MULTISTAGE SDDP APROACH TO RISK-ADJUSTED DISASTER PREPAREDNESS AND RELIEF DISTRIBUTION PROBLEM

(AFET ÖNCESİ HAZIRLIK VE YARDIM MALZEMESİ DAĞITIM PROBLEMİNE ÇOK AŞAMALI RİSK AYARLI SDDP YAKLAŞIMI)

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ABSTRACT

Disaster management subject is highly studied by academicians, researchers and municipals especially in the most recent years due to the increase of their tremendous and destructive effects to the human lives.

The increase of these events requires urgent and effective responses with well defined methodologies. However, because of the random occurrence of these events, it is hard to deal with these problems. This study aims to apply an effective methodology to disaster management problem where we cover a three layer supply chain with both the pre-disaster and post-disaster phase of a disaster management problem. The pre-disaster decisions are the inventory decisions at the main depots (suppliers) and the location decisions of the distribution centers. These decisions are made before observing the random data, which are jointly distributed demands and road capacities. After observing the randomness, at the second and later stages, the demands have to be satisfied using only the available inventories at the main depots and passing through the previously selected distribution centers. Mathematically, the first-stage problem is a mixed-integer linear optimization problem, whereas the problems at the later stages are simply linear programming problems. Assuming that the demands and road capacities are jointly and continuously distributed, the deterministic equivalent is obtained through the sample average approximation method. In addition, we built risk-adjusted multistage formulation using conditional value at risk and the problem is solved through the stochastic dual dynamic programming (SDDP) method under fairly general assumptions. The proposed algorithm is applied on a real life data that is obtained for Asian side of Istanbul.

RESUME

La gestion des catastrophes naturelles est un sujet largement étudié par les académiciens, chercheurs et agents municipaux pendant les dernières années du à l'accroissement de leur effet terrible et destructif sur les vies humaines

L'accroissement de ces évènements nécessite des réponses urgentes et efficaces en utilisant des méthodologies bien définies. Toutefois et en raison de l'apparition aléatoire de ces évènements il est difficile de gérer ces problèmes. Cette étude a pour objectif d'appliquer une méthodologie efficace à la gestion des catastrophes naturelles ou nous couvrirons 3 niveaux de chaine logistique avec à la fois la phase avant et la phase après de la gestion d'une catastrophe naturelle. Les décisions de la phase avant la catastrophe naturelle sont les choix de stock dans les dépôts principaux (fournisseurs) et le choix des emplacements des centres de distribution. Ces choix sont réalisés avant observation des données aléatoires que sont conjointement les demandes de distribution et les capacités routières. Apres observations des données aléatoires, dans un second temps et pendant les étapes ultérieures, les demandes doivent être satisfaites en utilisant seulement les stocks disponibles dans les dépôts principaux et en passant par les centres de distributions précédemment sélectionnés. Mathématiquement la première étape du problème est un problème mixte en nombre entier d'optimisation linéaire alors que lors des étapes suivantes il s'agit simplement de problèmes de programmation linéaires. Supposant que les demandes et les capacités routières sont distribuées conjointement et de façon continue, l'équivalent déterministe est obtenue par la méthode d'approximation d'échantillon moyen. En outre, nous avons construit une formulation ajustée du risque à plusieurs étapes en utilisant la valeur conditionnelle à risque et le problème est résolu grâce à la méthode de programmation dynamique stochastique double (SDDP) dans le cadre acceptable des hypothèses générales. L'algorithme proposé est testé avec les données réelles issues de la partie Asiatique d'Istanbul.

ÖZET

Afet yönetimi konusu insan üzerindeki büyük ve yıkıcı etkileri sebebiyle özellikle son yıllarda gerek akademisyen ve araştırmacıların gerekse belediyelerin sıklıkla çalıştığı bir konu olmuştur.

Bu olaylardaki artış, iyi tanımlanmış yöntemler ile acil ve etkili bir yanıt gerektirir. Ancak bu olayların rastgele oluşması bu problem ile başa çıkmayı zorlaştırır. Bu çalışma üç aşamalı tedarik zinciri problemi olarak ele alınarak çalışmada alınan kararlar afet öncesi ve afet sonrası olmak üzere ayrılmış, her iki problem de matematiksel olarak ifade edilmiştir. Afet öncesi kararlar ana depoların (tedarikçiler) envanter kararlarını ve açılması gereken dağıtım merkezleri kararlarını içermektedir. Bu kararlar ilk aşamada afet öncesinde alındığından rastgele verileri gözlemlemeden önce verilir. Afet sonrası kararlar ise problemde ikinci ve daha sonraki aşamalarda rastgelelik gözlemlendikten sonra sadece mevcut envanterler kullanılarak ve değişen yol kapasitelerini, talepleri göz önünde bulundurarak yollardan gönderilmesi gereken ürün miktarı ve taleplerin ne kadarının karşılanacağı kararlarıdır. Matematiksel olarak ilk aşama problemi karışık tamsayılı doğrusal optimizasyon problemi iken ikinci ve sonraki aşama problemleri doğrusal programlama problemleridir. Bu çalışmada talep ve yol kapasitelerinin ortak olasılık dağılımı olduğunu varsayarak sürekli dağılıma uyan bu verilerin deterministik eşleniği örnek ortalaması yöntemiyle (SAA) elde edilmiştir. Problem formülasyonu, risk altında koşullu değer (CV@R) kullanarak çok aşamalı olarak geliştirilmiş ve oldukça genel varsayımlar altında SDDP methodu ile çözlümüştür. Önerilen algoritma İstanbul'un Asya yakası için elde edilen gerçek bir problem üzerinde uygulanmıştır.

1 INTRODUCTION

Disasters are inevitable events that threatens vast majority of human lives and causes damage, destruction, human suffering, even loss of lives. International Federation of Red Cross and Red Crescent (IFRC) defines a 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”.

Disasters are either caused by natural phenomena or human action. IFRC definition for natural disasters is as follows: Natural disasters are naturally occurring physical phenomena caused either by rapid or slow onset events which can be geophysical (earthquakes, landslides, tsunamis and volcanic activity), hydrological (avalanches and floods), climatological (extreme temperatures, drought and wildfires), meteorological (cyclones and storms/wave surges), or biological (disease epidemics and insect/animal plagues). Some examples of man-made disasters are nuclear accidents, oil spills and terrorist actions.

Unfortunately, the frequency in the disasters has significantly increased in recent years. Many people died or suffered because of several devastating disasters. Especially, the increase of natural disasters as can be seen in Figure 1, directed this study to be focusing on natural disasters. The Figure 1.1 is taken from one of the disaster databases called EM-DAT.

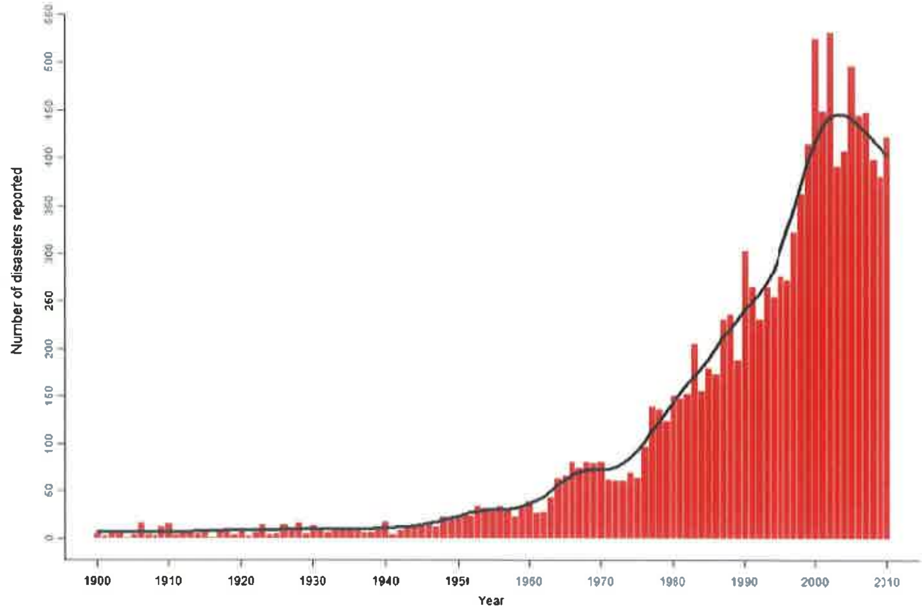

Figure 1.1 Natural Disasters Reported 1990-2010(source: http://www.emdat.be/natural-disasters-trends)

The frequency in the occurrence of disasters has also increased the attention of municipals, federal agencies and researchers on this subject in the recent years. Yet, disaster management issues are challenging due to its uncertain occurrence. However, there is a growing literature regarding this subject. [1] surveyed the OR/MS studies in the field and [2] surveyed the disaster problems with respect to humanitarian logistics as delivering goods and services to distribution points and casualties. After the recent large scale disasters, it has been clearly seen that disaster management operations has to be improved in the field as [3] provided the vital need for improved solution algorithms for relief and evacuation operations and also the logistics of humanitarian aid in this area.

No matter the type of disaster, the management of these events typically follows three phases: pre-disaster, response and post-disaster phase. Pre-disaster phase can be studied as two stages: mitigation and preparedness. Mitigation is action plans to help reducing or eliminating the future risks and effects of hazards of the disaster and take necessary precautions. Preparedness is a practiced state of being ready to respond under emergency circumstances. Federal Emergency Management Agency (FEMA) defines preparedness as a continuous cycle of planning, managing, organizing, training, equipping, exercising, creating, monitoring, evaluating and improving activities to ensure effective coordination and the enhancement of capabilities of concerned organizations. (source: http://www.fema.gov/prepared/index.shtm)

Response phase can be separated into two groups: relief distribution and evacuation. Relief distribution can be defined as emergency plan activation for municipals or emergency centers to satisfy basic humanitarian needs. With the help of organizations and agencies relief distribution concerns with delivering the necessary and urgent needs to casualties immediately. Evacuation operations on the other hand, is to mobilize emergency responders and services to the affected region and moving vulnerable people to non affected places or somewhere safe after a disaster hits.

Post-disaster phase includes recovery process which can be defined as the stabilization phase or restoration of affected regions or returning to former and normal life of people. Recovery can also be briefly defined as rebuilding of essential roads, properties and infrastructure. It also includes mental rehabilitation and re-employment processes which are essential needs for human no more to suffer of a disaster.

In study [1] it is summarized that the list of disaster activities that can be involved in four of the above mentioned phases separately. We have modified that table accordingly and modified version of the activities can be found in Table 1.1.

Table 1.1 Typical disaster operations (source: Altay and Green, 2006)

Mitigation
- Zoning and land use controls to prevent occupation of high hazard areas
- Barrier construction to deflect disaster forces
- Active preventive measures to control developing situations
- Building codes to improve disaster resistance of structures
- Risk analysis to measure the potential for extreme hazards
- Insurance to reduce the financial impact of disasters

Preparedness
- Recruiting personnel for the emergency services and for community volunteer groups
- Emergency planning
- Development of mutual aid agreements and memorandums of understanding
- Training for both response personnel and concerned citizens
- Threat based public education
- Budgeting for and acquiring vehicles and equipment
- Maintaining emergency supplies
- Construction of an emergency operations center
- Development of communications systems
- Conducting disaster exercises to train personnel and test capabilities

Response
- Activating the emergency operations plan
- Activating the emergency operations center
- Evacuation of threatened populations
- Opening of shelters and provision of mass care
- Emergency rescue and medical care
- Fire fighting
- Urban search and rescue
- Emergency infrastructure protection and recovery of lifeline services
- Fatality management

Recovery
- Disaster debris cleanup
- Financial assistance to individuals and governments
- Rebuilding of roads and bridges and key facilities
- Sustained mass care for displaced human and animal populations
- Reburial of displaced human remains
- Full restoration of lifeline services
- Mental health and pastoral care

The increase in the natural disasters and the urgent need of efficient solution methodologies in the area led us focus on natural disasters in this study. The remainder of this study is as follows: In chapter 2, literature review on disaster phases and various solving techniques will be provided. Chapter 3 summarizes this thesis and explains our motivation and contributions to the literature. Next, the problem will be defined in chapter 4. Chapter 5 will demonstrate the proposed methodology to solve the problem. Subsequent to that, in chapter 6 we provide an illustrative example in order to simply explain the problem. In chapter 7, a case study is provided with real life data that is obtained for Istanbul Asian side. This thesis is concluded in chapter 8.

2 LITERATURE REVIEW

We reviewed the literature of disaster management by classifying the studies into three groups as pre-disaster, recovery and post-disaster respectively. Pre-Disaster phase can be separated into two groups as mitigation and preparedness while recovery phase can also be separated into two groups as evacuation and relief distribution. We will discuss some of the key papers in each category.

2.1 MITIGATION

There are number of studies which focused on eliminating or reducing the risks of hazards of disasters. For instance, [4] dealt with mitigating natural disaster risks with occur with low probability but has high consequences. They studied with hypothetical data and compared two methods of expected utility theory and the value function under risk. They concluded value function under risk is more useful for evaluating public risks. [5] also focused on mitigation phase of a disaster by determining on which roads to strengthen on a stochastic network by minimizing the expected traversal cost. They modeled the problem as a two stage stochastic model where first stage determines the link to do investment and the second stage minimizes traversal costs. They implemented their model on Istanbul's urban highway system to determine the roads to strengthen in case of an earthquake.

2.2 PREPAREDNESS

In study [6] maximal covering problem to locate a possible facility for medical supplies in emergency situations so that demand of people can be satisfied maximally as a response is studied. They have proposed three different heuristics and obtained effective results for large scale problems. [7] focused on flood emergency planning operations in terms of determination a rescue resource distribution system under stochastic structure. They have modeled a scenario based stochastic problem and examined those problems with sample average approximation (SAA) method. They determined the amount of rescue equipment stored the location of those equipment and distribution of that equipment.

Study [8], focused on determining the locations and quantities of emergency supplies in a pre-disaster phase. They performed scenario analysis about the occurrence of a disaster. In addition, they performed two-stage stochastic mixed integer programming for the problem. They solved small sized problems with CPLEX solver. However for the large scaled problems they proposed a heuristic algorithm referred as Lagrangian L –shaped method. [9] has further studied the problem by including risk measure on the total cost by incorporating CV@R. In addition, [10] examined where to position the supplies in pre disaster phase of a disaster. They also take the tradeoff between closeness and riskiness into account by indicating the closer locations are chosen for the suppliers the more risky it would be for the deterioration of supplies. They derived equations and performed sensitivity analyses in order to determine the optimal stock quantity and associated total expected costs.

2.3 RESPONSE

There is a fast growing literature also in humanitarian logistics area. Some of them focused on response problems. Some consider relief distribution and some others studied evacuation problems and few of the researchers focused on both response and preparedness problems concurrently. One of the pioneer studies that addresses relief distribution is [11]. They have considered multi commodity multi modal network flow problem. They have built a mathematical model with cost minimization objective where they have also determined the routing and scheduling of transportation modes. Solving the problem, they have developed two different heuristics and examined their performances on the different sized problems. Similarly, [12] considered a relief distribution problem as multi commodity multi model vehicle routing problem with soft time windows where penalizing the excess of upper and lower time limits are employed.

They proposed two heuristic approaches to solve the problem while implementing their methodologies to a real life case.

In study [13] developed scenario based stochastic programming model formulated as two stage linear SP for multi-commodity multi-modal disaster relief operations. They provided exact solutions for the problem and validated their model on an occurred disaster in Turkey. Study [14] constructed multi objective mathematical model with three objectives for the three layer relief distribution problem. They considered minimizing total cost, minimizing total travel time and maximizing the minimal satisfaction within the planning period. They used fuzzy logic to combine the objective functions. They provided exact solution method.

In study [15] a prudent plan for relief routing operations is provided. They compared how the determined routes change regarding to efficiency, efficacy and equity measures. For small sized problems they used exact methods. However, for large scaled problems they proposed a heuristic algorithm which satisfies the urgent needs at different locations.

Evacuating casualties from affected regions and/or mobilizing hospitals and medicine is also highly studied in the literature. For example, [16] studied evacuation operations on a possible disaster. They have proposed to transport commodities from affected areas. In addition, they also proposed and developed a model to consider opening temporary emergency units in order to reach wounded people faster. In [17] evacuating casualties with a three step approach is shown. In the first step appropriate safe place for evacuees are selected. In the second step, optimum routes are determined to the safe regions. Finally, optimum distribution of the people to the safe areas is determined as the third step. Problem solutions are obtained via NSGA II algorithm in GIS environment. Study [18] suggested that the travel speed on any arc will decrease continuously in time after a disaster hits. They proposed a decrease function of speed and modeled the problem both with single and multi objective formulations. They solved the single objective mathematical model with modified Dijkstra Algorithm and for multi objective programming they used ant colony optimization method. Since this study only concentrated on travel speeds it will not be wrong to classify that sedulous work both as relief distribution and evacuation problem. Study [19] applied robust optimization (RO) to cell transmission model (CTM) for emergency evacuation problem by ensuring optimum dynamic traffic assignments. They proposed to use S-shaped curves for modeling uncertain demand.

2.4 RECOVERY

Although few compared to other studies, some studies focused both on relief distribution and preparedness such as [20] presented relief distribution approach for quick responding in emergency situations during the most crucial three day period. They proposed five considerable steps in the problem. These are demand forecasting, demand area grouping, distribution priority determining, relief distribution and dynamic relief supply unless the urgent demand is satisfied respectively. The proposed approach was implemented on real large scale earthquake data observed in Taiwan. Further, [21] implemented data fusion techniques to relief demand information and he classified the affected area into groups and he implemented multi criteria decision making tools to determine the priority of the demand groups. In addition, [22] consider where to store medical supplies at which inventory levels so as to use them aftermath of a disaster. They capture a two stage stochastic model which also determines alternative transportation plans. They perform a case study for operating earthquakes in Seattle area. Moreover, [23] considered a three layer supply chain model for delivering goods to casualties at the affected areas. They have built a deterministic mathematical model with three objectives (i.e. minimizing fixed cost, minimizing the budget and maximizing the demand sent to people) and employed both an exact and a heuristic approach for solving the problem.

To the best of our knowledge, not much attention is been given to recovery problems from mathematical modeling perspective. Study [24] is the initial paper which considers a mixed-integer multi objective mathematical model which aims to minimize length of time required for relief distribution and roadway repair. They have solved the problem both with an exact and a heuristic method. Moreover, [25] modeled disaster recovery planning problem with mixed integer programming method where the objective function maximizes the recovery capability of the set of sub-plans chosen. To solve the problem, they have used both optimal and heuristic approaches. Besides, [26] analyzed the effects of retail facilities during post disaster phase and with the questionnaires they concluded that negative changes in retail facilities weakens individuals satisfaction and so self-efficacy.

We provide the summary of classification of the above mentioned papers in Table 2.1.

Table 2.1 Classification of Literature

	Pre-Disaster		**Response**		**Post-Disaster**
	Mitigation	Preparedness	Relief Distribution	Evacuation	Recovery
Huang et al., 2011 [15]			x		
Tamura et al. 2000 [4]	x				
Bryson et al. 2002 [25]					x
Lin et al., 2011 [12]			x		
Rath and Gutjahr 2011 [23]		x	x		
Saadatseresht et al., 2009 [17]				x	
Haghani and Oh 1995 [11]			x		
Yie and Ozdamar 2007 [16]				x	
Chang et al., 2007 [7]		x			
Jia et al.,2007 [6]		x			
Barbarosoglu and Arda 2004 [13]			x		
Rawls and Turnquist 2010 [8]		x			
Liu et al., 2011 [26]					x
Tzeng et al., 2007 [14]			x		
Campbell and Jones 2010 [10]		x			
Yan and Shih 2009 [24]			x		x
Ben-Tal et al., 2010 [19]				x	
Mete and Zabinsky 2010 [22]		x	x		
Peeta et al., 2010 [5]	x				
Yuan and Wang 2009 [18]			x	x	
Sheu 2007 [20]		x	x		
Noyan 2011 []		x			
Sheu 2010 [21]			x		

3 SUMMARY OF THESIS

This aim of this chapter is to summarize the thesis and explain our motivation and contributions to the literature.

The increase in natural disasters - especially in the recent years - motivated us to focus on natural disasters in this study. The greatest issues while dealing with such a problem is the random occurrence of disasters and uncertainty in demand and road capacities. After reviewing the literature, we have seen that not many studies focused on both the pre and post phases of a disaster so that in that study, we focused on both phases. The pre-disaster decisions in this study are the inventory decisions at the main depots (relief suppliers) and the location decisions of the relief distribution centers. Since, no disaster has occurred until that point; these decisions are made before observing any random data. After a disaster hits, uncertain demand occurs. To the best of our knowledge, apart from all other studies in the literature so far, we have assumed the demand is jointly and continuously distributed. We have also considered the road capacities might have changed due to a building collapse on a road or for any other reason which led us to consider randomly changing road capacities that are also jointly and continuously distributed. After observing the randomness, aftermath of a disaster, the demands are satisfied using only the available inventories at the main depots and passing through the previously selected distribution centers. Mathematically, the first-stage problem is a mixed-integer linear optimization problem, whereas the problems at the later stages are simply linear programming problems. The deterministic equivalent is obtained through the sample average approximation method. In addition, we built risk-adjusted multistage formulation using conditional value at risk and the problem is solved through the stochastic dual dynamic programming (SDDP) method under fairly general assumptions. The proposed algorithm is applied on a real life data that is obtained for Asian side of Istanbul.

4 PROBLEM DEFINITION

We consider a T- stage stochastic program in which a sequence of decisions $\{x_t\}_{t=1}^{T}$ is made with respect to a random process $\{\widetilde{\xi}\}_{t=1}^{T}$ as follows. At stage t, the decision x_t is made with only the knowledge of past decisions $x_1, x_2, ..., x_{t-1}$, and the realizations of the random vectors $\widetilde{\xi}_1, \widetilde{\xi}_2, ..., \widetilde{\xi}_t$. We denote the history of the random process up to stage t by $\widetilde{\xi}_{[t]} = (\widetilde{\xi}_1, \widetilde{\xi}_2, ..., \widetilde{\xi}_t)$. Furthermore, the decision x_t does not depend on the future realizations of the random vectors $\widetilde{\xi}_{t+1}, \widetilde{\xi}_{t+2}, ..., \widetilde{\xi}_T$; i.e., the decision process is nonanticipative.

We formulate this T-stage problem through dynamic programming equations, as follows. At stage t =1, we solve the problem

$$\begin{aligned} &\operatorname*{Min}_{x_1 \geq 0} \ c_1^T x_1 + \mathrm{E}\left[Q_2\left(x_1, \widetilde{\xi}_{[2]}\right) | \ \widetilde{\xi}_{[1]}\right] \\ &\text{s.t.} \operatorname{Prob}\left\{Q_2\left(x_1, \widetilde{\xi}_{[2]}\right) \leq \eta_2 \ | \ \widetilde{\xi}_{[1]}\right\} \geq 1 - \alpha_2 \\ &A_1 x_1 = b_1 \end{aligned} \tag{4.1}$$

where for later stages t = $2, ..., T$, the so-called cost-to-go functions $Q_t\left(x_{t-1}, \widetilde{\xi}_{[t]}\right)$ are given by

$$\begin{aligned} Q_t\left(x_{t-1}, \widetilde{\xi}_{[t]}\right) = &\operatorname*{Min}_{x_t \geq 0} \ c_t^T x_t + \mathrm{E}\left[Q_{t+1}\left(x_t, \widetilde{\xi}_{[t+1]}\right) | \ \widetilde{\xi}_{[t]}\right] \\ &\text{s.t} \operatorname{Prob}\left\{Q_{t+1}\left(x_t, \widetilde{\xi}_{[t+1]}\right) \leq \eta_{t+1} \ | \ \widetilde{\xi}_{[t]}\right\} \geq 1 - \alpha_{t+1} \\ &\widetilde{B}_t x_{t-1} + A_t x_t = \widetilde{b}_t \end{aligned} \tag{4.2}$$

In the following, the notation in (4.1) and (4.2) is defined. $\mathrm{E}[.|.]$ and $\Pr ob\{.|.\}$ denote the conditional expectation and conditional probability, respectively. The random vector $\tilde{\xi}_t$ consists of the random components from $\left(\tilde{B}_t, \tilde{b}_t\right)$, a realization of $\tilde{\xi}_t$ is denoted by ξ_t, and $\tilde{\xi}_{[1]} = \tilde{\xi}_1 = b_1$ is deterministic; hence, the conditional expectation and the conditional probability in (4.1) are in fact unconditional. Furthermore, the conditional probability distribution $P_{t|\tilde{\xi}_{[t-1]}}$ of $\tilde{\xi}_t$ given $\tilde{\xi}_{[t-1]}$ is assumed to be known, and this $P_{t|\tilde{\xi}_{[t-1]}}$ is supported on set $\Xi_t \subset R^{d_t}$. The first-stage decision x_1 is partitioned into two subvectors $x_1 = \left(x_1^{'T}, x_1^{''T}\right)^T$, where $x_1^{'} \in R^{n_1^{'}}$, $x_1^{''} \in \{0,1\}^{n_1^{''}}$ and $n_1 = n_1^{'} + n_1^{''}$. The decisions x_t for later stages t = 2,..., T are real vectors; i.e. $x_t \in R^{n_t}$. The scalars η_t and α_t are given budget and significance levels, respectively, where $\alpha_t \in (0,1)$. The dimensions of the vectors and matrices are as follows: $c_t \in R^{n_t}$, $\tilde{b}_t \in R^{m_t}$, $A_t \in R^{m_t x n_t}$, and $\tilde{B}_t \in R^{m_t x n_{t-1}}$. We assume that the random process $\left\{\tilde{\xi}_t\right\}_{t=1}^T$ is stagewise independent; i.e. $\tilde{\xi}_{t+1}$ is independent of $\tilde{\xi}_{[t]}$. Under the independence assumption, (4.1) and (4.2) are simplified to

$$
\begin{aligned}
&\underset{x_1 \geq 0}{\text{Min}} \; c_1^T x_1 + \mathrm{E}\left[Q_2\left(x_1, \tilde{\xi}_2\right)\right] \\
&\text{s.t.} \;\; \Pr ob\left\{\mathrm{Q}_2\left(x_1, \tilde{\xi}_2\right) \leq \eta_2\right\} \geq 1 - \alpha_2 \\
&\qquad A_1 x_1 = b_1
\end{aligned}
\tag{4.3}
$$

and for t = 2, …, T-1

$$
\begin{aligned}
&\underset{x_1 \geq 0}{\text{Min}} \; c_1^T x_1 + \mathrm{E}\left[Q_{t+1}\left(x_t, \tilde{\xi}_{t+1}\right)\right] \\
&\text{s.t.} \;\; \Pr ob\left\{\mathrm{Q}_{t+1}\left(x_t, \tilde{\xi}_{t+1}\right) \leq \eta_{t+1}\right\} \geq 1 - \alpha_{t+1} \\
&\qquad \tilde{\mathrm{B}}_t x_{t-1} + A_t x_t = b_t
\end{aligned}
\tag{4.4}
$$

That is, both the conditional expectation and the conditional probability become unconditional. Additionally, at stage t = T, $\mathrm{E}\left[Q_{T+1}\left(x_T, \tilde{\xi}_{T+1}\right)\right] = 0$ by convention, and we assume that the chance constraint $\Pr ob\left\{\mathrm{Q}_{T+1}\left(x_T, \tilde{\xi}_{T+1}\right) \leq \eta_{T+1}\right\}$ holds with probability 1. Then, the problem (4.2) for t = T is further simplified to

$$\begin{aligned}&\operatorname*{Min}_{x_T \geq 0} c_T^T x_T\\&\text{s.t. } \widetilde{B}_T x_{T-1} + A_T x_T = \widetilde{b}_T\end{aligned} \tag{4.5}$$

The formulations (4.3) and (4.4) provide a risk-adjusted approach to the problem; i.e., they minimize the cost-to-go functions $Q_t\left(x_{t-1}, \widetilde{\xi}_t\right)$ on average while controlling the upper limits of the corresponding cost-to-go functions for different realizations of the random process. A well-known problem of such formulations is that chance constraints usually define non-convex feasible sets. It was suggested in [27] and [28] to replace chance constraints by conditional value-at-risk constraints, where the Conditional Value-at-Risk of a random variable Z at significance level α is defined as

$$\text{CV@R}_\alpha[Z] := \inf_{\eta \in R}\left\{\eta + \alpha^{-1}\text{E}[Z-\eta]_+\right\} \tag{4.6}$$

where $[Z-\eta]_+ = \max\{Z-\eta, 0\}$. It was further shown in [27] and [28] that (4.6) is a convex conservative approximation to its corresponding chance constraint; i.e., the feasible set defined by $\text{CV@R}_\alpha[Z] \leq \eta$ is contained in the feasible set defined by $\Pr ob\{Z \leq \eta\} \geq 1-\alpha$. Therefore, in our analysis, we will replace the chance constraints in (4.3) and (4.4) by their corresponding CV@R_α constraints.

We assume relatively complete recourse for the problems in (4.3), (4.4) and (4.5) ignoring the chance constraints in (4.3) and (4.4); i.e., given any feasible solution $(x_1, \ldots, x_{t-1})$ to any t -1 stage problem defined by a realization $\xi_{[t-1]}$ of the random data, there exists a feasible solution x_t for any t^{th} –stage problem for almost every realization of $\widetilde{\xi}_t$. However, the chance constraints are consequently the CV@R_α constraints can make (4.3) and (4.4) infeasible. Therefore, we relax the CV@R_α constraints as follows. Let

$$\rho\lambda_t\left[Q_t\left(x_{t-1}, \widetilde{\xi}_t\right)\right] := (1-\lambda_t)\text{E}\left[Q_t\left(x_{t-1}, \widetilde{\xi}_t\right)\right] + \lambda_t \text{CV@R}_{\alpha_t}\left[Q_t\left(x_{t-1}, \widetilde{\xi}_t\right)\right] \tag{4.7}$$

be real-valued functions of the random variables $Q_t\left(x_{t-1},\tilde{\xi}_t\right)$, where $\mathrm{E}\left[Q_t\left(x_{t-1},\tilde{\xi}_t\right)\right]$ are assumed to be well-defined and finite. In (4.7), $\lambda_t \in [0,1]$ are parameters that can be tuned for a tradeoff between minimizing on average and risk control. Using (4.6) and (4.7), we obtain the final formulations from (4.3) and (4.4), which we will use throughout the paper. Now, at $t = 1$, we solve

$$\begin{aligned} \underset{x_1^{'}\geq 0, x_1^{''}\in\{0,1\}^{n_1^{''}}, q_2\in R}{\text{Min}} \quad & c_1^T x_1 + \lambda_2\eta_2 + \mathrm{E}\left\{(1-\lambda_2)Q_2\left(x_1,\tilde{\xi}_2\right) + \lambda_2\alpha_2^{-1}\left[Q_2\left(x_1,\tilde{\xi}_2\right)-\eta_2\right]_+\right\} \\ \text{s.t.} \quad & A_1 x_1 = b_1 \end{aligned} \tag{4.8}$$

And at $t = 2, \ldots, T\text{-}1$, we solve

$$\begin{aligned} \underset{x_t\geq 0, q_{t+1}\in R}{\text{Min}} \quad & c_t^T x_t + \lambda_{t+1}\eta_{t+1} + \mathrm{E}\left\{(1-\lambda_{t+1})Q_{t+1}\left(x_t,\tilde{\xi}_{t+1}\right) + \lambda_{t+1}\alpha_{t+1}^{-1}\left[Q_{t+1}\left(x_t,\tilde{\xi}_{t+1}\right)-\eta_{t+1}\right]_+\right\} \\ \text{s.t.} \quad & \tilde{\mathrm{B}}_t x_{t-1} + A_t x_t = b_t \end{aligned} \tag{4.9}$$

At $t = T$, we solve (4.5). The solution procedure will be explained in section 5.

4.1 NOTATION

Sets

A : Set of all arcs

A_1 : Set of arcs from suppliers to distribution centers.

A_2 : Set of arcs from distribution centers to affected casualties

I : Set of all suppliers

J : Set of all distribution centers

K : Set of affected casualty nodes.

Variables at pre-disaster phase

$x_{i,t}$ = stock level of commodity at supplier i at stage t

$$q_j = \begin{cases} 1, \text{ if distribution center } j \text{ is opened} \\ 0, \text{ otherwise} \end{cases}$$

Variables at post-disaster phase

$y_{i,j,t}$ = amount of commodity send from supplier *i* to distribution center *j* at stage *t*

$y''_{j,k,t}$ = amount of commodity send from distribution center *j* to affected area *k* at stage *t*

$w_{k,t}$ = amount of short commodity in affected area *k* at stage *t*

$z_{k,t}$ = amount of excess commodity in affected area *k* at stage *t*

η = a variable enforces probabilistic constraint to be feasible

π_t = optimal dual solution for stage *t*.

Parameters

$s_{i,t}$ = supply limit (in volumes) of supplier *i* at stage *t*

$c_{i,t}$ = cost of keeping one unit of commodity in supplier *i* at stage *t*

f_j = fixed cost of opening distribution center *j*

$m_{i,j,t}$ = unit cost of transportation from supplier i to distribution center *j* at stage *t*

$m_{j,k',t}$ = unit cost of transportation from distribution center *j* to affected area *j* at stage *t*

$p_{k,t}$ = penalty cost of having short demand in affected area *k* at stage *t*

$h_{k,t}$ = penalty cost of having excess demand in affected area *k* at stage *t*

$\widetilde{d}_{k,t}$ = random demand of affected area *k* at stage *t*

$\widetilde{\delta}_{i,j,t}$ = random road capacity of link between supplier *i* and DC *j* at stage *t*

$\widetilde{\delta}'_{j,j,t'}$ = random road capacity of link between distribution center *j* and distribution center j' at stage *t*

$\widetilde{\delta}''_{j,k,t}$ = random road capacity of link between distribution center *j and* affected area *k* at stage *t*

v = a constant used for denoting volume of commodity with value $3m^3$

α = a constant used for denoting significance level at time *t*

λ = a constant used for denoting a tradeoff between expected cost and risk at time *t*

N = a constant used for denoting sample size for SAA

M = a constant used for denoting sub-sample size for SAA

4.2 MATHEMATICAL MODEL

In this section we are going to provide mathematical problem that we built for the dealt problem where first stage model is simply mixed integer linear programming and the second and later stages are linear programming problems. The first stage problem is modeled through set of equations as shown below.

$$\text{Min} \sum_{i \in I} c_{it} x_{it} + \sum_{j \in J} f_j q_j + \lambda \eta + \text{E}\left[(1-\lambda) Q_2(y_1, \xi_2) + \lambda \alpha^{-1} [Q_2(y_1, \xi_2) - \eta]_+\right] \quad (4.10)$$

subject to

$$v x_{it} \leq s_{it} \qquad \forall i \qquad (4.11)$$

$$\sum_{j \in J} q_j \geq 1 \qquad (4.12)$$

$$x_{it} \geq 0 \qquad \forall i \qquad (4.13)$$

$$q_j \in \{0,1\} \qquad \forall j \qquad (4.14)$$

In this model, the objective function (4.10) is minimizing total cost resulting from stock keeping, distribution center opening and second level cost. We compute deterministic equivalent of random components of $\tilde{\xi}_t$ with SAA method. Therefore, the equation (4.10) becomes the following form (4.15).

$$\text{Min} \sum_{i \in I} c_{it} x_{it} + \sum_{j \in J} f_j q_j + \lambda \eta + \frac{(1-\lambda)}{N} \sum_{n=1}^{N} Q_2(y_1, \xi_2) + \frac{\lambda}{\alpha N} \sum_{n=1}^{N} [Q_2(y_1, \xi_2) - \eta]_+ \quad (4.15)$$

Equation (4.15) defines the objective function after applying SAA method to stochastic data. Constraint (4.11) ensures stock kept in inventory in a supplier can not be higher than the capacity of that supplier as a volume. Constraint (4.12) ensures to open at least one distribution center to transport commodities to casualties at the affected areas. Constraints (4.13) and (4.14) define and constrain the variables as explained above.

After a disaster hits the realization of random vector $\tilde{\xi}_t$ as ξ_t, at stages t = 2,…, *T*. $Q_t(y_{t-1}, \tilde{\xi}_t)$ is given by the optimal value of the following second and later stages problem

$$\begin{aligned}\min_{y_t \in R^{|A|}, w_t \in R^K, z_t \in R^K} & \sum_{(i,j)\in A_1} m_{ijt} y_{ijt} + \sum_{(j,k)\in A_2} m_{jkt} y_{jkt} + \sum_{k\in K} p_{kt} w_{kt} + \sum_{k \in K} h_{kt} z_{kt} + \lambda \eta \\ & + \mathrm{E}\left[(1-\lambda) Q_{t+1}(y_t, \xi_{t+1}) + \lambda \alpha^{-1}\left[Q_{t+1}(y_t, \xi_{t+1}) - \eta\right]_+\right]\end{aligned} \tag{4.16}$$

subject to

$$\sum_{\{i:(i,j)\in A_1\}} y_{ijt} = \sum_{\{k:(j,k)\in A_3\}} y_{jkt} \qquad \forall j \tag{4.17}$$

$$\sum_{\{j:(j,k)\in A_3\}} y_{jkt} + w_{kt} - z_{kt} = \tilde{d}_{kt} \qquad \forall k \tag{4.18}$$

$$\sum_{\{j:(i,j)\in A_1\}} y_{ijt} \le x_{it} \qquad \forall i \tag{4.19}$$

$$v x_{it} + v\left(x_{i(t-1)} - \sum_{(i,j)\in A_1} y_{ijt}\right) \le s_{it} \qquad \forall i \tag{4.20}$$

$$v y_{ijt} \le \tilde{\delta}_{ijt} q_j \qquad \forall (i,j) \in A_1 \tag{4.21}$$

$$v y_{jkt} \le \tilde{\delta}_{jkt} q_j \qquad \forall (j,k) \in A_2 \tag{4.22}$$

$$y_{ijt} \ge 0 \qquad \forall (i,j,k) \in A \tag{4.23}$$

$$w_{kt}, z_{kt} \ge 0 \qquad \forall k \tag{4.24}$$

The objective function (4.16) minimizes the total transportation costs and expected cost of later stages. Similar to the first stage problem, we also find the discrete equal of the random data with SAA method and obtain a new objective function as it is shown in equation (4.25).

$$\begin{aligned}\underset{y_t \in R^{|A|}, w_t \in R^K, z_t \in R^K}{\text{Min}} & \sum_{(i,j)\in A_1} m_{i,j}^t y_{i,j}^k + \sum_{(j,k)\in A_3} m_{j,k}^t y_{j,k}^k + \sum_{k\in K} p_k^t w_k^t + \sum_{k\in K} h_k^t z_k^t \\ & + \lambda\eta + \frac{(1-\lambda)}{N}\sum_{n=1}^{N} Q_{t+1}(y_t,\xi_{t+1}) + \frac{\lambda}{\alpha N}\sum_{n=1}^{N}\left[Q_{t+1}(y_t,\xi_{t+1})-\eta\right]_+\end{aligned} \quad (4.25)$$

In this study, we assumed once a commodity arrives to a distribution center it has to be delivered to any demand point and so no inventory is kept in distribution centers. Constraint (4.17) is a well-known flow conservation constraint that ensures to transport all commodities that entered to a distribution center is transported. Constraint (4.18) ensures satisfying demands of affected areas. In case of shortage and overage quantities objective function would penalize these amounts and so the model is forced to meet the demands. Constraint (4.19) guarantees to use the amount of inventory that has been decided on the previous stages. Constraint (4.20) balances supplier limits at every stage for every supplier. Constraints (4.21) and (4.22) are built so as not to exceed road capacity of each arc. Constraints (4.23) and (4.24) define and constrain the variables as explained above.

5 METHODOLOGY

The goal of this chapter is to introduce SDDP approach to multistage risk adjusted disaster preparedness and relief distribution problem. To begin with, we assume that the random process $\{\tilde{\xi}_t\}_{t=1}^{T}$ is stagewise independent; i.e. $\tilde{\xi}_{t+1}$ is independent of $\tilde{\xi}_{[t]}$. We also assume that the implementation is performed in two steps. First, a finite scenario tree is generated by randomly sampling from the original distribution and then the constructed problem is solved by the SDDP algorithm. A current opinion is that the approach of random generation of scenarios (the so-called Sample Average Approximation (SAA) method) is computationally intractable for solving multistage stochastic programs because of the exponential growth of the number of scenarios with increase of the number of stages [29]. An interesting property of the SDDP method is that the computational complexity of one run of the involved backward and forward step procedures is proportional to the sum of sampled data points at every stage and not to the total number of scenarios given by their product. This makes it computationally feasible to run several such backward and forward steps. Of course, this still does not give a proof of computational tractability of the true multistage problem. It also the fact that, this nice property holds because of the stagewise independencency assumption.

We also assume that we can sample from the probability distribution P_t of the random vector ξ_t , t = 2, …, T (recall that ξ_t is deterministic, not random). A sample average approximation (SAA) of the true problem is constructed by replacing the true distribution of ξ_t, by the empirical distribution P_{N_t} based on a random sample $\tilde{\xi}_t = \left(\tilde{B}_t, \tilde{b}_t\right)$ from P_t of size N_t. Consequently the probability distribution of the random process is replaced by its finitely generated distribution [29].

A backward step of the SDDP algorithm, applied to the SAA problem, can be described as follows. Let $\bar{x}_t \in R^{n_t}$ be a trial decision at stage t = 1,..., T-1 and $Q_t(.)$ be a current approximation of the cost-to-go function $\widetilde{Q}_t(.)$, given by the maximum of a collection of cutting planes, at stage t = 2,..., T. At stage t = T we solve the problem (4.2) and let $\widetilde{y}_{T,n}$ be an optimal solution of problem (4.2) where n= 1,...,N and $\widetilde{\pi}_{T,n}$ be an optimal solution of its dual. Then equation (5.3)

$$\widetilde{Q}_T(x_{T-1}) = \frac{1}{N}\sum_{n=1}^{N} c^T y_{Tj} \tag{5.1}$$

has to be calculated as the SAA equivalent of the second stage problem. Similarly, in order to construct the supporting plane for $Q_T(.)$ at y_{T-1}, sub-gradient of second stage problem has also be calculated as given in equation (5.2)

$$\widetilde{g}_T = -\frac{1}{N}\sum_{n=1}^{N} \widetilde{B}_T \widetilde{\pi}_T \tag{5.2}$$

Then, the calculated supporting plane

$$l_T(x_{T-1}) = \widetilde{Q}_T(\bar{x}_{T-1}) + \widetilde{g}_T^T(x_{T-1} - \bar{x}_{T-1}) \tag{5.3}$$

is added to the problem as a new constraint as shown in equation (5.3). The problem (4.1) is solved with the new added constraint again.

The forward step of the SDDP algorithm consists in generating M random realizations (scenarios) of the data process and computing the respective optimal values

$$v_j = \sum_{t=1}^{T} c_t^T \bar{x}_t \qquad j = 1,...M \tag{5.4}$$

Consequently the sample average $\bar{\nu}$ and sample variance $\tilde{\sigma}_{\upsilon}^{2}$ are calculated, by using the formulas to construct the respective confidence intervals as $\bar{\upsilon} \pm z_{\alpha}\hat{\sigma}_{\alpha} / \sqrt{M}$.

One run of the backward step procedure requires solving 1 + N_2 + ...+ N_T linear programming problems. Each of these problems has a fixed number of decision variables and constraints with additional variables and constraints corresponding to cutting planes of the approximate functions $Q_t(.)$. That is, complexity of one run of the backward step procedure is more or less proportional to the sum of the sample sizes, while the total number of scenarios is given by the product of the sample sizes. Therefore, for a not too large number of N one can run a reasonable number of backward steps of the algorithm, while the total number of scenarios could be astronomically large. Similarly, one run of the forward step procedure involves solving T-1 linear programming problems and could be run for a reasonably large number of repetitions M. The forward step of the SDDP method on the other hand has two goals. It provides trial decisions for the backward steps and allows a construction of an upper bound for value of the considered policy [29].

6 ILLUSTRATIVE EXAMPLE

In this study, we consider a three layer supply chain where we have suppliers, distribution centers and affected casualties. Figure 6.1, represents our problem where we adopted and modified from [20]. Apart from [20] we also consider any material flow between each distribution center. Throughout the study, we assume random arc capacities and in case a direct arc from a distribution center to an affected area collapses aftermath of a disaster, it might be a better solution to transport the materials from an indirect arc. (i.e., transporting materials from another distribution center then to affected areas). Simply, by adding these arcs we built alternative arcs to reach casualties.

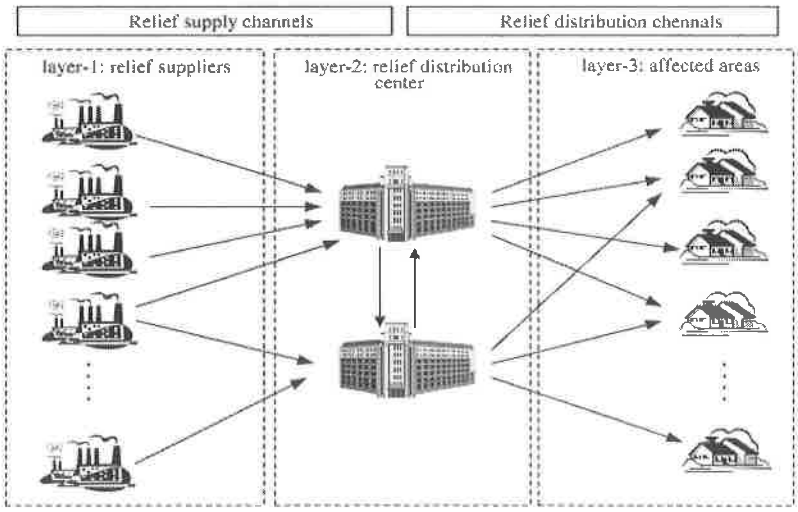

Figure 6.1 Framework of an emergency network (source: Sheu, 2007)

The primary role of a supplier in a supply chain is to source the required items downstream. When we interviewed with municipal agents, they informed us as the main sources in a humanitarian relief are vendors and donors. Vendors can be domestic to the region disaster occurred or they could be global. Donors might donate any type of material such as: products, services, etc.

All materials gathered from vendors and donors and materials also produced by suppliers are accumulated in suppliers and transported to distribution centers. In our study, we take first 72 hours of a disaster into account and so we consider relief supplies as first response items such as drugs, medicine, food, water, and shelter which are simply the necessary requirements for a person to survive in a short term when a disaster hits. Although, there is a multi-commodity transportation, we assume all of these materials are packed in suppliers and so that for each casualty, one single package of those commodities need to be transported to a distribution center.

Distribution centers are so called temporary delivery points in our study. However, once they are built, they are assumed to stay even after the disaster occurred. Because, suppliers generally located outside of cities, materials are transported with large capacitated trucks on wider roads. However, distribution centers are located inner side of cities for quicker transport on considerably narrower roads. Hence, transportation from any distribution center to an affected area is ensured by smaller trucks.

Disaster management subject contains many uncertainties and complexities. Once a disaster hits, one of the most challenging issues is to estimate demand. Due to uncertainty in time, magnitude and location of a disaster, high unpredictability exists in demand estimation. Also, several other factors such as population characteristics, geological and economical conditions complexes demand to estimate. Studies in literature are mostly built based on scenario based demand estimation. [7], [8]. However, one can not guarantee that only those scenarios will occur. Additionally, disasters are unique even if they occur in the exact same location, since other factors such as population structure or economic conditions could have changed since the previous occurrence. Thus, scenario based analyses may not be reliable. In addition, it is most likely to observe a correlation between affected areas aftermath of a disaster. For that reason, we assume our demand is jointly and continuously distributed following multivariate log-normal distribution.

Another most challenging issue in disaster management is unpredictable road capacities. Especially, in metropolises the risk of skyscrapers and respectively taller buildings may collapse on the roads and results of a decrease in road capacities. Figure 6.1 is a representation of capacity decrease in road capacity due to closure of one lane of a road because of building collapses.

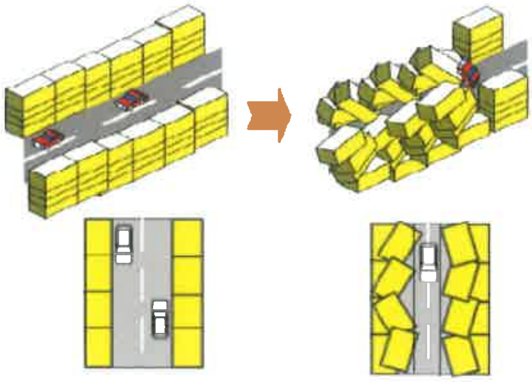

Figure 6.2 Definition of Road Capacity Decrease (Source: JICA Report, 2002 [30])

Measuring capacities of each road aftermath of a disaster is a very hard factor and road's highly unpredictable and unstable capacities differs relief distribution transportation form a regular supply chain. Also, there is no historical data or a reliable database that one can obtain a forecast for road capacities. In that study, we assume road capacities are jointly and continuously distributed as demands. Yet, [31] suggested using normal distribution for road capacities. Hence, we have obtained road capacities following multivariate normal distribution.

6.1 ILLUSTRATIVE EXAMPLE DATA SET

As an illustrative example we assumed two suppliers, three distribution centers and three affected areas (customers). The arc-node incidence and the boundaries of our problem are summarized with the following diagram shown in Figure 6.3

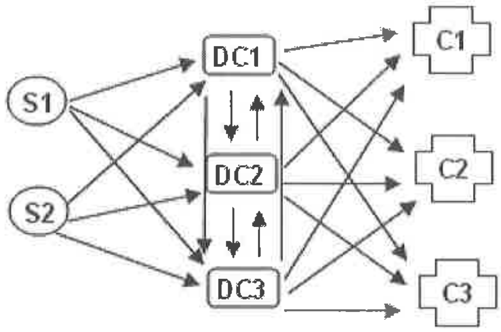

Figure 6.3 Illustrative example network diagram

Figure 6.3 summarizes that we allow transportation by denoting them with arcs from suppliers to distribution centers, from distribution centers to distribution centers and from distribution centers to affected areas (customers).

Problem data including costs (in terms of dollars), distances (in km) and transportation costs (in terms of dollars) are summarized in Table 6.1, Table 6.2 and in Table 6.3.

Table 6.1. Illustrative Problem Cost Data (in $)

Acquisition Costs		
Supplier 1 (S1)		10
Supplier 2 (S2)		20
Fixed Cost of Opening a Distribution Center		
DC 1		650,000
DC 2		450,000
DC 3		300,000

Table 6.2 Illustrative Problem Distance Data (in km)

From/To	DC1	DC2	DC3	AA1	AA2	AA3
S1	20	13	17	-	-	-
S2	23	25	36	-	-	-
DC1	-	10	28	8	10	17
DC2	10	-	16	15	5	20
DC3	28	16	-	31	19	33

We allow roads (arcs) between each distribution center. These roads should not have to be the same for all pointed distribution center. For instance, the road from DC1 to DC3 may be different than road from DC3 to DC1. However, for the sake of simplicity in this numerical example these roads are assumed to be the same roads. Hence, symmetric matrix has been constructed as can be seen in Table (6.3)

Table 6.4. Illustrative Problem Transportation Costs (in terms of dollars)

From/To	DC1	DC2	DC3	AA1	AA2	AA3
S1	48	34	40	-	-	-
S2	30	39	33	-	-	-
DC1	-	35	37	35	38	40
DC2	35	-	48	42	36	31
DC3	37	48	-	39	33	43

We traced the relief materials in volumes throughout the thesis and for our illustrative example we set the inventory limit for the first supplier as 500 cubic meters and 350 cubic meters for the second supplier. We also assumed that one box of relief material that is necessary for each casualty is three cubic meters.

We set penalty cost of not satisfying the demand of a casualty point as 7600$, 14000$ and 52000 $ for each affected areas respectively. The penalty cost of excess demand of a casualty point is set as the half of the penalty cost of not satisfying the demand of a customer.

Demand of an affected area at stage t (D_t) is calculated as the adding some error term which is the previous stage demand (i.e. $D_t = D_{t-1} + \varepsilon_t$). We have also assumed that the error terms are multivariate log normally distributed with mean zero and covariance matrix is randomly generated form uniform distribution between zero and one. Hence, we generated the demand data from multivariate log normal distribution.

Road capacities are generated from multivariate normal distribution as suggested in [31]. In this thesis we considered that all the supplies are delivered with trucks. In real life, it is normal to expect that a truck can drive faster from suppliers to distribution centers since suppliers are generally located outer parts of cities where the transportation is ensured through wider roads. In addition, to reduce the transportation costs, trucks are generally selected as fairly high capacitated. Capacity decrease on the roads from distribution centers to affected areas will be observed due to narrower roads in city. Thus, transportation will be ensured with smaller trucks at the inner sides of a city. Leaning on this observation, we calculated road capacities as follows;

In this study, we observe the system in the first three days which is a crucial period for casualties to survive. We divide 72 hrs (three days) into three parts where we obtained three 24 hr periods to observe the system. We obtained mean road capacities by defining a variable V_1 to represent velocity which is uniformly distributed between 70 km/hr and 80 km/hr (i.e., $V_1 \approx U[70,80]$) from suppliers to distribution centers. Because of the above mentioned reasons on speed and the road capacity changes mentioned above, we defined another variable for other arcs V_2 to represent velocity between distribution centers and from distribution centers to affected areas that is also uniformly distributed between 40 km/hr and 60 km/hr. (i.e., $V_2 \approx U[40,60]$). After obtaining velocity, distances given in Table 6.2 are divided to the generated velocity values to gather time need to be spent on one arc. Since we are observing the system as three 24 hour periods, we divide 24 to calculated time spent on an arc to find how many trucks can travel on that arc within a day. We also assumed that larger trucks which travel on wider roads, carries 50 cubic meter of relief supplies and truck capacity navigating on narrower roads are 30 cubic meter of relief supplies. We multiplied these capacity values with number of trucks found and obtain a road capacity on one arc. Thus, mean road capacity is calculated as stated in Equation (6.1).

$$\text{Mean Road Capacity from S to DC} = \frac{24\,hr}{d_{S,DC} / V_1\, km/hr} x 50 m^3 \tag{6.1}$$

Since distribution centers are located mostly inside of cities, mean road capacity from DC to DC is assumed to be the same as travelling inside of a city. Moving from one distribution center to another is symmetrically defined in our illustrative example so that we did not construct another equation for opposite arc. Equation (6.2) defines mean road capacity calculation from DC to DC

$$\text{Mean Road Capacity from DC to DC} = \frac{24\,hr}{d_{DC,DC'} / V_2\, km/hr} x 30 m^3 \tag{6.2}$$

Trucks that will carry relief materials from DC to DC will also travel directly to affected casualties also on relatively narrow roads on the inner sides of cities. Hence, we used equation (6.3) to evaluate mean road capacity for an arc from DC to affected area (AA).

$$\text{Mean Road Capacity from DC to AA} = \frac{24\,hr}{d_{DC,AA'} / V_2\ km/hr} x30m^3 \quad (6.3)$$

Variance and covariance matrix is randomly constructed using uniform distribution taking values from zero to one.

6.2 PROBLEM FORMULATION

In this study we model both the pre and post phase of a disaster. In the pre-disaster phase, the model determines strategic and long term inventory amounts and also where to locate distribution center(s). The post-disaster phase of a problem is simply network flow problem which can also be named as transshipment problem due to the existence of distribution centers.

Our goal is to transport certain amounts of a commodity from suppliers to distribution centers, from distribution centers to distribution centers and from distribution centers to demand points (affected casualties). Demand and supply does not have to be perfectly matched but we assume there is a penalty cost for the unsatisfied demand and also there is an overage cost for the excess demand. We can only transport limited amount of commodities on each arc that constrained with suppliers' limits and there is an associated transportation cost on each arc. Our goal is to find a flow such that the demand is maximally satisfied while incurring the minimum transportation cost.

The first stage problem of our model is mixed integer linear programming while the second and later stages of the problem are simply linear programming problems. For the first stage problem when $t = 1$ following model is written.

$$\text{Min}\, 10x_{1,1} + 20x_{2,1} + 650{,}000q_1 + 450{,}000q_2 + 300{,}000q_3 + \text{E}[Q_2(x,q,\xi)] \tag{6.4}$$

subject to

$$3x_{1,1} \le 500 \tag{6.5}$$

$$3x_{2,1} \le 350 \tag{6.6}$$

$$q_1 + q_2 + q_3 \ge 1 \tag{6.7}$$

$$\Pr\{Q_2(x,q,\xi) \le \eta_2\} \ge 1 - \alpha_2 \tag{6.8}$$

$$q_1, q_2, q_3 \in \{0,1\} \tag{6.9}$$

$$x_{1,1}, x_{2,1} \ge 0 \tag{6.10}$$

Equation (6.4) minimizes the total cost of keeping inventory and opening a distribution center plus expected value of the second stage cost function. Equation (6.5) and (6.6) shows that inventory kept in any supplier has to be less than or equal to the capacity of that supplier (as stated earlier; we assumed that one unit of relief material is 3 cubic meters). Equation (6.7) satisfies that at least one distribution center has to opened. It is likely that for any realization of random vector ξ, the second stage cost value might be greater than its expectation. Thus, with equation (6.8) we enforce all the realizations of random vector to be less than some η_2 value with probability $1-\alpha_2$. Equations (6.9) and (6.10) define and constrain the variables as explained above.

The probabilistic constraint stated in equation (6.8) can also be denoted as value at risk constraint as in equation (6.11)

$$\text{V@R}_{\alpha_2}[Q_2(x,q,\xi)] \le \eta_2 \tag{6.11}$$

The difficulty with above risk-averse formulation is that; the value at risk function is known to be non-convex in x and q. This type of constraint will violate the feasibility of the problem. Therefore, it was suggested in [29] to use conditional value at risk constraint instead. Conditional- value at risk constraint is explained in equation (4.6).

In order not to violate feasibility in the first stage, we moved the constraint (6.8) to the objective function with some constant λ value. Hence, the objective function became like in equation (6.12).

$$\text{Min}\,10x_{1,1} + 20x_{2,1} + 650{,}000q_1 + 450{,}000q_2 + 300{,}000q_3 + (1-\lambda)\text{E}[Q_2(x,q,\xi)] + \lambda \text{CV@R}_{\alpha_2}[Q_2(x,q,\xi)] \quad (6.12)$$

After solving first stage problem, we obtained how much inventory to keep in each supplier (i.e. $x_{i,t}$ values) and which distribution center to open. (i.e. q_j values). Before starting the second stage problem we also generate random values in our problem from related distributions using Monte Carlo Simulation method. We generate values of demands from multi-variate log normal distribution and we used multi-variate normal distribution for generating road capacity values as explained above.

We started solving the problem from the forward step. It is to construct a scenario tree for pre-selected sample size. For the illustrative problem we selected five as sample size. According to SDDP method forward step requires to select to sub-sample from the generated samples. We select one sub sample according to this we used following demand and road capacity values accordingly given in Table 6.4 and Table 6.5.

Table 3.4Generated Demand Values (m^3)

	AA1	AA2	AA3
Estimated Demand	600	850	500

Table 6.5 summarizes selected road capacity values in the selected sub sample. As can be seen, the capacity values from suppliers to distribution centers are way higher than the other roads as expected.

Table 6.5 Generated Road Capacity values (m^3)

From/To	DC1	DC2	DC3	AA1	AA2	AA3
S1	594	648	752	-	-	-
S2	646	875	633	-	-	-
DC1	-	235	337	127	211	347
DC2	235	-	268	317	252	363
DC3	337	268	-	214	320	142

For a realized value of x and q after solving first stage problem and obtaining ξ vector after generating random components from related distributions solving first stage problem, the second stage problem can be written as following;

$$\begin{aligned} \text{Min}\, & 10x_{1,1} + 20x_{2,1} + 48y_{112} + 34y_{122} + 40y_{122} + 30y_{212} + 39y_{222} + 33y_{232} \\ & + 35y'_{122} + 37y'_{132} + 35y'_{212} + 48y'_{232} + 37y'_{312} + 48y'_{322} + 35y''_{112} + \\ & + 38y''_{122} + 40y''_{132} + 42y''_{212} + 36y''_{222} + 31y''_{232} + 39y''_{312} + 33y''_{322} + \\ & + 43y''_{332} + 76{,}000w_{12} + 14{,}000w_{22} + 52{,}000w_{32} + 38{,}000z_{12} \\ & + 7{,}000z_{22} + 26{,}000z_{32} + (1-\lambda)\mathrm{E}[Q_3(x,q,\xi)] + \lambda \mathrm{CV@R}_{\alpha_3}[Q_3(x,q,\xi)] \end{aligned} \tag{6.13}$$

Equation (6.13) is the objective function of the second stage problem. It aims to minimize total cost regarding first stage inventory costs, transportation costs, and penalty and excess costs. We have also directly showed that probabilistic constraint that takes place in this stage (i.e. $\Pr\{Q_3(x,q,\xi) \le \eta_3\} \ge 1-\alpha_3$) is directly added to the objective function for earlier stated reasons.

$$\begin{aligned} & y_{112} + y_{212} + y'_{212} + y'_{312} - y'_{122} - y'_{132} - y''_{112} - y''_{122} - y''_{132} = 0 \\ & y_{122} + y_{222} + y'_{122} + y'_{322} - y'_{212} - y'_{232} - y''_{212} - y''_{222} - y''_{232} = 0 \\ & y_{132} + y_{232} + y'_{132} + y'_{232} - y'_{312} - y'_{322} - y''_{312} - y''_{322} - y''_{332} = 0 \end{aligned} \tag{6.14}$$

Equation set (6.14) is the flow conservation constraint set that can be found in network problems. It satisfies that no inventory is kept in any of the distribution centers.

$$y''_{112} + y''_{212} + y''_{312} + w_{12} - z_{32} = \tilde{d}_{12}$$

$$y''_{122} + y''_{222} + y''_{322} + w_{22} - z_{22} = \tilde{d}_{22} \quad (6.15)$$

$$y''_{132} + y''_{232} + y''_{332} + w_{32} - z_{32} = \tilde{d}_{32}$$

Equation set (6.15) ensures that commodity sent from all distribution centers and shortage/excess amounts has to satisfy the demand of the affected area.

$$y_{112} + y_{122} + y_{132} \leq x_{11}$$

$$y_{212} + y_{222} + y_{232} \leq x_{21} \quad (6.16)$$

Equations in (6.16) ensures that transported amount of commodities cannot be greater than the inventory decision made in first stage.

$$3x_{12} + 3(x_{11} - y_{112} - y_{122} - y_{132}) \leq 500$$

$$3x_{22} + 3(x_{21} - y_{212} - y_{222} - y_{232}) \leq 350 \quad (6.17)$$

Equations in (6.17) are written to update the inventory kept in hand at second stage. We assumed that after we deliver relief supplies to the affected areas, more precise demand can be observed. Hence, the second stage inventory has to be evaluated as the total capacity of the supplier less the inventory sent until that stage.

$$3y_{132} \leq 752\,q_1$$

$$3y_{232} \leq 633\,q_2$$

$$3y_{232} \leq 633\,q_2 \quad (6.18)$$

$$3y_{312} \leq 214\,q_1$$

$$3y_{322} \leq 320\,q_2$$

$$3y_{322} \leq 320\,q_2$$

Equation set (6.18) defines the road capacity constraints. Normally, these constraints are written for all arcs on the network. However, after solving first stage problem, the model will select only third distribution center to open since it has the lowest fixed cost. Thus, in equation set (6.18) only the third distribution center related equations are stated. The rest of all second stage y values will take the value zero so that they are not stated.

$$x_{i,t} y_{i,j,t} w_{kt}, z_{kt} \geq 0, \quad \forall (i, j, k) \tag{6.19}$$

Constraint (6.19) defines and constrains the variables as explained above.

As explained earlier, we observe the first 72 hours in the system which the most crucial period in real life for casualties to survive. For multistage problem we observe the system in equal 24 hour periods so that we have three stages. This stage problem is likely to the second stage problem only it does not contain any probabilistic constraint and expected value of the next stage cost function since it is the last stage observed in our problem. With this information we constructed the objective function of the third stage problem as follows;

$$\text{Min}\, 10x_{1,2} + 20x_{2,2} + 48y_{113} + 34y_{123} + 40y_{123} + \ldots \tag{6.20}$$

The logic behind equation (6.20) will be same like equation (6.13) except the y values belongs to third stage this time and no expectation or conditional value at risk values will be seen in (6.20).

Flow conservation, demand satisfaction and road capacity constraints are also built as they are in the second stage. However, apart from second stage, all y values belong to third stage at this point.

$$\begin{aligned} y_{113} + y_{123} + y_{133} &\leq x_{11} - y_{112} - y_{122} - y_{132} + x_{12} \\ y_{213} + y_{223} + y_{233} &\leq x_{21} - y_{212} - y_{222} - y_{232} + x_{22} \end{aligned} \tag{6.21}$$

The last time we need to update inventory decision in this stage. Equation (6.21) states that total inventory sent from any supplier has to be less than total inventory in the system. Thus, we write this constraint for every supplier. (we have two suppliers in this illustrative example)

6.2.3 Numerical Results of Illustrative Example

We started with constructing a scenario tree in order to use forward step. We generated five samples for each random component than we selected a sub- sample among them. Starting from the first stage we solved all stage problems until the final stage problem. Unfortunately, we were not able to find a tight upper bound so we set stopping criterion as the stabilization of lower bounds. We obtained lower bound values from the backward step of the process. In that process, we solved last stage problem and obtained a cutting plane as defined in section 5 with equation (5.3). Then we added this cut as shown in equation (6.22) as another constraint to the second stage problem which provides us lower bound. This process continues until the first stage is reached.

$$\theta_t \geq e_t + g_t^T (x_t - \overline{x_t}) + h_t^T (\eta_t - \overline{\eta_t}) \tag{6.22}$$

Where e, g and h are defines as in equation set (6.23) where $J_t = \{ j : Q_{t+1}(x_t, \tilde{\xi}_{t+1}) - \eta_{t+1} > 0 \}$.

$$e_t = \frac{1}{N_t} \left\{ \sum_{i=1}^{N_t} c_{t,i}^T x_{t,i} + \lambda_{t+1} \eta_{t+1,i} + \theta_{t,i} \right\}$$

$$g_t = (1 - \lambda_{t+1}) / N_t \left\{ \sum_{i=1}^{N_t} - \widetilde{B}_{t,i}^T \pi_{t,i} \right\} + (\lambda_{t+1} \alpha_{t+1}^{-1}) / N_t \left\{ \sum_{j \in J_t} - \widetilde{B}_{t,j}^T \pi_{t,j} \right\} \tag{6.23}$$

$$h_t = \lambda_{t+1} \alpha_{t+1}^{-1} \left\{ \sum_{j \in J_t} - 1 \right\}$$

We tested our problem with different λ and α values under different sizes of scenario trees.

7 CASE STUDY

In this study we intended to apply our methodology to real life data and this thesis is implemented to the Asian Side of Istanbul. Information is expected to be taken from government or municipals.

However, one can observe that the information the authorities and organizations have is generally missing, doubled or intertwined which is misleading most of the times. For that reason we have done some logical assumptions regarding the data needed.

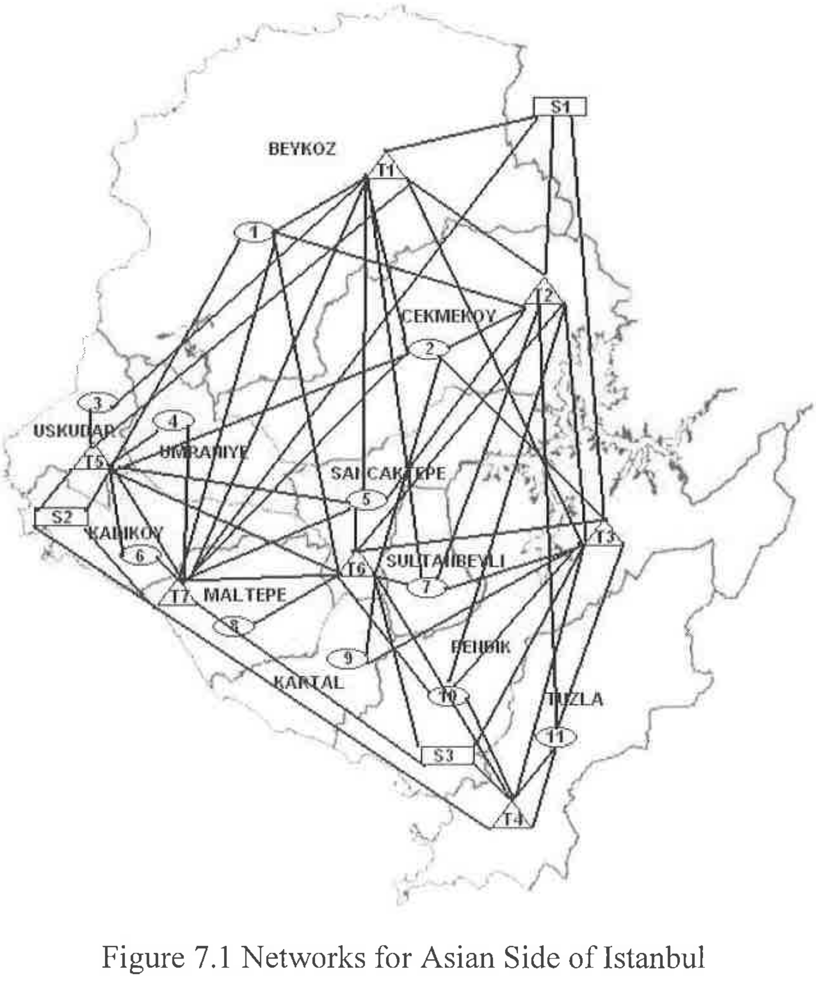

Figure 7.1 Networks for Asian Side of Istanbul

Figure 6.2 represents the districts of Asian Side of Istanbul. On the figure 6.2 each circle represents demand points or gathering areas of casualties. We assumed casualties are gathered on the shown nodes aftermath of a disaster. Each rectangle represents suppliers. In that study, we have considered three suppliers where first supplier represented as S1 is red-crescent, second supplier (S2) is Haydarpaşa Harbor and third supplier (S3) is Sabiha Gökçen Airport. All triangles in Figure 6.2 represent any possible transfer points or distribution centers. Normally, it is possible to open a distribution center at any place of a city. However, we have selected points closer to the inner sides of the cities and which are mostly located at the intersections of districts.

In our illustrative example problem, we have considered in total three suppliers, seven distribution centers and eleven affected areas. We assumed that there is one arc from each supplier to each distribution center, from each distribution center to any distribution center and from a distribution center to all demand points. However, in order not to confuse Figure 6.2 we have not shown all roads on that figure. We have measured the distances as Euclidean distances. Hence, the distance and so the road between two distribution center is assumed to be the same from a distribution center to another and the vice versa. That is, in total we dealt with 140 arcs in that study.

7.1 DATA COLLECTION

In order to calculate capacity of each arc, we have measured the distances with Google Earth by measuring Euclidean distances in km units. Table 7.1 provides the distances between all suppliers (S1, S2, S3) to all distribution centers (DC1, DC2, …, DC7).

Table 7.1 Distances (in km) from all Suppliers to all Distribution Centers

	DC1	DC2	DC3	DC4	DC5	DC6	DC7
S1	20,52	13,89	17,33	35,78	35,77	29,65	35,76
S2	23,02	25,38	36,38	28,6	3,54	12,84	5,63
S3	30,81	23,81	22,03	6,84	21,27	12,62	16,76

Table 7.2 also summarizes distances in km units between all distribution centers to all distribution centers. Since we measured Euclidean distances, the distance from a DC to the same DC has the same distance so that the table is symmetric.

Table 7.2 Distances (in km) from all Distribution Centers to all Distribution Centers

	DC1	DC2	DC3	DC4	DC5	DC6	DC7
DC1	0	10,57	28	35,29	19,73	19,38	21,59
DC2	10,57	0	16,65	26,76	21,24	15,53	20,9
DC3	28	16,65	0	20,48	33,21	23,52	30,9
DC4	35,29	26,76	20,48	0	27,91	18,64	23,95
DC5	19,73	21,24	33,21	27,91	0	10,09	4,71
DC6	19,38	15,53	23,52	18,64	10,09	0	6,83
DC7	21,59	20,9	30,9	23,95	4,71	6,83	0

Table 7.3 summarizes distances in km units from all distribution centers to all affected areas (AA1, AA2, …, AA11).

Table 7.3 Distances (in km) from all Distribution Centers to all Affected Areas

	AA1	AA2	AA3	AA4	AA5	AA6	AA7	AA8	AA9	AA10	AA11
DC1	8,27	10,49	17,42	17,84	16,62	23,04	20,01	23,55	27,29	24,75	33,48
DC2	15,18	5,23	20,68	16,83	7,59	23,92	13,77	20,66	21,33	15,48	23,53
DC3	31,07	19,68	33,16	27,86	14,65	34,02	19,72	28,64	22,17	12,28	15,77
DC4	33,42	24,33	29,57	23,58	19,66	25,91	16,47	19,94	10,18	11,72	4,57
DC5	11,95	16,53	2,65	5,43	19,03	4,06	14,19	8,09	17,64	23,22	28,18
DC6	15,45	10,8	11,28	5,03	10,06	10,37	3,92	5,29	8,9	13,28	18,31
DC7	15,03	16,25	6,94	4,27	17,44	2,79	10,78	3,92	12,94	19,97	24,1

In this study, we observe the system in the first three days which is a crucial period for casualties to survive. We divide 72 hrs (three days) into three parts where we obtained three 24 hr periods to observe the system. We obtained road capacities by defining a variable V to represent velocity which is uniformly distributed between 30 km/hr and 50 km/hr (i.e., $V \approx U[30,50]$). This value is divided to distances that are seen in Table 7.1, Table 6.2 and Table 6.3. After obtaining time to travel for one truck with this method, we find how many trucks can travel in 24 hr period simply by dividing 24 hrs to travel time of a truck. We assume bigger trucks which travel on arcs from suppliers to customers has a capacity of transporting 70m^3 products while smaller trucks expected to travel on arcs among distribution centers and from distribution centers to affected areas have 52m^3 transporting capacity of products. After computing number of trucks we multiplied this amounts with above mentioned capacity of trucks and we obtained mean capacity on each arc. We also assumed the variances on those arcs are 40% of the mean capacities.

Mean number of casualties are affected from several factors such as construction materials of the buildings, stability of the nearby bridges or even if the earth tends to have liquefaction effect during any types of disaster. Also night time and day time population differs for every district of Istanbul as stated in [32]. Figures 7.2 and 7.3 are taken from [32] to demonstrate the greatness of population change during night and day time.

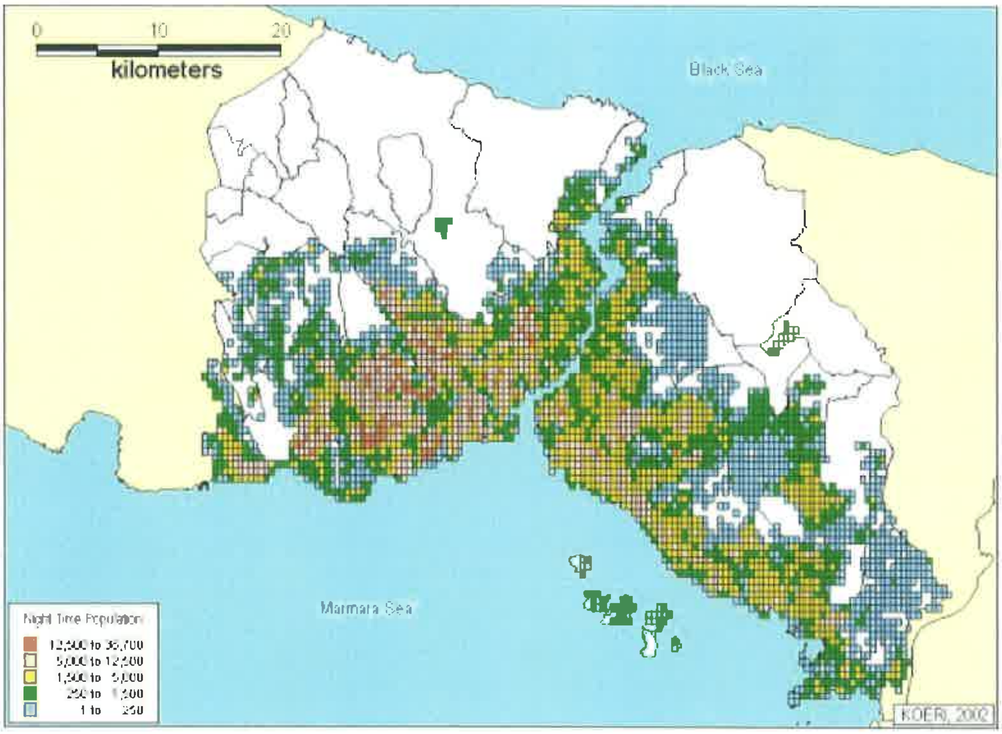

Figure 7.2Distribution of night time population in Istanbul (source: Erdik et al, 2003)

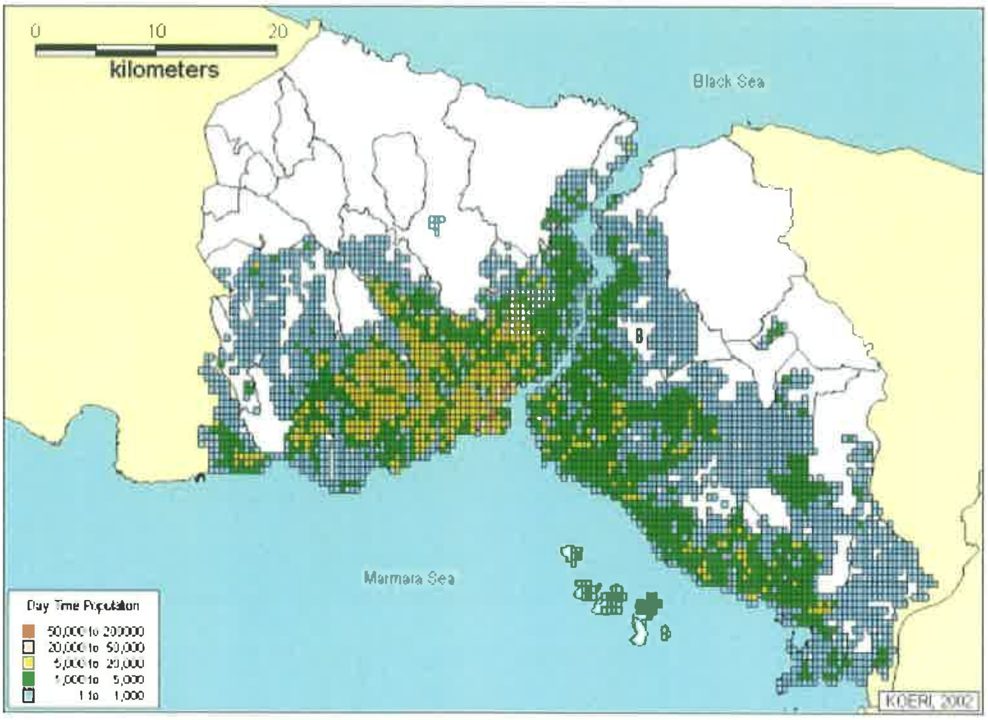

Figure 7.3 Distribution of day time population in Istanbul (source: Erdik et al, 2003)

We have selected the Asian side of Istanbul as our focus point. However, Figures 7.2 and 7.3 does not reflect the population for every Asian side district of Istanbul. Thus, we gathered mean number of casualties from JICA report that is established in 2002 [30]. Table 7.4 summarizes these values for every considered district in Asian Side of Istanbul.

Table 7.4 Number of Casualties in Asian Side (source: JICA Report, 2002)

<table>
<tr><td rowspan="11">CASUALTIES</td><td>Beykoz</td><td>7600</td></tr>
<tr><td>Üsküdar</td><td>34900</td></tr>
<tr><td>Çekmeköy</td><td>14000</td></tr>
<tr><td>Sultanbeyli</td><td>52000</td></tr>
<tr><td>Ümraniye</td><td>27300</td></tr>
<tr><td>Sancaktepe</td><td>24000</td></tr>
<tr><td>Kadıköy</td><td>72300</td></tr>
<tr><td>Maltepe</td><td>47100</td></tr>
<tr><td>Kartal</td><td>52900</td></tr>
<tr><td>Pendik</td><td>53300</td></tr>
<tr><td>Tuzla</td><td>15900</td></tr>
</table>

We take these amounts as the mean number of casualties. We also assumed that one casualty will require relief products which will result of $3m^3$ when they are packed in one package (i.e., v = $3m^3$). And so the mean demand values are calculated as the multiplication of values given in Table 6.4 with volume of relief supplies per casualty. The variance of demand values is assumed to be 40% of the expected demand values. Moreover, penalty cost of short demand for affected areas are assumed to be equal to expected number of casualties and penalty cost of overage demand is assumed as the quarter of shortage cost values.

We set inventory limits of suppliers S1, S2 and S3 as $700{,}000m^3$, $689{,}000m^3$ and $500{,}000m^3$ unit volumes respectively. In addition, acquisition costs of commodities at suppliers are assumed to be 10 TL, 20 TL and 25TL per unit volume respectively.

We applied expert opinion for determining fixed cost for opening a distribution center. We scaled our alternative distribution centers located on a $350m^2$ area each and Table 7.5 summarizes fixed costs for each of the seven distribution centers in TL.

Table 7.5 Fixed Costs of Distribution Center Openings in TL

Fixed DC Opening Costs	**DC1**	**DC2**	**DC3**	**DC4**	**DC5**	**DC6**	**DC7**
	650000	450000	300000	220000	600000	270000	340000

Transportation cost for one unit of relief commodity (relief package) is gathered from continuous uniform distribution between 30 TL and 50 TL per unit. Besides, we assumed our demand and road capacity values are continuously and jointly distributed. We obtained demand values from multivariate log-normal distribution and road capacity values from multivariate beta distribution [31]. Correlations among all roads are generated from continuous uniform distribution between 0 and 0.3. Correlations between affected areas are also generated from continuous uniform distribution based on study [32]. In their study, they provide a risk map for every district of Istanbul. We assume if two districts are expected to be highly damaged we generate correlation values having uniform distribution between 0 and 0.3. For fewer amounts of damage expectations we obtain correlation values having uniformly distributed from 0 and 0.2.

8 CONCLUSION

Disaster management issues are challenging due to disasters random occurrence. In addition, every single aspect has an effect on real life cases. For instance, the population in a city / district in the morning could differ very much from the population in the evening. Moreover, time period also affects the traffic congestion on the roads hence, the road capacities. Besides, every type of structures' (buildings, bridges, etc.) stability and durability challenges the decision maker to give appropriate decision. Moreover, the information gathered from databases or municipals are generally misleading, doubled or intertwined. Because of this complicated nature of the problem, good problem definitions and effective solution methodologies are needed.

In this study, multistage SDDP approach is introduced to disaster preparedness and relief distribution problem for the first time. The pre-disaster phase of the problem is modeled as mixed-integer linear programming model and the post-disaster phase of the problem is modeled as linear programming problem.

Instead of scenario based simulations that have been widely used in literature we have used Monte Carlo Simulation technique with jointly distributed demand and road capacities. The originality of this study mainly comes from above mentioned aspects.

Disaster Management is a fruitful subject that can be further studied. In this study, we do not take population or road capacity fluctuations during a day. These facts may also be included to obtain more realistic results. Furthermore, this study primarily focuses on multistage SDDP approach to the problem. However, Robust Optimization techniques could further enrich the approach to the problem. Moreover, we have used cost minimization as our main goal yet in disaster management subject it is not the only goal of a decision maker. Equity, efficacy and efficiency measures could also be added and the problem behavior may be observed.

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BIOGRAPHICAL SKETCH

Nihan Karaca, the candidate of Master of Science in Industrial Engineering Department in Galatasaray University, was born in 1987 in Istanbul. She started her bachelor education in Industrial Engineering Department in Istanbul Kultur University and she graduated with the second highest GPA among other Industrial Engineering students in 2009. During her undergraduate education she was rewarded as "High Honor Student" throughout years 2006-2009. She has three international proceedings of which one is presented in 23rd European Conference on Operational Research held in Bonn. The other one is presented in 16th International Working Seminar on Production Economics held in Innsbruck and the last one which is based on her Master's Thesis was presented in OR/2011 Conference held in Zurich.