availability of transport units, and the deployment of manpower. Much attention in the literature is given to the minimization of unmet demand. However, compromised handling capacity, which can be attributed to insufficient manpower, can deteriorate provision of supplies. The same is true of transport capacity of which there can be limited capability in the immediate aftermath of a disaster. Recently, there are some utilitarian approaches to address suffering as a result of delays in relief provision (Perez Rodriguez, 2011, Holguín-Veras et al., 2013). However, the manner in which suffering of affected population segments can be captured with respect temporal replenishment of supplies using pure mathematical modeling techniques has not been explicitly addressed in the literature.

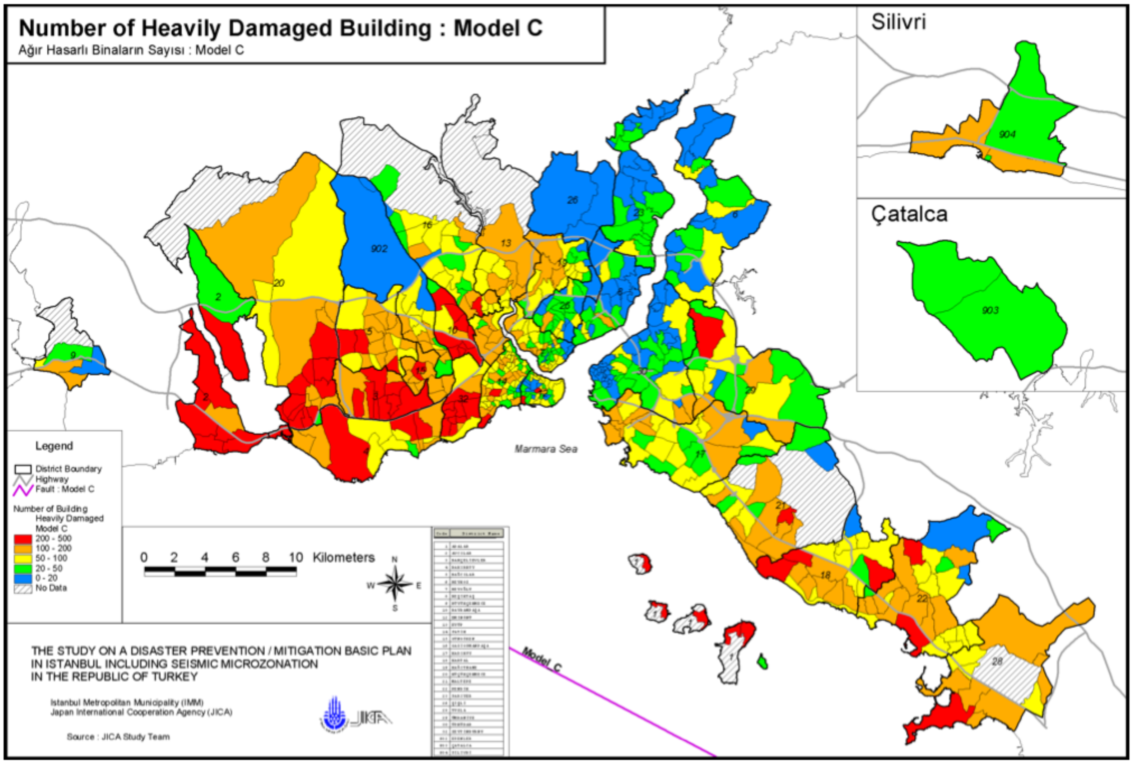


Figure 2.1: Number of heavily damaged buildings according to JICA et al. (2002)

One of the regions of the world that is prone to disasters is the greater Istanbul area, which faces a high probability of occurrence of a catastrophic earthquake over first thirty years of the 21st Century. The city is one of the most densely populated, and largest, cities of the world with over 12 million inhabitants. The probability of an earthquake in the greater Istanbul area is estimated to be 62$\pm$15% (Parsons, 2000). Japan International Cooperation Agency (JICA), in collaboration with Istanbul Metropolitan Municipality (IMM), published a report after they conducted a study on a disaster prevention/mitigation plan for Istanbul (JICA et al., 2002). The report provides estimates for seismic hazard and damage for the 30 districts of Istanbul. For each district, estimates are provided for the number of collapsed buildings; partly, moderately, and heavily damaged buildings; number of deaths, slightly and heavily injured people; number of refugees; and, extent of damage in infrastructure, e.g.

road networks, bridges, gas, electricity, water and sewage, and telecommunication networks, etc. The building damage estimation of the worst case scenario (Model C in the report) is pictorially represented in Figure 2.1 as it is given in the report. In this scenario, the total number of damaged buildings beyond repair will be 128,000 which is 17.7% of the total number buildings. The number of deaths is estimated to be 87,000 which is 0.8% of the total number of people living in the study area. And, the number of severely injured people is given as 120,000. The data provided has been used in recent literature to study the locating of disaster response and relief facilities in Istanbul (Görmez et al., 2011). In this dissertation, we make use of the same data, for a radically different purpose. That of studying the strategic planning of staging supplies over time and place in order to minimize criticality and destitution among affected populations.

In this chapter, the relationship between the lack of timely provision of relief supplies to, and suffering among, affected populations is formalized. Affected populations can be categorized with respect to the level of need for a set of specific types of supplies or commodities. Each commodity, which may represent one or more products, has an assumed replenishment frequency depending on the level of replenishment and the number of periods of time for which replenishment is adequate. Some commodities need to be provided only once, others may require replenishment based on their use or need. For instance, provision for tents in the aftermath of a disaster is not recurrent. Periodic replenishment is required only for *regular products*, such as food, water, sanitation products, etc. Replenishment can provide more than one commodity to an affected population at the same time. When multiple commodities are considered, they can be distributed in bundles of a subset of the commodities. The commodities included in a specific bundle depends on the availability of each type of commodity at a distribution region.

The modeling framework that is adopted in this dissertation is premised on critical shortages. Relief supplies are provided as survival kits, which we refer to as *commodities*, each of which is sufficient for a single person, or a number of persons, for a certain amount of time.[*] Each unit of a relief commodity, or a kit, e.g. medical kit, food kit, housing kit, etc., provides for a number of periods, which we refer to as the *days-of-provision*. As long as a commodity is replenished within this period, the population is *provided* for. If replenishment does not occur, the population faces a critical shortage which builds with each successive period. The number of periods before the shortage of a commodity becomes *destitute* is referred to as the *days-of-destitution*.

The modeling framework is presented in the following sections. The framework considers a single echelon multi-period, multi-commodity, multi-vehicle relief distribution model with the possibility of recurrence of demand over time seeking to minimize the extent of criticality among populations over the planning horizon. The developed model addresses the objectives of minimizing criticality and destitution as a mixed integer goal programming model for distribution of relief supplies. Supply is assumed to become available over time and the model determines its allocation to one of a set of supply sites and subsequent provision or replenishment to distribution regions. Distribution of commodities is considered in *bundles* that are constituted dynamically over time. The manner and timing of bundling takes into account the differing needs, over time, for specific commodities by different population segments, as well as the differing availability of commodities over time. The model tracks the relief state of portions of the population in each affected region from period to period.

Section 2.1 reviews the literature that focus on the suffering of affected populations in the aftermath of a disaster. Section 2.2 introduces *relief* states to track populations through *provided*, *destitute* and *critical* states. The section also elaborates on the manner in which the distribution of bundles of commodities over time defines the transitions of populations, from

[*]There are several brands of food or medical kits in the market which are specified as the number of days they can feed a single person or a number of persons, e.g., "Emergency Survival Kit Bucket - Deluxe - 4 Person" of Mayday Industries, Inc.

relief state to relief state. The model is developed step-by-step in the subsequent sections: The single commodity version of the model is introduced in Section 2.3. Since the focus of the model is the allocation and distribution of supplies with a view of alleviating destitution in the affected populations, transportation capacity is assumed to be unlimited. The single commodity model is extended to capture the multi-commodity case in Section 2.4. The complete multi-commodity multi-vehicle model is finalized by including vehicle dispatching requirements in Section 2.5. In Section 2.6, the model is applied to a disaster scenario for the greater Istanbul area. The chapter ends with concluding remarks in Section 2.7.

2.1 Literature on Suffering of Disaster Affected Populations

The majority of the models that are used for disaster operations use minimization of logistics costs in the objective function. The researchers that recognize the need to capture suffering, either consider optimizing demand satisfaction in their objective function, or use "equity constraints" to give visibility to suffering in their optimization models, though in a manner that computational efficiency is not compromised. These approaches, as pointed out by Holguín-Veras et al. (2013), do not take into account the time that a population may have been without supplies, the urgency with which supplies may be needed at different locations, and the optimal allocation of those resources to achieve the highest social benefit. Recently, there is an increasing recognition on that human suffering as result of probable delays in relief provision should be given a special attention in operations research studies. Holguin-Veras Ph.D. and Perez (2010) suggest to incorporate 'social costs' of suffering in the objective function, and to use valuation techniques from theoretical economics to estimate these costs. The authors propose a so-called deprivation function to use in the objective to minimize suffering in affected populations. The function is monotonic non-linear convex with respect to the deprivation time, which is defined as the time since last delivery. Yushimito et al. (2010) uses such a function to locate a finite number of distribution centers to provide a quick response time for disaster relief. The proposed model maximizes coverage of affected regions while minimizing human suffering through the use of a social cost function. Jaller Martelo (2011) consider the minimization of human suffering in their multi-period model which is to identify the optimal allocation of manpower required for the optimal distribution of critical supplies at the points of distribution by considering the effects of material convergence in order to expedite the flow of critical supplies. Perez Rodriguez (2011)presents and inventory allocation and vehicle routing model for the distribution of critical items post-disaster that minimizes deprivation costs along with total travel time and handling costs.

2.2 Replenishment of Relief Supplies and Population State

In any time period, segments of the population can be in one of several relief states. The *relief state* of a population segment with respect to a single commodity is the number of time periods since replenishment. For each commodity k in the set of commodities $\mathcal{K} = \{1, 2, \ldots, K\}$, the *days-of-provision*, denoted τ_k, is the number of time periods for which the replenished amount is adequate for a single person, and the *days-of-destitution*, denoted θ_k, is the number of time periods for which a person can survive without the commodity. For Type II commodities, denoted by the subset $\mathcal{K}^2$, the demand recurs every τ_k periods. For Type I commodities, denoted by the subset $\mathcal{K}^1$, there is no replenishment and we define, for modeling purposes, the days-of-provision to be 0, i.e. $\tau_k = 0$.

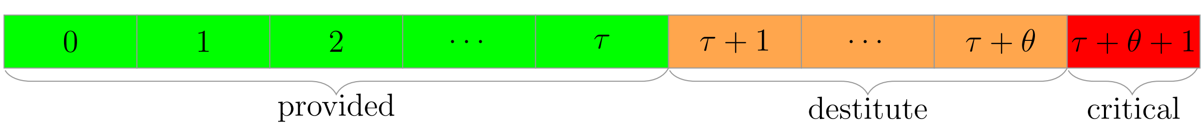


Figure 2.2: Relief States

The days-of-provision and days-of-destitution allow a categorization of the states with respect to a single commodity as either *provided*, *destitute*, or *critical* as shown in Figure

2.2. States $0, \ldots, \tau_k$ are *provided*, states $\tau_k + 1, \ldots, \tau_k + \theta_k$ are *destitute*, and state $\tau_k + \theta_k + 1$ is *critical*. A Type II commodity is assumed to provide a population enough supplies to last through the *provided* states. For example, for a Type II commodity with $\tau_k = 3$ days-of-provision and $\theta_k = 2$ days-of-destitution, the relief states range from 1 to 6 where states 1, 2, and 3 are *provided*, states 4 and 5 are *destitute*, and state 6 is *critical*. We note that for a Type I commodity, since the days-of-provision is defined to be 0, there is only one *provided* state, and all states $\{1, 2, \ldots, \theta_k\}$ are *destitute*.

The *relief state* of a population segment with respect to the entire set of commodities is denoted by a K-tuple $\alpha^r = [\alpha^r_1, \ldots, \alpha^r_K]$, where α^r_k is the relief state with respect to commodity k and the set of all relief states is denoted by $\mathcal{R}$. The state of a population segment is *provided* if the state with respect to all commodities is *provided*. The state is *destitute* if the state with respect to at least one commodity is *destitute*. The state is *critical* if the state with respect to at least one commodity is critical.

2.2.1 Transitions from state to state

A population segment may be replenished in any of the destitute states, and once replenished, it can either move to state 0 or 1. It moves to state $\{1\}$ in the following period if the commodity is Type II and to state 0 for a Type I commodity. When replenishment does not occur the population in any state other than $\{0\}$ move to the next higher state. Demand for a commodity is diminished in future periods for the portion of the population that enters a critical state.

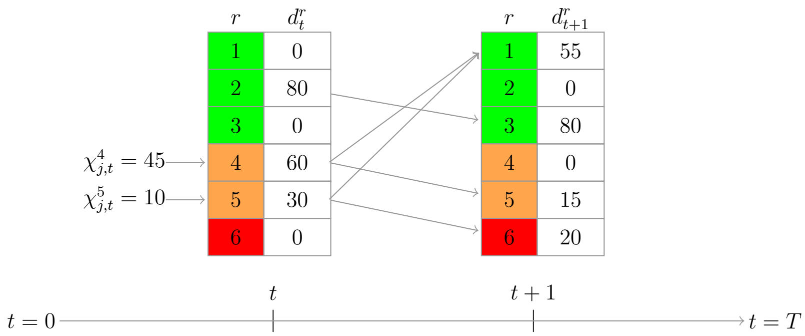


Figure 2.3: Transition from one relief state to another for a Type II commodity

We illustrate the transition of populations to different relief states from one period to the next for a Type II commodity with days-of-provision $\tau = 3$ and days-of-destitution $\theta = 2$, as pictorially represented in Figure 2.3. At the beginning of time period t, the population of 170 in a distribution region is in three different relief states and the total supply allocated to the region can satisfy 55 persons. The population, of 80, in provided state $\{2\}$ transitions to provided state $\{3\}$ in the next time period. Of the 60 persons in state $\{4\}$, 45 are replenished and the 15 who are not transition to destitute state $\{5\}$ in the next period. Of the 30 persons in state $\{5\}$, 10 are replenished and the 20 who are not transition to critical state $\{6\}$. The total population of 55 that is replenished transitions to provided state $\{1\}$.

Relief states with respect to more than one commodity are defined using the individual relief states. The set of commodities $\mathcal{K}$ is dichotomized with respect to the type of commodity, and the subset of commodities of Type I is denoted $\mathcal{K}^1$ and that of Type II is denoted $\mathcal{K}^2$. The set of relief states $\mathcal{R}$ is indexed by r and each state is defined with respect to the relief states of each of the commodities in the set of commodities $\mathcal{K}$. Each relief state is defined as a K-tuple, $\alpha^r = [\alpha_1^r, \ldots, \alpha_K^r]$. where $\alpha_k^r = \alpha_k^0, 1, \ldots, \tau_k, \tau_k + 1, \ldots, \tau_k + \theta_k, \tau_k + \theta_k + 1$ where if $\alpha_k^0 = 0, k \in \mathcal{K}^1$ and if $\alpha_k^0 = 1, k \in \mathcal{K}^2$.

Any state r that are provided with Type I commodities are identified by a relief state $\alpha_k^r = 0, \forall k \in \mathcal{K}^1$. As in the single commodity case, portions of the population, p_j, can be in one of any of three types of states, defined as follows:

- The subset of *provided states* is defined as $\mathcal{A} = \{r \in \mathcal{R} \mid 0, \forall k \in \mathcal{K}^1; 1 \leq \alpha_k^r \leq \tau_k, \forall k \in \mathcal{K}^2\}$
- The subset of *destitute states* is defined as $\mathcal{C} = \{r \in \mathcal{R} \mid \tau_k < \alpha_k^r \leq \tau_k + \theta_k, \exists k \in \mathcal{K}\}$.
- The subset of *critical states* is defined as $\mathcal{F} = \{r \in \mathcal{R} \mid \alpha_k^r = \tau_k + \theta_k + 1, \exists k \in \mathcal{K}\}$.

Populations are replenished with different bundles of commodities, $B \subseteq \mathcal{K}$. The superset of all possible bundles is denoted $\mathcal{B}$. The bundle can consist of only Type I commodities, only Type II commodities, or of both types of commodities. A population in any relief state can transition to a unique state which depends on the current state and whether or not they have been replenished, and if replenished, the specific commodities in the bundle they have been replenished with.

A population that is <u>not replenished</u> when in state $[\alpha_1^r, \ldots, \alpha_K^r], r \in \mathcal{R}/\mathcal{F}$ transitions to a unique state $\hat{r}$ in the next period, namely $[\alpha_1^{\hat{r}}, \ldots, \alpha_K^{\hat{r}}]$. The relief states with respect to each commodity are defined as follows:

$$\alpha_k^{\hat{r}} = \begin{cases} \alpha_k^r + 1, & \text{if } \alpha_k^r > 0, \forall k \in \mathcal{K} \\ \alpha_k^r = 0, & \text{if } \alpha_k^r = 0, \forall k \in \mathcal{K}. \end{cases}$$

Populations are <u>replenished</u> when in a state $r \in \mathcal{C}$, and the state that they transition to depends on the specific bundle, B, of replenished commodities. Transitions <u>into</u> a state can occur by receiving a bundle B, or its subsets, $\bar{B} \subseteq B$, each of which must necessarily contain all Type II commodities in bundle B, i.e. $\bar{B} \supset (B \cap \mathcal{K}^2)$, and can contain one or more Type I commodities in bundle B. The subset of states that the population can transition into is denoted $\mathcal{R}^B$ and defined as follows:

$$
\mathcal{R}^B = \left\{ r \in \mathcal{R} \mid \begin{cases} \alpha_k^r = 1 & \forall k \in \mathcal{K}^2 \cap B, \\ 1 < \alpha_k^r \leq \tau_k + \theta_k + 1 & \forall k \in \mathcal{K}^2/(B \cap \mathcal{K}^2), \\ \alpha_k^r = 0 & \forall k \in \mathcal{K}^1 \cap B, \\ 1 < \alpha_k^r \leq \theta_k + 1 & \forall k \in \mathcal{K}^1/(B \cap \mathcal{K}^1). \end{cases} \right\}
$$

Each state $r \in \mathcal{R}^B$ can be transitioned into from states $\bar{r} \in \bar{\mathcal{R}}$, when replenished by the commodities in specific subsets $\bar{B} \subseteq B$. The set $\bar{\mathcal{R}}$ is defined as follows:

$$
\bar{\mathcal{R}}^{\bar{B}} = \begin{cases} \alpha_k^{\bar{r}} = 0 & \forall k \in (\mathcal{K}^1 \cap B)/(\mathcal{K}^1 \cap \bar{B}), \\ 0 < \alpha_k^{\bar{r}} \leq \theta_k & \forall k \in \mathcal{K}^1 \cap \bar{B}, \\ \tau_k < \alpha_k^{\bar{r}} \leq \tau_k + \theta_k & \forall k \in \mathcal{K}^2 \cap B, \\ \alpha_k^{\bar{r}} = \alpha_k^r - 1 & \forall k \in \mathcal{K}/B. \end{cases}
$$

For a state $r \in \mathcal{R}^B$, Type I and Type II commodities in bundle B define commodities that are in state 0 and 1, respectively. State $\bar{r}$ transition to r if and only if $\bar{B}$ includes Type II commodities that are in B, and $\bar{B}$ includes Type I commodities that are in bundle B for which r is not in state 0.

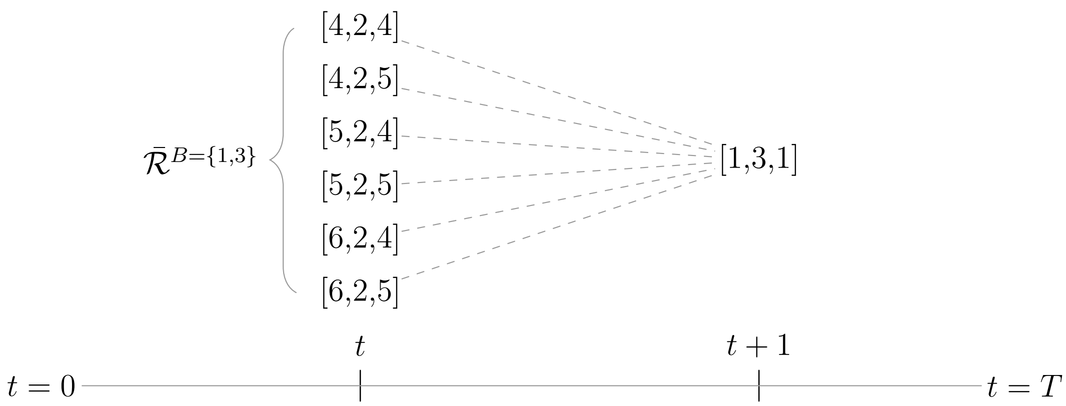


Figure 2.4: Transition of several relief states to the same relief state, Type II commodities only

We illustrate, in Figure 2.4, the possible states that transition into state [1,3,1] for three Type II commodities that have been replenished with the bundle {1,3}. We note that since no Type I commodities are considered, there are no possible subsets of the bundle to consider. The population groups, which receive the same bundle and which are in the same relief states for commodities which are not included in the bundle, transition to the same relief state in the following time period. In the picture, all possible combinations of relief states in the set of $\bar{\mathcal{R}}^B$ are given, where bundle B includes commodities 1 and 3, i.e., $B = \{1, 3\}$, and $\alpha_2 = 2$ for all the states. If any of these population groups receive B at time t, as many people as the total amount of shipment to this set transition to the state of [1,3,1] in the following time period, i.e. let $d^r_{j,t}$ and $\chi^r_{j,t}$, respectively, denote the population and the shipment to the population at distribution region $j \in \mathcal{N}$ in state r at time t, then $d^{[1,3,1]}_{j,t+1} = \sum_{r \in \bar{\mathcal{R}}^{\{1,3\}}} \chi^r_{j,t}$.

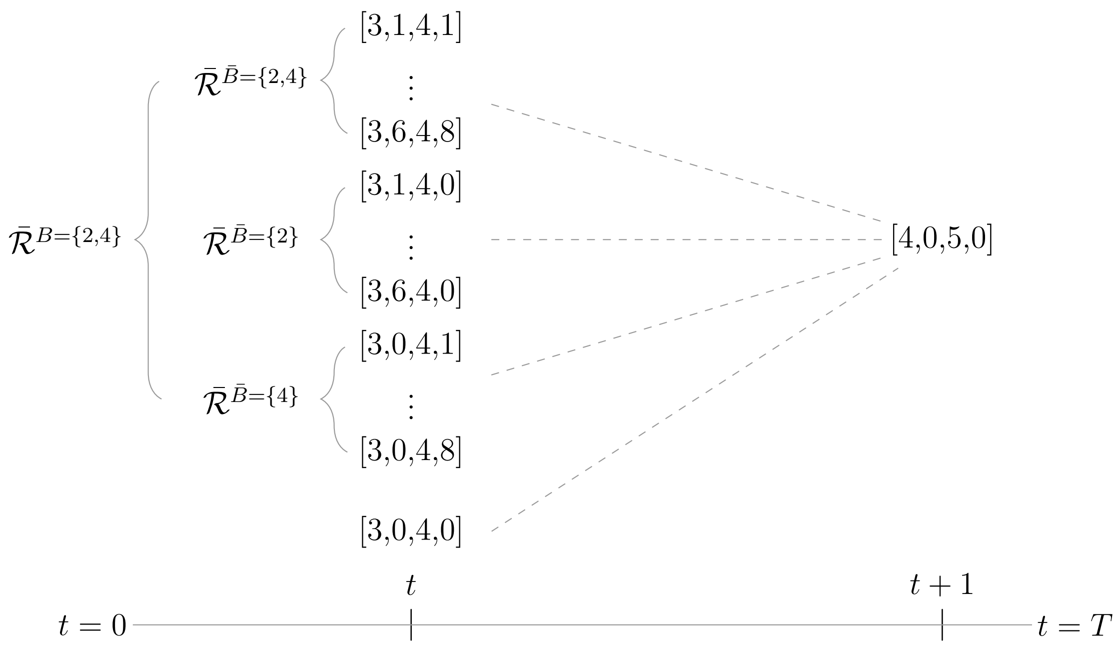


Figure 2.5: Transition of several relief states to the same relief state, Type I and Type II commodities together

The transitions into a single relief state from multiple states are more complex when the bundle includes a Type I commodity. In this case, to fully account for all possible states, it is necessary to consider replenishment by subsets of the bundle. For example, for three commodities with the first commodity being Type I, state $[0, 2, 1]$ can be transitioned into from five states that are replenished by bundle $\{1, 3\}$, and from two states that are replenished by bundle $\{3\}$. The five states, $[4, 1, 3]$, $[4, 1, 2]$, $[5, 1, 3]$, $[6, 1, 4]$, or $[6, 1, 5]$, all have the same state, namely 1, with respect to commodity 2 and both the two states, $[0, 1, 2]$, $[0, 1, 3]$ have the same states, 0 and 1 with respect to, respectively, commodities 1, and 2. In Figure 2.5, we illustrate how population segments in multiple states, when replenished with different subsets of a set of commodities, can transition to the same state. In this example, there are four commodities with $\mathcal{K}^1 = \{2, 3, 4\}$ and $\mathcal{K}^2 = \{1\}$ and $\tau_1 = 4, \tau_2 = 0, \tau_3 = 0, \tau_4 = 0$ days-of-provision, and $\theta_1 = 4, \theta_2 = 6, \theta_3 = 8, \theta_4 = 8$ days-of-destitution. With replenishment by bundle $B = \{2, 4\}$, to account for all states that can transition into state [4,0,5,0], we must consider replenishment by all subsets of commodities, i.e. $\{\{2\}, \{4\}, \{2, 4\}\}$. All population segments that are replenished by any of these bundles, together with persons in the *destitute* state [3,0,4,0], who are not replenished, transition into [4,0,5,0]. For example, any state with three days since replenishment of commodity 1 and four days since replenishment of commodity 3 that is replenished with commodities 2 and 4, i.e. bundle $\{2, 4\}$ will transition into this state.

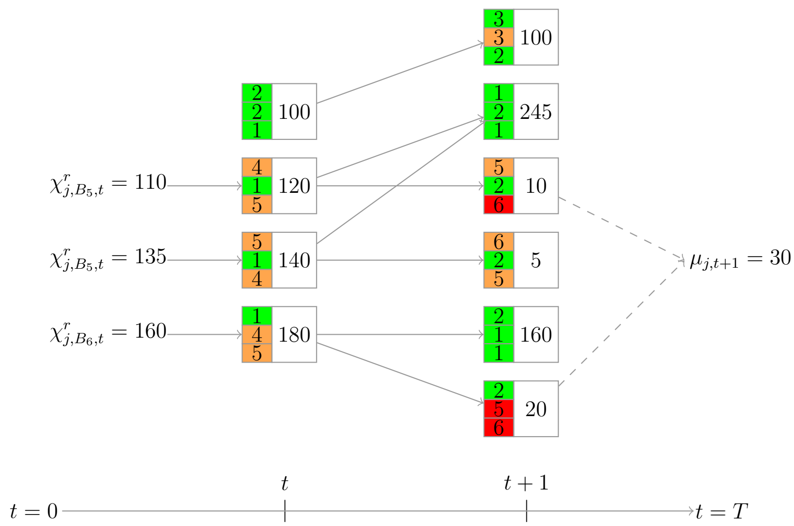


Figure 2.6: Transition from one relief state to another by receiving shipment, Type II commodity only

In Figure 2.6, we illustrate transitions of population segments using three Type II commodities with $\tau_1 = 3, \tau_2 = 2, \tau_3 = 3$ days-of-provision and $\theta_1 = 3, \theta_2 = 2, \theta_3 = 2$ days-of-destitution. The population in state [2,2,1] is 100. This is a provided state, since the state for each commodity indicates that the time since replenishment is less than the days-of-provision. States [4,1,5], [5,1,4], and [1,4,5] have populations of, respectively, 120, 140, and 180. These three states are *destitute* since the time since replenishment for at least one of the commodities 1, 2, and 3, is larger than, respectively, 3, 2, and 3. A total of 245 units of bundle $\{1,3\}$ is distributed to 110 persons in state [4,1,5] and to 135 in state [5,1,4], and 160 units of bundle $\{2,3\}$ is distributed to the persons in state [1,4,5]. A total of 245 persons transition into state [1,2,1], 110 from state [4,1,5] and 135 from state [5,1,4], since both have the same state for commodity 2, which is not in the bundle. Of the 180 persons in state [1,4,5], 160 transition to *provided* state [2,1,1] and the remaining 20 transition to the *critical* state [2,5,6]. We note that, here, any state for which the time since replenishment for at least one of the commodities 1, 2, and 3, is respectively, $3+3+1=7$, $2+2+1=5$, and $3+2+1=6$ is *critical*. The days since replenishment for the 10 persons in state [4,1,5] that are not replenished increase by one for each commodity and they transition, on the next day, to state [5,2,6], which is *critical*. Similarly, the 5 persons in state [5,1,4], who are not replenished, transition to state [6,2,5], which is *destitute*.

2.3 Single Commodity Model

For the purpose of clarity of exposition, we present the single commodity model in this section to facilitate the understanding of the transition of population segments from a state state in one period to another in the following period. Before presenting the model, the index sets, parameters, and variables are defined.

Index sets

$\mathcal{M}$ Set of supply sites, $\{1, \ldots, M\}$

$\mathcal{N}$ Set of distribution sites, $\{1, \ldots, N\}$

$\mathcal{T}$ Set of days of planning horizon, $\{1, \ldots, T\}$

$\mathcal{K}$ Set of relief commodities, $\{1, \ldots, K\}$

$\mathcal{R}$ Set of relief states r, $\{0, 1, \ldots, \theta + \tau + 1\}$

$\mathcal{A}$ Subset of *provided* states; $\{0\}$, if Type I commodity, and $\{1, 2, ..., \tau\}$, otherwise

$\mathcal{C}$ Subset of *destitute* states, $\{\tau + 1, \ldots, \theta + \tau\}$

Parameters

S Total available supply at the beginning of planning horizon

r^F *Critical* state, $\{\tau + \theta + 1\}$

p_j Population at distribution region $j \in \mathcal{N}$

θ Days-of-destitution

τ Days-of-provision

r^0 Initial state of replenishment cycle; 0, if commodity is of Type I, and 1, otherwise

$\mathbf{P}_1, \mathbf{P}_2$ Preemptive priorities corresponding to two objectives

Variables

σ_t Total available supply at time $t \in \mathcal{T}$

$s_{i,t}$ Available supply at supplier site $i \in \mathcal{M}$ at time $t \in \mathcal{T}$

$I_{i,t}$ Inventory at supplier site $i \in \mathcal{M}$ at time $t \in \mathcal{T}$

$x_{i,j,t}$ Amount of flow from $i \in \mathcal{M}$ to $j \in \mathcal{N}$ at time $t \in \mathcal{T}$, which is specified as the number of people it can satisfy

$\chi^r_{j,t}$ Amount of replenishment, in the number of people that it can satisfy in a population group which is in a *destitute* state $r \in \mathcal{C}$ at distribution region $j \in \mathcal{N}$ at time $t \in \mathcal{T}$

$d^r_{j,t}$ Number of people in a population group in a relief state $r \in \mathcal{R}$ at distribution region $j \in \mathcal{N}$ at time $t \in \mathcal{T}$

$\mu_{j,t}$ Total criticality at distribution region $j \in \mathcal{N}$ due to shortage of commodity

z_1, z_2 Deviation variables for the goals of two objectives

$$
\begin{aligned}
&\text{minimize} \quad \mathbf{P}_1 z_1 + \mathbf{P}_2 z_2 && && (2.1)\\
&\text{subject to} \quad \sum_{t\in\mathcal{T}}\sum_{j\in\mathcal{N}} \mu_{j,t} - z_1 = 0 && && (2.2)\\
&\sum_{t\in\mathcal{T}}\sum_{j\in\mathcal{N}}\sum_{r\in\mathcal{C}} (d^r_{j,t} - \chi^r_{j,t}) - z_2 = 0 && && (2.3)\\
&\sum_{t\in\mathcal{T}} \sigma_t \leq S && && (2.4)\\
&\sum_{i\in\mathcal{M}} s_{i,t} - \sigma_t = 0 && \forall t \in \mathcal{T} && (2.5)\\
&I_{i,0} - s_{i,0} = 0 && \forall i \in \mathcal{M} && (2.6)\\
&I_{i,t-1} + s_{i,t} - \sum_{j\in\mathcal{N}} x_{ij,t} - I_{i,t} = 0 && \forall i \in \mathcal{M}, \forall t \in \mathcal{T}, t \geq 1 && (2.7)\\
&J_{j,0} = 0 && \forall j \in \mathcal{N} && (2.8)\\
&J_{j,t-1} + \sum_{i\in\mathcal{M}} x_{i,j,t} - \sum_{r\in\mathcal{R}} \chi^r_{j,t} - J_{i,t} = 0 && \forall j \in \mathcal{N}, \forall t \in \mathcal{T}, t \geq 1 && (2.9)\\
&d^r_{j,1} = p_j && \forall j \in \mathcal{N}, r = \tau + 1 && (2.10)\\
&d^r_{j,1} = 0 && \forall j \in \mathcal{N}, \forall r \in \mathcal{R}, r \neq \tau + 1 && (2.11)\\
&d^{r^0}_{j,t} - \sum_{r\in\mathcal{C}} \chi^r_{j,t-1} = 0 && \forall j \in \mathcal{N}, \forall t \in \mathcal{T}, t > 1 && (2.12)\\
&d^{r+1}_{j,t} - (d^r_{j,t-1} - \chi^r_{j,t-1}) = 0 && \forall j \in \mathcal{N}, \forall t \in \mathcal{T}, t > 1, \forall r \in \mathcal{C} && (2.13)\\
&d^{r+1}_{j,t} - d^r_{j,t-1} = 0 && \forall j \in \mathcal{N}, \forall t \in \mathcal{T}, t > 1, \forall r \in \mathcal{R}/\mathcal{C}, r > 0 && (2.14)\\
&d^r_{j,t} - d^r_{j,t-1} = 0 && \forall j \in \mathcal{N}, \forall t \in \mathcal{T}, t > 1, \forall r \in \mathcal{R}/\mathcal{C}, r = 0 && (2.15)\\
&d^r_{j,t} - \mu_{j,t} = 0 && \forall j \in \mathcal{N}, \forall t \in \mathcal{T}, r = r^F && (2.16)\\
&\chi^r_{j,t} - d^r_{j,t} \leq 0 && \forall j \in \mathcal{N}, \forall t \in \mathcal{T}, t \geq 1, \forall r \in \mathcal{C} && (2.17)\\
&I_{i,t}, s_{i,t}, \sigma_t, x_{i,j,t} \geq 0 && i \in \mathcal{M}, \forall j \in \mathcal{N}, \forall t \in \mathcal{T} && (2.18)\\
&d^r_{j,t}, \mu_{j,t}, z_1, z_2 \in \mathbb{Z}^+ && \forall j \in \mathcal{N}, \forall r \in \mathcal{R}, \forall t \in \mathcal{T} && (2.19)\\
&\chi^r_{j,t} \in \mathbb{Z}^+ && \forall j \in \mathcal{N}, r \in \mathcal{C}, \forall t \in \mathcal{T} && (2.20)
\end{aligned}
$$

The two goals in the model are to minimize the overachivement of a target of zero criticality at priority one, and to minimize the overachievement of a target of zero destitution at priority two. The ordinal weights $\mathbf{P}_1$ and $\mathbf{P}_2$, reflect the priorities of the two goals which are defined in the two goal constraints, namely, 2.2, and 2.3. Constraint 2.4 allocate total supply over time, and and constraint set 2.5 allocates supply to supply sites in each time period. We note that Constraint 2.4 can be omitted when supplies are known for each time period, i.e. the variables σ_t are parameters instead of variables. Constraints 2.6 and 2.7 enforce the conservation of flow and tracks inventory at each supply site, in each time period. Constraints 2.8 and 2.9 enforce conservation of flow and tracks inventory at each distribution region when allocating relief to populations in one of the relief states. Constraint 2.10 and 2.11 initialize the entire population in each distribution region to the first destitute state, $\tau + 1$. Constraints 2.12 - 2.16 track the progression of the population with respect to both time and relief state. Constraint 2.12 accumulates the total population in destitute states in the previous period that is replenished. If the commodity is Type I, accumulation is for state $r^0 = 0$ and for commodity Type II for state $r^0 = 1$. Constraint 2.13 moves the population in a destitute state that is not replenished to the next destitute state or to the critical state. Constraint 2.14 tracks the movement of the population that is in a provided state, to the next provided state or first destitute state for a Type II commodity. If the commodity is Type I this constraint is not active and, instead, constraint set 2.15, ensures that the provided population is retained in the provided state, $r = 0$. Constraint 2.16, which is definitional, tracks the population in the critical state. Constraint 2.17 ensures that no supply is allocated to a relief state if it has a zero population. Finally, Constraints 2.18 - 2.20 specify non-negativity and integrality of the variables.

We note that for the single commodity model, constraints 2.12 - 2.16 can be simplified. Rather than tracking the replenished population through each of the days-of-provision, the replenished population in any time period t can be moved directly to the first destitute state, $\tau + 1$ in time period $t + \tau$.

$$d^{r^0}_{j,t} - \sum_{r=1}^{\theta} \chi^r_{j,t-\tau} = 0 \qquad \forall j \in \mathcal{N}, \forall t \in \mathcal{T}, t > 2 \tag{2.21}$$

$$d^{r+1}_{j,t} - (d^r_{j,t-1} - \chi^r_{j,t-1}) = 0 \qquad \forall j \in \mathcal{N}, \forall t \in \mathcal{T}, t > 1, \forall r \in \mathcal{R}, r > 1 \tag{2.22}$$

$$d^r_{j,t} - d^r_{j,t-1} = 0 \qquad \forall j \in \mathcal{N}, \forall t \in \mathcal{T}, t > 1, \forall r \in \mathcal{R}, r = 1 \tag{2.23}$$

$$\chi^r_{j,t} - d^r_{j,t} \leq 0 \qquad \forall j \in \mathcal{N}, \forall t \in \mathcal{T}, t \geq 1, \forall r \in \mathcal{R} \tag{2.24}$$

$$d^{\theta+1}_{j,t} - \mu_{j,t} = 0 \qquad \forall j \in \mathcal{N}, \forall t \in \mathcal{T} \tag{2.25}$$

In this alternative approach $R = \{0, 1, \ldots, \theta + 1\}$. Constraint sets 2.21 - 2.23 defines the demand in each time period, more specifically, the recurrence of demand every τ periods. However, this simplification applies only to the single commodity model: The extension of this model to the multi-commodity case requires tracking each population with respect to each commodity and hence requires the multi-commodity extension of the constraint set 2.21 to 2.25 as in the presentation of the model.

2.3.1 Illustrative examples for the single commodity case

To illustrate key aspects of the model, in this section, we present two examples and depict the manner in which populations transition from state to state depending on the objective that is optimized, destitution or criticality. In the examples, we illustrate the transition of segments of a population of 200 in one of seven different states $[1], [2], ..., [7]$, at a single distribution site when replenished by a single Type II commodity with $\theta = 3$ days-of-destitution and $\tau = 3$ days-of-provision from a single supply site over a planning horizon of 12 days.

Example 2.1 This example demonstrates the impact of the amount of initially available supply, S, on destitution and criticality, and the tradeoff between two objectives when one objective is optimized while the other being relaxed. A total initial supply of 400 is assumed. The transition of the population from one state to another with respect to replenishment is displayed in Figure 2.7 and 2.8, respectively, when criticality and destitution is optimized.

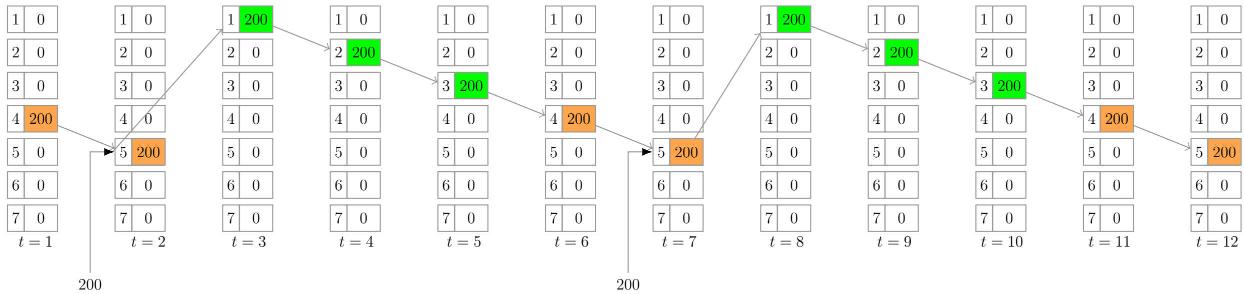


Figure 2.7: Relief state transition in Example 2.1. Criticality is minimized

As shown in Figure 2.7, when criticality is minimized, with an initial supply of 400, the population does not face critical shortage, i.e. number of persons at critical state of 7 is zero. Actually, 400 is a lower bound in initial supply before criticality occurs. By a simple sensitivity analysis it can be seen that an initial supply of 399 results a total criticality of 1. Minimizing criticality leads to a total destitution of 800: 200 persons are not replenished in periods 1, 6, 11 and 12, and thus, destitute for four periods. Note that replenishment occurs only when population transition into a destitute state. Since they are replenished immediately, the objective does not deem them to be destitute.

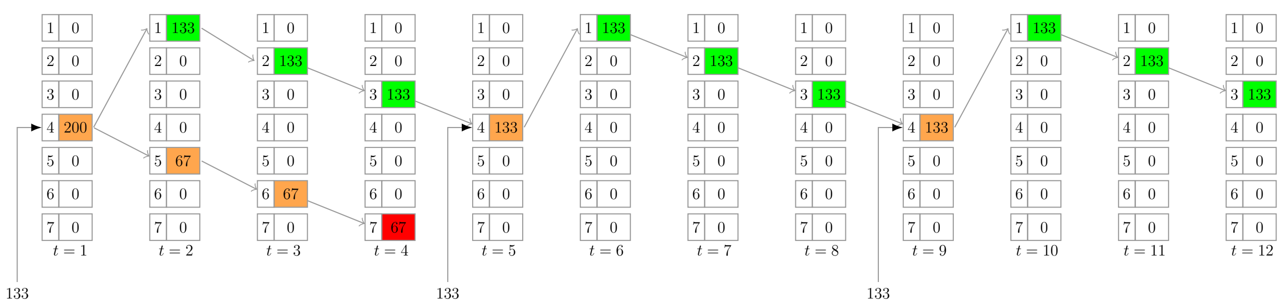


Figure 2.8: Relief state transition in Example 2.1. Destitution is minimized

Figure 2.8 shows the results for minimizing destitution. Total criticality and total destitution, respectively, are 67 and 201: 67 persons, not being replenished in the first four periods, are destitute in periods 1, 2, and 3, and critical in period 4.

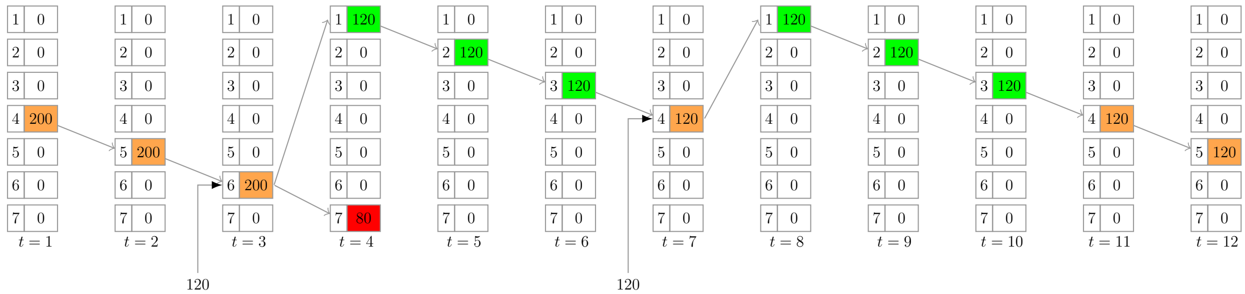


Figure 2.9: Relief state transition in Example 2.2. Criticality is minimized

Example 2.2 This example is to demonstrate how criticality and destitution are impacted by the case that supply becomes available over time, which might be a consequence of limited transportation capacity. The supply of the commodity available over the first six time periods is in amounts of 20 ,40, 60, 80, 100, and 120. The minimum criticality becomes 80 that occur in period 4, while total destitution is 640 (Figure 2.9): 200 persons are destitute for the first two periods; 80 persons are critical in period 4; 120 persons are destitute for the last two periods.

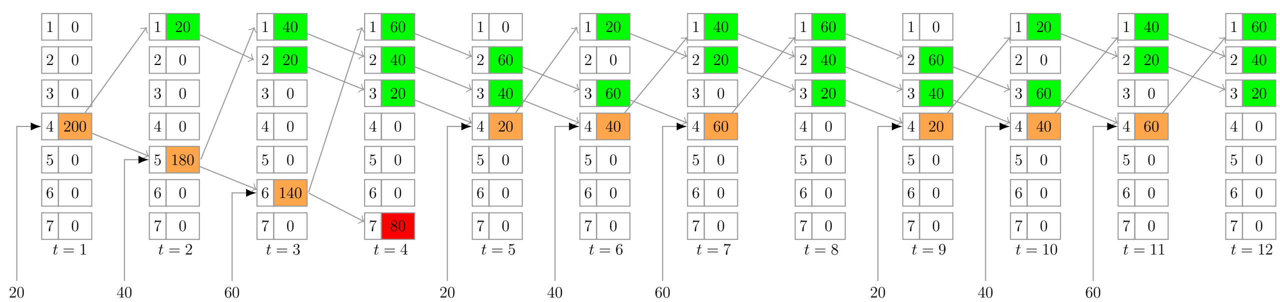


Figure 2.10: Relief state transition in Example 2.2. Destitution is minimized

When destitution is optimized, the minimum destitution with this availability is 400, with a consequent criticality of 80 (Figure 2.10). In the first time period, 180 persons are not replenished, in the second 140, and in the third 80. The distribution of supply is spread over the planning horizon. Note that inventory of the commodity being held, replenishment occurs only for population segments that transition into a destitute state.

2.4 Multi-Commodity Model

In the multi-commodity scenario the bundling of commodities introduces significant complexity. Further, the tracking of populations from a state in one period to another in the next period becomes more complex because commodities can be provided in bundles and may be of either Type I or Type II, as introduced in Section 2.1. Before presenting the model, the index sets, parameters, and variables are defined.

Index sets

- $\mathcal{M}$ Set of supply sites, $\{1, \ldots, M\}$
- $\mathcal{N}$ Set of distribution sites, $\{1, \ldots, N\}$
- $\mathcal{T}$ Set of days of planning horizon, $\{1, \ldots, T\}$
- $\mathcal{K}$ Set of relief commodities $\{1, \ldots, K\}$
- $\mathcal{K}^1$ Subset of relief commodities of Type 1, $\subseteq \mathcal{K}$
- $\mathcal{K}^2$ Subset of relief commodities of Type 2, $\subseteq \mathcal{K}$
- B Subset of commodities that a population is replenished with.
- $\mathcal{B}$ Superset of commodity bundles, $\{B_1, \ldots, B_{2^K-1}\}$
- $\bar{\mathcal{B}}_k$ Superset of bundles of commodities that include commodity k
- $\bar{B}$ Subset of bundles of commodities in bundle $B \in \mathcal{B}$, $\{\bar{B} \subseteq B \mid \bar{B} \supset (B \cap \mathcal{K}^2), \forall k \in \mathcal{K}^2; \bar{B} \supset (B \cap \mathcal{K}^1), \exists k \in \mathcal{K}^1\}$

$\bar{\mathcal{B}}$ Superset of subsets of bundles of commodities in $B \in \mathcal{B}$, $\{\bar{B} \mid \forall \bar{B} \subseteq B\}$

$\mathcal{R}$ Set of states, r

α^r Relief state r, a vector of relief states with respect to each commodity, $[\alpha_1^r, \ldots, \alpha_K^r]$, where

$$\alpha_k^r = \begin{cases} 0, 1, \ldots, 2, \tau_k, \tau_k + 1, \ldots, \tau_k + \theta_k, \tau_k + \theta_k + 1 & \text{if } k \in \mathcal{K}^1, \\ 1, 2, \ldots, \tau_k, \tau_k + 1, \ldots, \tau_k + \theta_k, \tau_k + \theta_k + 1 & \text{if } k \in \mathcal{K}^2. \end{cases}$$

$\mathcal{A}$ Subset of *provided* states $r \in \mathcal{R}$ where $\forall k \in \mathcal{K}^1, \alpha_k^r = 0$ and, $\forall k \in \mathcal{K}^2, 1 \leq \alpha_k^r \leq \tau_k$

$\mathcal{C}$ Subset of *destitute* states $r \in \mathcal{R}$ where $\exists k \in \mathcal{K} \mid \tau_k < \alpha_k^r \leq \tau_k + \theta_k$

$\mathcal{F}$ Subset of *critical* states $r \in \mathcal{R}$ where $\exists k \in \mathcal{K} \mid \alpha_k^r = \tau_k + \theta_k + 1$

$\mathcal{R}^B$ Subset of states $r \in \mathcal{R}$ that the population can transition into by receiving a bundle $B \in \mathcal{B}$ or its subset $\bar{B} \subseteq B$ in the previous time period, where

$$\begin{aligned} &\alpha_k^r = 1 && \forall k \in \mathcal{K}^2 \cap B, \\ &1 < \alpha_k^r \leq \tau_k + \theta_k + 1 && \forall k \in \mathcal{K}^2 / (B \cap \mathcal{K}^2), \\ &\alpha_k^r = 0 && \forall k \in \mathcal{K}^1 \cap B, \\ &1 < \alpha_k^r \leq \theta_k + 1 && \forall k \in \mathcal{K}^1 / (B \cap \mathcal{K}^1). \end{aligned}$$

$\bar{\mathcal{R}}^{\bar{\mathcal{B}}}$ Subset of states $\bar{r} \in \mathcal{R}$ that the population can transition from by receiving a bundle $B \in \mathcal{B}$ or its subset $\bar{B} \subseteq B$ in the previous time period, where

$$\begin{aligned} &\alpha_k^{\bar{r}} = 0 && \forall k \in (\mathcal{K}^1 \cap B) / (\mathcal{K}^1 \cap \bar{B}), \\ &0 < \alpha_k^{\bar{r}} \leq \theta_k && \forall k \in \mathcal{K}^1 \cap \bar{B}, \\ &\tau_k < \alpha_k^{\bar{r}} \leq \tau_k + \theta_k && \forall k \in \mathcal{K}^2 \cap B, \\ &\alpha_k^{\bar{r}} = \alpha_k^r - 1 && \forall k \in \mathcal{K} / B. \end{aligned}$$

$\hat{r}$ Relief state that a population segment in state r transitions if not replenished $\alpha_k^{\hat{r}} = \alpha_k^r + 1, \alpha_k^r > 0, \forall k \in K, \forall r \in \mathcal{R}$

B^r Bundle of commodities that allows a population segment in r to transition to a provided state

r' State of a population segment that transitions to state r if not replenished $\alpha_k^{r'} = \alpha_k^r - 1, \alpha_k^{r'} > 0, \forall k \in K, \forall r \in \mathcal{R}$

Parameters

S_k Total available supply of commodity $k \in \mathcal{K}$ at the beginning of planning horizon

p_j Population at distribution region $j \in \mathcal{N}$

κ_i Storage capacity of supplier site $i \in \mathcal{M}$ in lbs/day

θ_k Days-of-destitution $k \in \mathcal{K}$

τ_k Days-of-provision; $\tau_k = 0, \forall k \in K^1$

α_k^0 Initial state of replenishment cycle for commodity $k \in \mathcal{K}$, defined to be $\alpha_k^0 = 0,\ \forall k \in \mathcal{K}_1; \alpha_k^0 = 1,\ \forall k \in \mathcal{K}_2$

$\mathbf{P}_1, \mathbf{P}_2$ Preemptive priorities corresponding to two objectives

Variables

$\sigma_{k,t}$ Total available supply of commodity $k \in \mathcal{K}$ at time $t \in \mathcal{T}$

$s_{i,k,t}$ Available supply of commodity $k \in \mathcal{K}$ at supplier site $i \in \mathcal{M}$ at time $t \in \mathcal{T}$

$I_{i,k,t}$ Inventory for commodity $k \in \mathcal{K}$ at supplier site $i \in \mathcal{M}$ at time $t \in \mathcal{T}$

$x^h_{i,j,k,t}$ Amount of flow of commodity $k \in \mathcal{K}$ from $i \in \mathcal{M}$ to $j \in \mathcal{N}$ at time $t \in \mathcal{T}$ in time slot $h \in \mathcal{H}$ which is specified as the number of people it can satisfy

$\chi^r_{j,B,t}$ Number of people that bundle $B \in \mathcal{B}$ can satisfy in a population group which is in a *destitute* state $r \in \mathcal{C}$ at distribution region $j \in \mathcal{N}$ at time $t \in \mathcal{T}$

$d^r_{j,t}$ Number of people in a population group in a relief state $r \in \mathcal{R}$ at distribution region $j \in \mathcal{N}$ at time $t \in \mathcal{T}$

$\mu_{j,k,t}$ Total criticality at distribution region $j \in \mathcal{N}$ due to shortage of commodity k in time $t \in \mathcal{T}$

$\zeta_{j,B,k,t}$ Amount of bundle $B \in \mathcal{B}$ that is generated at distribution site $j \in \mathcal{N}$ by $k \in \mathcal{K}$ at time $t \in \mathcal{T}$

$\xi_{j,B,t}$ Total amount of bundle $B \in \mathcal{B}$ that is generated at distribution site $j \in \mathcal{N}$ at time $t \in \mathcal{T}$

z_1, z_2 Deviation variables for the goals of two objectives

Model

$$
\begin{aligned}
&\text{minimize} && \mathbf{P}_1 z_1 + \mathbf{P}_2 z_2 && && (2.26)\\
&\text{subject to} && \sum_{t\in\mathcal{T}}\sum_{j\in\mathcal{N}}\sum_{k\in\mathcal{K}} \mu_{j,k,t} - z_1 = 0 && && (2.27)\\
& && \sum_{t\in\mathcal{T}}\sum_{j\in\mathcal{N}}\sum_{r\in\mathcal{C}} \left(d^r_{j,t} - \chi^r_{j,B^r,t}\right) - z_2 = 0 && && (2.28)\\
& && \sum_{t\in\mathcal{T}} \sigma_{k,t} \le S_k && \forall k\in\mathcal{K} && (2.29)\\
& && \sum_{i\in\mathcal{M}} s_{i,k,t} - \sigma_{k,t} = 0 && \forall k\in\mathcal{K}, \forall t\in\mathcal{T} && (2.30)\\
& && I_{i,k,0} - s_{i,k,0} = 0 && \forall i\in\mathcal{M}, \forall k\in\mathcal{K} && (2.31)\\
& && I_{i,k,t-1} + s_{i,k,t} - \sum_{h\in\mathcal{H}}\sum_{j\in\mathcal{N}} x^h_{i,j,k,t} - I_{i,k,t} = 0 && \forall i\in\mathcal{M}, \forall k\in\mathcal{K}, \forall t\in\mathcal{T}, t\ge 1 && (2.32)\\
& && \sum_{k\in\mathcal{K}} I_{i,k,t} \le \kappa_i && \forall i\in\mathcal{M}, \forall t\in\mathcal{T} && (2.33)\\
& && \sum_{B\in\mathcal{B}_k} \zeta_{j,k,B,t} - \sum_{h\in\mathcal{H}}\sum_{i\in\mathcal{M}} x^h_{i,j,k,t} = 0 && \forall j\in\mathcal{N}, \forall k\in\mathcal{K}, \forall t\in\mathcal{T} && (2.34)\\
& && \xi_{j,B,t} - \zeta_{j,k,B,t} = 0 && \forall j\in\mathcal{N}, \forall B\in\mathcal{B}_k, \forall k\in\mathcal{K}, \forall t\in\mathcal{T} && (2.35)\\
& && J_{j,B,0} = 0 && \forall j\in\mathcal{N}, \forall B\in\mathcal{B} && (2.36)\\
& && J_{j,B,t} + \xi_{j,B,t} - \sum_{r\in\mathcal{C}} \chi^r_{j,B,t} - J_{j,B,t-1} = 0 && \forall j\in\mathcal{N}, \forall B\in\mathcal{B}, \forall t\in\mathcal{T}, t\ge 1 && (2.37)\\
& && d^{r''}_{j,1} = p_j && \alpha^{r''}_k = \tau_k + 1, \forall k\in\mathcal{K}, \forall j\in\mathcal{N} && (2.38)\\
& && d^r_{j,1} = 0 && \forall r\in\mathcal{R}, r\ne r'', \forall j\in\mathcal{N} && (2.39)\\
& && d^r_{j,t} - \sum_{\bar r\in\bar{\mathcal{R}}^{\bar B}}\sum_{\bar B\in\bar{\mathcal{B}}} \chi^{\bar r}_{j,\bar B,t-1} && &&\\
& && -(d^{r'}_{j,t-1} - \sum_{B'\in\mathcal{B}} \chi^{r'}_{j,B',t-1}) = 0 && \forall j\in\mathcal{N}, \forall r\in\mathcal{R}^B, \forall B\in\mathcal{B}, \forall t\in\mathcal{T}, t>1 && (2.40)\\
& && d^{\hat r}_{j,t} - (d^r_{j,t-1} - \sum_{B\in\mathcal{B}} \chi^r_{j,B,t-1}) = 0 && \forall j\in\mathcal{N}, \forall r\in\mathcal{R}/(\cup_B\mathcal{R}^B), \forall t\in\mathcal{T}, t>1 && (2.41)\\
& && d^r_{j,t} - \mu_{j,k,t} = 0 && \forall j\in\mathcal{N}, \forall r\in\mathcal{F}, \forall k\in\mathcal{K}, \forall t\in\mathcal{T}, t\ge 1 && (2.42)\\
& && \sum_{B\in B_k} \chi^r_{j,B,t} - d^r_{j,t} \le 0 && \forall j\in\mathcal{N}, \forall k\in\mathcal{K}, \forall r\in\mathcal{R}, \forall t\in\mathcal{T}, t\ge 1 && (2.43)\\
& && I_{i,k,t}, s_{i,k,t}, \sigma_{k,t}, x^h_{i,j,k,t}, z_1, z_2 \ge 0 && \forall i\in\mathcal{M}, \forall j\in\mathcal{N}, \forall k\in\mathcal{K}, \forall h\in\mathcal{H}, \forall t\in\mathcal{T} && (2.44)\\
& && d^r_{j,t}, \mu_{j,k,t}, \xi_{j,B,t}, \zeta_{j,k,B,t} \in \mathbb{Z}^+ && \forall j\in\mathcal{N}, \forall k\in\mathcal{K}, \forall B\in\mathcal{B}, \forall r\in\mathcal{R}, \forall t\in\mathcal{T} && (2.45)\\
& && y^h_{i,j,t}, \gamma^h_{i,j,t}, v^h_{i,t}, \varphi^h_t, g^h_{i,t}, \rho^h_{j,t} \in \mathbb{Z}^+ && \forall\, i\in\mathcal{M}, \forall\, j\in\mathcal{N}, \forall h\in\mathcal{H}, \forall\, t\in\mathcal{T} && (2.46)\\
& && \chi^r_{j,B,t} \in \mathbb{Z}^+ && \forall j\in\mathcal{N}, \forall B\in\mathcal{B}, \forall r\in\mathcal{C}, \forall t\in\mathcal{T} && (2.47)
\end{aligned}
$$

The two goals in the model are to minimize the overachivement of a target of zero criticality at priority one, and to minimize the overachievement of a target of zero destitution at priority two. The ordinal weights, $\mathbf{P}_1$ and $\mathbf{P}_2$, reflect the priorities of the two goals which are defined in the two goal constraints, namely, 2.27, and 2.28. Constraint 2.29 allocates total supply over time, and Constraint 2.30 allocates supply to supply sites in each time period. We note that Constraint 2.29 can be omitted when supplies are known for each time period, i.e. the variables $\sigma_{k,t}$ are parameters instead of variables. Constraints 2.31 and 2.32 enforce the conservation of flow of each commodity and tracks inventory at each supply site, in each time period. Constraint 2.33 enforces inventory capacity at supply sites. Constraints 2.34 and 2.35 create bundles of commodities flowing from all supply sites. Constraints 2.36 and 2.37 enforce conservation of flow of bundles at each distribution site, allocating bundles to populations in one of the relief states and tracking their inventory. Constraints 2.38 and 2.39 initialize the population at each distribution site to the first *destitute* state, $\tau_k + 1$, for each commodity. Constraints 2.40 - 2.42 track the progression of the population with respect to both time and relief state. Constraint 2.40 accumulates transitions into each state $r \in \mathcal{R}^B$ for all bundles B, namely population segments in (i) state $\bar{r}$ which are replenished with a bundle $B \in \mathcal{B}$ or its feasible subsets $\bar{B} \in \bar{\mathcal{B}}$; (ii) the population segment in state r' that are not replenished by any bundle. Each state $r \in \mathcal{R}^B$ can be transitioned into from states $\bar{r}$, when replenished by the commodities in specific subsets $\bar{B} \subseteq B$. The subsets, $\bar{B}$, of the bundle B that need to be taken into account must necessarily contain all the Type II commodities and can contain none or several of the Type I commodities. Constraint 2.41 moves the portion of the population that is not replenished in state $[\alpha_1^r, \ldots, \alpha_K^r]$ to a unique state $\hat{r}$ where $\alpha_k^{\hat{r}} = \alpha_k^r + 1$ if $\alpha_k^r > 0$, and $\alpha_k^{\hat{r}} = 0$ if $\alpha_k^r = 0$. Constraint 2.42, which is definitional, tracks the population in the *critical* states. Constraint 2.43 ensures that no supply is allocated to a relief state if it has a zero population. Finally, Constraint 2.44 - 2.47 specify non-negativity and integrality of the variables.

2.4.1 Illustrative examples for the multi-commodity case

In this section, we present two examples and depict the manner in which populations transition from state to state with respect to replenishment with commodities in bundles. In the examples, we illustrate the transition of segments of a population of 200 at a single distribution site over a planning horizon of 12 days. The first example considers three Type II commodities, and the second example considers one Type I and two Type II commodities. The model multi-commodity has been run for two objectives, i.e., destitution and criticality, separately.

Example 2.3 Three commodities of Type II with $\tau_1 = 2$, $\tau_2 = 3$, $\tau_3 = 4$ days-of-provision and $\theta_1 = 3$, $\theta_2 = 4$, $\theta_3 = 5$ days-of-destitution are considered. At the beginning of the planning horizon it is assumed that each commodity is available to satisfy 400 people, i.e., $S_1 = S_2 = S_3 = 400$.

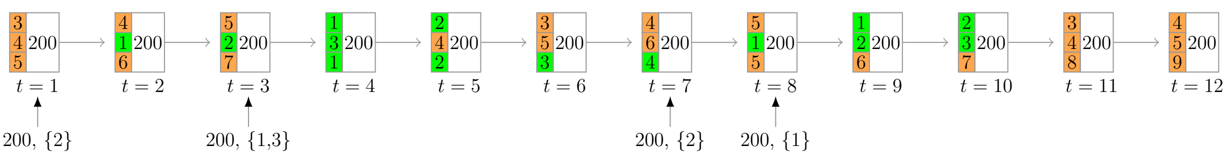


Figure 2.11: Relief state transition in Example 2.3. Criticality is minimized

The product bundle sets corresponding to three commodities are $B_1 = \{1\}$, $B_2 = \{2\}$, $B_3 = \{3\}$, $B_4 = \{1, 2\}$, $B_5 = \{1, 3\}$, $B_6 = \{2, 3\}$, $B_7 = \{1, 2, 3\}$. When minimizing total criticality, while total criticality is zero, total destitution becomes 3,400: 200 persons are destitute of the first commodity for 6 periods, of the second commodity for 4 periods, and of the third commodity for 7 periods. The transition of the population through relief states over time with respect to replenishments is shown in Figure 2.11.

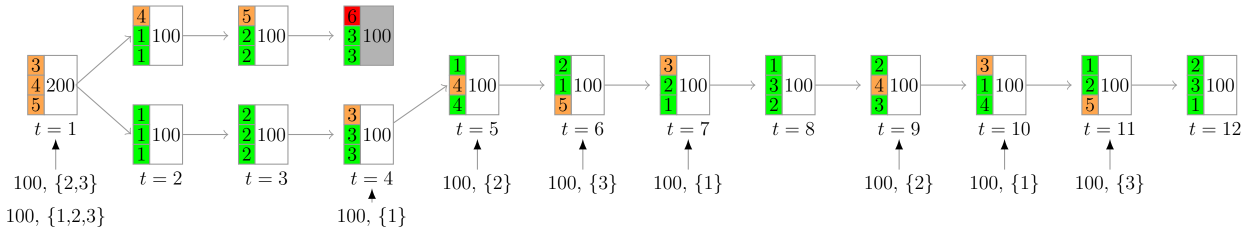


Figure 2.12: Relief state transition in Example 2.3. Destitution is minimized

Minimizing total destitution leads to total criticality of 100 by the deficiency of the first commodity, while total destitution becomes 300: 100 persons are destitute of the first commodity for the first three time periods (Figure 2.12). We note that, for zero destitution, and hence zero criticality, the minimum initial allocation of supply should be in the amounts of $S_1 = 800$, $S_2 = 600$, $S_3 = 800$.

Example 2.4 In this example, we consider one Type I commodity and two Type II commodities with $\tau_1 = 0$, $\tau_2 = 3$, $\tau_3 = 4$ days-of-provision and $\theta_1 = 13$, $\theta_2 = 4$, $\theta_3 = 5$ days-of-destitution, respectively. $\theta_1 = 13$ suggests that destitution of the Type I commodity, $k = 1$, does not lead to critical shortage. The initial allocation of supplies are $S_1 = 200$, $S_2 = 400$, and $S_3 = 400$.

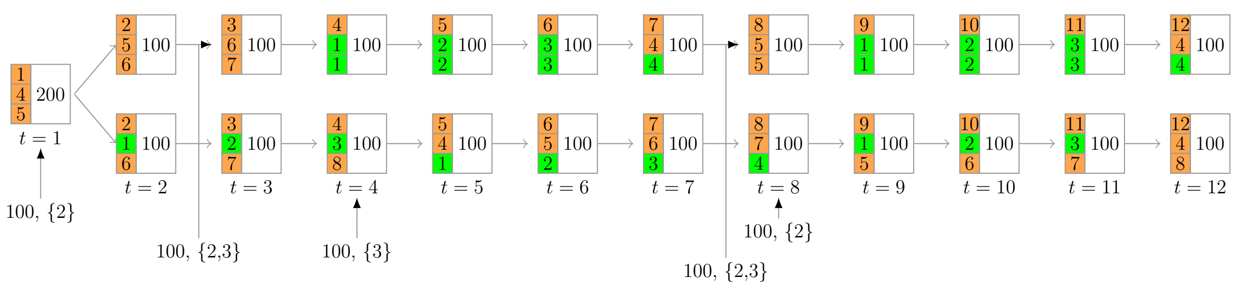


Figure 2.13: Relief state transition in Example 2.4. Criticality is minimized

As shown in Figure 2.13, minimizing criticality leads to zero criticality, while total destitution becomes 4,100: 200 persons are destitute of the commodity $k = 1$ for 12 periods; 100

persons are destitute of the commodity $k = 2$ for 8 periods; and, 100 persons are destitute of the commodity $k = 3$ for 9 periods.

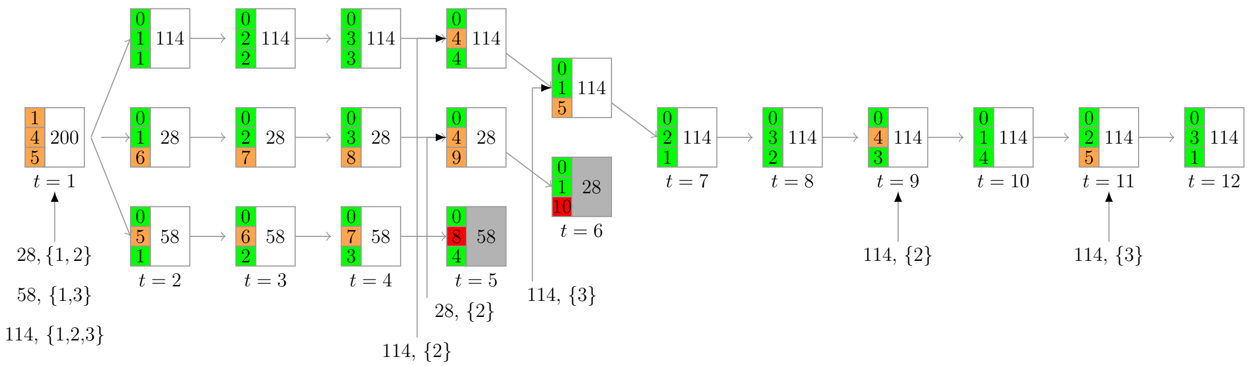


Figure 2.14: Relief state transition in Example 2.4. Destitution is minimized

Minimizing total destitution causes a total criticality of 86 (Figure 2.14): 58 persons face critical shortage by the deficiency of the commodity $k = 2$ in period 5; 28 persons are critical by the deficiency of the commodity $k = 3$ in period 6. Total destitution is 372: 58 persons are destitute of commodity $k = 2$ for the first four periods; 28 persons are destitute by the deficiency of commodity $k = 3$ for the first five periods of the planning horizon.

2.5 Multi-period Multi-vehicle Model

In this section, we present the model that we develop for the two-echelon network in which commodities are shipped from supply sites to distribution sites in vehicles of differing capacities over a planning horizon. The model discussed here is an expansion of the model presented in Section 2.4 with additional vehicle dispatching constraints that allow us to expose the impact of delays in the availability of vehicles, along with the impact of delays in the availability of supplies and handling capacity. The commodities that are included in an application of the model would be chosen to reflect need in specific population segments, such as injured, and also extenuating factors such as weather. The planning horizon is defined in days, where each day is further divided into time slots to better reflect the time windows during which vehicles transport commodities. Vehicles may be available at the beginning of the planning horizon or become available gradually. Vehicles may return, after delivery, to any of the supply sites for subsequent trips. Vehicles that are not deployed in any time period may remain at either a supply or a distribution site. Supplies are bundled at distribution sites. We assume that bundles are distributed to population segments in the time slot that a vehicle arrives at a distribution site. The model tracks the states of specific segments of the population with respect to replenishment by different bundles of commodities across the planning horizon and a multi-criteria objective captures the extents of destitution and criticality in populations over the planning horizon. Before presenting the model, the index sets, parameters, and variables are defined.

Index sets

$\mathcal{M}$ Set of supply sites, $\{1, \ldots, M\}$

$\mathcal{N}$ Set of distribution sites, $\{1, \ldots, N\}$

$\mathcal{T}$ Set of days of planning horizon, $\{1, \ldots, T\}$

$\mathcal{H}$ Set of time slots in each day $\{0, \ldots, H-1\}$

$\mathcal{L}$ Set of vehicle types $\{1, \ldots, L\}$

$\mathcal{K}$ Set of relief commodities $\{1, \ldots, K\}$

$\mathcal{K}^1$ Subset of relief commodities of Type 1, $\subseteq \mathcal{K}$

$\mathcal{K}^2$ Subset of relief commodities of Type 2, $\subseteq \mathcal{K}$

B Subset of commodities that a population is replenished with.

$\mathcal{B}$ Superset of commodity bundles, $\{B_1, \ldots, B_{2^K-1}\}$

$\bar{\mathcal{B}}_k$ Superset of bundles of commodities that include commodity k

$\bar{B}$ Subset of bundles of commodities in bundle $B \in \mathcal{B}$, $\{\bar{B} \subseteq B \mid \bar{B} \supset (B \cap \mathcal{K}^2), \forall k \in \mathcal{K}^2; \bar{B} \supset (B \cap \mathcal{K}^1), \exists k \in \mathcal{K}^1\}$

$\bar{\mathcal{B}}$ Superset of subsets of bundles of commodities in $B \in \mathcal{B}$, $\{\bar{B} \mid \forall \bar{B} \subseteq B\}$

$\mathcal{R}$ Set of states, r

α^r Relief state r, a vector of relief states with respect to each commodity, $[\alpha^r_1, \ldots, \alpha^r_K]$, where α^r_k can be $0, \ldots, \tau_k, \tau_k + 1, \ldots, \tau_k + \theta_k, \tau_k + \theta_k + 1$ if $k \in \mathcal{K}^1$ or can be $1, 2, \tau_k, \tau_k + 1, \ldots, \tau_k + \theta_k, \tau_k + \theta_k + 1$ if $k \in \mathcal{K}^2$

$\mathcal{A}$ Subset of *provided* states $r \in \mathcal{R}$ where $\forall k \in \mathcal{K}^1, \alpha^r_k = 0$ and, $\forall k \in \mathcal{K}^2, 1 \leq \alpha^r_k \leq \tau_k$

$\mathcal{C}$ Subset of *destitute* states $r \in \mathcal{R}$ where $\exists k \in \mathcal{K} \mid \tau_k < \alpha^r_k \leq \tau_k + \theta_k$

$\mathcal{F}$ Subset of *critical* states $r \in \mathcal{R}$ where $\exists k \in \mathcal{K} \mid \alpha^r_k = \tau_k + \theta_k + 1$

$\mathcal{R}^B$ Subset of states $r \in \mathcal{R}$ that the population can transition into by receiving a bundle $B \in \mathcal{B}$ or its subset $\bar{B} \subseteq B$ in the previous time period, where

$$
\begin{array}{ll}
\alpha^r_k = 1 & \forall k \in \mathcal{K}^2 \cap B, \\
1 < \alpha^r_k \leq \tau_k + \theta_k + 1 & \forall k \in \mathcal{K}^2 / (B \cap \mathcal{K}^2), \\
\alpha^r_k = 0 & \forall k \in \mathcal{K}^1 \cap B, \\
1 < \alpha^r_k \leq \theta_k + 1 & \forall k \in \mathcal{K}^1 / (B \cap \mathcal{K}^1).
\end{array}
$$

$\bar{\mathcal{R}}^{\bar{\mathcal{B}}}$ Subset of states $\bar{r} \in \mathcal{R}$ that the population can transition from by receiving a bundle $B \in \mathcal{B}$ or its subset $\bar{B} \subseteq B$ in the previous time period, where

$$\begin{array}{ll} \alpha_k^{\bar{r}} = 0 & \forall k \in (\mathcal{K}^1 \cap B)/(\mathcal{K}^1 \cap \bar{B}), \\ 0 < \alpha_k^{\bar{r}} \leq \theta_k & \forall k \in \mathcal{K}^1 \cap \bar{B}, \\ \tau_k < \alpha_k^{\bar{r}} \leq \tau_k + \theta_k & \forall k \in \mathcal{K}^2 \cap B, \\ \alpha_k^{\bar{r}} = \alpha_k^r - 1 & \forall k \in \mathcal{K}/B. \end{array}$$

$\hat{r}$ Relief state that a population segment in state r transitions if not replenished $\alpha_k^{\hat{r}} = \alpha_k^r + 1, \alpha_k^r > 0, \forall k \in K, \forall r \in \mathcal{R}$

B^r Bundle of commodities that allows a population segment in r to transition to a provided state

r' State of a population segment that transitions to state r if not replenished $\alpha_k^{r'} = \alpha_k^r - 1, \alpha_k^{r'} > 0, \forall k \in K, \forall r \in \mathcal{R}$

Parameters

S_k Total available supply of commodity $k \in \mathcal{K}$ at the beginning of planning horizon

p_j Population at distribution region $j \in \mathcal{N}$

κ_i Storage capacity of supplier site $i \in \mathcal{M}$ in lbs/day

t_{ij} Travel time (hrs) from $i \in \mathcal{M}$ to $j \in \mathcal{N}$

V_ℓ Number of available vehicles at the beginning of planning horizon $\ell \in \mathcal{L}$

W_ℓ Vehicle capacity in lbs, $\ell \in \mathcal{L}$

θ_k Days-of-destitution $k \in \mathcal{K}$

τ_k Days-of-provision; $\tau_k = 0, \forall k \in K^1$

α_k^0 Initial state of replenishment cycle for commodity $k \in \mathcal{K}$, defined to be $\alpha_k^0 = 0,\ \forall k \in \mathcal{K}_1; \alpha_k^0 = 1,\ \forall k \in \mathcal{K}_2$

$\mathbf{P}_1, \mathbf{P}_2$ Preemptive priorities corresponding to two objectives

Ω_i Handling capacity with respect to number of vehicles at $i \in \mathcal{M}$

Variables

$\sigma_{k,t}$ Total available supply of commodity $k \in \mathcal{K}$ at time $t \in \mathcal{T}$

$s_{i,k,t}$ Available supply of commodity $k \in \mathcal{K}$ at supplier site $i \in \mathcal{M}$ at time $t \in \mathcal{T}$

$I_{i,k,t}$ Inventory for commodity $k \in \mathcal{K}$ at supplier site $i \in \mathcal{M}$ at time $t \in \mathcal{T}$

$x^h_{i,j,k,t}$ Amount of flow of commodity $k \in \mathcal{K}$ from $i \in \mathcal{M}$ to $j \in \mathcal{N}$ at time $t \in \mathcal{T}$ in time slot $h \in \mathcal{H}$ which is specified as the number of people it can satisfy

$\chi^r_{j,B,t}$ Number of people that bundle $B \in \mathcal{B}$ can satisfy in a population group which is in a *destitute* state $r \in \mathcal{C}$ at distribution region $j \in \mathcal{N}$ at time $t \in \mathcal{T}$

$d^r_{j,t}$ Number of people in a population group in a relief state $r \in \mathcal{R}$ at distribution region $j \in \mathcal{N}$ at time $t \in \mathcal{T}$

$\mu_{j,k,t}$ Total criticality at distribution region $j \in \mathcal{N}$ due to shortage of commodity k in time $t \in \mathcal{T}$

$\zeta_{j,B,k,t}$ Amount of bundle $B \in \mathcal{B}$ that is generated at distribution site $j \in \mathcal{N}$ by $k \in \mathcal{K}$ at time $t \in \mathcal{T}$

$\xi_{j,B,t}$ Total amount of bundle $B \in \mathcal{B}$ that is generated at distribution site $j \in \mathcal{N}$ at time $t \in \mathcal{T}$

$\varphi_{\ell,t}$ Total number of available vehicles of type $\ell \in \mathcal{L}$ at time $t \in \mathcal{T}$

$v^h_{i,\ell,t}$ Number of vehicles of type $\ell \in \mathcal{L}$, dispatched to demand site $i \in \mathcal{M}$, in time slot $h \in \mathcal{H}$, on day $t \in \mathcal{T}$

$y^h_{i,j,\ell,t}$ Number of vehicles of type $\ell \in \mathcal{L}$ en route to distribution site $j \in \mathcal{N}$, from demand site $i \in \mathcal{M}$, in time slot $h \in \mathcal{H}$, on day $t \in \mathcal{T}$

$\gamma^h_{j,i,\ell,t}$ Number of vehicles of type $\ell \in \mathcal{L}$, en route from distribution site $j \in \mathcal{N}$, to demand site $i \in \mathcal{M}$, in time slot $h \in \mathcal{H}$, on day $t \in \mathcal{T}$

$g^h_{i,\ell,t}$ Number of idle vehicles of type $\ell \in \mathcal{L}$, at demand site $i \in \mathcal{M}$, in time slot $h \in \mathcal{H}$, on day $t \in \mathcal{T}$

$\rho^h_{j,\ell,t}$ Number of idle vehicles of type $\ell \in \mathcal{L}$, at distribution site $j \in \mathcal{N}$, in time slot $h \in \mathcal{H}$ on day $t \in \mathcal{T}$

z_1, z_2 Deviation variables for the goals of two objectives

Model

$$\text{minimize} \quad \mathbf{P}_1 z_1 + \mathbf{P}_2 z_2 \tag{2.48}$$

$$\text{subject to} \quad \sum_{t\in\mathcal{T}}\sum_{j\in\mathcal{N}}\sum_{k\in\mathcal{K}} \mu_{j,k,t} - z_1 = 0 \tag{2.49}$$

$$\sum_{t\in\mathcal{T}}\sum_{j\in\mathcal{N}}\sum_{r\in\mathcal{C}} \left(d^r_{j,t} - \chi^r_{j,B^r,t}\right) - z_2 = 0 \tag{2.50}$$

$$\sum_{t\in\mathcal{T}} \sigma_{k,t} \leq S_k \qquad \forall k \in \mathcal{K} \tag{2.51}$$

$$\sum_{i\in\mathcal{M}} s_{i,k,t} - \sigma_{k,t} = 0 \qquad \forall k \in \mathcal{K}, \forall t \in \mathcal{T} \tag{2.52}$$

$$I_{i,k,0} - s_{i,k,0} = 0 \qquad \forall i \in \mathcal{M}, \forall k \in \mathcal{K} \tag{2.53}$$

$$I_{i,k,t-1} + s_{i,k,t} - \sum_{h\in\mathcal{H}}\sum_{j\in\mathcal{N}} x^h_{i,j,k,t} - I_{i,k,t} = 0 \qquad \forall i \in \mathcal{M}, \forall k \in \mathcal{K}, \forall t \in \mathcal{T}, t \geq 1 \tag{2.54}$$

$$\sum_{k\in\mathcal{K}} I_{i,k,t} \leq \kappa_i \qquad \forall i \in \mathcal{M}, \forall t \in \mathcal{T} \tag{2.55}$$

$$\sum_{B\in\mathcal{B}_k} \zeta_{j,k,B,t} - \sum_{h\in\mathcal{H}}\sum_{i\in\mathcal{M}} x^h_{i,j,k,t} = 0 \qquad \forall j \in \mathcal{N}, \forall k \in \mathcal{K}, \forall t \in \mathcal{T} \tag{2.56}$$

$$\xi_{j,B,t} - \zeta_{j,k,B,t} = 0 \qquad \forall j \in \mathcal{N}, \forall B \in \mathcal{B}_k, \forall k \in \mathcal{K}, \forall t \in \mathcal{T} \tag{2.57}$$

$$J_{j,B,0} = 0 \qquad \forall j \in \mathcal{N}, \forall B \in \mathcal{B} \tag{2.58}$$

$$J_{j,B,t} + \xi_{j,B,t} - \sum_{r\in\mathcal{C}} \chi^r_{j,B,t} - J_{j,B,t-1} = 0 \qquad \forall j \in \mathcal{N}, \forall B \in \mathcal{B}, \forall t \in \mathcal{T}, t \geq 1 \tag{2.59}$$

$$d^{r''}_{j,1} = p_j \qquad \alpha^{r''}_k = \tau_k + 1, \forall k \in \mathcal{K}, \forall j \in \mathcal{N} \tag{2.60}$$

$$d^r_{j,1} = 0 \qquad \forall r \in \mathcal{R}, r \neq r'', \forall j \in \mathcal{N} \tag{2.61}$$

$$\begin{aligned} d^r_{j,t} &- \sum_{\bar{r}\in\bar{\mathcal{R}}^{\bar{B}}}\sum_{\bar{B}\in\bar{\mathcal{B}}} \chi^{\bar{r}}_{j,\bar{B},t-1} \\ &-(d^{r'}_{j,t-1} - \sum_{B'\in\mathcal{B}} \chi^{r'}_{j,B',t-1}) = 0 \qquad \forall j \in \mathcal{N}, \forall r \in \mathcal{R}^B, \forall B \in \mathcal{B}, \forall t \in \mathcal{T}, t > 1 \end{aligned} \tag{2.62}$$

$$d^{\hat{r}}_{j,t} - (d^r_{j,t-1} - \sum_{B\in\mathcal{B}} \chi^r_{j,B,t-1}) = 0 \qquad \forall j \in \mathcal{N}, \forall r \in \mathcal{R}/(\cup_B \mathcal{R}^B), \forall t \in \mathcal{T}, t > 1 \tag{2.63}$$

$$d^r_{j,t} - \mu_{j,k,t} = 0 \qquad \forall j \in \mathcal{N}, \forall r \in \mathcal{F}, \forall k \in \mathcal{K}, \forall t \in \mathcal{T}, t \geq 1 \tag{2.64}$$

$$\sum_{B\in B_k} \chi^r_{j,B,t} - d^r_{j,t} \leq 0 \qquad \forall j \in \mathcal{N}, \forall k \in \mathcal{K}, \forall r \in \mathcal{R}, \forall t \in \mathcal{T}, t \geq 1 \tag{2.65}$$

$$\sum_{t\in\mathcal{T}} \varphi_{\ell,t} \leq V_\ell \qquad \forall\ \ell \in \mathcal{L} \tag{2.66}$$

$$\sum_{i\in\mathcal{M}} v^0_{i,\ell,t} - \varphi_{\ell,t} \leq 0 \qquad \forall\ \ell \in \mathcal{L}, \forall\ t \in \mathcal{T} \tag{2.67}$$

$$g^0_{i,\ell,1} = 0 \qquad \forall\ i \in \mathcal{M}, \forall\ \ell \in \mathcal{L} \tag{2.68}$$

$$\rho^0_{j,\ell,1} = 0 \qquad \forall\ j \in \mathcal{N}, \forall\ \ell \in \mathcal{L} \tag{2.69}$$

$$g^{(h-1) \bmod H}_{i,\ell,t+\lfloor (h-1)/H \rfloor} + \sum_{j\in\mathcal{N}} \gamma^{(h-t_{ji}) \bmod H}_{j,i,\ell,t+\lfloor (h-t_{ji})/H \rfloor}$$

$$+v_{i,\ell,t}^{h} - g_{i,\ell,t}^{h} - \sum_{j\in\mathcal{N}} y_{i,j,\ell,t}^{h} = 0 \qquad \forall\, i \in \mathcal{M},\, \forall\, t \in \mathcal{T}, \forall\, h \in \mathcal{H}, \forall\, \ell \in \mathcal{L} \tag{2.70}$$

$$\rho_{j,\ell,t+\lfloor (h-1)/H \rfloor}^{(h-1) \bmod H} + \sum_{i\in\mathcal{M}} y_{i,j,\ell,t+\lfloor (h-t_{ij})/H \rfloor}^{(h-t_{ij}) \bmod H}$$

$$-\rho_{j,\ell,t}^{h} - \sum_{i\in\mathcal{M}} \gamma_{j,i,\ell,t}^{h} = 0 \qquad \forall\, j \in \mathcal{N},\, \forall\, t \in \mathcal{T}, \forall\, h \in \mathcal{H}, \forall\, \ell \in \mathcal{L} \tag{2.71}$$

$$\sum_{\ell\in\mathcal{L}} W_\ell y_{i,j,\ell,t}^{h} - \sum_{k\in\mathcal{K}} w_k x_{i,j,k,t}^{h} \geq 0 \qquad \forall\, i \in \mathcal{M},\, \forall\, j \in \mathcal{N}, \forall\, h \in \mathcal{H},\, t \in \mathcal{T} \tag{2.72}$$

$$\sum_{j\in\mathcal{N}} \sum_{l\in\mathcal{L}} y_{i,j,\ell,t}^{h} \leq \Omega_i \qquad \forall i \in \mathcal{M}, \forall t \in \mathcal{T}, \forall h \in \mathcal{H} \tag{2.73}$$

$$I_{i,k,t}, s_{i,k,t}, \sigma_{k,t}, x_{i,j,k,t}^{h}, z_1, z_2 \geq 0 \qquad \forall i \in \mathcal{M}, \forall j \in \mathcal{N}, \forall k \in \mathcal{K}, \forall h \in \mathcal{H}, \forall t \in \mathcal{T} \tag{2.74}$$

$$d_{j,t}^{r}, \mu_{j,k,t}, \xi_{j,B,t}, \zeta_{j,k,B,t} \in \mathbb{Z}^+ \qquad \forall j \in \mathcal{N}, \forall k \in \mathcal{K}, \forall B \in \mathcal{B}, \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \tag{2.75}$$

$$y_{i,j,t}^{h}, \gamma_{i,j,t}^{h}, v_{i,t}^{h}, \varphi_t^{h}, g_{i,t}^{h}, \rho_{j,t}^{h} \in \mathbb{Z}^+ \qquad \forall\, i \in \mathcal{M},\, \forall\, j \in \mathcal{N}, \forall h \in \mathcal{H}, \forall\, t \in \mathcal{T} \tag{2.76}$$

$$\chi_{j,B,t}^{r} \in \mathbb{Z}^+ \qquad \forall j \in \mathcal{N}, \forall B \in \mathcal{B}, \forall r \in \mathcal{C}, \forall t \in \mathcal{T} \tag{2.77}$$

The two goals in the model are to minimize the overachivement of a target of zero criticality at priority one, and to minimize the overachievement of a target of zero destitution at priority two. The ordinal weights, $\mathbf{P}_1$ and $\mathbf{P}_2$, reflect the priorities of the two goals which are defined in the two goal constraints, namely, 2.49, and 2.50. Constraint 2.51 allocates total supply over time, and Constraint 2.52 allocates supply to supply sites in each time period. We note that Constraint 2.51 can be omitted when supplies are known for each time period, i.e. the variables $\sigma_{k,t}$ are parameters instead of variables. Constraints 2.53 and 2.54 enforce the conservation of flow of each commodity and tracks inventory at each supply site, in each time period. Constraint 2.55 enforces inventory capacity at supply sites. Constraints 2.56 and 2.57 create bundles of commodities flowing from all supply sites. Constraints 2.58 and 2.59 enforce conservation of flow of bundles at each distribution site, allocating bundles to populations in one of the relief states and tracking their inventory. Constraints 2.60 and 2.61 initialize the population at each distribution site to the first *destitute* state, $\tau_k + 1$, for each commodity. Constraints 2.62 - 2.64 track the progression of the population with respect to both time and relief state. Constraint 2.62 accumulates transitions into each state

$r \in \mathcal{R}^B$ for all bundles B, namely population segments in (i) state $\bar{r}$ which are replenished with a bundle $B \in \mathcal{B}$ or its feasible subsets $\bar{B} \in \bar{\mathcal{B}}$; (ii) the population segment in state r' that are not replenished by any bundle. Each state $r \in \mathcal{R}^B$ can be transitioned into from states $\bar{r}$, when replenished by the commodities in specific subsets $\bar{B} \subseteq B$. The subsets, $\bar{B}$, of the bundle B that need to be taken into account must necessarily contain all the Type II commodities and can contain none or several of the Type I commodities. Constraint 2.63 moves the portion of the population that is not replenished in state $[\alpha_1^r, \ldots, \alpha_K^r]$ to a unique state $\hat{r}$ where $\alpha_k^{\hat{r}} = \alpha_k^r + 1$ if $\alpha_k^r > 0$, and $\alpha_k^{\hat{r}} = 0$ if $\alpha_k^r = 0$. Constraint 2.64, which is definitional, tracks the population in the *critical* states. Constraint 2.65 ensures that no supply is allocated to a relief state if it has a zero population.

The structural constraints that specify the movement of vehicles begin with Constraint 2.66. Constraints 2.66 and 2.67 allocate vehicles over the planning horizon to specific time periods and to supplier sites. Constraint 2.68 initializes the vehicle inventory at each supply site. Constraint 2.69 initializes the vehicle inventory at the demand sites. Constraints 2.70 and 2.71 enforce the conservation of flow and track vehicle inventory at, respectively, each supply site and demand site in each time slot. Constraint 2.72 ensures that the vehicle capacity in any shipment is not exceeded. Constraint 2.73 ensures that the handling capacity at each supply site is not violated. Finally, Constraint 2.74 - 2.77 specify non-negativity and integrality of the variables.

2.5.1 Model Alterations

As presented, the model minimizes destitution and criticality for given levels of supply and vehicle availability over time. However, for our purposes, it is necessary to make four slight modifications to reveal impacts of supply, and vehicle and handling capacity delays. These modifications are enumerated below:

1. In order to determine the required minimum amount of supplies, $\mathbf{S}_k, k = 1, \ldots, K$ and minimum number of pre-allocated vehicles for zero destitution and criticality, the parameters, V_ℓ and S_k are converted to variables. The destitution and criticality levels are forced to zero by setting the variables z_1 and z_2, in Constraint 2.49 and Constraint 2.50, respectively, to zero. The objective is altered to min $\sum_{k \in \mathcal{K}} S_k$ and the optimal values of these variables are retained. Subsequently, these levels of supply are used to determine the minimum number of vehicles, $\mathbf{V}_\ell$, by altering the objective to min $\sum_{\ell \in \mathcal{L}} V_\ell$.

2. Delays in availability of supply, the total amounts of which are $\mathbf{S}_k, k = 1, \ldots, K$, are effected by imposing bounds on the variables that specify the supply of each commodity in each time period, $\sigma_{k,t}$.

3. Delays in the availability of vehicles, the total amounts of which are $\mathbf{V}_\ell$, are effected by imposing bounds on the variables $\varphi_{\ell,t}$, which specify the availability of vehicles over time.

4. Delays in handling capacity are effected by discounting the capacity Ω_i in Constraint 2.73 by an ascribed percentage in each time period.

2.6 Planning Relief Replenishment for Istanbul

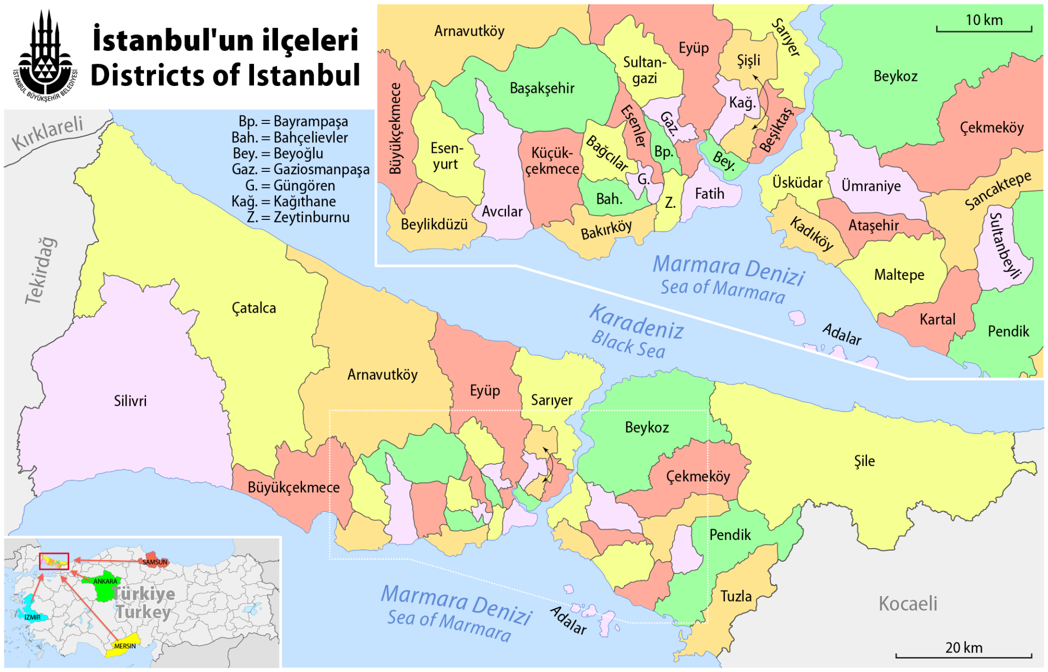


Figure 2.15: Districts of Istanbul

In this section, we present the computational study for our examination of the impact of delays in availability of supplies in initial time periods, delayed availability of vehicles, and compromised handling capacity at supply sites on the destitution of affected populations. We examine four scenarios of damage that correspond to the four fault scenarios (JICA et al., 2002) of the North Anatolian Fault (NAF) lines under the Marmara Sea, as shown in Figure 2.16. The fault was impacted on the western side during the 1912 earthquake, and on the eastern side during the 1999 Kocaeli Earthquake. Of the four scenarios, based on the characteristics of the fault, Scenarios A, B, D assume a partial break with magnitudes of, respectively, 7.5, 7.4, and 6.9m whereas Scenario C, of magnitude 7.7, assumes a break in the entire 170km section of NAF. Scenario A is documented to be the most probable model of the four scenarios, impacting a 120km long section from west of the 1999 Izmit earthquake fault to Silivri, based on the observation that seismic activity has progressed to the west in recent years. Scenario B impacts a 110km section of the fault from the eastern part of the 1912 Murefte-Sarkoy earthquake fault to Bakirkoy. Scenario C, the worst-case scenario, assumes a simultaneous break of the entire 170km NAF. However, this is less probable since there has been no evidence of a simultaneous break of the entire section. Scenario D impacts the continuous fault north of the Marmara Sea, i.e. the the northern slope of the Cinarcik Basin.

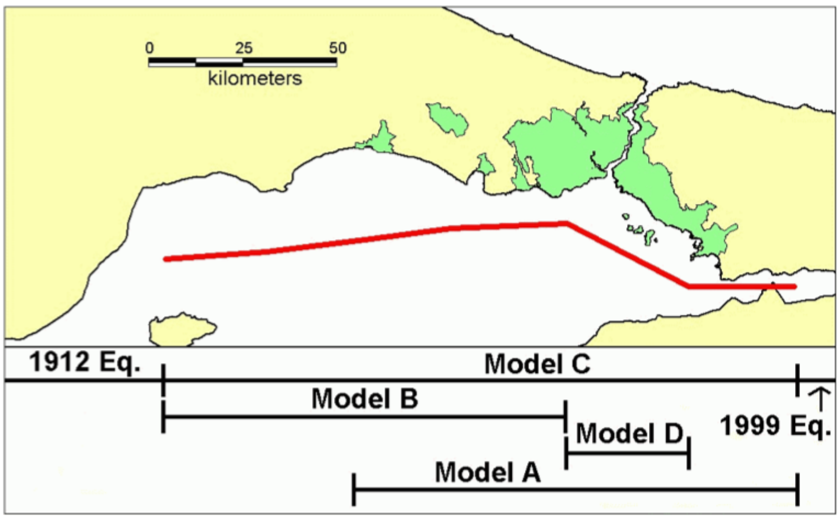


Figure 2.16: Fault Scenarios for Istanbul (JICA et al., 2002)

Estimates of damage in the thirty districts of Istanbul for the four scenarios in the JICA report are based on computations on seismic motion distribution. Patterns of damage for Scenario A and D are similar due to the similarity in the distribution of peak ground acceleration for the two. The same is true for Scenarios B and C, which impact the European side of Istanbul. The JICA report includes, for all four scenarios, the numbers of heavily, moderately, and partially damaged buildings. It also includes for Scenario C (pictorially represented in Figure 2.1), the worst-case scenario, estimates of the number of affected people, the number of deaths, slightly and heavily injured people, number of refugees, and extent of damage in infrastructure (e.g. road networks, bridges, gas, electricity, water and sewage, and telecommunication networks). For the other three scenarios, we compute the number of persons affected for each district using the average number of persons per building factored by, the number of heavily damaged buildings, fifty percent of moderately damaged buildings, and ten percent of partially damaged buildings.†

Table 2.1: Days-of-Provision and Days-of-Destitution for Six Commodities

	Commodity					
	Tents	Water	Food	Toiletries	Medical kits	Heating Equipment
Days-of-provision, τ_k	0	3	5	6	5	0
Days-of-destitution, θ_k	†	4	7	†	6	2
Weight in lbs, w_k	25	33	3	19	3	25

†For Type I commodities, the days-of-destitution is larger than the number of days in the planning horizon.

For each scenario, we assume that the supply sites used for distribution of supplies to the thirty districts of Istanbul are among the seven largest harbors in Turkey that are controlled by The General Directorate of Turkish State Railways Ports Department.‡ These ports are the most fundamental hubs of the main traffic network of Turkey, which includes highways, airports, and harbor facilities, and serve to connect people and goods coming from all around the world. The storage and handling capacities of these ports that are used in our computations are also given in the JICA report. For the deployment of vehicles, we assume that the fourteen more severely affected districts can be replenished only by smaller capacity vehicles; The other sixteen districts can be served by large vehicles. Further, we consider provision of different subsets of the commodities summarized in Table 2.1 that are required for three differently affected subgroups of populations.

†The total number of affected persons in Scenario C is 1,489,800. The numbers computed for scenarios A, B, and D are, respectively, 1,252,300, 1,044,900, 923,700.

‡Haydarpasa, Derince, Bandirma, Izmir, Samsun, Mersin, Iskenderun

1. *Subgroup Injured* Bundling of tents (Type I), heating equipment (Type I), and medical kits (Type II) for supplying injured populations of a particular earthquake scenario.

2. *Subgroup Non-injured* Bundling of tents (Type I), food (Type II), and water (Type II) for supplying non-injured populations of a particular earthquake scenario.

3. *Subgroup All* Bundling of food (Type II), water (Type II), and toiletries (Type II) for supplying the entire affected population of a particular earthquake scenario.

Table 2.2: Required Vehicles and Supplies for Zero criticality and destitution

		Supply Amounts			Vehicles			Trips		
Scenario	Population	I	II	III	Large	Small	Total	Total	/vehicle	%Day 1
iA	115250	115250	115250	230500	127	309	436	982	2.25	89
iB	95000	95000	95000	190000	109	248	357	834	2.37	85
iC	135100	135100	135100	270200	148	362	510	1153	2.26	88
iD	83700	83700	83700	167400	90	230	320	732	2.29	87
nA	1252300	1252300	3756900	2504600	1431	3997	5428	23308	4.29	47
nB	1044900	1044900	3134700	2089800	1228	3279	4507	20607	4.57	48
nC	1354700	1354700	4064100	2709400	1561	4300	5861	28258	4.82	41
nD	923700	923700	2771100	1847400	1049	2962	4011	17263	4.30	46
aA	1367550	2735100	4102650	2735100	1416	3920	5336	29778	5.58	36
aB	1139900	2279800	3419700	2279800	1217	3209	4426	24422	5.52	36
aC	1489800	2979600	4469400	2979600	1557	4250	5807	30791	5.30	38
aD	1007400	2014800	3022200	2014800	1035	2906	3941	28737	7.29	27

2.6.1 Baseline for required supplies and transport capacity

To determine a baseline for required supplies and transport capacity, we determine the minimum number of vehicles and supplies required for zero destitution and criticality using the model in Subsection 2.5 for twelve scenarios: For each of the four scenarios, A - D, we create three instances using the three above subgroups of differently affected populations.

Table 2.2 reports for each instance, the total affected population, in column 2, the required amounts of supply, in columns 3-5, the number of large, small and total vehicles in columns 6-8, and the total trips, trips per vehicle and percentage of trips completed on the first day of the planning horizon in columns 9-11. Each instance is identified by the scenario (A, B, C,

D) and the type of subgroup ('i' for subgroup Injured, 'n' for subgroup Non-injured, and 'a' for subgroup All). We see that the required amounts of Type I commodities are exactly the number persons affected since there are no subsequent replenishments. Further, the number of units of Type II commodities are a multiple, dictated by the number of replenishments, of the number of persons. With $\tau_2 = 3$ days-of-provision, water needs to be replenished every four days, and with $\tau_3 = 5$ days-of-provision, food every six days. For example, for Scenario nC with a population of 1,354,700, exactly that many units of the first commodity, tents, are required; three times as many units of the second commodity, water; and, twice as many units of the third commodity, food. Thus we can conclude that to ensure zero destitution and criticality using the minimum required amounts of supply, replenishments are made only for populations segments that are at the end of provided supplies and no earlier.

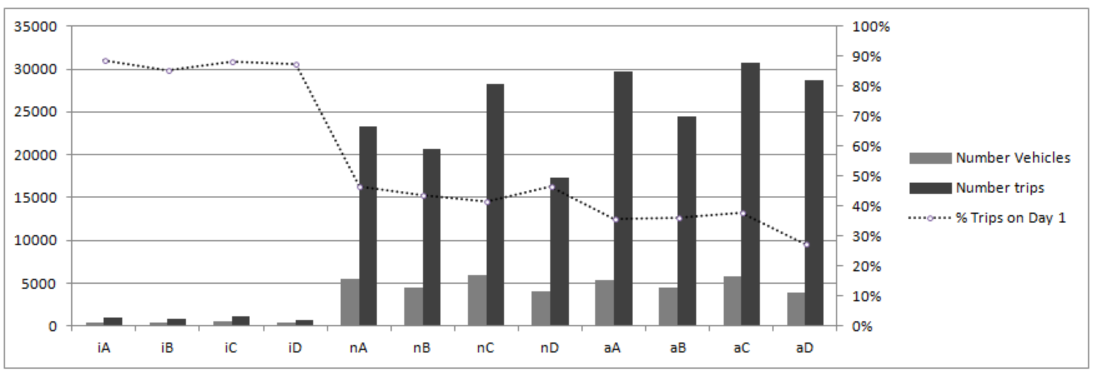


Figure 2.17: Vehicle Requirements for Twelve Scenarios

The number of required vehicles are a function not only of the associated weight that is transported but also of capacity of the vehicle that can service a district, i.e. distribution site. For instance nC, a total of 5,861 vehicles are used, of which 1,561 are large and 4,300 are small. Fewer large vehicles are required because the total population in the sixteen districts that can be served by large vehicles is 509,800 whereas that in the fourteen districts served by small vehicles is 844,900. We also see that for this instance the vehicles make, on average more than four trips, and that 41% of the trips are completed on the first day. In Figure 2.17, we pictorially represent the number of vehicles, number of trips, and percent trips on the first day for the twelve scenarios. The number of trips, as well as the number of vehicles, is partly related to the size of the population which implies the total weight that needs to be transported. The associated weight of the mix of Type I and Type II commodities explains the trips per vehicle and the percent trips on the first day. For the four instances for the injured population subgroup, we see that the brunt of the weight is in Type I commodities which do not require subsequent replenishment. As such, a larger percentage of the trips are required to distribute Type I commodities on the first day to avoid destitution. Further, the number of trips is much smaller because the type II commodities require much less weight.

2.6.2 Impacts of delays

To see the impact of delays in the (i) availability of supplies, (ii) availability of vehicles, and (iii) fully established handling capacity, we focus on the worst-case scenario, namely Scenario C. For each of the three potential causes, two levels of delay are considered in a total of seven combinations for each of the three populations subgroups, thereby leading to 21 additional model instances. For these instances, the model is altered to reflect the type of restriction and then the multi-criteria objective model is solved with criticality being minimized at priority one and destitution at priority two.

The two levels of delay in supplies are encapsulated by the values ascribed to supply availability over time, which is reflected in the model by the variable $\sigma_{k,t}$. Different proportions of the total supply required for zero criticality and destitution obtained in the base instance are imposed. In the first instance, 50% of the total supply is available in the initial time period, with 25% becoming available in each of periods 1 and 2. The second instance is more restrictive, with 25% available in the initial time period and 25% becoming available in each of periods 1, 2, and 3.

The delays in availability of vehicles is reflected in the percentage of the total number of required vehicles that become available over time, reflected in the parameters $\varphi_{\ell,t}$. In the lower level delay, 25% of the required number of vehicles is initially available. Another 25% become available in the first period and 50% in the second period. In the second, more restrictive, instance 25% of the required number of vehicles is initially available. Another 25% become available in the second period and 50% in the fourth period.

The extent to which handling capacity is compromised is reflected in the model by altering the capacity Ω_i in Constraint 2.73 to ascribed available percentages of the total capacity. For the scenario with no delay, we assume that all seven ports can operate at 50% of their total capacities for relief operations. For the scenarios with delays, four ports (Izmir, Samsun, Mersin, Iskenderun) operate at 20% capacity on the first, second and third days, 50% on days 4-12 and the three ports that are in the greater Istanbul area (Haydarpasa, Derince, Bandirma) are assumed to operate at 0% capacity for the first three periods. For the lower level delay, these three ports operate at 50% in periods 4-12. For the higher level delay, these three ports operate at 20% on day 4, and 50% on days 5-12.

In Table 2.3, we report the results for the 21 obtained instances. Each instance is identified by four digits, the first of which is the population subgroup (either i, n, or a). The three digits that follow reflect the level of compromised readiness for respectively, the available supplies, the available vehicles, and the available handling. We use 'x' to represent no delay, '1' to represent low level delay, and '2' to represent high level delay. For each instance, the destitution per capita for each of the commodities is reported in columns 2-4, the total in column 5. The total and percent criticality is reported in columns 6 and 7 and the percent trips on day 1 and on days 1-3 in columns 8 and 9. In analyzing these data, we point out that, in the scenarios with no delay (ixxx, nxxx, and axxx) the maximum handling capacities are assumed to be 50% of the port handling capacity. We assume that half of the manpower will be needed to continue required operations at the ports. For these three scenarios, we

Table 2.3: Delayed Relief Provision Instances – Scenario C

	Destitution per Capita				Criticality		Percent Trips	
Scenario	1	2	3	Total	Total	Percent	Day 1	Days 1-3
ixxx	0	0	0	0	0	0	94	97
i11x	0.79	0.25	0	1.04	0	0	48	96
i111	1.50	0.58	0	2.08	0	0	24	94
i211	1.25	0.83	0	2.08	33,775	25	32	94
i121	2.37	0.92	2.00	5.29	25,900	19	15	74
i112	1.50	0.58	0	2.08	0	0	24	94
i222	2.24	1.04	1.03	4.31	33,775	25	17	80
nxxx	1.60	0.37	0	1.96	0	0	17	47
n11x	1.74	0.48	0	2.22	0	0	15	47
n111	4.04	2.09	0	6.12	0	0	4	12
n211	4.04	2.09	0	6.12	0	0	4	12
n121	4.00	2.18	0	6.17	0	0	4	12
n112	4.34	1.85	4.00	10.19	12,962	1	4	12
n222	4.27	1.98	4.00	10.25	12,962	1	4	12
axxx	0.31	1.20	0	1.50	0	0	14	39
a11x	0.27	1.43	0	1.70	0	0	12	39
a111	4.04	2.16	1.91	8.11	0	0	3	10
a211	4.04	2.16	1.91	8.11	0	0	3	10
a121	4.04	2.22	1.91	8.17	0	0	3	10
a112	4.00	2.16	4.00	10.17	126,422	8	4	11
a222	4.00	2.22	4.00	10.22	126,422	8	4	11

see that handling capacity can be a significant contributor to destitution per capita when the amounts of commodity to be handled are large. The commodities required for the *non-injured* and *all* population subgroups require greater handling and the consequent impact is seen in the destitution per capita of, respectively, 1.96 for nxxx, and 1.50 for axxx. However, handling capacity is not paramount for the *injured* subgroup since the total number of affected persons is lower, and there is no impact on destitution and criticality, which are both zero.

The impacts of delays in distribution due to compromised availability of supplies, transport, and handling/manpower capacities are reflected in the total destitution per capita, the percent criticality and percent trips on days 1-3. What can be gleaned from the results is that the impact of each type of delay on destitution and criticality is not uniform across all types of supplies, i.e. population subgroups. We see that the impact of delays in supplies and transport capability can be significant for one type of population subgroup, namely 'i', whereas delays in effecting fully deployed handling capacity can be significant for other subgroups, namely 'n' and 'a'. For the 'i' scenarios, the criticality is the highest when there is a heavy delay in supply availability (as in i211 and i222). However the need for transport availability is underscored by instance i121 for which the destitution per capita is the highest with a slightly lower criticality. The commodities for the injured scenarios have low days-of-destitution and as such, the population is more vulnerable. Hence, the immediacy of supply and transport availability. For the 'n' and 'a' scenarios, we see that criticality occurs only when the delays in manpower/handling capacity are heavy, i.e. Scenarios n112, n222, a112, and a222. For these four scenarios, the total destitution per capita is above 10. For both the 'n' and 'a' instances, we see that the degradation in destitution per capita due to heavier delays in handling capacity are significant. For example, destitution per capita deteriorates from 2.22 to 6.12 (n11x vs. n111) and from 6.12 to 10.19 (n111 vs. n112) when the manpower availability is further delayed. Since the volume associated with the commodities in the ‘a’ scenarios is larger than that for the ‘n’ scenarios, the criticality is also much higher, i.e. 126,422 as opposed to 12,962. Hence, the immediacy of manpower availability. The required patterns for distribution of the commodities required for the three population subgroups is also seen in the percent trips on the first day and the first three days. For the ‘i’ scenarios much of the transport is required earlier as reflected by the higher percent of trips when compared with the ‘n’ and ‘a’ scenarios. The brunt of the supplies for the ‘i’ scenarios need to be delivered early as opposed to the ‘a’ scenarios in which there is recurrent pattern of distribution over the planning horizon.

2.7 Summary and Conclusions

Restricted availability of vehicles, and supplies, and restricted handling capacity have varying impacts on destitution and criticality. The model that has been developed in the dissertation establishes a means of finding the relationship between the extent of delay in availability of supplies, transport capacity, and handling capacity and the extent of destitution and criticality among affected populations. As might be expected, more heavily compromised availability of supplies, transport capacity, and handling/manpower capacity will cause greater destitution. We find that, though true for essential supplies such as medical equipment, it is not necessarily delays in making supplies available that is the most significant contributor to the suffering of affected populations. Delays in full attainment of required handling capacity, which subsumes manpower, can significantly impact destitution.

This study leads to the conclusion that strategic planning, beyond establishment of infrastructure and storage of supplies, should also give attention to establishing protocols for hastening transport and manpower capacity. Historically, both these have been provided in significant proportions by the military. Establishing protocols for quick re-deployment of manpower and transport capacity to relief operations will lead to significant alleviation in the destitution and criticality of disaster victims.

CHAPTER 3

RELIEF CENTER LOCATION

In this chapter, we examine a salient issue that arises in the strategic planning of disaster management operations for providing relief to populations that are impacted by a disaster, such as an earthquake. That of the establishment of an infrastructure for on-going provision of relief, whether supplies, resources, or information until full normalcy is restored. Key to such relief provision is the establishment of relief centers that are easily accessible by affected populations using the available transport network. As indicated by Balcik and Beamon (2008), current relief agencies typically resort to ad-hoc methods to support decision making on facility location and stock pre-positioning decisions which does not identify the most efficient and effective response. We are motivated by enabling better planning and management of the implementation of the relief centers by revealing the inherent trade-offs in the quality of access and the numbers and selected location for relief centers. Locating relief centers can be informed by a quantification of the impacts of two determinants of access, namely the total travel time on the available transportation network during representative hours and the available options in desired access levels for each population segment, i.e. neighborhood in the context of this study. The issue is addressed in the context of strategic planning of relief provision to the 1.7 million affected people in the aftermath of a probable catastrophic earthquake in Greater Istanbul.

A significant majority of the population of Istanbul, one of the five largest cities of the world, lives within 5 miles of the coastline. The estimated 1.7 million impacted people are dispersed in 123 neighborhoods of Greater Istanbul varying from 500 to 37,833 with an aver-

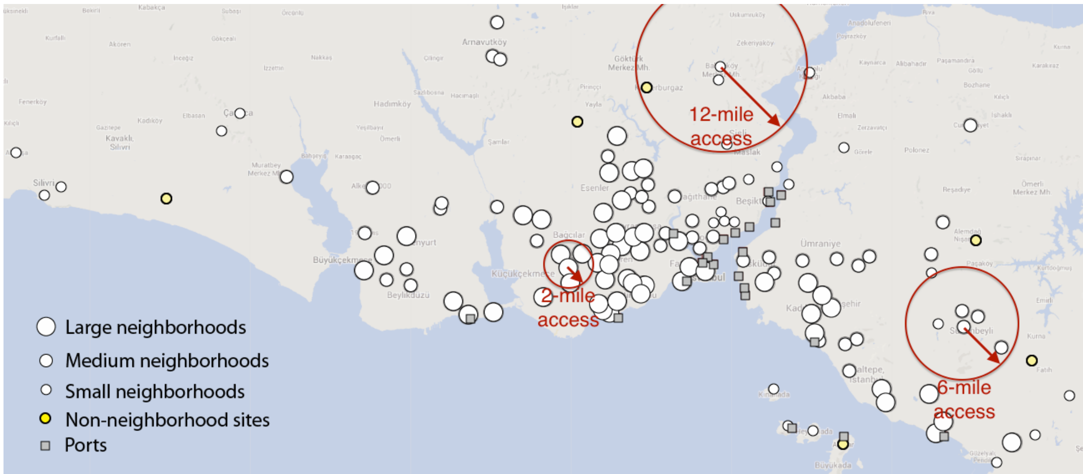


Figure 3.1: Spatial Dispersion of 1.7M people in Greater Istanbul

age of 13,622 in a neighborhood. The median neighborhood population is 11,775 with twenty neighborhoods having populations of less than 5,000.* The distance between a neighborhood and its most closely adjacent neighborhoods varies from 0.3 to 9.0 miles. The entire expanse of the neighborhoods is 69.8 miles, i.e. the longest distance between any two neighborhoods. The levels of access decided upon by government and other non-governmental organization officials are largely determined based on the size of the populations in neighborhoods. For example, closer, better, access might be enabled for neighborhoods with a larger number of affected people whereas less affected or smaller population neighborhoods might be provided access requiring longer travel distances. As shown in Figure 3.1, much of the larger neighborhoods are centrally located and the smaller neighborhoods tend to be peripheral, with some being relatively isolated. Thus, for instance, a peripheral neighborhood may be provided a relief center within twelve miles, a medium sized neighborhood one within six miles, and a larger central neighborhood within two miles. Thus, the question of the type of access afforded to populations in each of the neighborhoods is pertinent in the strategic

*The first quartile is 8000 and the third quartile is 17,767.

planning process.[†] A population in a neighborhood will access a located relief center that is most easily accessible. Potential candidates for relief center sites under consideration by the Istanbul Metropolitan Municipality include one in each of the 123 neighborhoods and others that are in-between. An access level for a neighborhood defines the set of potential centers that can be accessed by the population in that neighborhood. Thus, access for a population in a neighborhood is determined by the number of relief centers chosen from among the candidate locations within a specified proximity and the travel times to access centers. A larger number of relief centers will disperse the demand, or respond to the dispersion of the population that needs to access the centers, thereby providing a better quality of access. The travel times subsume not only the distance traveled but also the traffic on the links traversed. Any link on the network can become congested and thereby degrade the time it takes to traverse the link, and hence, to access to relief center.

Two significant aspects of locating centers are addressed in this paper: First, the number of, and locations for, the centers to be established to provide a given level of access to populations in various neighborhoods of the affected region. Second, the implementation plan for the centers, detailing the identification of the specific centers that are made available over time. Further, the percentage of the population that access the centers is used to impute the implied capacity for each center thereby providing information on the levels of required manpower. The capacity that a center needs to offer is largely dictated by two factors, namely the physical capacity and the manpower capacity. That is, a large facility that is manned by only two people will not be able to provide required level of service in specific areas. Pre-determined capacity levels are largely artificial in the context of relief center planning

[†]The quality of access has received attention in the literature in the context of medical supplies. For example, Murali et al. (2012), use distance-dependent coverage for supplying medicine to populations. Jia et al. (2007a) considers multiple facility quantity-of-coverage and quality-of-coverage (coverage of demand in varying distances) requirements for the location-allocation problem of medical supplies in response to large-scale emergencies.

since they can bias decision making. The capacity at which a center needs to operate at is particularly relevant during the period of time when centers are being established. As more centers are implemented, the capacities of any one center will change as demand is dispersed across successively more centers. The demand at a center when fewer relief centers are located can be expected to be much larger than when a larger number are located.

The literature on location-allocation of centers for humanitarian logistics have employed location methodology which comprises a suite of models such as the p-median or maximal cover models. These models have not accounted for traffic networks, the travel times on links of the network, and the potential delays that can occur due to congestion on the links. The centrality of the existing traffic network and travel times on links of the network as the flow of traffic increases in locating relief centers is not accounted for in such models. In this study we make use a nonlinear congestion-related travel time, which, we believe, better captures the traffic on a network and, further, better reflects the behavior of populations headed from any neighborhood, i.e. population center, to any one of centers that can be made available to them. In Section 3.1, we review the literature using the classification of emergency facility location (Subsection 3.1.1), and stochasticity in facility location (Subsection 3.1.2).

The optimization model that is developed to determine locations of supply sites and locations of centers is a stochastic, mixed integer, non-linear programming model over a transportation network in which supplies move from selected supply sites to selected relief centers and are subsequently acquired by affected populations accessing the relief centers over the traffic network. The non-linearity is reflected in the objective which makes use of a monotonically increasing separable convex travel time function. The inherent stochasticity of frequency of access is accounted for when determining the locations of centers. In Section 3.2, we formalize the relationship between the location of relief center sites and congestion. Subsection 3.2.2 presents the stochastic multi-commodity mixed-integer network programming model that is used to address the strategic planning of relief centers. The model identifies relief centers to locate from among a set of potential sites for centers such that the total travel time over the network is optimized, and assumes different levels of access for populations in different neighborhoods that are defined by pre-specified distance thresholds for access to a center. Further, the model can be used to address the two key issues of the implied capacity of each center, and of the assumed patterns of access to, and demand at, each center. These two issues are intertwined in that varying frequencies of access among different population segments dictate that populations be provided with equally, with respect to travel time, accessible alternative relief centers. The solution of the model is addressed via a piece-wise linear approximation of the separable, convex, and monotone increasing objective function, which is introduced in Subsection 3.2.1. The model is employed in a computational study for the identification of supply sites and relief centers for stochastically varying frequencies of access by populations in the neighborhoods of Greater Istanbul. The impact of different access levels on travel times can inform the decision making on relief center location. The stochastic variations examined range from fixed daily, bi-weekly, and weekly access frequencies to totally randomized access frequencies during an hour. In Section 3.3, we present the results of a three-part computational study of relief center location in the context of a catastrophic earthquake in the greater Istanbul area.We make use of the estimates for seismic hazard and damage for the neighborhoods of Greater Istanbul based on the report published by Japan International Cooperation Agency (JICA) in collaboration with Istanbul Metropolitan Municipality (IMM)(JICA et al., 2002), which has been widely used to study the locating of disaster response and relief facilities in Istanbul (Görmez et al., 2011). In Section 3.4, we conclude the study with summarizing comments.

3.1 Literature on Facility Location

Literature on the location of supply and distribution sites falls within the what is formalized by the Federal Emergency Management Agency (FEMA) as the preparedness and response stages of humanitarian logistics planning. The literature on location of facilities is vast, and a number of reviews have appeared. Owen and Daskin (1998) reviews mathematical formulations that consider stochastic and dynamic characteristics of facility location problems, and Snyder (2006) reviews the literature on stochastic and robust facility location models up to 2004. Daskin (2013) gives a detailed discussion on strategic facility location problems primarily focusing on the deterministic models in literature. Drezner and Hamacher (2004) reviews a large variety of facility location problems. Caunhye et al. (2012) reviews optimization models utilized in emergency logistics. The review categorizes location studies in emergency logistics literature into (i) location-evacuation models and (ii) Location models with relief distribution and stock pre-positioning. Berman and Krass (2002) gives a thorough discussion on the models that consider facility location problems with congested facilities, which attempt to capture the possibility that a customer may need service from a facility that is occupied with another customer.

In Subsection 3.1.1 we provide a summary of the literature on the location of emergency facilities, and in Subsection 3.1.2 of the literature that addresses stochasticity in the location of facilities.

3.1.1 Location of Emergency Facilities

Toregas et al. (1971) consider the location of emergency facilities as a set covering problem with equal costs in the objective. The sets are composed of the potential facility points within a specified time or distance of each demand point. Jia et al. (2007b) propose a general facility location model that is suited for large-scale emergencies, which can be cast as a covering model, a p-median model or a p-center model, each suited for different needs in a large-scale emergency. Dessouky et al. (2006), after providing a survey on covering, p-median, and p-center models in literature that are related to different emergencies settings, provides a variant of p-median model, where different types of coverage, or quality of coverage, are imposed which can be classified in terms of the distance (time) between facilities and demand points. The approach is illustrated on a hypothetical anthrax emergency in Los Angeles County. Yi and Ozdamar (2007) propose a mixed integer multi-commodity network flow model in a location-routing formulation to be used in coordinating logistics support and evacuation operations in disaster response activities. The model identifies the best locations of temporary emergency units with a goal to minimize delays in providing prioritized commodity and health care service. Jia et al. (2007a) considers location-allocation of medical supplies in response to large-scale emergencies and formulates the problem as a maximal covering problem with multiple facility quantity-of-coverage and quality-of-coverage (coverage of demand in varying distances) requirements. Balcik and Beamon (2008) consider location of relief agency distribution centers using a variant of the maximal covering model that integrates facility location and inventory decisions. Horner and Downs (2010a) present a variant of the capacitated warehouse location model that can be used to manage the flow of goods shipments to people in need in the aftermath of hurricane disasters. The model is used with protocols set forth in Florida's Comprehensive Emergency Plan and tested in a smaller city in north Florida. Cui et al. (2010) propose a compact mixed integer program formulation and a continuum approximation model to study the reliable un-capacitated fixed charge location problem which seeks to minimize initial setup costs and expected transportation costs in normal and failure scenarios. Duran et al. (2011) study the optimal number and location of pre-positioning warehouses given that demand for relief supplies can be met from both pre-positioned warehouses and suppliers. In that sense the work is closely related to that of Balcik and Beamon (2008) with a difference that the authors allow multiple events to occur within a replenishment period, thus capturing the adverse effect of warehouse replenishment lead time. The mixed-integer programming inventory-location model considers a set of typical demand instances and finds the configuration of the supply network that minimizes the average response time over all the demand instances. Görmez et al. (2011)

study the problem of locating disaster response facilities to serve as storage and distribution points. They decompose the problem into a two-stage approach, where in the first stage, they decide the locations of the local dispensing sites, and in the second stage they treat the local dispensing sites as demand points and decide the locations of the response facilities. The model is applied to the worst-case earthquake scenario for the greater city of Istanbul reported by JICA.

3.1.2 Stochasticity in facility location

Louveaux (1986) discusses the transformation of the plant location problem and the p-median problem, into a two-stage stochastic program with recourse when uncertainty on demands, variable production and transportation costs, and selling prices is introduced. Gutiérrez et al. (1996) develop algorithms adapted from Benders framework and aimed at finding robust network designs for the un-capacitated network design problem. MirHassani et al. (2000) formulate the supply chain network design problem as a two-stage stochastic program with fixed recourse, where plant and distribution center openings, and their capacity levels are decided in the first stage, prior to the realization of future demand. Uncertainty is represented in demand or capacity. Tsiakis et al. (2001) consider a two-stage stochastic mixed integer programming model for design of a multi-product, multi-echelon supply chain under demand uncertainty. The objective is to determine the facility locations and capacities, transportation links, and distribution flows to minimize the expected cost. Santoso et al. (2005) propose a stochastic programming model to formulate a global supply chain network design problem with random costs, demands, and capacities. The problem is to decide where to build facilities and what machines to build at each facility in order to minimize the total expected cost. Chang et al. (2007) presents a formulation for the flood emergency logistics preparation problem with uncertain rescue demand as two stochastic programming models that determine the rescue resource distribution plan for urban flood disasters, the location of rescue resource storehouses, the allocation of rescue resources within capacity restrictions, and the distribution of rescue resources. Berman and Drezner (2008) consider the p-median problem under uncertainty, which is defined as to locate p facilities, with a possibility of expanding the network with additional q facilities, such that the expected value of the objective function in the future is minimized. Song et al. (2009) formulates the transit evacuation operation in the aftermath of a natural disaster as a location-routing problem under demand uncertainty. The objective is to minimize the total evacuation time. Mete and Zabinsky (2010) develop a stochastic programming model to select the storage locations of medical supplies and required inventory levels for each type of medical supply to optimize warehouse operations costs and total transportation time together. The authors consider earthquake scenarios threatening Seattle area to determine demand for medical supplies at hospitals, and also a number of additional scenarios to distinguish working hours, rush hours and non-working hours. Döyen et al. (2011) develop a two-stage stochastic programming model for a humanitarian relief logistics problem where decisions are made for pre- and post-disaster rescue centers, the amount of relief items to be stocked at the pre-disaster rescue centers, the amount of relief item flows at each echelon, and the amount of relief item shortage. The objective is to minimize the total cost of facility location, inventory holding, transportation and shortage. Cardona-Valdés et al. (2011) consider the design of a two-echelon production distribution network with multiple manufacturing plants, customers and a set of candidate distribution centers under demand uncertainty, and model the problem as two-stage integer recourse problem to find a set of optimal network configuration and assignment of transportation modes and the respective flows in order to minimize total cost and total service time. Murali et al. (2012) formulate a location-allocation model to supply medicine to populations, taking into account a distance-dependent coverage function and demand uncertainty. The model formulates a special case of the maximal covering location problem with a loss function, to account for the distance-sensitive demand, and chance-constraints to address the demand uncertainty.

3.2 Strategic Planning of Location of Relief Centers

The strategic planning of the location of relief centers can be informed by determining the impacts of the number of centers, their placements, and their importance in the implementation of the centers on the provided access to affected populations. While the locations and the number of supply sites which replenish relief centers can constrain the location of relief centers, we assume that the supply sites are not capacity constrained. The supply sites can be considered to be either points of supply or points of supply consolidation. In our examination of the strategic planning for relief center location in Istanbul, we assume that the supply sites are points of consolidation. In the location of relief centers, it is not necessary to distinguish among different types of products that might be supplied at relief centers. The location of centers is impacted largely by the total volume of supplies that are required. The locations for relief centers that are decided upon must necessarily take into account the inherent stochasticity in the size of the populations from neighborhoods that access the centers during any given hour of operation. The demand during a representative hour is a function of the assumed planning horizon and the assumed frequency of access of the populations in the neighborhoods. For example, if the planning horizon is a month, then the demand during an hour can be further determined by monthly, fortnightly, weekly, bi-weekly, or daily access patterns. For any assumed pattern, the volume of supplies demanded will, consequently change. Monthly patterns assume that provisions that will suffice for an entire month are demanded, whereas, at the other extreme, daily patterns assume that the amount of provisions will be only that which are necessary for a day. In order to provide the best possible access, the capacities of each of the centers must be variable: Centers that are located in high population neighborhoods will need to be much larger than those in peripherally located smaller neighborhoods. The data that can be provided to inform decision about relief center location can be obtained by use of a mathematical model that determines the locations of a pre-specified number of centers, for pre-determined access levels for the populations in each neighborhood that are optimal with respect to the total travel time that is manifested over the available transportation network during a representative hour. The traffic generated by the transportation of supplies is impacted by the total volume that is required by one person for a day, or week or month. In locating relief centers, different modes of access, such as pedestrian, bus, are pertinent and would serve to reduce the total traffic generated. It is plausible that pedestrian traffic will not congest a segment of a highway, and further, use of public transportation will only reduce the traffic in the network. For planning purposes, we assume that the heaviest possible contributor to traffic will be from assuming that all populations access relief centers via utilization of the traffic network. We frame the planning approach with respect to the minimization of total travel times for affected populations to access the centers during a representative hour. We first present the travel time function that is employed for the time taken to traverse a particular link of the transportation network in Subsection 3.2.1 and then present the model development in Subsection 3.2.2.

3.2.1 Objective function - Travel times

In this section we present a piece-wise linear approximation for the total travel time on a network which is computed using a convex, monotonically increasing, non-linear function, developed by the U.S. Bureau of Public Roads, to represent travel time on a transportation network link. The function has been widely used in the literature.[‡]

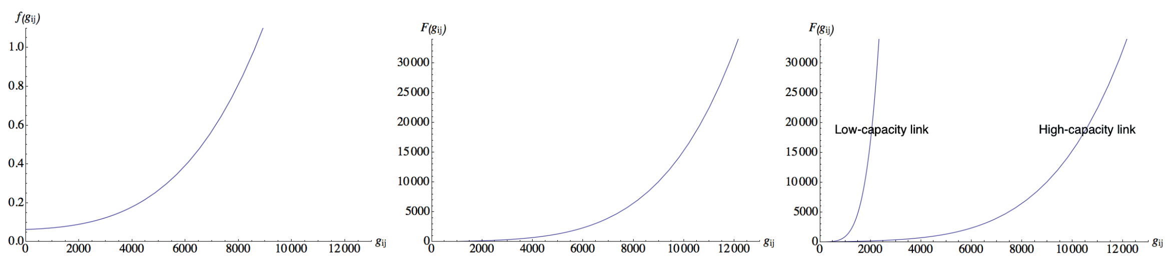
[‡]For example, Bai et al. (2011) employ it in a mixed integer program for bio-refinery location and shipment routing decisions. de Camargo et al. (2011) employ the function in selecting hub locations and allocation of non-hub nodes in order to minimize an aggregation of the costs of hub location, traffic routing, and congestion effects on the located hubs. Taniguchi et al. (1999) employ the function in determining the

The travel time on the link (i, j) when $g_{i,j}$ vehicles traverse it is stated as:

$$f(g_{ij}) = \eta_{ij} \left(1 + \alpha \left(\frac{g_{ij} + \lambda_{ij}}{\gamma_{ij}} \right)^{\beta} \right), \qquad \forall (i, j) \in \mathcal{A}$$

where, α and β are the non-linear model parameters, which are typically 0.15 and 4.0, respectively. The parameters η_{ij} and γ_{ij} refer to, respectively, the free-flow time on, and free-flow capacity of, link $(i, j) \in \mathcal{A}$. The total hourly steady-state flow of vehicles on the link comprises the regular hourly traffic flow, λ_{ij}, and the hourly flow of vehicles on the link attributed to relief operations, g_{ij}. That is, trucks plying supplies from supply sites to relief centers and vehicles used by the populations to access the relief centers. Since this travel time is that for any vehicle when there are $g_{i,j}$ vehicles on the link, the total time for vehicles on any link $(i, j) \in \mathcal{A}$ is

$$F(g_{ij}) = \eta_{ij} g_{ij} \left(1 + \alpha \left(\frac{g_{ij} + \lambda_{ij}}{\gamma_{ij}} \right)^{\beta} \right), \qquad \forall (i, j) \in \mathcal{A} \tag{3.1}$$



(a) Travel time of a vehicle on a high-capacity link

(b) Total travel time on a high-capacity link

(c) Total travel time on a low-capacity and a high-capacity link

Figure 3.2: Travel time function and total travel time function of a high-capacity link

The values of the parameters are specific to particular hours of the week as well as the assumed state of repair/damage of the segment of the road that is represented by the link.

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optimal size and location of public logistics terminals. In Sherali et al. (1991), the function is used as the objective in selecting a subset of shelters from among a set of potential centers in the context of an evacuation plan.

Further, the regular traffic on a segment, $\lambda_{i,j}$, is higher for morning and evening hours of traffic and is specific to each link which may be a segment of a six-lane highway, a segment of a four-lane highway, a segment of an arterial road, a bridge, or a seaway. The parameter that reflects the capacity of the link, $\gamma_{i,j}$, may be much smaller for links that are more heavily damaged as a result of the disaster. The total number of vehicles, $g_{i,j}$, on the link is determined by the number of vehicles on the link emanating from particular neighborhoods and from supply sites. Figure 3.2(a) and Figure 3.2(b), respectively, displays the travel time, $f(g_{ij})$, and the total travel time, $F(g_{ij})$, functions for a link of length 3 miles for a highway segment. The parameters of the travel time function have values $\gamma_{ij} = 3600$, $\lambda_{ij} = 2800$, $\eta_{ij} = 0.05$ hrs, $\alpha = 0.15$, and $\beta_{ij} = 4$. If there are 2000 vehicles on the segment, the travel time for each is about five minutes, whereas if the number increase to 4000, the travel time of each increases to about 11 minutes and for 8000 vehicles, it increases to about 49 minutes. Travel times on lower capacity links increase very quickly. Figure 3.2(c) illustrates this with the inclusion of the total time for vehicles traveling on a link with a lower capacity, $\gamma_{ij} = 400$, and the same free-flow travel time, $\eta_{ij} = 0.05$. For the higher capacity link, i.e. the highway segment, the travel time is about 5 minutes when there are 2000 vehicles traversing it, whereas for the lower capacity link the travel time is over 8 hours.

The piece-wise linear approximation of the function $F(g_{ij})$ is motivated by capturing rates of change within particular intervals of the number of vehicles, $g_{i,j}$, that flow across link (i,j). We find breakpoints, $\tilde{g}_{i,j,\ell}, \ell = 1, ..., L-1$ at which the tangent to the function has pre-determined slope of τ_s, i.e. $F'(\tilde{g}_{i,j,\ell}) = \tau_\ell$. The last breakpoint, $\tilde{g}_{i,j,L}$ is selected to be a large number. The slope $m_{i,j,\ell}$ for each piece $\ell = 1, ...L$ is then determined as $m_{i,j,\ell} = (F(\tilde{g}_{i,j,\ell}) - F(\tilde{g}_{i,j,\ell-1}))/(\tilde{g}_{i,j,\ell} - \tilde{g}_{i,j,\ell-1})$ where $\tilde{g}_{i,j,0} = 0$. The approximation is then stated as

$$F(g_{i,j}) \approx \sum_{\ell=1}^{L} m_{i,j,\ell} g_{i,j,\ell}$$

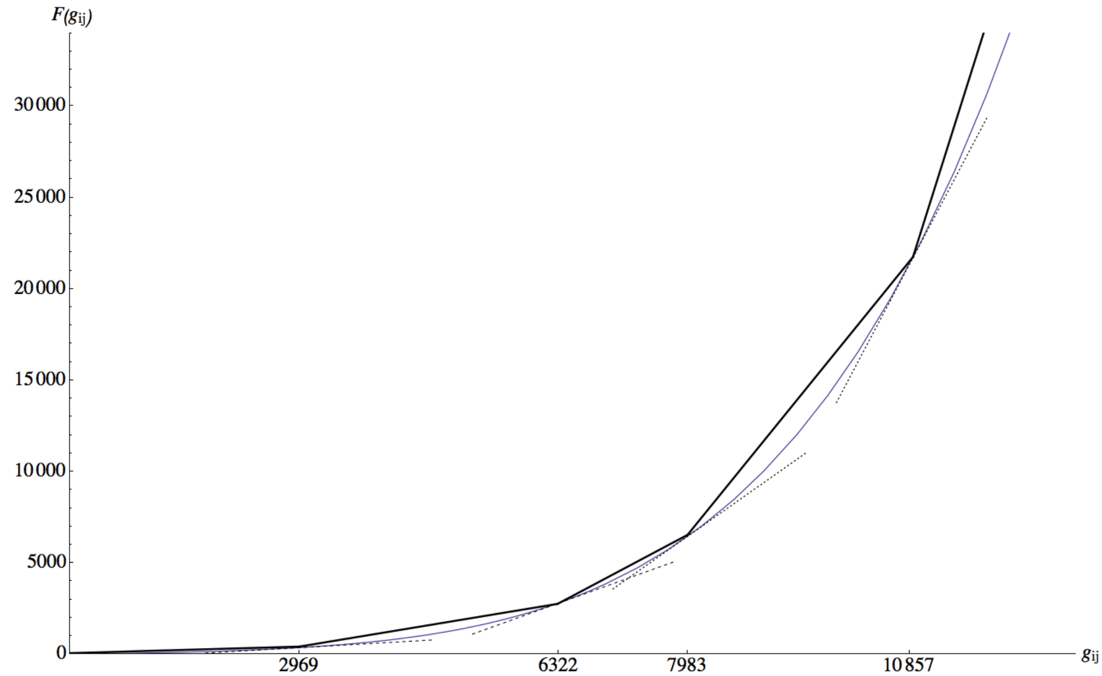

Figure 3.3: Nonlinear total travel time function with piece-wise linear approximation

with the additional stipulation that

$$g_{i,j,\ell} \leq \tilde{g}_{i,j,\ell} - \tilde{g}_{i,j,\ell-1}, \ell =, 1, ..., L$$

We use a five-piece approximation, i.e. $L = 5$, using $\tau_1 = 0.25, \tau_2 = 1.5, \tau_3 = 3.0$, and $\tau_4 = 8.0$. We illustrate the piece-wise linear approximation for the highway segment link introduced earlier in Figure 3.3. The five-piece approximation with the chosen values for slopes of tangents serve to very closely approximate the total travel time function. Using these slopes to identify the breakpoints ($\tilde{g}_{i,j,1} = 2969, \tilde{g}_{i,j,2} = 6322, \tilde{g}_{i,j,3} = 7983, \tilde{g}_{i,j,4} = 10857, \tilde{g}_{i,j,5} = 50000$) affords better approximation than that for five intervals of equal length. The computed slopes for the approximation are $m_{i,j,1} = 0.10, m_{i,j,2} = 0.73, m_{i,j,3} = 2.18, m_{i,j,4} = 5.20$, and $m_{i,j,5} = 38.67$. For this link the approximation is stated as

$$F(g_{i,j}) \approx 0.10 \times g_{i,j,1} + 0.73 \times g_{i,j,2} + 2.18 \times g_{i,j,3} + 5.20 \times g_{i,j,4} + 38.67 \times g_{i,j,5}$$

with the further stipulation that $g_{i,j,1} \leq 2969, g_{i,j,2} \leq 3353, g_{i,j,3} \leq 1661, g_{i,j,4} \leq 2874$ and $g_{i,j,3} \leq 39143$. The approximation captures total travel times closely, especially for the first three segments. It can be expected that for the given objective, the likelihood of traffic on a single link increasing to a level requiring more than the third segment to be activated in a solution is low.

3.2.2 Stochastic Programming Model

In this section, we present a stochastic programming model that can aid in the strategic planning of relief centers. Each neighborhood's population size is different and, further, the percentage of the population that is on a link of the transportation network during a particular hour varies stochastically from hour to hour of the week. The stochastic variation is expected due to a variety of behavior patterns of the affected population in a neighborhood among which the frequency of access is a primary contributor. For example, the frequency with which relief centers are accessed, daily, bi-weekly or weekly, can be impacted by the extent of rationing or proximity of the neighborhood to the epicenter of earthquake. The model takes into account scenarios $s = 1, ..., S$. Each scenario reflects different demands represented by the number of persons from a neighborhood that access a relief center during a representative hour, based on the access frequency of populations to the relief centers. The population in a neighborhood that will access a relief center in any hour of operation is denoted $P_{n,s}$ for a scenario $s \in S$. Assuming H hours of operation per day and T days during a work-week, the hourly access demand, $P_{n,s}$, to a relief center is given as $P_{n,s} = P_n/(2H)$ for a scenario that reflects daily access, $P_{n,s} = P_n/(2H)$ for bi-weekly access, and $P_{n,s} = P_n/(TH)$ for weekly access. In the model, the number of persons is a surrogate for supplies that flow in the network.

The model seeks to locate δ relief centers using π supply sites while minimizing the total travel time on a transportation network, where the network is used by vehicles plying supplies in trucks from supply sites to relief centers and by vehicles of persons in neighborhoods that access the relief centers to procure supplies. The relief centers that can be potentially accessed by a specific neighborhood $n \in \mathcal{N}$ is limited to those centers that can be accessed within a pre-specified maximum distance of r_n that is predetermined by the chosen access level provided to neighborhoods in the model instance. The flow, $x_{i,j,k,s}$, in the network is represented in the number of persons flowing on arc $(i,j) \in \mathcal{A}$ during an hour that either emanates from a supply point $k \in \mathcal{P}$ or from a neighborhood $k \in \mathcal{N}$ in scenario s. Thus, the model conforms to a multi-commodity network model in which the commodities are defined by the the sources of supply, i.e., $\mathcal{P}$, and the sources of demand $\mathcal{N}$. The flow balance at the relief center aggregates in-bound flow from all sources of supply as well as out-bound flow to all neighborhoods.

The traffic generated by the populations in the neighborhood further depends on the capacity of each vehicle used by populations. The rate of regular traffic flow on each arc is assumed, for ease of exposition, to be fixed to a particular percentage of the total capacity of the link. The capacity of vehicles that transport supplies from ports to relief centers and of vehicles that are used to obtain supplies from relief centers are stated in the number of persons. For example, if the total volume of supplies required to meet the needs of one person in demand scenario s is v_s then a vehicle of capacity of V cubic ft can accommodate supplies for V/v_s persons. The capacity of a vehicle plying supplies from supply sites to the relief centers, μ_s^P, in scenario s will be much larger than that of a vehicle, μ_s^N, used to procure supplies from a center. The travel time for each scenario in the model is accounted for by the number of vehicles $g_{i,j,s} = \sum_{k \in \mathcal{P} \cup \mathcal{N}} u_{i,j,k,s}$ traversing arc $(i,j) \in \mathcal{A}$, where $u_{i,j,k,s} = \lceil x_{i,j,k,s}/\mu_s^P \rceil, (i,j) \in \mathcal{A}$ and $k \in \mathcal{P}$ and $u_{i,j,k,s} = \lceil x_{i,j,k,s}/\mu_s^N \rceil, (i,j) \in \mathcal{A}$ and $k \in \mathcal{N}$.

Below, before presenting the model, the parameters, index sets, and variables are defined.

Index sets

$\mathcal{P}$ Set of supply sites, $\{1, \ldots, P\}$

$\mathcal{D}$ Set of potential relief centers, $\{1, \ldots, D\}$

$\mathcal{N}$ Set of neighborhoods, $\{1, \ldots, N\}$

$\mathcal{T}$ Set of points of transshipment, $\{1, \ldots, T\}$

$\mathcal{A}$ Set of arcs as ordered pairs of nodes $\{(i, j)|i, j \in \mathcal{P} \cup \mathcal{D} \cup \mathcal{N} \cup \mathcal{T}\}$

$\mathcal{D}_n$ Set of relief centers that neighborhood n can access within its access distance, r_n

$\mathcal{S}$ Set of access scenarios, $\{1, \ldots, S\}$

$\mathcal{F}_i$ Forward-star of i, comprised of nodes j where $(i, j) \in \mathcal{A}$

$\mathcal{B}_i$ Reverse-star of i, comprised of nodes j where $(j, i) \in \mathcal{A}$

Parameters

α, β Model parameters of the non-linear travel time function

δ Number of relief center sites that can be activated

η_{ij} Free-flow time on arc $(i, j) \in \mathcal{A}$

κ_d Capacity of relief center site $d \in \mathcal{D}$ in the number of people

γ_{ij} Free-flow capacity on arc $(i, j) \in \mathcal{A}$

L Number of pieces in the piece-wise approximation

λ_{ij} Regular flow on arc $(i, j) \in \mathcal{A}$

μ_s^P Capacity of a truck for shipments from supply sites to relief centers in scenario $s \in \mathcal{S}$

μ_s^N Capacity of a vehicle used to access relief centers from neighborhoods in scenario $s \in \mathcal{S}$

ν_j The maximum number of relief center outlets that can be at relief center site $j \in \mathcal{D}$

Ω_p Supply capacity of port $p \in \mathcal{P}$

π Number of ports that can be activated

$P_{n,s}$ Population at neighborhood $n \in \mathcal{N}$ for scenario $s \in \mathcal{S}$

r_n Access distance to a relief center for neighborhood $n \in \mathcal{N}$

S Number of scenarios

Variables

$x_{i,j,n,s}$ Total flow of populations from neighborhood $n \in \mathcal{N}$ on arc $(i, j) \in \mathcal{A}$, $s \in \mathcal{S}$

$x_{i,j,p,s}$ Total flow of supply from port $p \in \mathcal{P}$ on arc $(i, j) \in \mathcal{A}$, $s \in \mathcal{S}$

$g_{i,j,\ell,s}$ Total flow in piece $\ell = 1, ..., L$ on arc $(i, j) \in \mathcal{A}$, $s \in \mathcal{S}$

$w_{j,s}$ The number of relief center outlets at relief center site $j \in \mathcal{D}$, $s \in \mathcal{S}$

y_i Binary variable that takes the value of 1 if port $i \in \mathcal{P}$ is used, 0 otherwise

z_j Binary variable that takes a value of 1 if relief center site $j \in \mathcal{D}$ is activated, 0 otherwise

$u_{i,j,k,s}$ Number of vehicles of capacity μ^P on arc (i, j) for $k \in \mathcal{P}$, $s \in \mathcal{S}$

$u_{i,j,n,s}$ Number of vehicles of capacity μ^N on arc (i, j) for $n \in \mathcal{N}$, $s \in \mathcal{S}$

Model

$$\text{minimize} \quad \sum_{s=1}^{S} \phi_s \left(\sum_{(i,j)\in\mathcal{A}} \sum_{\ell=1}^{L} m_{i,j,\ell} g_{i,j,\ell,s} \right) \tag{3.2}$$

$$\text{subject to} \quad \sum_{j\in\mathcal{F}_i} x_{i,j,k,s} - \sum_{j\in\mathcal{B}_i} x_{j,i,k,s} \leq \Omega_i y_i \qquad i \in \mathcal{P}, k = i, s \in \mathcal{S} \tag{3.3}$$

$$\sum_{j\in\mathcal{F}_i} x_{i,j,k,s} - \sum_{j\in\mathcal{B}_i} x_{j,i,k,s} = 0 \qquad i \in \mathcal{P}, k \in (\mathcal{N} \cup \mathcal{P})/\{i\}, s \in \mathcal{S} \tag{3.4}$$

$$\sum_{j\in\mathcal{F}_n} x_{n,j,k,s} - \sum_{j\in\mathcal{B}_n} x_{j,n,k,s} = -P_{n,s} \qquad n \in \mathcal{N}, k = n, s \in \mathcal{S} \tag{3.5}$$

$$\sum_{j\in\mathcal{F}_i} x_{i,j,k,s} - \sum_{j\in\mathcal{B}_i} x_{j,i,k,s} = 0 \qquad i \in \mathcal{N}, k \in (\mathcal{P} \cup \mathcal{N})/\{i\}, s \in \mathcal{S} \tag{3.6}$$

$$\sum_{j\in\mathcal{F}_i} x_{i,j,k,s} - \sum_{j\in\mathcal{B}_i} x_{j,i,k,s} = 0 \qquad i \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S} \tag{3.7}$$

$$\sum_{k\in\mathcal{P}\cup\mathcal{N}} \sum_{j\in\mathcal{F}_d} x_{d,j,k,s} - \sum_{k\in\mathcal{P}\cup\mathcal{N}} \sum_{j\in\mathcal{B}_d} x_{j,d,k,s} = 0 \qquad d \in \mathcal{D}, s \in \mathcal{S} \tag{3.8}$$

$$\sum_{j\in\mathcal{D}} z_j \leq \delta \tag{3.9}$$

$$\sum_{k\in\mathcal{N}} \sum_{j\in\mathcal{F}_d} x_{d,j,k,s} \leq w_{d,s} \kappa_d \qquad d \in \mathcal{D}, s \in \mathcal{S} \tag{3.10}$$

$$\sum_{k\in\mathcal{P}} \sum_{j\in\mathcal{B}_d} x_{j,d,k,s} \leq w_{d,s} \kappa_d \qquad d \in \mathcal{D}, s \in \mathcal{S} \tag{3.11}$$

$$w_{d,s} \leq \nu_d z_d \qquad d \in \mathcal{D}, s \in \mathcal{S} \tag{3.12}$$

$$\sum_{i\in\mathcal{P}} y_i \leq \pi \tag{3.13}$$

$$x_{i,j,k,s} \leq \mu_s^P u_{i,j,k,s} \qquad (i,j) \in \mathcal{A}, k \in \mathcal{P}, s \in \mathcal{S} \tag{3.14}$$

$$x_{i,j,n,s} \leq \mu_s^N u_{i,j,n,s} \qquad (i,j) \in \mathcal{A}, n \in \mathcal{N}, s \in \mathcal{S} \tag{3.15}$$

$$\sum_{j\in\mathcal{F}_d} x_{d,j,n,s} \leq 0 \qquad n \in \mathcal{N}, d \in (\mathcal{D}/\mathcal{D}_n), s \in \mathcal{S} \tag{3.16}$$

$$\sum_{j\in\mathcal{F}_d} x_{d,j,n,s} \leq P_{n,s} z_d \qquad n \in \mathcal{N}, d \in \mathcal{D}_n, s \in \mathcal{S} \tag{3.17}$$

$$\sum_{k\in\mathcal{P}\cup\mathcal{N}} u_{i,j,k,s} = \sum_{\ell=1}^{L} g_{i,j,\ell,s} \qquad (i,j) \in \mathcal{A}, s \in \mathcal{S} \tag{3.18}$$

$$g_{i,j,\ell,s} \leq g_{i,j,\ell}^U \qquad (i,j) \in \mathcal{A}, s \in \mathcal{S}, s \in \mathcal{S} \tag{3.19}$$

$$x_{i,j,k,s}, u_{i,j,k,s}, g_{i,j,\ell,s}, w_{d,s} \geq 0 \qquad \forall\ (i,j) \in \mathcal{A},\ \forall\ k \in (\mathcal{N} \cup \mathcal{P})$$
$$d \in \mathcal{D}, \ell = 1, ...L, s \in \mathcal{S} \tag{3.20}$$

$$y_i, z_j \in \{0,1\} \qquad \forall i \in \mathcal{P}, \forall j \in \mathcal{D} \tag{3.21}$$

The model takes into account a chosen number of realizations of frequency of access, i.e. the number of scenarios, and the probability of each scenario $s \in \mathcal{S}$ is denoted ϕ_s. The objective function in the model is the expected total travel time over all demand scenarios. Constraints 3.3 and 3.4 ensure conservation of flow at supply sites. Constraints 3.5 and 3.6 ensure conservation of flow at neighborhoods. Constraint 3.7 ensures conservation of flow at transshipment points of the network. Constraints 3.8 - 3.12 pertain to conservation of flow and capacity at relief centers. Constraint 3.8 balances total in-bound flow from all points of supply and total out-bound flow by aggregating across all supply sites and all neighborhoods. Constraint 3.9 - 3.12 prevent in-bound and out-bound flows into a relief center that has not been located. Constraint 3.13 limits the number of supply sites that are used. Constraints 3.14 and 3.15 translate commodity flow to vehicular flow. Constraint 3.16 restricts access to relief centers which are not within the distance threshold of access to a center for a neighborhood and constraint 3.17 further constraints the capacity of a center to the population of a neighborhood that accesses it. This latter constraint is, in fact, redundant, but serves to strengthen the model. Constraints 3.18 and 3.19 allow the computation of the travel time in the network. The former aggregates total flow on a link of the network and the latter effects the piece-wise linear approximation. Constraints 3.20 and 3.21 define the linear and binary variables of the model, respectively.

3.3 Computational Study

In this section, we report the results of a computational study to determine alternative plans, with respect to the number and locations of relief centers and the locations of supply sites, in providing on-going relief to affected populations in 123 neighborhoods of Greater Istanbul based on the estimates for the worst-case earthquake scenario given in the JICA report. The computational study employs the model developed in Subsection 3.2.2 and is in three parts: The first part of the computational study validates the use of three extreme scenarios via a study of six 16-scenario instances that examines the sensitivity of selected relief centers to stochastic realizations of demand. The second part of the study requires twenty-one model instances and addresses the impact of patterns of access on total travel times and implied capacities for different access levels and numbers of relief centers. The third part, requiring another six instances, demonstrates the planning of the implementation of relief centers in the aftermath of a disaster for a set of relief centers that has been decided upon.

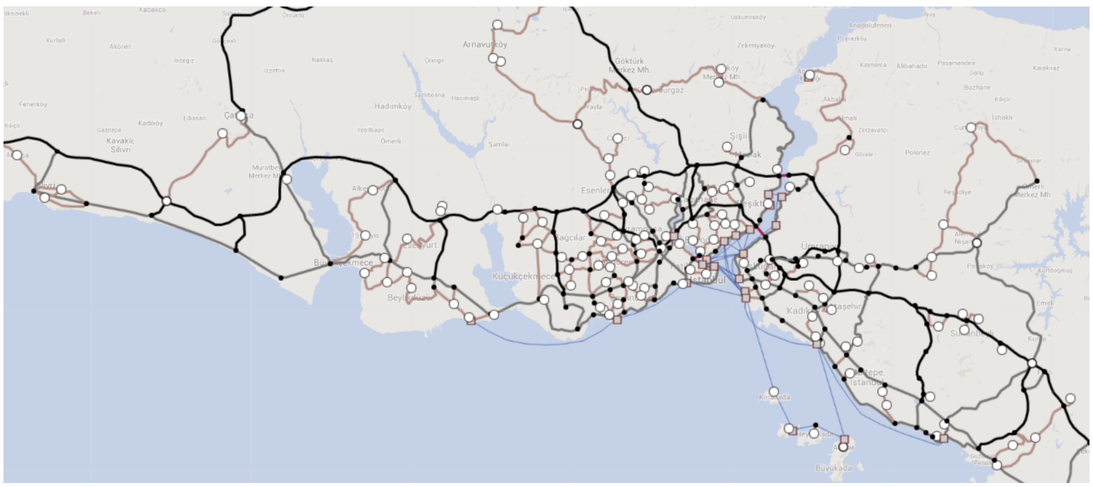

Figure 3.4: Istanbul transportation network for relief provision

For all studies what remains common to the implementation of the model is the transportation network, pictorially represented in Figure 3.4. The nodes of the network that can be supply sites, of which there are 24; potential relief center sites, of which there are 129; neighborhoods, of which there are 123; and, points of transshipment, of which there are 155.[§] Ports in the Istanbul area are either controlled and managed by the General Directorate of Turkish State Railways Ports Department or the Istanbul Municipality, and, as pointed by

[§]The data for nodes in the network has been generated using Google Maps Engine; The link distances have been computed using the Google Distance Matrix API.

Tanyas et al. (2013), can be mobilized to serve as supply sites. Among these are large ports, such as Haydarpasa and Sirkeci, which are among the fundamental hubs of the main traffic network of Istanbul. We assume that any one of twenty-four ports that are along both sides of the Bosphorus Strait, the northern coast of the Marmara sea, and island coasts can serve as a supply consolidation site. The total number of links in the transportation network is 1642, of which 376 are segments of six-lane highways, 302 are segments of four-lane highways, 66 are sea-links, 10 are bridges, and 888 are segments of arterial roads with hourly capacities of, respectively, 3600 vehicles, 2400 vehicles, 20 to 40 vehicles, 600 to 3600 vehicles and 300 to 500 vehicles.

Relief centers may be located in any one of the 129 potential locations corresponding to the 123 neighborhoods and six other sites. Of the 129 possible sites for relief centers, 53 are in neighborhoods with populations of larger than 15,000, 44 are in neighborhoods with populations between 7,500 and 15,000, 26 are in neighborhoods with populations of less than 7,500, and six are in the non-neighborhood sites. Further, we assume that their capacities are largely non-restrictive since the number of people required to serve the relief centers is part of the strategic planning process.

Table 3.1: Maximum Number of Miles for Access to a Relief Center

	Population		
Access	$\geq 15,000$	7,500 - 15,000	$\leq$ 7,500
A1	2	3	3
A2	2	3	6
A3	2	4	6
A4	2	4	12
A5	3	6	12
A6	12	12	12

Access distance thresholds that are imposed vary from 2 miles to 12 miles. Each set of distance thresholds defines a specific level of access of which we consider six. Each access level is defined by the maximum travel distance r_n, $n \in \mathcal{N}$, to a relief center for a neighborhood based on its population P_n. A neighborhood with a high population can expect to have better access, reflected by relatively shorter distances to a relief center, whereas smaller population neighborhoods are more likely to travel relatively longer distances. Table 3.1 reports these threshold distances for the six levels of access that are used in this computational study. For example, in the first five access levels, neighborhoods with populations greater than 15,000 have the shortest travel distances ranging from 2 to 3 miles, whereas neighborhoods with populations less than 7,500 can travel anywhere from 3 to 12 miles. The sixth access level assumes that populations in all neighborhoods can travel as much as 12 miles. As the distance thresholds increase, the number of relief centers that can potentially be accessed, naturally, increases. For small neighborhoods, the number of relief centers that are within a threshold of 3 miles (A1) varies from 1 to 8, within 6 miles varies from 1 to 24 (A2 and A3), and within 12 miles varies from 2 to 70 (A4 - A6). For medium neighborhoods, the number of relief centers that are within a threshold of 3 miles varies from 1 to 9 (A1 and A2), within 4 miles varies from 1 to 14 (A3 and A4), within 6 miles varies from 2 to 35 (A5), and within 12 miles varies from 4 to 72 (A6). For large neighborhoods, the number of relief centers that are within a threshold of 2 miles varies from 1 to 6 (A1 - A4), within 3 miles varies from 1 to 9 (A5), and within 12 miles varies from 13 to 72 (A6).

As access distances become smaller, a larger number of relief centers can be expected to be required. For example, we can expect the number of required relief centers to be much lower when each neighborhood is given a very low level of access, e.g. A6, when compared with the number required for a high level of access, e.g. A1. It is therefore necessary to determine the minimum number of relief centers required to provide a specific level of access. The minimum number of required relief centers δ, is easily determined by solving the following set-cover model: $\min\{\sum_{d\in\mathcal{D}} z_d | \sum_{d\in\mathcal{D}} \alpha_{n,d} \geq 1, n \in \mathcal{N}; \Delta_{n,d}\alpha_{n,d} \leq r_n z_d, \forall n \in \mathcal{N}, \forall d \in \mathcal{D}; \alpha_{n,d}, z_d \in \{0,1\} \forall n \in \mathcal{N}, \forall d \in \mathcal{D}\}$ where z_d is the binary variable for relief center opening; $\alpha_{n,d}$ is the binary variable for relief center-neighborhood assignment; and, $\Delta_{n,d}$ is the neighborhood-relief center shortest path distance. The obtained minimum number of centers for access level A1 is 54; for A2 is 48; for A3 is 44; for A4 is 38; for A5 is 28; for A6 is 8.

The drawback in the models that have a larger number of scenarios is that the size of the model increases very significantly making the resulting model computationally intractable.[¶] We use three extreme scenarios for different frequencies of access, namely daily, bi-weekly, and weekly that are representative of the trade-offs in relief center location for different stochastic realizations of access frequencies on the part of neighborhood populations. In the daily access, the entire population accesses a relief center in one of the 10 hours of operation. Thus, the population that accesses the center in one hour is $P_n/10$; for bi-weekly access frequency it is $P_n/20$ and for weekly it is $P_n/50$. In the following three subsections we present the details of the computations and discuss the computational results and their implications. In Subsection 3.3.1 we present the results of a computational study to validate using the three-extreme-scenario model. In Subsection 3.3.2 we report the results of a computational study with twenty-one different instances with a variable number of instances for each of the access levels. The study aims to establish the tradeoffs in deciding upon a specific number of relief centers with the implications on access and requisite sizes of the relief centers. In Subsection 3.3.3 we demonstrate the manner in which the relief centers can be implemented over a period of time.

3.3.1 Robustness of Relief Centers Obtained Using Three Extreme Scenarios

In this subsection, we report the results of a computational study to substantiate the use of three extreme scenarios to account for the stochasticity in frequency of access to relief

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[¶]The models are implemented in C++ using Cplex API v12.6, on a computer operated by Mac OS X v10.6.8 with 2.66 GHz Intel Core 2 Duo processor and 4 GB 1067 MHz memory. The average computational times of the instances are 0.7 hrs for 3-scenario instances, about 6 hrs for 16-scenario instances, and about 3 min for implementation instances. The maximum computational time is about 18 hrs, which corresponds to a 16-scenario instance, namely I/A6/8.

centers by populations in the neighborhoods. We compute the total travel times for the corresponding solution, i.e. the identified relief centers for 6 pairs of instances of the model, in which the number of relief centers to be established are 8, 28, 38, 44, 48, and 54 with, respectively, corresponding access levels A6, A5, A4, A3, A2, and A1. The first of the pair of models is the 3-scenario model in which the three demand scenarios are the three extreme scenarios reflecting daily, bi-weekly, and weekly access. The second is a 16-scenario model in which each demand scenario has access frequencies randomly generated for each of the 123 neighborhoods. For each scenario in the 16-scenario model, the population that accesses a center from a neighborhood n is uniform over $(P_n/50, P_n/10)$.

Table 3.2: Robustness of relief centers - Problem Instances Sizes and Solution Times

	Three Extreme Demand Scenario			Sixteen Random Demand Scenario		
Instance	Seconds	Rows	Columns	Seconds	Rows	Columns
I/A6/8	100,824	768,834	3,326,625	11,115	144,193	623,847
I/A5/28	11,470	692,985	3,114,591	817	129,968	584,089
I/A4/38	4,670	686,329	3,095,271	187	128,720	580,460
I/A3/44	4,798	674,510	3,064,181	310	126,508	574,629
I/A2/48	7,404	672,321	3,058,226	252	126,100	573,510
I/A1/54	3,484	669,618	3,050,956	381	125,594	572,142

The 16-scenario models are computationally time-consuming due the the complexity of the model. The complexity is not only due to the large number of variables, but more so, because it addresses the intrinsic trade-offs between the selection of relief centers among as many as 16 scenarios. As reported in Table 3.2, the 16-scenario model has over five times the number of constraints and variables when compared with the 3-scenario model. Further, the computation times for the 16-scenario model can be close to 30 times more than the corresponding 3-scenario model.

Table 3.3: Robustness of Relief Centers - Total Travel Time for 16 Random Access Frequencies

	I/A6/8		I/A5/28		I/A4/38		I/A3/44		I/A2/48		I/A1/54	
Scenario	16s	3s	16s	3s	16s	3s	16s	3s	16s	3s	16s	3s
1	14070	14070	3470	3600	2767	2776	2609	2662	2538	2530	2411	2408
2	12130	12130	3122	3079	2594	2581	2372	2428	2273	2212	2082	2078
3	14564	14564	3604	3635	2909	2895	2689	2650	2574	2512	2419	2395
4	12192	12192	3138	3169	2580	2622	2460	2473	2319	2232	2161	2201
5	11585	11585	2964	3061	2330	2333	2183	2243	2076	2032	1972	1986
6	14480	14480	3349	3324	2553	2547	2344	2383	2360	2309	2192	2174
7	12722	12722	3278	3241	2608	2605	2435	2461	2273	2295	2222	2196
8	12402	12402	3395	3329	2683	2665	2524	2523	2416	2380	2276	2278
9	12757	12757	3479	3344	2838	2798	2622	2621	2527	2544	2441	2426
10	13005	13005	3171	3184	2599	2629	2411	2435	2288	2260	2228	2230
11	11005	11005	3055	3062	2408	2407	2271	2306	1996	2031	1960	1965
12	11861	11861	3030	3127	2502	2506	2279	2308	2131	2135	2054	2060
13	11926	11926	3350	3476	2604	2621	2442	2466	2343	2324	2222	2249
14	11974	11974	3170	3168	2561	2562	2372	2429	2272	2287	2122	2118
15	10893	10893	2989	2931	2351	2348	2183	2170	2018	1996	1923	1952
16	13392	13392	3372	3549	2831	2824	2611	2664	2459	2446	2385	2378
Mean	12560	12560	3246	3267	2607	2607	2425	2451	2304	2283	2192	2193
Std Dev	1116	1116	193	210	168	163	156	149	179	175	168	159
Common Centers	8		22		35		40		43		51	

In Table 3.3, we report the results for the 16-scenario model for the six instances labeled to reflect the access level and the number of relief centers to be located. To establish a comparison, we also solve the corresponding 3-scenario instances. The solution to the 3-scenario model is then used to evaluate the total travel time for each of the 16 scenarios with the set of relief centers fixed to the solutions obtained for the corresponding 3-scenario instance. For each of the six instances, a pair of columns reports the total travel time obtained for each of the 16 scenarios. The first of the pair reports the total travel time for the 16-scenario model and the second reports the obtained travel time for the scenario when the relief centers are those obtained with the corresponding 3-scenario instance. We also report the number of centers that are common to the two sets of located relief centers for each of the six instances. In only one instance, I/A6/8, the set of relief centers is exactly the same, differing by up to six centers for the other instances. We see that the travel times do not alter significantly, thereby supporting the conclusion that the sets of centers obtained with the 3-scenario models are robust. The 3-scenario model hones in on a slightly different set of centers, since it addresses the trade-off with respect to three extreme scenarios. We see that the travel times for the 16 scenarios with respect to the centers identified in the 3-scenario instances can, in fact be lower than for the 16 scenario model. For instance I/A1/54 it is lower for 8 scenarios, for instance I/A3/44 lower for 12 scenarios. The average travel times for the scenarios, reported at the bottom of the table, differ by at most 26 for instance I/A3/44, and are the same for instances I/A4/38 and I/A6/8.

3.3.2 Access Levels and Total Travel Times

In this section, we present the computational study for our examination of the alternatives in the location of supply sites and relief center sites. The model is applied to identify patterns of the usage of the links in the transportation network for given numbers of relief centers and assumed access distances from neighborhoods to relief centers.

Table 3.4: Computational Results of the 3-scenario Model

				Average Access		Daily Access	
	Travel Time	Links	Vehicle-Links	Links	Vehicles	Links	Vehicles
I/A6/8	111928	435	161655	13%	20%	24%	32%
I/A6/28	4316	357	47790	3%	4%	7%	11%
I/A6/38	3445	344	40518	2%	2%	5%	7%
I/A6/44	3096	331	37324	2%	2%	5%	6%
I/A6/48	2894	332	35678	2%	2%	4%	6%
I/A6/54	2633	334	33466	1%	1%	3%	4%
I/A5/28	5003	398	55061	5%	6%	10%	14%
I/A5/38	3541	345	41924	2%	3%	6%	9%
I/A5/44	3117	339	37825	2%	2%	4%	6%
I/A5/48	2896	330	35868	2%	2%	4%	5%
I/A5/54	2633	332	33466	1%	1%	3%	4%
I/A4/38	3899	359	36754	3%	2%	7%	6%
I/A4/44	3201	343	39496	2%	2%	4%	6%
I/A4/48	2936	332	36753	1%	2%	4%	6%
I/A4/54	2634	332	33846	1%	1%	3%	4%
I/A3/44	3583	353	43239	2%	4%	5%	9%
I/A3/48	3134	342	39112	2%	2%	4%	5%
I/A3/54	2745	332	35026	2%	2%	4%	5%
I/A2/48	3403	349	41538	2%	4%	5%	11%
I/A2/54	2838	328	36052	1%	2%	3%	5%
I/A1/54	3281	365	40195	2%	4%	5%	10%

Table 3.4 reports the results for the 21 instances of the 3-scenario model. The first column identifies the model instance in terms of the number of relief centers and the access levels.

Total travel times, the total number of links used, and the total number of vehicle-links are reported in the next three columns. Columns 5 and 6 report, respectively, the percentage of links that are at or beyond capacity and the percentage of vehicle-links that are on these links for the average for the three extreme scenarios and column 7 and 8 report the same only for the extreme daily access scenario. We present these data pictorially in Figure 3.5, which

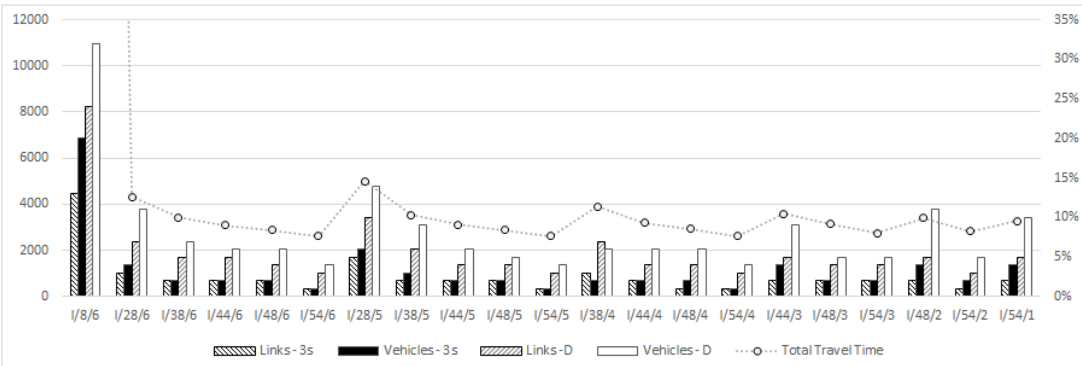


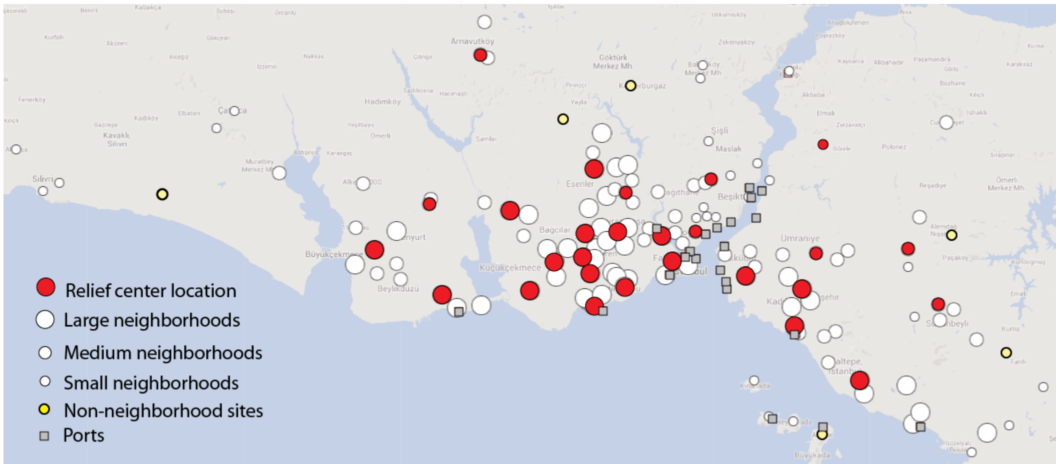
Figure 3.5: Impacts of access level and number of relief centers on Total Travel Times

makes it apparent that as the number of centers increases, travel times and the percentage of links that are at capacity and the percentage of vehicles on these links decreases. Beyond the reduction in travel times, we see that the reduction percentage of links that are at or beyond capacity reduces to below five percent for the average case only for larger numbers of centers. The clear distinction in the average behavior versus the extreme behavior reflected by daily access can be useful in making decisions about the potential of congestion.

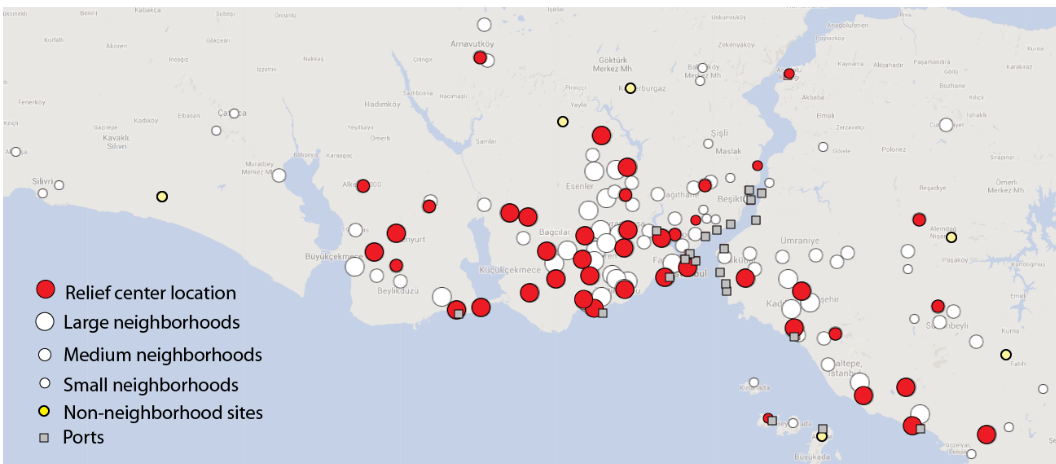
As the access level is tightened, from A6 to A1, the percent increase in total travel time relative to the travel times for A6 is 0% from A6 to A5, and A4, 4% from A6 to A3, 8% from A6 to A2, 25% from A6 to A1 for 54 centers. Thus, the major impact on travel time is when the threshold access distance changes from 12 miles to 6 miles for small neighborhoods, from 4 to 3 miles for medium-sized neighborhoods, and, most significantly, from 6 to 3 miles for small-sized neighborhoods. We note that the increase in travel times is partly attributed to the use of a larger number of links and a consequent increase in the number of vehicle-links. For each access level, we see that impact of an increase in the number of centers is most significant initially. For example, in going from 8 to 28 centers for A6, the decrease is by 96% and only 9% for 48 to 54. Similarly, the travel time decreases by 29% in going from 28 to 38 centers for A5. Interestingly, as the access level becomes looser, the reduction in travel time is more significant when there is a change in the access level for particular size neighborhoods. For example, the reduction in total travel time is 11% in going from access level A3 to A4 for 44 centers, which is attributed to the fact that populations in small neighborhoods are afforded much worse access, i.e. up to 12 miles as opposed to only 6 miles. For the same number of centers, as the access level loosens, the number of links that are used to access centers decreases. This is most apparent in going from A1 to A2 (10% fewer links) for 54 centers and from A5 to A6 for 28 centers. In a similar vein the number of vehicle-links decreases (13%) in going from A5 to A6 for 28 centers.

The optimal placement of centers changes as the number of centers increases. For example, for access level A6, only 16 of the 28 centers identified in instance I/A6/28 remain optimal for instances I/A6/44 and I/A6/54. Figure 3.6 allows a pictorial view of the size of the neighborhoods in which relief centers are located optimally. Regardless of the number of centers, the predominant number of centers are located in the large neighborhoods (64%, 66% and 63%, respectively for I/A6/28, I/A6/44, and I/A6/54) and medium neighborhoods (29%, 23% and 28%, respectively for I/A6/28, I/A6/44, and I/A6/54) and a much lower percentage located in smaller ones (8%, 11%, and 9%, respectively for I/A6/28, I/A6/44, and I/A6/54). When fewer centers are possible for the same access level, centers can be located at sites that are not in neighborhoods.[‖]

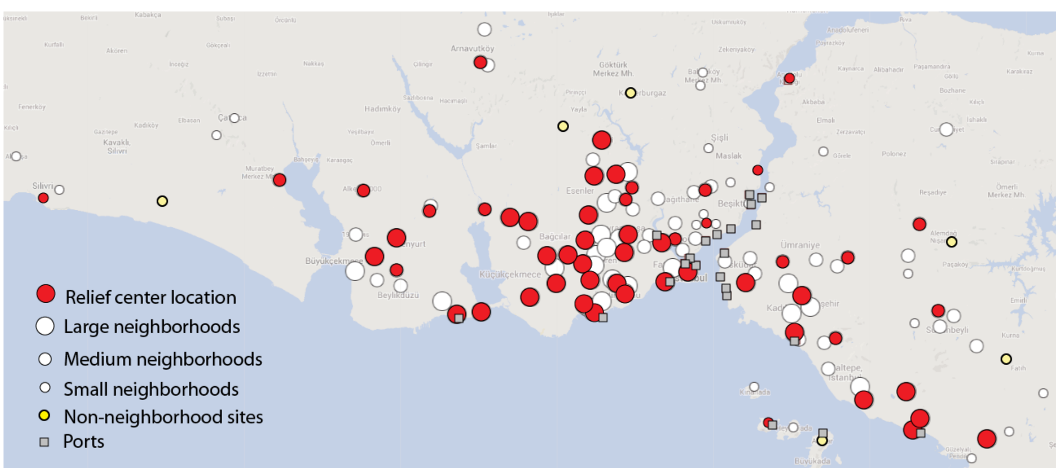
[‖]The mix of centers located in small medium and large neighborhoods for the 28, 44, and 54 centers is respectively, (1,8,18), (4,10,29), and (5,15,34). One center is located in a 'non-neighborhood' location for 28 and 44 centers.



(a) 28 relief centers (I/A6/28)



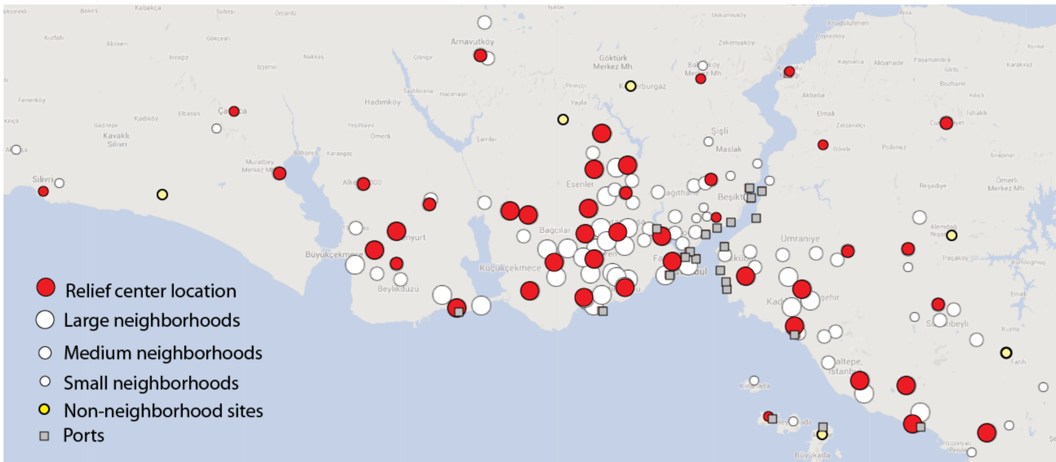
(b) 44 relief centers (I/A6/44)



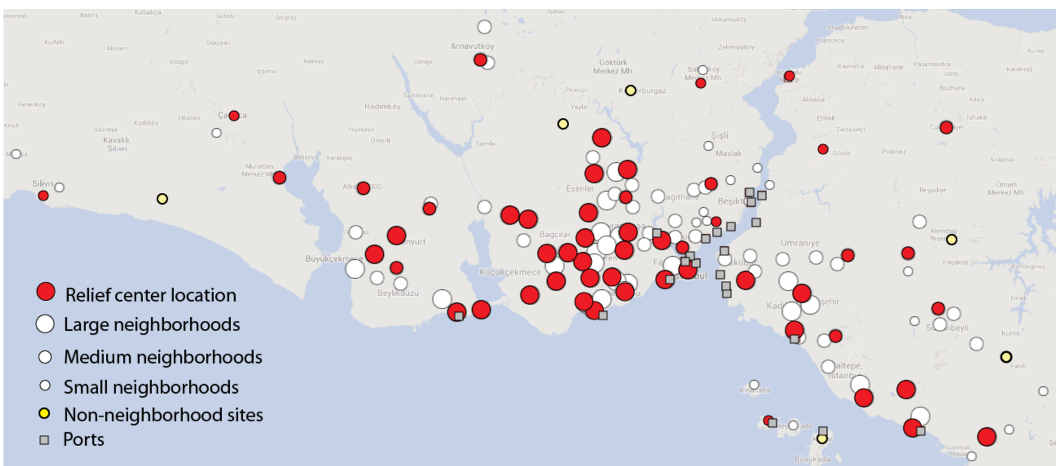
(c) 54 relief centers (I/A6/54)

Figure 3.6: Locations of Relief Centers for Access Level A6

With a larger number of centers, it is possible to locate more centers in smaller neighborhoods. For example, for when only 28 centers are located, only 1 is in a small neighborhood (the only center towards the east in Figure 3.6(a)) whereas when 54 centers are located, there are five (such as the one on the islands to the south as in Figure 3.6(c)).



(a) 44 relief centers (I/A3/44)



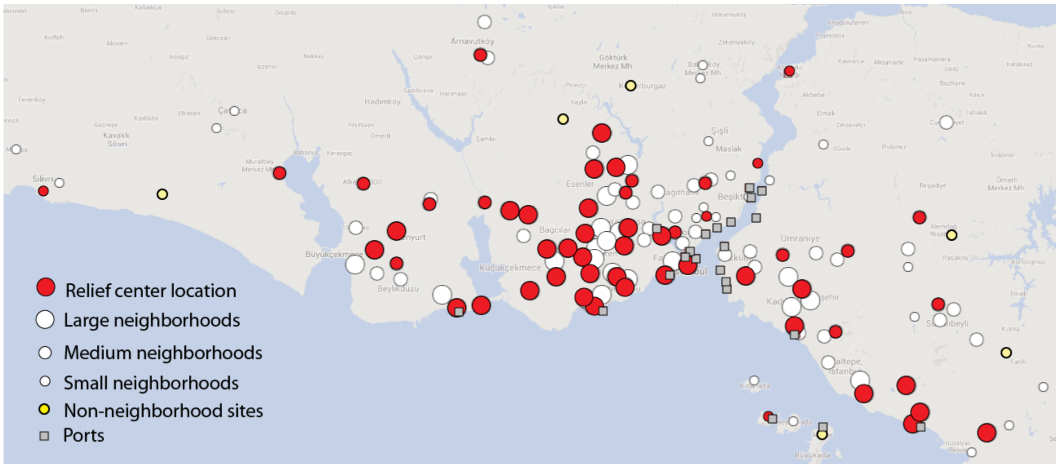
(b) 54 relief centers (I/A3/54)

Figure 3.7: Locations of Relief Centers for Access Level A3

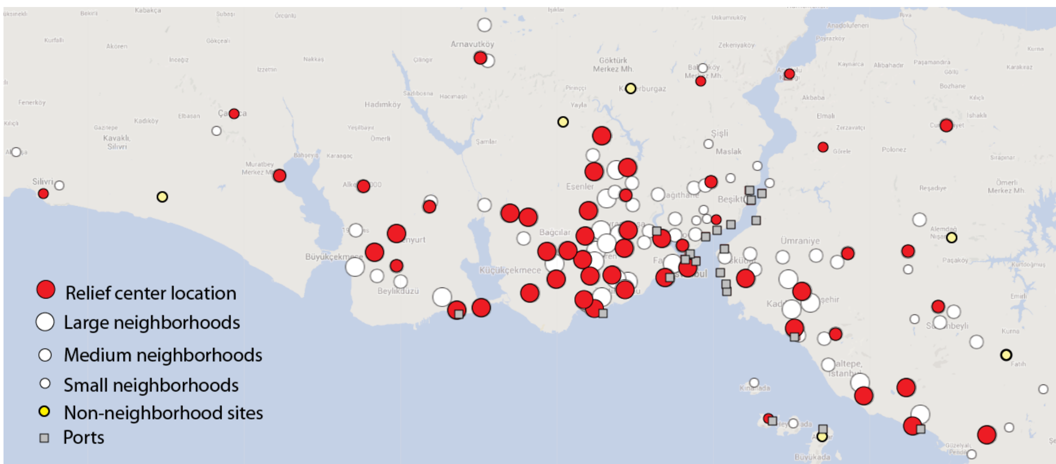
As would be expected, for a tighter access level, feasibility dictates that more centers be located in or closer to smaller neighborhoods. For example, comparing access level A6 to access level A3, pictorially represented in Figure 3.7 the percentage of centers located in large and medium neighborhoods decreases from 89% to 82% for 44 centers and 91% to 85% for 54 centers.** For access level A6, all neighborhoods can access a center within up to 12 miles. However, for access level A3, small neighborhoods are ensured a center within six miles, medium-sized neighborhoods within four miles, and large neighborhoods within two miles. In Figure 3.7 the located centers with access level A3 are more uniformly located over the region when compared with those with access level A6 in Figure 3.6.

In Figure 3.8 we illustrate the effect of improved access for the optimal location of 54 relief centers. Here the essential impact of the provision of closer access for each neighborhood with a lower distance threshold is made even clearer. Even though longer mileage thresholds obtain reduced overall travel times, shorter mileage thresholds can better meet the expectations of the populations in neighborhoods. For access level A6, all neighborhoods have a mileage threshold of 12 miles and, we see in Figure 3.8(a) that more centers are located centrally where the larger neighborhoods are. Thus smaller, peripheral neighborhoods are expected to travel further to access a relief center. For access level A3, small neighborhoods are ensured access within 6 miles, medium neighborhoods within four miles, and large neighborhoods within three miles. The improvement then impacts all three segments of neighborhoods. The dispersion of the relief centers is partly an artifact of the dispersion and overall relative size of the three segments of neighborhoods. Whereas about 5% of the affected population resides in the small neighborhoods and 26% in medium neighborhoods, the predominant portion of the affected population, 69%, is in large neighborhoods. Both small and medium neighborhoods drop to three-mile access distance thresholds and large neighborhoods to two-mile thresholds in access level A1, thereby further dispersing the location of relief centers.

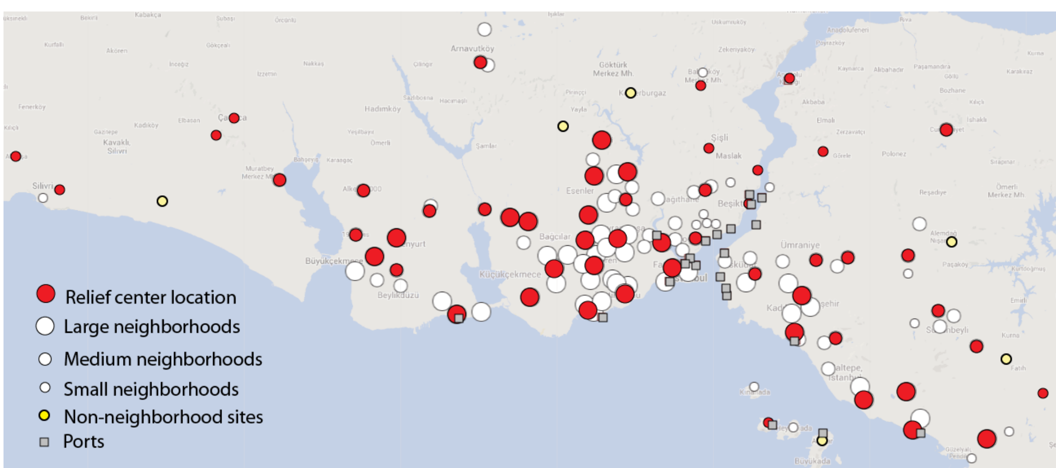
**The mix of neighborhood sizes changes from 1,4,10,29 for I/A6/44 to 1,7,11,25 for I/A3/44 and from 0,5,15,34 for I/A6/54 to 1,7,13,33 for I/A3/54



(a) Access Level A6 (I/A6/54)



(b) Access Level A3 (I/A3/54)



(c) Access Level A1 (I/A1/54)

Figure 3.8: Locations of 54 Relief Centers for Three Access Levels

Some neighborhoods can be afforded more than one relief center that is equally accessible because of the manner in which traffic manifests the travel times to these centers is comparable. This is less an artifact of any specific access level or neighborhood size and more an artifact of the optimal location of centers. [††] To achieve minimum travel times and alleviate the possibility of network congestion, the number of persons accessing relief centers will, naturally, differ. Some centers will be accessed by fewer people, others by more. In Table 3.5 we report the number of relief centers of a specific size and the total workforce required for them for each of the three extreme demand scenarios for seven different categories of relief centers by size determined by the required manpower per hour. The required manpower for each center can be determined by an assumption about the specific number of transactions per hour per worker. Assuming that each transaction represents a household of 4.11 and that each worker can execute 60 transactions per hour, the required workforce can range from 776 to 807 assuming daily access, 428 to 465 for bi-weekly access, and 233 to 262 for weekly access. While expected, it is interesting that more smaller centers are established as the number of centers located increases.

[††]For example, one small neighborhood, N25, can access 3 potential centers in access level A1, 4 in A3, and 13 in A6. However, it accesses a more than one relief center only for A6 (95% of its population going to one and only 5% accessing another). Whereas another small neighborhoods, N128 accesses only a single relief center despite the fact that it has potentially available as many as 8, 24, and 68 for, respectively, access levels A1, A3, and A6. One medium neighborhood, N136, can access 5 potential centers in access A1, 10 in A3, and 72 in A6. It accesses more than one relief center for all access levels: Two for A1 (with a 67%-33% split); three for A6 (with a 15%, 11% and 74% split); and two for A6 (with an 89% and 11% split). Whereas another medium neighborhood, N57 accesses only a single relief center despite the fact that it has potentially available as many as 5, 6, and 16 for, respectively, access levels A1, A3, and A6. One large neighborhood, N37, can access 5 potential centers in access A1, 5 in A3, and 60 in A6. It accesses more than one relief center only for access level A1 (with a 88%-12% split). Another large neighborhood, N44 accesses only a single relief center despite the fact that it has potentially available as many as 5, 5, and 57 for, respectively, access levels A1, A3, and A6.

Table 3.5: Required Number of Relief Centers of Specific Capacities for Different Access Frequencies

	XS			S			M			L			XL			XXL			MEGA		
Instance	D	B	W	D	B	W	D	B	W	D	B	W	D	B	W	D	B	W	D	B	W
I/A6/8	0/0	0/0	0/0	0/0	2/7	2/4	2/12	0/0	2/13	0/0	1/14	2/36	0/0	1/25	0/0	1/32	0/0	0/0	5/642	4/298	2/88
I/A6/18	0/0	0/0	1/1	1/5	2/5	5/17	1/6	3/24	6/51	2/30	4/71	6/76	2/54	6/149	0/0	2/72	3/101	0/0	10/524	0/0	0/0
I/A6/28	0/0	0/0	1/1	1/4	2/5	14/54	1/6	9/77	13/97	8/143	14/210	0/0	9/214	3/64	0/0	7/244	0/0	0/0	2/85	0/0	0/0
I/A6/38	0/0	1/1	2/2	2/6	4/14	28/104	3/23	17/131	8/52	18/284	16/214	0/0	12/284	0/0	0/0	3/104	0/0	0/0	0/0	0/0	0/0
I/A6/44	0/0	3/3	3/3	3/6	6/29	36/121	6/56	24/178	5/34	24/350	11/151	0/0	8/189	0/0	0/0	3/102	0/0	0/0	0/0	0/0	0/0
I/A6/48	0/0	3/3	3/3	3/6	8/37	41/132	7/64	29/217	4/25	28/395	8/106	0/0	10/241	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
I/A6/54	0/0	3/3	6/6	6/19	15/60	45/139	11/93	30/224	3/18	31/447	6/78	0/0	6/149	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
I/A5/28	0/0	1/1	3/3	3/10	6/21	13/41	3/23	8/63	9/72	9/137	7/118	3/36	3/80	6/152	0/0	4/142	0/0	0/0	6/302	0/0	0/0
I/A5/38	0/0	2/2	4/4	4/12	7/26	24/86	5/42	13/105	10/67	14/230	16/225	0/0	9/211	0/0	0/0	6/206	0/0	0/0	0/0	0/0	0/0
I/A5/44	0/0	2/2	4/4	4/12	8/31	35/120	6/51	23/178	5/34	23/349	11/151	0/0	8/188	0/0	0/0	3/104	0/0	0/0	0/0	0/0	0/0
I/A5/48	0/0	3/3	4/4	4/10	9/39	40/129	8/70	28/212	4/26	27/395	8/108	0/0	8/195	0/0	0/0	1/35	0/0	0/0	0/0	0/0	0/0
I/A5/54	0/0	3/3	6/6	6/19	15/60	45/139	11/93	30/224	3/18	31/447	6/78	0/0	6/149	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
I/A4/38	0/0	1/1	4/4	4/14	12/44	23/73	9/72	11/90	11/80	11/178	13/204	0/0	6/150	1/22	0/0	7/248	0/0	0/0	1/40	0/0	0/0
I/A4/44	0/0	2/2	5/5	5/16	13/49	31/104	10/81	15/122	8/52	16/264	14/189	0/0	10/242	0/0	0/0	3/102	0/0	0/0	0/0	0/0	0/0
I/A4/48	0/0	3/3	5/5	5/14	13/52	38/123	11/91	21/162	5/33	22/337	11/148	0/0	8/197	0/0	0/0	2/67	0/0	0/0	0/0	0/0	0/0
I/A4/54	0/0	3/3	6/6	6/18	15/58	45/139	12/99	30/226	3/18	29/420	6/77	0/0	7/170	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
I/A3/44	1/1	5/5	8/8	7/19	13/47	26/82	10/78	13/104	10/71	13/205	12/184	0/0	6/151	1/22	0/0	6/213	0/0	0/0	1/40	0/0	0/0
I/A3/48	1/1	5/5	8/8	7/19	13/47	32/104	10/78	18/142	8/52	18/279	12/171	0/0	8/197	0/0	0/0	4/134	0/0	0/0	0/0	0/0	0/0
I/A3/54	1/1	5/5	8/8	7/19	14/52	42/132	11/87	27/204	4/25	26/379	8/106	0/0	8/194	0/0	0/0	1/31	0/0	0/0	0/0	0/0	0/0
I/A2/48	1/1	5/5	11/11	10/32	15/50	28/87	9/71	17/133	9/63	17/260	10/152	0/0	6/159	1/25	0/0	4/137	0/0	0/0	1/50	0/0	0/0
I/A2/54	1/1	5/5	12/12	11/36	17/57	37/120	10/80	22/169	5/33	23/353	10/135	0/0	7/172	0/0	0/0	2/68	0/0	0/0	0/0	0/0	0/0
I/A1/54	3/3	8/8	19/19	16/51	19/57	27/88	8/65	15/113	8/58	14/207	10/152	0/0	7/168	1/22	0/0	5/179	0/0	0/0	1/40	0/0	0/0

†Required manpower per hour: XS, 1; S, $1-5$; M, $5-10$; L, $10-20$; XL, $20-30$; XXL $30-40$.

3.3.3 Computational Study - Implementation of Relief Centers

We demonstrate the development of an implementation plan for establishing a set of relief centers over a period of time. It is expected that a number of these centers should be ready to be operationalized with immediacy and that the full implementation would take more time. The question then is, what should be the progression of establishing the centers? We demonstrate the issues that can arise pertaining to access and the accompanying deployment of supplies in implementing the 54 relief centers obtained in the solution to instance I/A54/1. For access level A1, the minimum number of centers required, as determined in Section 3.3 is 54. As such, to determine an implementation plan in which a subset of centers is gradually implemented requires that a succession of subsets of centers to be identified. We assume that the implementation is to be in six phases corresponding to the access levels that are provided. The first phase implements a subset of centers that are identified with respect to access level A6, gradually increasing the number of centers to provide access in line with access levels A5 through A1. The process requires that of the 54 centers, for each level of access, the number of additional centers to be established needs to be determined first. The set of established centers, denoted $\widehat{\mathcal{D}}$ is initialized to $\emptyset$ and the set of centers to be established, denoted $\mathcal{D}$, is initialized to the 54 centers in solution of I/A54/1. To determine the number of centers from among those in $\mathcal{D}$ that need to be established for the current access level, the access mileage thresholds r_n are updated. The number of centers is obtained by solving the set cover model $\hat{\delta} = \min\{\sum_{d\in\mathcal{D}} z_d | \sum_{d\in\mathcal{D}} \alpha_{n,d} \geq 1, n \in \mathcal{N}; \quad \Delta_{n,d}\alpha_{n,d} \leq r_n z_d, \forall n \in \mathcal{N}, \forall d \in \mathcal{D} \setminus \widehat{\mathcal{D}}; \quad z_d = 1, \forall d \in \widehat{\mathcal{D}}; \quad \alpha_{n,d}, z_d \in \{0,1\} \forall n \in \mathcal{N}, \forall d \in \mathcal{D} \setminus \widehat{\mathcal{D}}\}$. The 3-scenario model is then solved to determine the augmented set of $\hat{\delta}$ centers which constitute the updated set $\widehat{\mathcal{D}}$. The procedure is formally presented below:

Implementation Procedure

1. Initialize. $AccessLevel \leftarrow 6$, $\widehat{\mathcal{D}} \leftarrow \emptyset$; $\mathcal{D} \leftarrow \{$*54 centers in solution of I/A54/1*$\}$

Loop. While $AccessLevel > 0$

{

2. Obtain $\hat{\delta}$.

2.1 Set access mileages. Set r_n to mileages for *AccessLevel*.

2.2 Solve set-cover model. Solve $\hat{\delta} = \min\{\sum_{d\in\mathcal{D}} z_d | \sum_{d\in\mathcal{D}} \alpha_{n,d} \geq 1, n \in \mathcal{N}; \Delta_{n,d}\alpha_{n,d} \leq r_n z_d, \forall n \in \mathcal{N}, \forall d \in \mathcal{D} \setminus \widehat{\mathcal{D}};$

$z_d = 1, \forall d \in \widehat{\mathcal{D}}; \quad \alpha_{n,d}, z_d \in \{0,1\} \forall n \in \mathcal{N}, \forall d \in \mathcal{D} \setminus \widehat{\mathcal{D}}\}$.

3. Determine centers.

3.1 Update centers $\mathcal{D}_n$ accessible to neighborhoods $n \in \mathcal{N}$. Update $\mathcal{D}_n$ for the access milages r_n for *AccessLevel*.

3.2 Obtain $z_d^* \forall d \in \mathcal{D}$. Solve the 3-scenario model for *AccessLevel* for $\delta = \hat{\delta}; z_d = 1, \forall d \in \widehat{\mathcal{D}}$;

3.3 Update established centers. $\widehat{\mathcal{D}} \leftarrow \{d | z_d^* = 1\}$

4. Update $AccessLevel \leftarrow AccessLevel - 1$

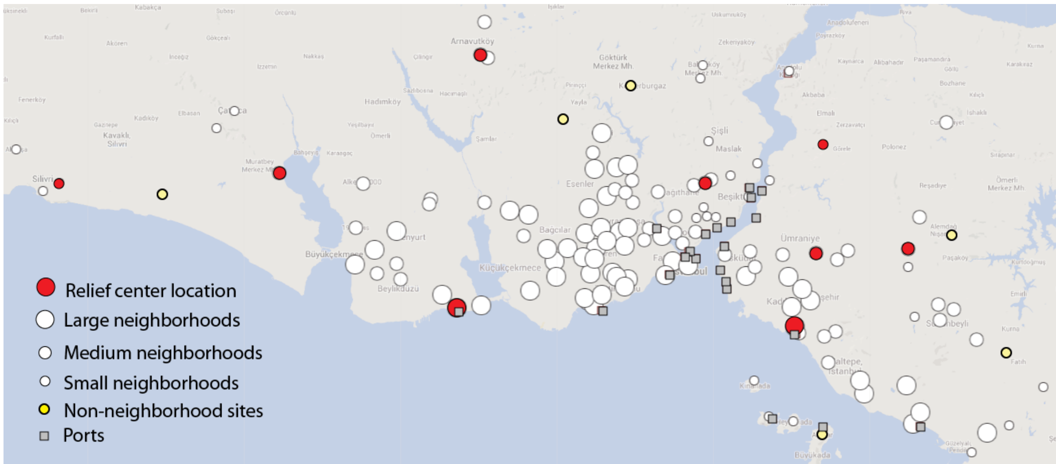
}

Table 3.6: Computational results - Implementation of Relief Centers

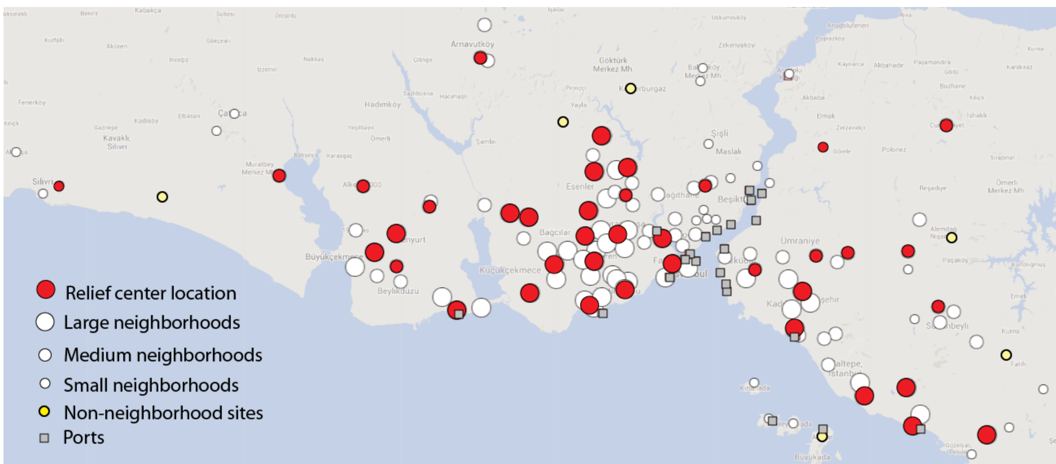
	Travel Time	Links	Vehicle-Links	Average Access		Daily Access	
				Links	Vehicles	Links	Vehicles
I/A6/9	199640	447	174655	13%	23%	24%	35%
I/A5/30	4677	391	52775	3%	6%	7%	12%
I/A4/39	3895	363	45160	3%	5%	7%	12%
I/A3/45	3664	364	43914	2%	4%	5%	11%
I/A2/50	3330	361	40651	2%	4%	5%	10%
I/A1/54	3281	365	40195	2%	4%	5%	10%

The minimum number of centers that can be established for access levels A6, A5, A4, A3, A2, A1 are, respectively, 9, 30, 39, 45, 50 and 54. The slightly larger numbers required (than when the entire set of 129 potential centers is available) is due to feasibility. For example, even though a minimum of 8 centers is required for access level 6, here an additional center must be located since there are only 54 potential centers. We report the computational results in the same format as in the previous section for these six instances in Table 3.6. The total travel times become smaller as more centers are established making it clear that the initial number of centers that need to be planned for is closer to 30 than the bare minimum of 9.

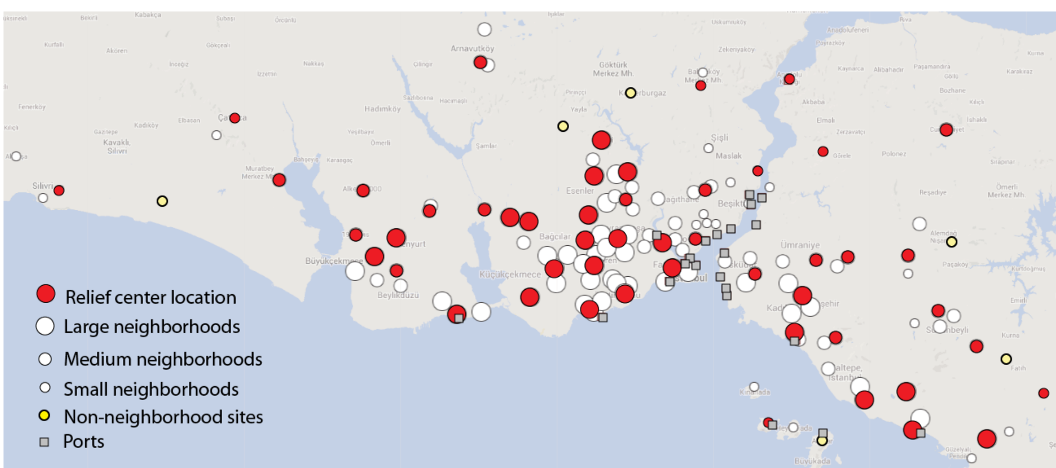
Of the 54 centers to be located, 44% (24/54) are in large neighborhoods, 33% (18/54) are in medium neighborhoods, and 22% (12/54) are in small neighborhoods. However, the initial mix has less to do with size and more to do with spatial dispersion. As we see for X/A6/9 in Figure 3.9(a), the dispersion is such that each neighborhood can access at least one center within 12 miles. For X/A4/39, in Figure 3.9(b), we see that all the centers that are to be established in large neighborhoods are located. For X/A2/50, in Figure 3.9(c), all the centers in medium neighborhoods are located. Thus, we see that initially the focus is to provide a minimal level of access for the entire population and then to gradually improve the access for the largest segment of the populations.



(a) Access Level A6 (X/A6/9)



(b) Access Level A4 (X/A4/39)



(c) Access Level A2 (X/A2/50)

Figure 3.9: Implementation of 9, 39 and 50 Relief Centers

Table 3.7: Required number of relief centers of specific capacities for different access frequencies

	XS			S			M			L			XL			XXL			MEGA		
Instance	D	B	W	D	B	W	D	B	W	D	B	W	D	B	W	D	B	W	D	B	W
X/A6/9	0/0	1/1	1/1	1/2	1/4	3/11	1/6	0/0	1/6	0/0	3/38	0/0	2/46	0/0	2/46	1/31	0/0	1/31	4/601	4/302	1/47
X/A5/30	0/0	1/1	5/5	5/18	7/21	13/44	2/15	8/63	10/78	9/138	9/149	2/23	3/85	5/121	0/0	6/207	0/0	0/0	5/235	0/0	0/0
X/A4/39	0/0	1/1	5/5	5/18	13/46	23/72	9/72	11/88	11/80	11/174	13/204	0/0	6/150	1/22	0/0	7/249	0/0	0/0	1/40	0/0	0/0
X/A3/45	1/1	5/5	10/10	9/26	15/52	25/79	10/79	11/87	10/72	11/170	13/199	0/0	6/145	1/22	0/0	7/245	0/0	0/0	1/40	0/0	0/0
X/A2/50	1/1	5/5	14/14	13/43	18/57	28/90	9/72	14/106	8/58	14/207	12/177	0/0	7/168	1/22	0/0	5/179	0/0	0/0	1/40	0/0	0/0
X/A1/54	3/3	8/8	19/19	16/51	19/57	27/88	8/65	14/106	8/58	14/207	12/177	0/0	7/168	1/22	0/0	5/179	0/0	0/0	1/40	0/0	0/0

†Transactions per hour: XS, < 240; S, 240 − 1200; M, 1200 − 2400; L, 2400 − 4800; XL, 4800 − 7200; XXL 7200 − 9600.

In Table 3.7 we report the number of relief centers of a specific size. The required workforce can range from 686 to 713 assuming daily access, 345 to 370 for bi-weekly access, and 142 to 165 for weekly access.

3.4 Summary and Conclusions

The strategic planning of the location of relief centers must necessarily account for varying frequencies of access during a planning horizon and further, the quality of access provided to populations. The number of relief centers determines the distance that populations that are relatively isolated or in peripheral neighborhoods must travel to access a relief center. The fewer the number of centers, the greater the total travel times and increased potential for congestion. The number of centers, is more a managerial decision about what might be an acceptable level of congestion. While much of the literature has focused on the location of fixed outlets, this study points to logic in making the very small relief centers mobile outlets in that they can provide easy access to smaller populations without the overhead of a fixed facility. We demonstrate that an acceptable level of the number of links in the traffic network that can be expected to reach capacity during an hour can be effective in determining the number of centers.

It is sufficient and computationally expedient to take into account only a few judiciously identified extreme demand scenarios for the strategic planning exercise. Including a relatively larger number of randomly generated scenarios for planning purposes obfuscates the true extreme scenarios that must be taken into account. Further, incorporation of extreme demand scenarios leads to more robust locations for relief centers.

CHAPTER 4

CONCLUSION AND FUTURE STUDY

In this dissertation, two strategic planning problems associated with disaster management operations are investigated in a scenario-based disaster setting for the greater Istanbul area. The first problem is the strategic planning of relief allocation to alleviate destitution among affected populations that is caused by critical shortages of essential supplies in the aftermath of a disaster. Critical shortages are associated with delays in the provision of supplies that can be caused by limited availability of supplies, transport capacity, and handling power. The developed mixed integer goal programming model categorizes population segments with respect to the level of need for a set of supplies by keeping track of replenishment over time, and proposes optimal distribution plans to minimize destitution and criticality with respect to the level of need and the -temporal- availability of resources.

The second strategic planning problem is the establishment of an infrastructure to sustain an on-going provision of relief until normalcy in the aftermath of a disaster is restored. Key to such relief provision is the establishment of relief centers that are easily accessible by affected populations using the available transport network. The modeling framework that is considered for this study account for traffic networks, the travel times on links of the network, the potential delays that can occur due to congestion on the links, and uncertainty in demand to access relief centers. A suite of models is used to identify the number and locations of relief centers to provide a given level of access to populations in various neighborhoods of the affected region. A new optimization model that is developed to determine locations of supply sites and locations of relief centers is a stochastic mixed integer non-linear programming model that considers a two-echelon network in which supplies move from selected supply sites to selected relief centers and subsequently acquired by affected populations accessing the relief centers over the traffic network. The model identifies relief centers to locate from among a set of potential sites for centers such that the total travel time over the network is optimized.

In Section 4.1 future directives are elaborated upon for the study of Alleviation of Destitution in the Aftermath of a Disaster and in Section 4.2 for the study of Relief Center Location.

4.1 Alleviation of Destitution in the Aftermath of a Disaster

Being recently recognized, capturing destitution with respect to critical shortages is an emerging area of study in disaster operations research. Other than the studies that try to cover suffering by implications in their modeling approaches, such as that of Özdamar et al. (2004), Tzeng et al. (2007), Yi and Ozdamar (2007), and Rawls and Turnquist (2012), there are only a couple of studies, such as in Holguin-Veras Ph.D. and Perez (2010), (Yushimito et al., 2010), (Jaller Martelo, 2011), and (Perez Rodriguez, 2011), that directly address suffering as a function of time spent in the deficiency of supplies. These studies utilize deprivation functions derived from theoretical economics, whereas the study herein uses a modeling approach that relies on pure linear programming techniques, and unique in this regard.

The computational study that is conducted for the probable disaster scenarios for the greater Istanbul area reveals that more heavily compromised availability of supplies, transport capacity, and handling/manpower capacity will cause greater destitution. It is found that, though true for essential supplies such as medical equipment, it is not necessarily delays in making supplies available that is the most significant contributor to the suffering of affected populations. Delays in full attainment of required handling capacity, which subsumes manpower, can significantly impact destitution. This study leads to the conclusion that strategic planning, beyond establishment of infrastructure and storage of supplies, should also give attention to establishing protocols for hastening transport and manpower capacity.

The computational study is based on four disaster scenarios, and associated demand estimations, for the greater Istanbul area that have been widely used in literature for similar studies. To study the impact of temporal availability of resources on destitution, for each disaster scenario, we also considered a limited number of resource realization scenarios. To test the model more extensively and derive more insights, the study can be expanded by considering inherent stochasticity in the availability of resources, and taking sufficiently large number of randomly generated resource realization scenarios into account.

The maximum computational time is about an hour, which might be acceptable for instances of similar size. However, for a larger set of demand locations, i.e. districts, efficient heuristics might be considered to ease computations. For instance, one possible heuristic can rely on the pattern of deliveries over time. The solutions of the model instances reveal that, especially when supply and resources are limited, the model tends to deliver supplies in the last day just before population transitions into a destitute state. With respect to the availability of resources, one can derive a heuristic that forces the model to perform deliveries within a certain feasible range of periods in a pattern close to the optimal.

4.2 Relief Center Location

The model is employed in a computational study for the identification of supply sites and relief centers for stochastically varying frequencies of access by populations in the one hundred twenty-three neighborhood of Greater Istanbul. The stochastic variations examined range from fixed daily, bi-weekly, and weekly access frequencies to totally randomized access frequencies during an hour. Further, a computational study reveals an implementation plan for establishing relief centers to ensure that easy access with minimal degradation of travel times is enabled for all populations in the neighborhoods of Greater Istanbul.

To get more insights on the relation between congestion on traffic links and relief center locations, the modeling framework of this study can be extended in two ways: (i) In the current setting of the computational study, the model simulates the operation of relief provision during an hour of the planning horizon and given an access frequency, whether daily, bi-weekly, or weekly, a uniform distribution of access over the operational hours of planning horizon is assumed. In fact, a more realistic probability distribution can be assumed to reflect the variations of access with respect to the hour of operation. Concordantly, the data for the parameter of the non-linear travel time function that represents the regular traffic flow on a link (i, j), $\lambda_{i,j}$ can be modified with respect to the hour of operation. This would put another valuable dimension of stochasticity, and yet another complication, into the optimization framework. (ii) In the current study, it is assumed that supplies that are delivered to relief centers are immediately acquired by affected populations. An expansion of the model might be that of which accounts for the multi-period aspects of the problem. If additional computational complications could be ruled out, the multi-period expansion of the model would add two important assets into the relief provision operation: First, inventory of supplies can come into play, which, in the modeling framework, can allow to take into account possible delays in replenishment of relief centers by supply sites. And, second, in a multi-period setting one can consider -partly- relocation of relief centers from one period to another, i.e. as in mobile servers, throughout the planning horizon. Dynamic relocation of relief centers can lessen the load of network traffic significantly by allowing access in closer distances.

Operational aspects of relief provision, such as the previously mentioned inventory replenishment and mobile outlets that move to different neighborhoods during the hours of the week can be incorporated into the developed model. For a model that is to be implemented for such operational decision making, computation time for the model is critical, which is not as much the case for strategic planning purposes. Examining specialized solution methods that capitalize on the underlying network structure of the model can prove to be worthwhile in reducing the required computation time for solution of an instance of the resulting operational model. For example, a specialization that makes use of the Benders' framework will lend itself to this model.

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