7

Using Earthquake Risk Data to Assign Cities to Disaster-Response Facilities in Turkey

AYŞENUR SAHIN, MUSTAFA ALP ERTEM, AND EMEL EMUR

Contents

7.1 Introduction

Turkey is located at one of the most active earthquake regions of the world. It is the third in the world in terms of human loss and eighth in terms of the number of people affected by an earthquake (AFAD 2012). The only unchanging reality of Turkey besides the political events and the changes of economic conditions that took place during the years is *the earthquake*.

Most of Turkey's population can be considered as risky because of the North Anatolian Fault (NAF) line. Several earthquakes have been reported in this geographical region. In August 17, 1999, Marmara earthquake took place on the western part of NAF line with a magnitude of 7.4 on the Richter scale (Görmez et al. 2011). This major earthquake marks a turning point in the field of disaster management and coordination of disaster relief activities in Turkey. This earthquake, which caused a great loss of life and property, has revealed that the issue of disaster management in Turkey needed to be reconsidered (AFAD 2012).

There is uncertainty in the nature of disasters (e.g., earthquakes) because the timing and location them cannot be predicted beforehand. This uncertainty affects the proper management of disaster relief operations. It has been observed that in different locations of Turkey, earthquakes show different destruction powers. The severity of the earthquake and building quality might be considered as the main source of this difference. On the other hand, when a particular fault line is taken into account, it can be inevitably seen that some locations in Turkey have a higher risk of experiencing devastating earthquakes than the others. In our study, we defined this potential as "the earthquake risk."

Humanitarian logistics is defined 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" (Thomas and Kopczak 2005). Activities in humanitarian logistics include preparedness, planning, procurement, transport, warehousing, tracking and tracing, and customs clearance (Thomas and Kopczak 2005). Similar to the business supply chain and logistics activities, humanitarian logistics includes diverse activities like procurement and prepositioning. Before the onset of disaster, the relief items are procured from global or local sources and stored in the warehouses. Therefore, prepositioning provides time and place utility since the time and location of the disasters cannot be predicted beforehand. Moreover, after the disaster onset the warehouses are continuously supplied with amenities from the suppliers because of the flow of relief items from warehouses to disaster locations. Therefore, planning the storage locations of relief supplies and selecting these locations in terms of vulnerability is a crucial job before disasters for humanitarian relief organizations. This study aims to assign demand points to prepositioned disaster-response facilities (DRFs) in terms of population in order to minimize the distance between demand points and DRFs considering the earthquake risk. The DRFs of the new container warehouses proposed by AFAD (Turkish Prime Ministry Disaster and Emergency Management Presidency), Turkish Red Crescent warehouses, and AFAD Civil Defense Search and Rescue City Directorates are considered in this study. Turkish Red Crescent Society is a humanitarian organization that provides relief to the vulnerable and those in need by mobilizing the power and resources of the community, and AFAD is the government agency concerning disasters and emergencies, and works like an umbrella organization, collaborating with the Ministry of Foreign Affairs, the Ministry of Health, the Ministry of Forests and Hydraulic Works, and other relevant ministries as well as nongovernmental organizations. We develop a mathematical model that determines the assignment of each demand point to each DRF by restricting the destruction powers and restricting the capacities of each DRF with its population size.

The rest of the chapter is organized as follows: In Section 7.2, we provide an overview of prepositioning in humanitarian logistics and risk management in disasters. In Section 7.3, we describe the system and problem in detail and present an integer programming model formulation. In Section 7.4, we test the model with case studies and report the computational results. Finally, we conclude and discuss future work in Section 7.5.

7.2 Literature Review

Despite humanitarian logistics' importance, the literature in this area is limited (Van Wassenhove 2006). Altay and Green (2006) survey the literature to identify potential research directions in disaster operations, discuss relevant issues, and provide a starting point for interested researchers.

In the fall of 2005, since hurricanes Katrina, Wilma, and Rita caused damage of more than $100 billion and highlighted the inadequacy of existing preparedness strategies, some research effort was aimed at devising prepositioning plans for emergency supplies (Rawls and Turnquist 2010).

Ukkusuri and Yushimoto (2008) modeled the prepositioning of supplies as a location-routing problem. Their model incorporates the reliability of the ground transportation network in case of any destruction happened. They maximize the probability that all the demand points can be served by a service location given fixed probabilities of link/node failure and a specified budget constraint. This model is related to our study in terms of demand points and service locations.

Balcik and Beamon (2008) developed a model to design a prepositioning system that balances the costs against the risks in the relief chain, which is a variant of the maximal covering location model, integrates facility location and inventory decisions, considers multiple item types, and captures budgetary constraints and capacity restrictions. It is revealed by the results of computational experiments that there are effects of pre- and postdisaster relief funding on relief system's performance, specifically on response time and the proportion of demand satisfied.

Duran et al. (2011) developed a mixed-integer programming inventory-location model to find the optimal configuration while considering a set of typical demand instances given a specified upfront investment (in terms of the maximum number of warehouses to open and the total inventory available to allocate) to determine the configuration of the supply network that minimizes the average response time over all the demand instances all over the world. The model obtains the typical demand instances from historical data; the supply network consists of the number and the location of warehouses and the quantity and type of items held in inventory in each warehouse. The basic differences between this study and our study are stock prepositioning, response times, and coverage area since our model provides an emergency response by assigning demand points to the DRFs with minimum earthquake risk in Turkey.

Görmez et al. (2011) developed a mathematical model to determine the locations of DRFs for Istanbul with the objectives of minimizing the average-weighted distance between casualty locations and DRFs, and opening a small number of facilities, subject to distance limits and backup requirements under regional vulnerability considerations. They analyzed the trade-offs between these two objectives under various disaster scenarios and investigated the solutions for several modeling extensions. The main difference of our study is our aim of covering all of Turkey and considering a single objective of minimizing total traveled distance.

Dükkancı et al. (2011) developed a model for Turkish Red Crescent Society (i.e., Kızılay in Turkish) that determined the DRF locations by evaluating demographic and past disasters' information to cover maximum number of people.

Risk is a widely used term in everyday life and businesses. Knight (1921) defined risk as "if you don't know the for sure what will happen, but you know the odds, that's risk, and if you don't even know the odds, that's uncertainty." The concept of resilience is closely related to the capability and ability of an element to return to a predisturbance state after a disruption (Bhamra et al. 2011). After the disaster, there might be risks related to the disruption of transportation roads and long delivery time, which should be well analyzed. In this study, we used an earthquake risk map, including destruction powers to integrate risk concept into our model.

To the best of our knowledge, the assignment of demand points to prepositioned DRF locations (in terms of cities) throughout Turkey considering that the earthquake risk has not been analyzed thoroughly. The next section presents an integer programming model for assigning city demand points to prepositioned DRF locations in Turkey considering the earthquake risk.

7.3 Solution Methodology

When the prepositioning literature is analyzed, it is seen that either the distance traveled between DRFs and affected areas or elapsed time is minimized by considering the closeness of DRFs to the disaster-prone areas. In this study, the affected areas by the disaster are called as *demand points*. The assumptions used in the problem are given in the following:

- The DRFs can cover a maximum 15,000,000 population, because we limit the coverage with the population sizes of the cities that have DRFs.
- The DRFs can satisfy their own requirements from an infinite supply.

7.3.1 Mathematical Model

The objective is to minimize the distances between demand points and DRFs in order to quickly respond to the requirements of beneficiaries. The following notation is used for the DRF assignment model:

Sets

C set of DRF locations; $i \in C$
T set of demand points; $j \in T$

Parameters

D_{ij}: Distance between DRF i and demand point j
K_j: Population of demand point j
P_i: Capacity of DRF i in terms of population
R_{ij}: Average destruction power based on the magnitude of the earthquake for DRF i and demand point j

Decision Variables

$$x_{ij} = \begin{cases} 1 & \text{if demand point } j \text{ is covered by DRF } i \\ 0 & \text{Otherwise} \end{cases}$$

The mathematical model for the problem is as follows:

$$\min \sum\sum D_{ij} x_{ij} \quad (7.1)$$

subject to

$$\sum K_j x_{ij} \leq P_i \quad \forall i \in C \quad (7.2)$$

$$\sum x_{ij} \geq 1 \quad \forall j \in T \quad (7.3)$$

$$\sum_j R_{ij} x_{ij} \geq 1 \quad \forall i \in C \quad (7.4)$$

$$x_{ij} \in \{0,1\} \quad \forall i \in C, \quad \forall j \in T \quad (7.5)$$

The objective function (7.1) minimizes the distance between the DRFs and demand points. Constraint set (7.2) ensures that a DRF can cover the population of a demand point *j* up to its population capacity. Constraint set (7.3) ensures that every demand point must be covered by at least one facility. Constraint set (7.4) satisfies that the total average destruction power between DRFs and demand points must be greater than or equal to one. Thus, the DRFs cover the demand points that have large destruction powers. Constraint set (7.5) ensures that the location coverage variables are binary.

7.4 Experimental Studies

The proposed mathematical model is tested for DRFs of the new container warehouses proposed by AFAD, Turkish Red Crescent warehouses, and AFAD Civil Defense Search and Rescue City Directorates in the following sections. Only the data set and computational results of the first case will be given in detail, and the visual representation of the results will be given for others. The data set (i.e., risk, population, distance) used for all these cases are the same.

7.4.1 First Case

This experiment is conducted for 27 container warehouse locations proposed by AFAD recently. Earthquake risk data are taken from the earthquake risk map at city and town level, which was prepared by Prof. Dr. Ahmet ERCAN (Ercan 2010). The distances between cities are taken from KGM (General Directorates for Highways 2013). Demographic information of cities and towns (populations) is taken from TUIK (Turkish Statistical Institute 2012).

The average destruction powers given in Table 7.1 are derived from the minimum and maximum destruction powers in the earthquake map (Ercan 2010). The first column of the table shows cities, the second column shows the populations, and the third column shows the corresponding risk regions. Fourth and fifth columns show minimum and maximum destruction powers corresponding to risk regions. The sixth column is the average destruction power value calculated by taking average of minimum and maximum destruction powers. This is taken as the average to have a moderate representation of the

Table 7.1 Sample from the Data Set

CITY	2012 POPULATION	RISK REGION	MIN. DESTRUCTION POWER (A-CM/SN^2)	MAX. DESTRUCTION POWER (A-CM/SN^2)	AVG. DESTRUCTION POWER (A-CM/SN^2)
Adana	2,125,635	IX	0.31	0.71	0.51
Adıyaman	595,261	IX	0.31	0.71	0.51
Afyon	703,948	IX	0.31	0.71	0.51
Ağrı	552,404	XI	1.50	3.1	2.30
Amasya	322,283	X	0.71	1.50	1.10
Ankara	4,965,542	VIII	0.15	0.31	0.23
Antalya	2,092,537	IX	0.31	0.71	0.51
Artvin	167,082	VIII	0.15	0.31	0.23
Aydın	1,006,541	X	0.71	1.50	1.10
Balıkesir	1,160,731	X	0.71	1.50	1.10
...					
Kilis	124,320	VI	0.03	0.07	0.05
Osmaniye	492,135	VII	0.07	0.15	0.11
Düzce	346,493	XII	3.10	7.10	5.10

destruction power. According to Table 7.1, the maximum average destruction power is 7.1g for Düzce in the most risky area (XII). The minimum average destruction power is 0.051g for Kilis in the least risky area (VI).

The proposed mathematical model was solved using GAMS 23.7 with CPLEX 11 Solver. The total traveled distance is 10,778 km with 59 (i, j) pairs. The (i, j) pair stands for the assignment of demand point j to DRF i. We identified them as pair since our model determines the (i, j) pair, and we make comparison among each cases by the pair assignments. The total average destruction power between (i, j) pairs is 60.92.

The assignment of demand points to DRFs is given in Table 7.2 for this case. In the first and fifth columns, the prepositioned DRFs are listed. In the second and sixth columns, the assigned demand points to DRFs are listed. In the third and seventh columns, the distances between the DRFs and the demand points are given as (i, j) pairs. In the fourth and eighth columns, the average destruction power between (i, j) pairs is given. The results show that demand points are assigned to DRFs with an ability to serve the demand points in at most 4 h by highways in normal conditions except for Elazığ-Rize assignment with 570 km. It can be concluded that each DRF covers at

Table 7.2 Assignment of Demand Points to DRFs for Container Warehouses Proposed by AFAD

DRFS	COVERED DEMAND POINTS	DISTANCE BETWEEN (*I*, *J*) PAIRS	AVG. DESTRUCTION POWER BETWEEN (*I*, *J*) PAIRS	DRFS	COVERED DEMAND POINTS	DISTANCE BETWEEN (*I*, *J*) PAIRS	AVG. DESTRUCTION POWER BETWEEN (*I*, *J*) PAIRS
Adana	Mersin	69	0.37	Manisa	Aydın	156	0.81
	Niğde	205	0.31		Uşak	195	0.51
	Karaman	289	0.37	Kahramanmaraş	Gaziantep	80	0.17
Adıyaman	Bingöl	349	0.81		Tokat	415	0.67
	Şanlıurfa	110	0.31		Osmaniye	100	0.17
Afyon	Eskişehir	144	0.37	Muğla	Aydın	99	0.81
	Kütahya	100	1.41		Isparta	292	0.51
Ankara	İstanbul	453	1.27	Muş	Bitlis	83	0.51
Antalya	Burdur	122	0.51		Siirt	180	0.31
	Isparta	130	0.51		Şırnak	275	0.51
Balıkesir	Kütahya	224	1.70	Samsun	Giresun	196	1.27
Bursa	İzmir	322	2.00		Ordu	152	1.27
Denizli	Aydın	126	0.81		Sinop	163	1.27
	Uşak	150	0.51	Sivas	Amasya	222	1.11
Diyarbakır	Bingöl	144	0.81		Kayseri	195	0.67
	Mardin	95	0.31	Tekirdağ	Çanakkale	188	1.41
	Batman	100	0.31		Edirne	140	1.27
Elazığ	Malatya	98	0.37		Kırklareli	121	1.27

(*Continued*)

Table 7.2 (*Continued*) Assignment of Demand Points to DRFs for Container Warehouses Proposed by AFAD

DRFS	COVERED DEMAND POINTS	DISTANCE BETWEEN (*I*, *J*) PAIRS	AVG. DESTRUCTION POWER BETWEEN (*I*, *J*) PAIRS	DRFS	COVERED DEMAND POINTS	DISTANCE BETWEEN (*I*, *J*) PAIRS	AVG. DESTRUCTION POWER BETWEEN (*I*, *J*) PAIRS
	Rize	570	2.67	Van	Hakkari	202	1.41
Erzincan	Gümüşhane	131	2.61		Iğdır	225	1.27
	Trabzon	231	2.67	Aksaray	Çorum	326	0.61
	Tunceli	130	2.81		Kırşehir	110	0.17
Erzurum	Ağrı	184	1.41		Konya	148	0.17
	Artvin	226	0.37		Nevşehir	75	0.11
	Kars	203	0.51	Kırıkkale	Çankırı	105	0.37
	Bayburt	125	0.31		Çorum	167	0.67
	Ardahan	230	0.37		Yozgat	141	0.23
Hatay	Kilis	147	1.18	Yalova	Bilecik	129	1.21
Kastamonu	Bartın	181	0.67	Düzce	Bolu	45	3.10
	Karabük	114	0.67		Zonguldak	114	2.67
Kocaeli	Sakarya	37	5.10				

least one demand point and at most five demand points such as Bursa and Erzurum DRFs. The demand points receive relief supplies from one facility since the facility sizes are limited with their population sizes. Few demand points receive relief supplies from more than one facility like Kütahya, Aydın, Uşak, and Bingöl.

The demonstration of the assignments for (i, j) pairs is given in Figure 7.1. It shows the assignment of demand points to DRFs, which are symbolized by a container.

7.4.2 Second Case

This experiment is conducted for 30 Turkish Red Crescent warehouses. The proposed mathematical model was solved using GAMS 23.7 with CPLEX 11 Solver. The total distance traveled is 10,617 km with 59 (i, j) pairs. The total average destruction power between (i, j) pairs is 47, which is less than the value observed in the first case. The visual representation of the assignment of demand points to DRFs is given in Figure 7.2 for the second case. As seen from Figure 7.2, the demand points are assigned to DRFs with an ability to serve the demand points in at most 4 h by highways in normal conditions except for Gaziantep-Çorum and Rize-Amasya assignments with 630 and 535 km, respectively. Each DRF covers at least one demand point and at most five demand points such as Ağrı and Gaziantep DRFs. The demand points receive relief supplies from one facility since the facility sizes are limited with their population sizes. Few demand points receive relief supplies from more than one facility like Kütahya, Çankırı, Aydın, Bitlis, and Bingöl.

7.4.3 Third Case

This experiment is conducted for 11 DRFs of AFAD Civil Defense Search and Rescue City Directorates. The total traveled distance is 13,997 km with 71 (i, j) pairs. The total distance traveled is higher than the first and second case studies because the number of DRFs is fewer. The total average destruction power between (i, j) pairs is 72.71, which is more than the observed value in the first and second case studies. The visual representation of the assignment of demand points to DRFs is given in Figure 7.3 for this case. As seen from

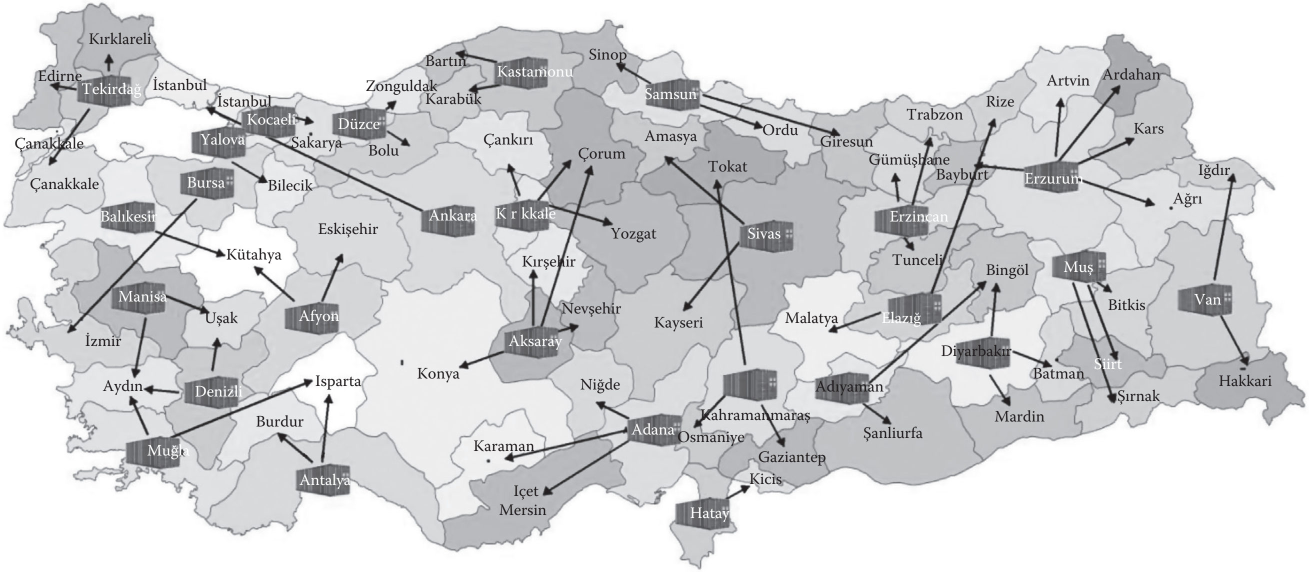

Figure 7.1 Assignment of cities for container warehouses proposed by AFAD.

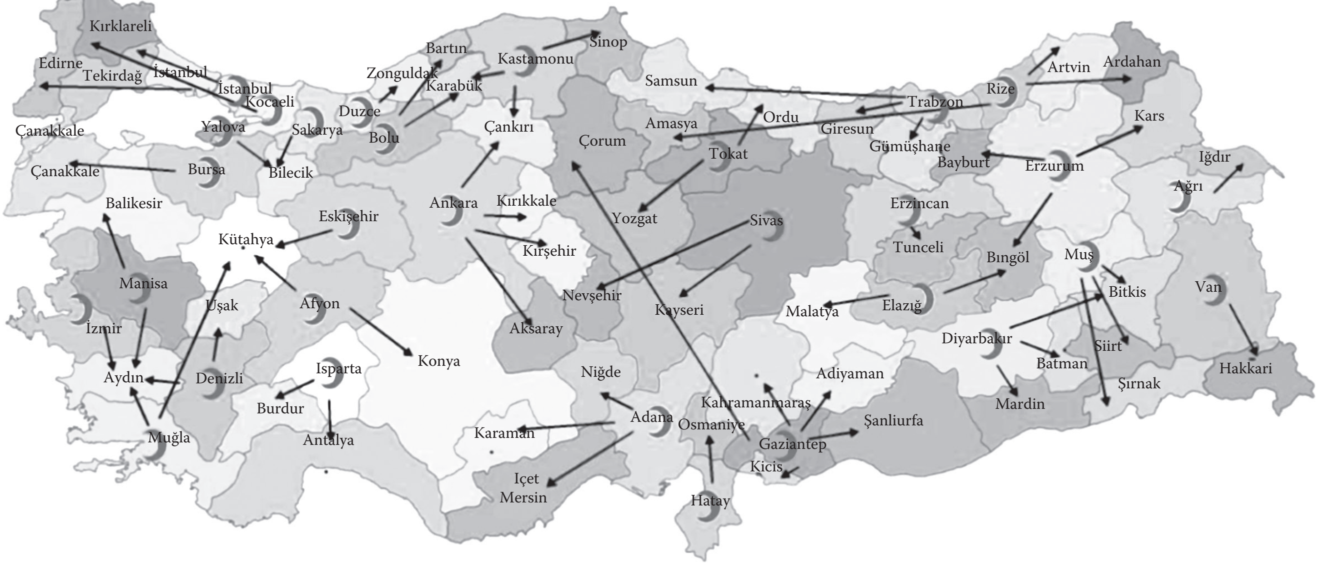

Figure 7.2 Assignment of cities for Turkish Red Crescent warehouses.

Figure 7.3 Assignment of cities for AFAD Civil Defence and Rescue City Directorates.

Figure 7.3, the demand points are assigned to DRFs with an ability to serve the demand points in at most 4 h by highways in normal conditions except for Van-Erzincan assignment with 602 km. Each DRF covers at least 1 demand point and at most 12 demand points such as Diyarbakır DRF. The demand points receive relief supplies from one facility since the facility sizes are limited with their population sizes. Kütahya is an exception since it receives relief supplies from two facilities.

The set of the warehouses used in the first, second, and third cases are given in Figure 7.4 by displaying the overlapping DRFs among them. There are 12 overlapping cities for container warehouses and Turkish Red Crescent warehouses, 3 overlapping cities for AFAD warehouses and Turkish Red Crescent warehouses, and 1 overlapping city for container warehouses and AFAD warehouses. Eight cities belong to only Turkish Red Crescent warehouses, and seven cities

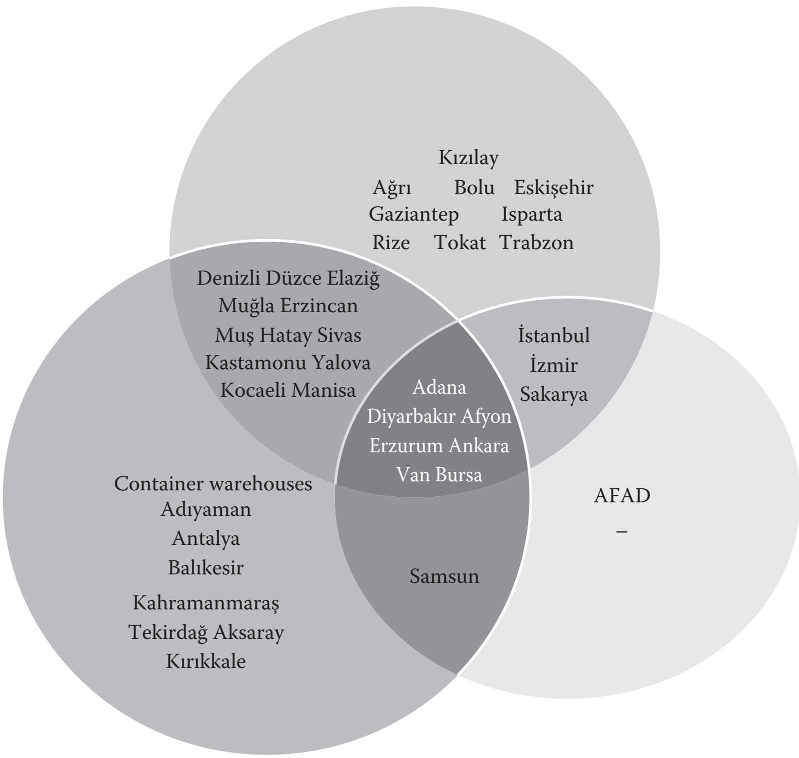

Figure 7.4 The set of the warehouses used in the case studies.

Table 7.3 Comparison of the Cases according to Numerical Results

	(A)	(B)	(C)	(D)	(E)	(F) = (E)/(B)
CASE	NO. OF DRFS	NO. OF (*I*, *J*) PAIR	NO. OF DEMAND POINTS COVERED BY TWO DRFS	TOTAL TRAVELED DISTANCE (KM)	TOTAL AVG. DESTRUCTION POWER	AVG. DESTRUCTION POWER OF (*I*, *J*) PAIR
First case	27	59	5	10,778	60.92	1.033
Second case	30	59	8	10,617	47.00	0.797
Third case	11	71	1	13,997	72.71	1.024

belong to only container warehouses. Seven DRFs are common in all cases: Adana, Diyarbakır, Afyon, Erzurum, Ankara, Van, and Bursa.

The summary of three cases is depicted in Table 7.3 for comparison. In the first column of the table, three cases are given for container warehouses, Turkish Red Crescent warehouses, and AFAD warehouses, respectively. In the second and third columns, the number of DRFs belonging to each case and the number of (i, j) pair by the assignment model are shown. In the fourth column, the number of demand points covered by more than one DRF is given. In the results of the model for three cases, we observed that five, eight, and one demand points are covered by two DRFs. The coverage by two DRFs is induced by the model parameters and could be increased when the capacity limits of the DRFs are increased. The fifth and sixth columns are for the total distance traveled and total average destruction powers obtained by the assignment model. In the last column of Table 7.3, the average destruction power of (i, j) pair for each cases is calculated by dividing the total average destruction power to the number of (i, j) pair obtained in the result of the assignment model. Thus, the average destruction power is found per (i, j) pair. This value could be compared with the situation when it is thought as there are 81 DRFs (i.e., one warehouse in each city) and 81 demand points. If each demand point is assigned to each DRF, then we have 81×81 assignment, and the overall average destruction power per assignment is found as 0.85 by dividing the average destruction powers of each (i, j) pair to the number of demand points, which is 81. This means that when all cities behave like DRFs and are able to serve to all cities, the average destruction value of any assignment is 0.85. However, we take into account the population capacity of each DRF as well as destruction powers. It can be said that the assignment of demand points to the prepositioned DRFs are less risky when the obtained value is less than 0.85, so 0.85 is taken as a *moderate value*. When considered from this point of view, the second case is superior to the other cases, and it has the least average destruction power per (i, j) pair.

7.5 Conclusion and Future Work

In this study, our aim was to minimize the total distance between prepositioned DRFs and the demand points in cities by considering facility capacities and the average earthquake destruction powers between them. We developed an integer programming model for the assignment of demand points to the prepositioned DRFs. We tested our model with three cases, namely, container warehouses proposed by AFAD (Turkish Prime Ministry Disaster and Emergency Management Presidency), Turkish Red Crescent warehouses, and AFAD Civil Defense Search and Rescue City Directorates. In the results, we obtained the total distance traveled, the number of covered demand points by each DRF, and the total average earthquake destruction power. In the study, we observed that humanitarian relief organization considered in experimental studies has common cities to store the relief items being unaware of the warehouse decisions of each other. It shows that those common cities are suitable to have DRFs. This also reveals that some of the factors they consider in selecting the DRF locations are the same.

This study can be utilized to see the assignment effects on the average destruction powers and the number of the assigned demand points. In the study, we observed the total average destruction powers for each case, and we observed that they have different average destruction powers per (i, j) pair, two of them are above the moderate value, which is 0.85, and one of them is below the moderate value. The assignment for Turkish Red Crescent warehouses is the best in terms of all performance measures.

The study can be extended by considering the exact locations and capacities of DRFs. In future studies, the distances of exact locations for DRFs would support the implementation of the model and improve the analysis. Backup facility concept can be introduced to the model in order to be safe in the risks of not delivering the relief items to demand points when the warehouse or roads are destroyed.

Acknowledgments

We are grateful to Turkish Prime Ministry Disaster and Emergency Management Presidency (AFAD) personnel and the Scientific and Technological Research Council of Turkey (TUBITAK) who partially supported this study with the research Grant No. 113M493.

References

AFAD. T.C. başbakanlık Afet ve Acil Durum Yönetimi Başkanlığı [cited December 2012]. Available from http://www.afad.gov.tr.

Altay, N. and W. G. Green. 2006. OR/MS research in disaster operations management. *European Journal of Operational Research* 175(1): 475–493.

Balcik, B. and B. M. Beamon. 2008. Facility location in humanitarian relief. *International Journal of Logistics: Research and Applications* 11(2): 101–121.

Bhamra, R., S. Dani, and K. Burnard. 2011. Resilience: The concept, a literature review and future directions. *International Journal of Production Research* 49(18): 5735–5793.

Dükkancı, O., Ö. Koşak, A. İ. Mahmutoğulları, H. Özlü, and N. Timurlenk. 2011. Merkezi Afet Yönetiminde Karar Destek Sistemi Tasarımı. Bilkent University, Ankara, Turkey.

Duran, S., M. A. Gutierrez, and P. Keskinocak. 2011. Pre-positioning of emergency items worldwide for CARE international. *Interfaces* 41(3): 223–237.

Ercan, A. Ö. S. 2010/12. Türkiye'nin Deprem Çekincesi: İl il, ilçe ilçe Deprem Belgeseli. PARA Dergisi, 14–20 Mart.

Görmez, N., M. Köksalan, and F. S. Salman. 2011. Locating disaster response facilities in Istanbul. *Journal of the Operational Research Society* 62(7): 1239–1252.

KGM. General Directorates for Highways [cited December 2013]. Available from http://www.kgm.gov.tr.

Knight, F. H. 1921. *Risk, Uncertainty and Profit*. Hart, Schaffner & Marx, Boston, MA.

Rawls, C. G. and M. A. Turnquist. 2010. Pre-positioning of emergency supplies for disaster response. *Transportation research part B: Methodological* 44(4): 521–534.

Thomas, A. S. and L. R. Kopczak. 2005. From logistics to supply chain management: The path forward in the humanitarian sector. Fritz Institute, San Francisco, CA.

TUIK. Turkish Statistical Institute [cited December 2012]. Available from http://tuik.gov.tr.

Ukkusuri, S. V. and W. F. Yushimoto. 2008. Location routing approach for the humanitarian prepositioning problem. *Transportation Research Record: Journal of the Transportation Research Board* 2089(1): 18–25.

Van Wassenhove, L. N. 2006. Humanitarian aid logistics: Supply chain management in high gear. *Journal of the Operational Research Society* 57(5): 475–489.