POST-DISASTER RELIEF DISTRIBUTION UNDER ROAD VULNERABILITIES AND AFTERSHOCKS

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ABSTRACT

POST-DISASTER RELIEF DISTRIBUTION UNDER ROAD VULNERABILITIES AND AFTERSHOCKS

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In this thesis, a two-stage stochastic mixed integer programming approach is proposed to determine the two types of post-disaster decisions, namely relief distribution with direct/ lateral transshipment and emergency roadway repair simultaneously, under the risk of potential aftershocks. Two objective functions are considered: minimization of the demand-weighted total travel time subject to satisfying all demand (efficacy-based), and minimizing the maximum unsatisfied demand over all demand points (equity-based). A case study for a potential earthquake in Istanbul, Turkey is implemented, through which it is shown that (i) ignoring the potential effects of aftershocks may lead to detrimental results, (ii) without road repair, relief transportation is significantly hampered, (iii) the decisions are quite robust to the number of roads that are affected by the disaster, and (iv) lateral transshipment leads to improvements in transportation times to a certain extent.

Keywords: Humanitarian Logistics, Relief Distribution, Road Repair, Aftershocks, Two-Stage Stochastic Programming

ÖZ

YOL KIRILGANLIĞI VE ARTÇI ŞOK RİSKLERİ ALTINDA FELAKET SONRASI YARDIM MALZEMESİ DAĞITIMI

Baksı, Bikem Bennu

Yüksek Lisans, Endüstri Mühendisliği Bölümü

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Bu tez çalışmasında, artçı şok riski altındaki bir insani yardım ağı için felaket sonrası direct/yanal sevkiyat ve yol tamiri kararlarının verilmesi için bir iki aşamalı karışık tam sayılı stokastik programlama yaklaşımı ortaya konmaktadır. Önerilen model, etkililik temelli talep ağırlıklı toplam seyahat süresinin eşitlik temelli maksimum karşılanmayan talep miktarının en azlanması olmak üzere iki amaç fonksiyonu altında incelenmiştir. İstanbul'da olası bir deprem için bir vaka çalışması kullanılarak olası artçı şokların ihmal edilmesinin sonuçları oldukça olumsuz etkilediği, yol tamirinin göz ardı edilmesinin malzeme dağıtımını önemli ölçüde geciktirdiği, model sonuçlarının felaket sonrasında kullanılamaz hale gelen yol sayısına duyarlı olmadığı ve yanal sevkiyatın dağıtım sürelerini belli ölçüde iyileştirdiği gösterilmiştir.

Anahtar Kelimeler: İnsanı Yardım Lojistiği, Yardım Dağıtımı, Artçı Depremler, İki Aşamalı Stokastik Programlama

To my parents

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CHAPTER 1

INTRODUCTION AND MOTIVATION

In recent years, disasters have had crucial impacts on economy and social welfare in both developed and developing countries. The International Federal of Red Cross and Red Crescent Societies [1] 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.

Similarly, The United Nations Office for Disaster Risk Reduction [2] defines a disaster as

> A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources.

Disasters can be classified as natural disasters and man-made/technological disasters. The Centre for Research on the Epidemiology of Disasters (EM-DAT) further divides natural disasters into five categories: geophysical (e.g., earthquakes, landslides, tsunamis), hydrological (e.g., floods), climatological (e.g., drought, water shortages), meteorological (hurricanes, tropical storms, tornadoes), and biological (e.g., epidemics) [3]. One of the deadliest natural disasters in history is the Indian Ocean Earthquake and Tsunami in December 26, 2004, which is the third-largest earthquake ever recorded, with a magnitude of 9.1, near the west coast of Sumatra.

Man-made and technological disasters include climate change, cyber-attacks, nuclear explosions, nuclear and biochemical warfare, and terrorism. An example for a large-scale man-made disaster is the Chernobyl Nuclear Explosion in April 26,1986, which has been one of the only two disasters classified as level 7 on the International Nuclear Event Scale [4]. The Human Cost of Natural Disaster Report [5] released by Centre for Research on the Epidemiology of Disasters (CRED) records 6,873 disasters, which resulted in 1.35 million deaths between 1994 and 2013. Over this period, earthquakes killed 750,000 people in total, greater than the total deaths in any other types of disaster such as flood, epidemic, and volcanic activity. The period includes several mega disasters such as the 2004 Asian Tsunami and the 2010 Haitian earthquake.

In recent years, humanitarian logistics has become a popular research area due to the complex needs that arise from the natural and man-made disasters. Bean et al. [6] states that 80% of all disaster-related efforts relate to logistics, which underlines the importance of efficient and effective humanitarian logistics management in preparing for and responding to disasters. Van Vassenhove [7] defines humanitarian logistics as "the processes and systems involved in mobilizing people, resources, skills and knowledge to help vulnerable people affected by disaster". In the seminal review paper, Altay and Green [8] study OR/MS research in disaster operations management and underline the necessity for research in emergency logistics and humanitarian logistics areas.

In the humanitarian logistics literature, decisions that are related to the disaster are divided into pre-disaster and post-disaster phases. Decisions in the pre-disaster phase include facility location and pre-positioning of relief items. The decisions related to the post-disaster phase include distribution of relief items, implementing evacuation and rescue operations, clearance of debris, and location of emergency centers such as operations centers. The events in these two phases are further divided into four phases: mitigation, preparedness, response, and recovery. These four phases form the disaster management cycle, which can be seen in Figure 1.

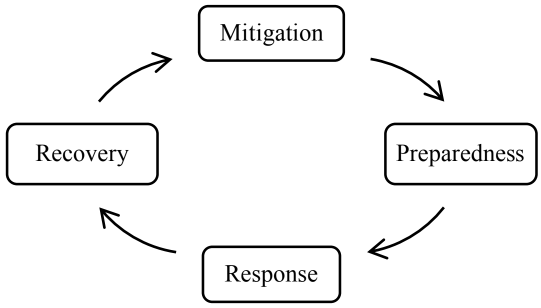


Figure 1: Disaster Management Cycle

The United States Federal Emergency Management Agency (FEMA) defines the events in the disaster management cycle in detail in [9]. Mitigation activities are performed before the occurrence of a potential disaster to either prevent it from happening or reduce its possible impacts. Some examples for the mitigation activities are strengthening of structures and investing in infrastructural projects. Preparedness activities are performed before the occurrence of a disaster to reduce its effects on people and economy, such as planning relief item distribution and locating the supplies that may be needed in an emergency. Response activities are performed in the immediate aftermath (e.g., within the first 72 hours) of the disaster. Response activities involve putting the preparedness plans into to action such as rebuilding damaged structures and infrastructural facilities. Recovery activities are performed in the medium and long-term following the disaster such as development of economic programmes for small businesses and provide psychological support for disaster victims.

Turkey is mainly vulnerable to three types of natural disasters: earthquakes, floods, and landslides. Due to the geographical position of the country, Turkey is located on several dangerous seismic zones and has 553 active fault segments, making it one of the most earthquake-prone countries in the world. Gökkaya [10] studies the earthquake damage between 1900 and 2012 in Turkey and states that 93 earthquakes with a magnitude greater than or equal to 5.0 resulted in 80,574 deaths between 1900 and 2012. Table 1.1 represents a summary data on earthquakes in Turkey.

Table 1.1. Summary Data on Earthquakes in Turkey from 1990 to present [10]

Earthquake	Year	Loss of Life	Injured	Homeless	Financial Loss (million US $)
Erzincan	1992	653	3,850	95,000	750
Dinar	1995	94	240	40,000	100
Ceyhan-Adana	1998	145	1,600	88,000	500
İzmit Körfezi	1999	17,480	43,953	675,000	13,000
Düzce	1999	763	4,948	35,000	750
Afyon	2002	42	327	30,000	96
Bingöl	2003	177	520	520	135
Van-Erciş	2011	601	4,152	302,479	1,000-2,000
TOTAL		19,995	59,590	1,265.999	16,331-17,331

Major earthquakes that affected the Marmara Region are due to the different segments of the North Anatolian Fault, which lies on the boundary between the Eurasian and African-Arabian plates. Major earthquakes affecting İstanbul have occurred in 1509, 1719, 1754, 1766, 1766, 1894, 1912, and lastly 1999 [11]. Statistical analysis by Erdik et al. [12] shows that the probability of earthquake occurrence in Istanbul and Marmara Region has increased after the Kocaeli and Düzce earthquakes in 1999. Thus, it is inevitable that a major earthquake is likely to occur in Istanbul within the next few decades. In addition, Erdik and Durukal [13] list the factors that increase the destruction raised from an earthquake in Istanbul as urbanization, overpopulation, and infrastructure. According to the Istanbul Seismic Risk Mitigation and Emergency Preparedness Project [14], the probability of occurrence of an earthquake in Istanbul within 30 years and 10 years are nearly 50 percent and 20 percent, respectively. Furthermore, the project addresses the fact that there are stupendous shortcomings in disaster management plan and activities in Turkey. While there exist numerous academic studies related to the estimation and mitigation of an earthquake in Istanbul, there also exists a gap for those that address the post-disaster phase, particularly regarding humanitarian logistics operations.

To distribute the needed relief items to the affected areas, relief item distribution network should be designed in a way to correspond to the rapid changes and asymmetric information. Like general distribution networks, relief item distribution networks consist of three main entities: supply points, transshipment points, and demand points (i.e., affected areas). The main objective of relief item distribution is to transport the needed relief items to the right place at the right time. The affected people may have many primary needs such as canned foods, blankets, first aid kits, clean drinking water, tents, cleaning supplies, communication devices and specific medicine to cope with infectious diseases after natural disasters [15]. It should be noted that a disrupted transportation system results in an inefficient relief item distribution.

During and after an earthquake, roadway systems of a city are crucial because of their support for effective and sustainable search-and-rescue and relief transportation operations. The deterioration of these networks could arise from the damaged buildings and the post-disaster debris. Yan and Shih [16] divide post-disaster roadway repair into long-term and short-term repairs. In this thesis, we focus on short-term roadway repairs, which are usually carried out quickly to facilitate search-and-rescue and transportation of the relief items to the affected areas within the first 72-hours. To underline the importance of these repairs, according to a survey with 18 international organizations following the 2004 earthquake and tsunami in the South Asia and Africa, 94% of the respondents' state that the destruction in the transportation networks resulted in major delays in humanitarian efforts [17]. Since a disrupted transportation system results in an inefficient relief item distribution, relief item distribution and emergency roadway repair should be considered simultaneously to overcome operational inefficiencies in humanitarian operations.

After the main shock of a large-scale earthquake, probability of a high-magnitude aftershock is usually very high. For this reason, disaster management activities in the post-disaster phase of the disaster management cycle should consider the probability of such aftershocks for more effective and efficient humanitarian logistics management. It is obvious that the magnitude, time, and the number of

aftershocks are strongly correlated with the characteristics of the main shocks. Omi et al. [18] state that most of the aftershocks usually occur within the first 24 hours after the main shock and increase the number of deaths, number of affected people, and damage in the infrastructural network of a city. Rottkemper et al. [19] define the "overlapping disaster" concept, which means reacting to a new disruption while continuing the previous humanitarian efforts. In the content of this thesis, "overlapping disaster" can be considered as taking into account the potential effects of aftershocks or secondary disasters while planning for the response stage.

There are several aftershock recordings with varying magnitudes in history after major earthquakes. For instance, after the 2010 Haiti earthquake with a magnitude of 7.0, at least 52 aftershocks were recorded during the following 12-day period [20]. The 2015 Nepal earthquake with a magnitude of 7.8 was followed by an aftershock with a magnitude of 7.3 [21]. The 2006 Yogyakarta earthquake, whose magnitude was 6.3, was followed by two major aftershocks within the first six hours with magnitudes of 4.8 and 4.6, respectively [22]. Intuitively, an increase in the magnitude of an earthquake will result in increase in the number and frequency of aftershocks. After the Kocaeli earthquake in 1999, thousands of aftershocks have been observed and recorded. Görgün et al. [23] state that there were 2,414 aftershocks after the Izmit earthquake, covering the regions Sakarya, Karadere, and Düzce. The aftershocks continued until October 10, 1999, whereas the biggest aftershock occurred in September 13, 1999. The crucial conclusion of this study is that the late aftershocks of Izmit earthquake activated the half of the rupture plane which is related to the Düzce earthquake in November 1999, which occurred only

87 days after the Izmit earthquake. Thus, a major earthquake in Istanbul is also likely to be followed by large-scale aftershocks as well.

This thesis mainly focuses on the decisions in the post-disaster phase, specifically the response phase of the disaster management cycle and constructs a mathematical model to analyze and interpret the impacts of a possible Istanbul earthquake of magnitude of greater than or equal to 7.0 and proposes an efficient approach to restore the transportation network and deliver relief items to the beneficiaries in a timely manner. As stated above, the main decisions involve the combination of emergency road repair and relief item distribution. Furthermore, although there are several studies in the literature that propose different mathematical models and solution approaches for network repair and relief distribution, there is little research about the effects of secondary disaster(s) namely aftershocks, a gap this thesis aims to fill.

The main contribution of this thesis is to propose a useful decision-making tool for decision-makers and analyze the effects of an aftershock to the humanitarian logistics network. To reflect the stochastic nature of an earthquake, a scenario-based approach is generated. Thus, each scenario with different repair costs, demands, which roads are disrupted by the aftershock, and what kind of aftershock will occur, if any, represents uncertainty. These generated scenarios are the representation of the different earthquakes and their possible outcomes. Herewith, a two-stage stochastic mixed-integer programming approach is implemented to analyze the interrelation between the relief item distribution decisions and emergency roadway repair decisions with the occurrence probability of an aftershock. In each stage, it is aimed to construct a relief item distribution plan and emergency roadway repair plan consecutively, while minimizing the total demand-weighted arrival time.

The remainder of this thesis organized as follows: Chapter 2 discusses the literature review about related humanitarian logistics studies and two-stage stochastic programming approaches. The detailed problem definition and suggested mathematical model with thorough explanations is discussed in Chapter 3. Thereafter, to implement the proposed model into to real-life disasters, a case study for a potential earthquake in Istanbul is introduced in Chapter 4. Chapter 5 incorporates the computational experiments and sensitivity analysis of the case study in Chapter 4. Finally, Chapter 6 is the conclusion of the thesis with the several suggestions for the future researches.

CHAPTER 2

LITERATURE REVIEW

In recent years, there is increased interest in humanitarian logistics as research area due to the increasing number and complexity of natural and man-made disasters as well as long-term humanitarian issues. Consequently, the methods of Operations Research (OR) and Management Science (MS) have been increasingly used in disaster operations management as a decision-making tool. Altay and Green [8] survey the OR/MS research in disaster operations management and underline the necessity for researches in emergency logistics and humanitarian logistics areas. In this study, of the 109 papers reviewed, approximately 71% are published in OR/MS journals. In addition, Altay and Green [8] conclude that about 44% and 21.1% of the 109 papers reviewed are related with the mitigation and preparedness phases, respectively. Overstreet et al. [24] review 51 articles and conclude that approximately 56% of the articles are related with the planning phase of disaster management. Leiras et al. [25] study 230 conceptual and analytical papers in humanitarian logistics literature 228 of which have been published between 1982 and 2012. Total number of papers that are related to the post-disaster phase of the disaster operations management cycle is 102. Leiras et al. [25] come to the conclusion that the disaster response activities in the 228 papers that are reviewed are mostly related with the preparedness and response phases of the disaster management cycle. Galindo and Batta [26] review the related articles in terms of the phases of the disaster management cycle and conclude that 33.5% and 3.2% of the articles are related with response and recovery phase, respectively. Consequently, there is a significant necessity in the humanitarian logistics literature about the response and recovery phases.

Caunhye et al. [27] list the most challenging fields in the humanitarian logistics as the dynamic and unpredictable nature of the disasters, uncertain number of the disaster victims, uncertainties in demand, debris amount, routes, facility capacities and asymmetric information. Thus, the uncertainty in various parameters influence the efficiency and effectiveness of the pre-disaster and post-disaster operations, which implies a need for the formulation of the stochastic models to represent the corresponding problem situations.

A limited number of papers on humanitarian logistics use two-stage stochastic programming to reflect the uncertainty in the problem environment. Altay and Green [8] indicate that over the 109 articles that are reviewed, only 3.7% use the stochastic programming technique. Leiras et al. [25] show the dominance of the deterministic studies in the literature with 49 deterministic studies over 34 stochastic studies in their review. Similarly, Galindo and Batta [26] review 155 articles with only 9.6% using stochastic programming. However, the interest stochastic programming nature has recently increased due to the need to cope with the uncertainties in the problem nature.

In this chapter, we review three streams of the literature relevant to the work in this thesis. In Section 2.1, studies on relief item distribution and commodity flow without emergency roadway repair in humanitarian logistics literature are examined. Section 2.2 discusses studies about relief item distribution and commodity flow with emergency roadway repair. Section 2.3. discusses the main characteristics of an aftershock and the impacts of the aftershock to the humanitarian logistics network in the relevant literature. It should be noted that there are few research papers related with the effects of aftershocks to the disaster response and humanitarian relief operations.

2.1. Relief Item Distribution and Commodity Flow without Emergency Roadway Repair

In the humanitarian logistics literature, several papers study relief item distribution in different perspectives. Relief item distribution problems aim to determine the amount of flow of supplies in the specified relief item distribution network, such as medical supplies and foods, by using different transportation modes from supply points to the affected areas. Each paper in this stream differs from the others in terms of methodology, assumptions, disaster type, and operational stages.

Haghani and Oh [28] is one of the pioneering studies for a deterministic approach in disaster operations management. A multi-commodity, multi-model network flow problem is proposed with the objective function that minimizes transportation costs, transfer costs and carry-over costs over a multi-period planning time horizon. A time-space network approach is implemented in favor of dealing with the importance of the timing of the decisions in the disaster operations management. The study proposes two solution approaches: (i) decomposition of the problem into two sub-problems (commodity flow subproblem and vehicle flow subproblem) followed by a Lagrangian relaxation approach and (ii) a fix-and-run process. An empirical study is constructed to measure robustness of the proposed mathematical model. In addition, several sensitivity analyses are constructed to measure the performance of the mathematical model in terms of different parameters.

Özdamar et al. [29] construct a mathematical model which is also divided into two sub-problems: relief item distribution and vehicle routing. The objective function is the minimization of total amount of unsatisfied demand for each relief item throughout planning time horizon. This paper differs from its counterparts in the humanitarian logistics literature with a re-planning approach. Supply, demand and vehicle capacities are updated over time. Since both sub-problems are NP-hard and computationally difficult to solve, Lagrangian relaxation based iterative algorithm which links two sub-problems is generated. An earthquake scenario with real-life data from Kocaeli earthquake in 1999 to measure performance of the model. It is shown that the proposed Lagrangian relaxation based heuristics result in convergence to optimal solution with reasonable computational time.

Dessouky et al. [30] formulate a facility location and vehicle routing problem simultaneously in a large-scale emergency. The objective function of the facility location problem is to minimize the distance between the selected facilities and the demand points. For relatively small size problems, efficient algorithms are generated to solve facility location and vehicle routing problems. A numerical case study is illustrated for anthrax attack emergency in Los Angeles, United States of America.

Sheu [31] addresses the importance of quick response to the affected areas after the disaster by using a hybrid fuzzy clustering-optimization approach with multi-objective dynamic programming model. Preliminarily, demand forecasting for two types of relief item is generated. Then, affected area is classified with regards to priority levels by using a fuzzy-based affected-area clustering procedure, which is followed by dynamic relief supply. For the group-based relief distribution, it is aimed to minimize the time-varying distribution costs and maximize the time-varying demand fill rate aggregated by priority level of each group. For the dynamic relief supply, the objective is minimization of weighted transportation costs. A case study is illustrated for the earthquake in central Taiwan on September 21, 1999 with a magnitude of 7.3 to measure effectiveness of the proposed model.

Yi and Kumar [32] study the relief item distribution network and transportation of wounded people from the affected areas together, which constitute two types of flow in the arcs. The first and second parts of the objective function are minimizing the weighted sum of unsatisfied demand over all commodities and minimizing the number of people that are waiting for medical care in the affected areas, respectively. Due to the complexity of the problem, an ant colony optimization algorithm is developed by decomposing the model into two parts: vehicle routing and relief item distribution. These two sub-problems are solved sequentially, where the first phase constructs the vehicle routes and the multi-commodity flow problem is solved based on the resulting vehicle routes. Thus, a solution to the original problem is given. The iterative solution approach yields a good communication between the two phases for continuous improvement of solution quality.

Vitoriano et al. [33] formulate a goal programming-based humanitarian aid distribution model with three different objectives: (i) minimizing total cost, (ii) minimizing ransack probability, and (iii) maximizing reliability. In the proposed model, it is aimed to distribute relief items while considering the optimal routing of the vehicles. The decision-maker could assign different priorities to each objective with regards to allocating scarce resources in the post-disaster environment. A numerical case study is illustrated for 2005-2006 Niger food crisis in the regions of northern Maradi, Tahoua, Tillabri, and Zinder of Niger.

Nolz et al. [34] propose a metaheuristic solution approach for drinking water distribution after a disaster to minimize the total distance between the affected areas and the water distribution point, and minimize the tour length subject to a specified budget. The two objective functions reflect a trade-off between short distribution tours and adequate coverage. The multi-objective formulation results in a set of alternative optimal solutions and usually the decision-maker choose among these solutions. Hence, two solution concepts; Pareto-optimal solution and dominated feasible solution are introduced to allow the decision-maker to choose from a set of alternative solutions. A case study is illustrated for Aceh, northwest of Sumatra, Indonesia.

Horner and Downs [35] construct a humanitarian logistics network to distribute relief items effectively and efficiently during a hurricane. After the onset of the disaster, related parties must be prepared to distribute emergency supplies to the people in the disaster areas. The supplies are distributed from special distribution facilities whose locations are pre-determined before the hurricane. The distribution system consists of Logistical Staging Areas (LSAs) and Points of Distribution (PODs). The flow of relief item is from the LSAs to the PODs. People in the affected areas usually travel to the PODs to receive the goods. The model is solved with an objective function to minimize the costs of distributing relief items from LSAs to the affected people through several types of intermediate distribution facilities. There are two types of cost in the designed logistics network: the transportation costs of moving relief items from LSAs to the affected areas and the additional cost that may arise due to the affected people to access the goods in the PODs. Finally, a case study is illustrated for a potential hurricane in Leon County, Florida by creating three different scenarios having 45%, 60%, and 75% of the population needing for relief item, respectively.

Hamedi et al. [36] study a multi-objective optimization problem for routing and scheduling of relief items such as food, water, and medicine in the post-disaster environment. Two objective functions of the proposed model aim to minimize total travel cost and reliability cost. The solution algorithm aims to determine the shortest-path that minimizes these two objective functions. In addition, the solution algorithm transforms the multi-objective characteristic of the problem into a single objective function by assigning weights. A shortest-path based genetic algorithm is proposed to handle large-scale problems. A numerical example is generated to measure robustness of the proposed mathematical model and heuristic.

Berkoune et al. [37] formulate a transportation model for the response phase of the disaster management cycle with three different solution approaches for large-scale problems: branch-and-bound procedure, set enumeration heuristic, and genetic algorithm. Several numerical solutions for each solution procedure are generated with different number of distribution centers, number of delivery points and number of products. A detailed sensitivity analysis is conducted to measure robustness of the genetic algorithm.

Cui et al. [38] formulate a nonconvex mixed-integer nonlinear programming model for evacuation and rescue operations during the post-disaster phase. In the proposed network, flows are in terms of number of people evacuated or rescued. Thus, this modified minimum-cost network flow problem can be transformed into relief item distribution problem easily. The objective function of the model is divided into four parts: (i) evacuation-flow time cost, (ii) rescue-flow time cost, (iii) conflict cost for evacuation and rescue flows, and (iv) reversal cost. A case study is illustrated for downtown area of Nanyang District, Harbin City, China.

Baskaya et al. [39] propose a mixed-integer programming model for facility location and relief item distribution with three different shipment options: direct shipment, lateral transshipment and maritime lateral transshipment. The objective function in each case is minimization of average distance that is travelled for each relief item including the vulnerability effect. A case study is illustrated for a potential earthquake in Istanbul.

Table 2.1 summarizes the relief item distribution papers without stochastic programming approach that are reviewed above in terms of decisions, objective functions, and solution approaches.

Table 2.1. Classification of Papers without Stochastic Programming with respect to the Decisions, Objective Functions, and Solution Approaches

Authors	Decisions	Objective Function	Solution Approaches
Haghani and Oh (1996)	-Relief Distribution -Vehicle Routing	-Minimize transportation, transfer, and carry-over costs	-Lagrangian relaxation -Fix-and-run process
Özdamar et al. (2004)	-Relief distribution -Vehicle Routing	-Minimize total amount of unsatisfied demand	-Lagrangian relaxation based heuristic
Dessousky et al. (2006)	-Facility location -Vehicle routing	-Minimize the distance between facilities and demand points	-For large-scale problems, an efficient heuristic should be implemented
Sheu (2007)	-Group-based relief distribution -Transport optimal relief supply	-Minimize the weighted transportation costs	-Hybrid fuzzy clustering-optimization method
Yi and Kumar (2007)	-Multi-commodity relief distribution	-Minimize weighted sum of unsatisfied demand for different type of relief items	-Ant colony optimization algorithm

Table 2.1 (continued). Classification of Papers without Stochastic Programming with respect to the Decisions, Objective Functions, and Solution Approaches

Authors	Decisions	Objective Function	Solution Approaches
Nolz et al. (2010)	-Vehicle routing and Aid team assignment -Water distribution	-Minimize tour length -Maximize covering location	-Multi-objective Optimization
Horner and Downs (2010)	-Facility Location -Relief distribution	-Minimize the costs of distributing relief items	-Spatial optimization model
Hamedi et al. (2012)	-Relief distribution -Vehicle routing	-Minimize total travel and reliability cost	-Genetic algorithm based heuristic
Berkoune et al. (2012)	-Number of people evacuated or rescued	-Minimize the total duration of all trips	-Branch-and-bound process -Set enumeration heuristic -Genetic algorithm
Cui et al. (2014)	-Evacuation flow -Rescue flow	-Minimize evacuation-flow time, rescue-flow time, conflict, and reversal cost.	-BARON is used to solve non-convex mixed integer programming
Baskaya et al. (2017)	-Facility location -Relief distribution via direct shipment and lateral transshipment	-Minimize average distance that is travelled for each relief item	-Both models give optimal solution using GAMS

There are many studies in the relief distribution literature that make use of stochastic programming with different characteristics of formulation, solution algorithm, and objective function.

Barbarosoğlu and Arda [40] propose a two-stage stochastic programming approach to formulate a multi-commodity multi-modal relief transportation problem. The decisions are affected by the earthquake scenarios and impact scenarios, which represent the uncertainty that arise from the epicenter and magnitude of earthquake and estimation of the impact(s) of the earthquake, respectively. These scenarios involve different supply, demand, and capacity values. Specifically, first-stage and second-stage decisions are related with the total amount, excess amount, and shortage amount of commodity flow. The objective function is the total cost of the first-stage decisions and second-stage decisions, which includes transportation cost and penalty cost for each unit of unsatisfied demand. To measure the effectiveness of the proposed model, data generated from the Kocaeli earthquake in 1999 is used for the case study.

Chang et al. [41] formulate a two-stage stochastic programming model to create an effective emergency logistics plan after the occurrence of a flood. In the first-stage, the disaster areas are classified with respect to their emergency levels (i.e., risk of flood) and in the second-stage, a location-allocation model for the selected local rescue and transportation plans for rescue equipment is solved. The objectives for the first and second-stage are minimizing the expected shipping distance and minimizing the setup costs, procurement costs, penalty costs and expected transportation costs, respectively. Scenario development is generated by a geographic information system. The proposed model is implemented on a case study in Taipei City, located in Northern Taiwan. Sample average approximation technique is used to solve the proposed model for different rainfall scenarios.

Shen et al. [42] propose a two-stage stochastic programming model for a large-scale bioterrorism emergency attack (i.e., anthrax) with both planning and operational stages. In the planning stage, a stochastic vehicle routing problem is considered. The stochastic nature of the problem arises from the uncertainty in demand and traffic condition. Thus, a chance-constrained programming technique with uncertain travel times and demand is used. After the disaster (in the operational stage), the values of the uncertain parameters become available, which should be implemented into the planning stage to make (if necessary) adjustments in the selected routes. To measure the robustness of the second-stage model, three different solution techniques are used; linear programming recourse, knapsack recourse, and re-planning. Due to restrictions in computational time, a tabu search heuristic is implemented.

Mete and Zabinsky [43] present a two-stage stochastic programming model related to both preparedness and response phases of the disaster management cycle. The preparedness phase decisions are warehouse selection and inventory levels. The response phase decisions include a transportation plan for the medical supply under each scenario by taking into consideration the first stage decisions. The objective function is to minimize total operation cost of the warehouses, total transportation time, and the total cost for unsatisfied demand. The optimal deliveries of medical supplies in the second-stage of the model are used to construct a secondary mixed-integer programming model which gives the optimal routing plans from warehouses to demand points. The same MIP model can also be used during response phase after an earthquake, with updated information on road conditions, the need for medical supplies, and the availability of medical supplies to provide a revised transportation plan with detailed routes relatively quickly. A case study for the model is illustrated for an expected earthquake in Seattle.

Zhan and Liu [44] construct a humanitarian logistics network with multi-supplier, multi-demand points, multi-relief items, and multi-transportation modes. Before the disaster, location of facilities from the candidate points is determined. After the disaster, vehicle routing and relief item distribution decisions are made. The objective function can be divided into two parts: minimizing the expected total travel time and minimizing the expected amount of unmet demand. The stochastic nature of the proposed model arises from the uncertainty in demand, supply, and availability of the path. Three types of scenarios are generated for the disaster magnitude: mild, medium, and severe disaster. The stochastic model is transformed into a deterministic equivalent model by using chance constraints. A goal programming approach is implemented to allow the decision-maker to assign weights to each objective with respect to importance level.

Döyen et al. [45] study a two-stage stochastic programming model which covers both pre-disaster and post-disaster decisions. The first-stage decisions are the location of regional rescue centers (RRCs) and their inventory levels. The second-stage decisions are the location of local rescue centers (LRCs) and flow of relief items on each echelon. The objective function is the minimization of total cost which includes transportation cost, inventory holding cost, penalty cost, and fixed cost of opening RRCs and LRCs. A discrete and finite set of scenarios is generated to reflect the uncertainty that arises from the timing and magnitude of the disaster. Due to the increase in the computational time of the proposed mathematical model, a Lagrangian heuristic approach with an addition of local search analysis is constituted.

Bozorgi-Amiri et al. [46] formulate a robust stochastic programming model to determine the optimal numbers, locations, and capacity levels of the supply points (relief distribution centers) to transport relief items to the demand points (affected areas) to minimize total cost and unsatisfied demand. There are three main types of uncertainty in the proposed model: supply, demand, and cost. To identify the importance of uncertainty in a post-disaster environment, different models are constructed, each one having a different degree of uncertainty. In the first-stage of the problem, the locations of the relief distribution centers and their respective inventory levels for each type of relief item are determined. In the second-stage, the amount of relief item flows from relief distribution centers to the affected areas is determined. Finally, a case study is illustrated for southern Central Alborz, Iran, to measure the robustness of the proposed model.

Alem and Clark [47] study a mathematical model for relief item allocation in warehouses and vehicle routing problems for possible disasters. The objective is to minimize the total cost incurred in the pre-allocation of stock, stocking of inventory, and unmet demand over multiple scenarios. The scenario generation process assumes that it is not possible to estimate the exact value of the supply, demand, arc capacities or any other parameter that is related in the post-disaster environment.

By following this procedure, 40 different scenarios are generated. Uncertain parameters in the scenarios are demand, supply, donation amounts, and arc capacities. Furthermore, for each scenario, cumulative unsatisfied demands for each relief item is calculated to analyze the service levels. A case study is illustrated the flood in Rio de Janerio, 2011, the largest disaster in Brazil in terms of number of deaths.

Rezaei-Malek and Tavakkoli-Moghaddam [48] study a robust bi-objective mixed-integer programming model for the pre-disaster phase of the disaster management cycle, which aims to find the optimal warehouse locations and optimal relief item amounts. To reflect the uncertainty, different scenarios are generated based on the timing and magnitude of a disaster. The two objective functions are aimed to minimize average weighted response time and total cost for all scenarios.

Reservation level Tchebycheff procedure is used to solve the proposed model. The case study for a potential Seattle earthquake by Mete and Zabinsky [43] is illustrated for the proposed model. For sensitivity analysis, three models are defined to find a relationship between average response time, total cost, and fairness level.

Noyan et al. [49] study the last mile optimization of relief items from Local Distribution Centers (LDCs) to Points of Distribution (PODs). The decisions that are made in the proposed last mile network problem are the locations and capacities of PODs and the allocation of available relief item supply to the PODs. The post-disaster environment results in an uncertainty in relief item demand and the conditions of the transportation network, which is captured by a finite set of scenarios. To generate demand amounts for the post-disaster environment, a deviation factor is used. This deviation factor is used to generate demand values of relief item (tent) for each scenario. A case study is illustrated for October 23, 2011 Van earthquake, with a network of 94 nodes.

Gonçalvez et al. [50] discuss a two-stage stochastic optimization model for food aid supply and distribution planning decisions. The uncertainty in the problem arises from the amount of demand and road accessibility in the post-disaster environment. The first-stage and second-stage decisions are pre-positioning of food aid and flow of food aid from supply points to demand points while considering the unmet demand in each demand point, respectively. To illustrate a case study, comprehensive data is collected from the headquarter of World Food Programme in Ethiopia for WFP's operations in 2009 and 2010. Several scenarios are defined to capture stochasticity of the proposed model with regards to uncertainty in demand and road accessibility.

Aslan [51] proposes a two-stage stochastic optimization model for pre-disaster and post-disaster phases of the disaster management cycle. For the pre-disaster and post-disaster phases, the humanitarian relief decisions are item prepositioning, warehouse and distribution center locations and relief item transportation, respectively. The objective function of the baseline model is the minimization of total expected demand weighted arrival time for both transportation modes while penalizing the weighted arrival time of unsatisfied demand under each scenario. A

case study is illustrated for a potential earthquake in Istanbul, Turkey. Different size of scenario sets is generated to reflect the uncertainty in road vulnerabilities, facility vulnerabilities and demand. A sample average approximation heuristic is constructed to handle large-scale instances.

Table 2.2 summarizes the relief distribution papers with stochastic programming approach that are reviewed above in terms of decisions, objective functions, and solution approaches.

Table 2.2. Classification of Papers with Stochastic Programming with respect to the Decisions, Objective Functions, and Solution Approaches

Authors	First-stage Decisions	Second-stage Decisions	Objective Function	Solution Approaches	Exact Solution	Heuristic
Barbarasoğlu and Arda (2004)	-Relief distribution	-Relief distribution -Excess and shortage amount of relief item	Minimize total cost and expected recourse cost for first-stage and second-stage of the problem	-Two-stage stochastic programming approach	Yes	
Chang et al. (2007)	-Facility location -Allocation of rescue resources	Allocation of rescue resources	Minimize total cost and expected shipping distance	-Sample average approximation heuristic		Yes
Mete and Zabinsky (2010)	Warehouse selection and inventory levels	Transportation plan	-Minimize total operation cost, total transportation cost	Deterministic equivalent of the stochastic model	Yes	
Shen et al. (2009)	-Vehicle Routing	-Vehicle Routing -Relief distribution	Minimize the unsatisfied demand and arrival time at each node	Approximation heuristic for the proposed recourse strategies		Yes
Zhan and Liu (2011)	-Facility Location	-Vehicle routing -Relief distribution	-Minimize expected total travel time, unsatisfied demand	-Goal-programming approach	Yes	

Table 2.2 (continued). Classification of Papers with Stochastic Programming with respect to the Decisions, Objective Functions, and Solution Approaches

Authors	First-stage Decisions	Second-stage Decisions	Objective Function	Solution Approaches	Exact Solution	Heuristic
Döyen et al. (2012)	-Location of RRCs and their inventory levels	-Location of LRCs -Relief distribution -Amount of shortage	-Minimize total cost: transportation, holding, penalty, and fixed cost	-Lagrangean heuristic improved by a local search algorithm		Yes
Bozorgi-Amiri et al. (2013)	-Facility location and its storage capacities	-Relief distribution	-Minimize total cost, and maximum shortage in the affected areas	-Compromise programming	Yes	
Rezaei-Malek and Tavakkoli-Moghaddam (2013)	-Facility Location Prepositioning of relief items	-Relief distribution -Amount of shortage	-Minimize the average expected response time under scenario s	-Reservation Level Tchebycheff Procedure (RLTP) method	Yes	
Gonçalvez et al.	Preposition of relief items	-Relief distribution -Amount of unsatisfied demand	-Minimize total cost, and the expected total cost	-Model gives optimal solution by using AIMMS	Yes	
Aslan (2016)	-Facility Location -Preposition of relief items	-Relief distribution	-Minimize of total expected demand weighted arrival time	-Sample Average Approximation Method		Yes

2.2. Relief Item Distribution and Commodity Flow with Emergency Roadway Repair

A limited number of studies in the humanitarian logistics literature consider combining emergency roadway decisions with relief distribution.

Wang and Hu [52] discuss a bi-level optimization problem with two decisions: (i) network reconstruction and (ii) emergency evacuation, which are the upper and lower levels of the problem, respectively. The decisions in the lower level could change when there is a change in network reconstruction problem (i.e., upper level). Thus, the upper and the lower level of the bi-level optimization could be treated as the leader and the follower of the Stackelberg game, respectively. Four different solution algorithms are generated: variational inequality sensitivity analysis method, generalized inverse matrix method, diagonalization method, and gradient projection method. To measure robustness of the proposed model, different types of networks are constructed with different parameters.

Tzeng et al. [53] study a basic relief item distribution problem with a fuzzy multi-objective linear programming methodology. The planning horizon is divided into discrete periods. The solution procedure proceeds as follows: after the data colletion, the extent of road destruction and the expected time for road restoration is determined. After the prediction of the commodity demand, the quickest route from commodity collection depots to the transfer depots is selected. Three objectives are to (i) minimize setup and operational costs, (ii) minimize total travel time in the overall network, and (iii) minimize unfair distribution among the disaster victims over planning time horizon. A case study for an earthquake in September 21, 1999 in Taichung, Nantou City and Nantou Country is used to test the proposed model on real-life instances.

Yan and Shih [16] study emergency roadway repair and relief item distribution simultaneously to analyze the interrelationship between these two major decisions in humanitarian supply chains. The model is formulated as a multi-objective, mixed-integer, multiple commodity network flow problem. Due to the complexity of the model, a heuristic solution approach is developed. The objective function is to minimize the length of time required for both emergency roadway repair and relief item distribution. To rank the objective functions with respect to their importance levels, weighting method is used in which decision-maker could assign weights to the objectives with regards to their importance levels. In addition, a decomposition algorithm is constructed for dividing the integrated model into two sub-problems: roadway repair and relief item distribution to test the effectiveness of the proposed model. A case study is illustrated for 1999 Chi-Chi earthquake in Taiwan by randomly generating two-large scale and two-medium scale problems.

Edrissi et al. [54] formulate a multi-agent optimization problem with three sub-problems: (i) renovation of the damaged buildings and houses, (ii) recovery of infrastructural systems and (iii) location/allocation of relief items with the objective function of minimizing the total number of casualties (CTDL). This paper differs from the vast of the relief transportation and road repair literature because of considering the coordination between agencies. The value of CTDL is smaller in the presence of coordination between agencies when compared to lack of coordination. To handle more realistic and large-scale problems, a heuristic approach is proposed. To measure robustness of the proposed model, sensitivity analysis on different levels of budgets is performed. Furthermore, a real-life city and transportation network example is introduced, which results in an 11.13% increase in the objective function valuwith coordination between agencies.

Torabi et al. [55] focus on a multi-objective, multi-period, multi-commodity optimization problem while considering (i) relief item distribution, (ii) road restoration, and (iii) location of depots near the affected areas. The three objective functions aim to minimize total cost, minimize sum of arriving times of relief items to the affected areas, and maximize reliability of routes, respectively. In the post-disaster environment, there are candidate depots for relief item distribution. For road restoration part of the proposed model, each road has a priority in terms of its importance level. A numerical example is generated for an earthquake in Tehran, Iran. A metaheuristic approach is generated to handle large-scale problems, which is significantly faster in terms of computational time.

Liberatore et al. [56] study a hierarchical model with two sub-problems: relief item distribution and recovery of the damaged areas in the post-disaster environment. The proposed model aims to construct an optimization plan for recovery operations such as clearance of debris from the roads or building a temporary bridge. Then, these optimization plans are incorporated into a relief item distribution model to have effective and efficient distribution plans. A multi-objective model is proposed to leave the trade-off decisions to the decision- makers. To solve the multi-objective model, a three-level lexicographic optimization model with different objective functions in each level is proposed. The objective function of each level is the maximization of total served demand, minimization of the Chebyshev distance and minimization of the norm one distance, respectively. A case study is illustrated for January, 12 2010 earthquake in Haiti.

Ransikarbum and Mason [57] propose a multi-objective optimization problem which considers relief item distribution and network restoration simultaneously. The two objectives are aimed to maximize equity and minimize the total unsatisfied demand, respectively. The third objective function is aimed to minimize the total network restoration cots. Since the proposed model is NP-hard and very difficult to solve, several experiments are designed. Pareto-optimal solutions are found to allow decision-maker to choose among a set of alternative solutions. A case study is illustrated for a potential earthquake in the Columbia, South Carolina with a magnitude of 9.0.

To the best of our knowledge, there is only one research paper related with relief item distribution and commodity flow with emergency roadway repair that incorporates the uncertainty of the problem environment. Çelik et al. [58] study a stochastic optimization problem for the response phase of the disaster management cycle which is aimed to obtain a sequence of roads that should be cleared from debris while considering the demand satisfaction. The stochastic nature of the mathematical model arises from uncertainty in debris amounts and road prioritization. The objective function is maximization of the total weighted flow sent to demand nodes by connecting the supply and demand nodes via debris clearance. Three heuristics are implemented to handle large-scale problems. Ultimately, a case study is illustrated for a potential earthquake in Boston, Massachusetts with a magnitude of 6.5.

2.3. Literature Review on Aftershock(s) in Humanitarian Logistics

In one of the several review papers that are related to humanitarian logistics, Safeer et al. [59] show that until now, in the humanitarian logistics literature, network design/vehicle routing and relief item distribution problems are only taken into consideration in post-disaster environment without regard to the uncertainties arising from potential aftershocks.

As explained in Chapter 1, considering and forecasting the aftershocks in the disaster management and emergency response activities is crucial. Ebel et al. [60] use well-known Omori's Law to model aftershock activity. Omori's Law assumes that the rate of aftershocks at time T decreases proportional to $1/T$. Lee et al. [61] conclude that the rates of aftershocks could be found by Omori's law and the distribution of interoccurance time of aftershocks are nonhomogeneous Poisson process. Furthermore, Lee et al. [61] analyze the aftershock records of the Chi-Chi, Taiwan earthquake in September 20, 1999 in which 42,952 aftershocks were recorded within a 1,000-day interval.

There is a limited number of papers in the literature that study the optimal allocation of emergency resources considering aftershocks.

Sherali and Subramanian [62] study a mixed-integer programming model for effective response to traffic accidents. The study considers additional accidents by adding a new term related with the opportunity cost for future accidents each having a probability distribution, which in this thesis, corresponds to the aftershocks. The objective function is the sum of primary response cost of the traffic accidents and expected secondary response cost of additional accidents. The expected secondary response cost is the opportunity cost of handling an additional future accident. An LP relaxation of the primary model is constructed to reduce computational time. An LP-based heuristic approach is generated to handle large-scale problems which are significantly faster in terms of computational time.

Fiedrich et al. [63] propose a mathematical model for search-and-rescue operations during the first 72 hours after the earthquake, with an objective function to minimize the number of fatalities over all times. In this study, secondary disasters or aftershocks include landslides, dam failures, damaged buildings, fire, delayed rescue and lack of medical treatment. With the occurrence of secondary disasters, the nodes in the humanitarian logistics network may be increased. Probability of secondary disasters or aftershocks is generated by a Weibull distribution. In addition, to handle large-scale problems two commonly known metaheuristics, simulated annealing and tabu search are implemented and compared in terms of time with hill climbing procedures.

Zhang et al. [64] propose a multiple-resource multiple-depot emergency response problem in an environment with the possibility of a secondary disaster. The objective function of the problem is the minimization of the cost of emergency resource allocation of primary and secondary disasters. The cost of emergency resource allocation that arises from the secondary disaster could be considered as the opportunity cost of assigning an available resource to the candidate aftershock locations, each having a certain probability. The proposed model is a mixed-integer programming model, which is hard and complex to solve for large-scale real-life problems. Thus, a heuristic algorithm is proposed which relaxes the LP solutions and by using the secondary disasters' probability of occurrence, the allocation of resources is determined.

2.4. Contributions of this Thesis

As can be seen in Table 2.1, a majority of the papers in the literature on disaster response consider relief distribution without regard to concurrent road repair. Furthermore, as can be inferred from Table 2.2, those that consider there two activities together ignore the inherent uncertainty in the environment. Most of the papers have a single objective function and do not include any uncertainty. In addition, majority of the relevant papers are both related with pre-disaster (i.e., facility location and item pre-positioning) and post-disaster (i.e., relief distribution) humanitarian logistics decisions and focus solely on uncertainties faced in the pre-disaster stage. Hence, there is a gap in the literature in terms of modeling uncertainties faced after the disaster. Furthermore, Tables 2.1 and 2.2 demonstrate that on relief transportation and roadway repair most of the existing papers focus on the minimization of the total cost. This thesis contributes to the humanitarian logistics literature in two main ways: (i) by including uncertainties (i.e., demand levels, and conditions of the roads) in the proposed model, and (ii) by solving relief distribution and roadway repair model simultaneously while minimizing the total demand-weighted arrival time.

As presented in Section 2.3, very few of the studies in the humanitarian logistics literature consider the importance of secondary disasters or aftershocks for sustainable and effective humanitarian relief operations. Several statistical techniques are used in geological engineering literature to generate and analyze aftershocks. However, surprisingly these techniques are rarely a point of interest in planning for and implementing humanitarian logistics decisions. This thesis varies from the vast of the humanitarian logistics literature in a way that, to the best of our knowledge, it is the first study to consider relief item distribution and emergency roadway repair optimization problems simultaneously in conjunction with the possibility of aftershock occurrence, taking into account the re-planning prospect of the overall relief operations.

CHAPTER 3

PROBLEM DEFINITION AND THE PROPOSED MATHEMATICAL MODEL

In this thesis, a two-stage stochastic mixed integer programming approach is implemented for post-disaster optimization decisions on emergency roadway repair and relief item distribution simultaneously. Minimizing the demand-weighted total travel time is the objective function of the proposed mathematical model. Although this thesis covers the operational decisions after an earthquake, the proposed models could be applicable to several other disasters such as floods, landslides and tsunamis, particularly when these disasters show cascading effects.

The two-stage stochastic programming approach is implemented in order to optimize relief distribution and emergency roadway repair problems in an integrated framework. In this modelling approach, these two different decisions should be made at two different time stages in the humanitarian logistics network: after the main shock (i.e., first-stage decisions) and after the aftershock (i.e., second-stage decisions), if any.

Both in the first-stage and second-stage of the problem, the number of roads that are cleared and the amount of relief item that is transported from the selected roads are decided after the occurrence of the disaster. After selecting the amount of relief item flow and the sequence of roads, an aftershock may occur. It should be noted that the magnitude, location and time of the aftershock is not known in advance, resulting in uncertainty in the problem environment. This stochastic nature of

problem leads to uncertainty in repair cost, quantity demanded in each demand point, and the operational status of each road segment.

The remainder of this chapter organized as follows: Section 3.1 characterizes the problem definition and related assumptions. In Section 3.2, the proposed two-stage stochastic mixed integer programming is detailed in terms of the objective function, constraints, parameters, and decision variables.

3.1. Problem Definition

After occurrence of an earthquake, the related parties should implement diverse decisions related with the emergency response while taking into account the lack of information on the affected population's needs. Emergency roadway repair decisions are crucial in post-disaster operations to transport relief items to the affected areas and manage evacuation activities. To analyze the sequence of events and decisions for the problem considered in this thesis, Figure 2 represents a decision tree of events. After the main disaster, there are two possible decisions to be made; a blocked road is either repaired, which means that the becomes traversable, or it is not repaired which means it remains blocked. The occurrence of aftershocks with different magnitudes is represented with discrete number of scenarios that results in randomness in our proposed model. Thus, to reflect uncertainty, several scenarios are defined and constructed. Each scenario is constructed by different values of repair cost, demand, and new disrupted roads. Scenario probabilities are retrieved from aftershock probabilities estimated by Japan Meteorological Agency [75]. As a result, the aftershock results in an additional decision for the clearance of the roads based on if they are operating or not after the aftershock. In other words, each operational decision should be updated when the new information is available (i.e., the effect of the aftershock(s) becomes known).

Relief items are transported from the supply points to the affected areas (demand points) via the roads that are not affected from main shock/aftershock(s) and/or the repaired roads. It is obvious that in the post-disaster environment, relief items are usually scarce due to asymmetric information and lack of communication between related parties. Hence, the needs of the affected population are usually higher than the available resources; making it impossible to match available supply with demand. In addition, the amount of demand may increase significantly after an aftershock, further exacerbating this mismatch.

Figure 3 represents the proposed network for the relief item distribution. There are two types of shipments taken into consideration in this thesis: direct shipment and lateral transshipment. Direct shipment is the transportation of relief item from supply points to demand points. In addition, supply points could engage in lateral transshipment by acting as consolidation points from other supply points to demand points. After any type of disaster, the effective relief item distribution is simply based on operational planning: "right" amount of relief item at the "right" place in the "right" time. In addition, at each supply point, there is a pre-determined amount of relief item that is ready to be distributed. Likewise, each demand point has a pre-determined amount of relief item that is required for the affected people. All relief item distribution decisions in both first-stage and second-stage of the problem should be made such that the total flow-weighted travel time is minimized. Relief item distribution decisions should be updated simultaneously with emergency roadway repair decisions concerning the roads affected by the main shock and aftershock after realization of the uncertainties (magnitude of the aftershock and amount of demand).

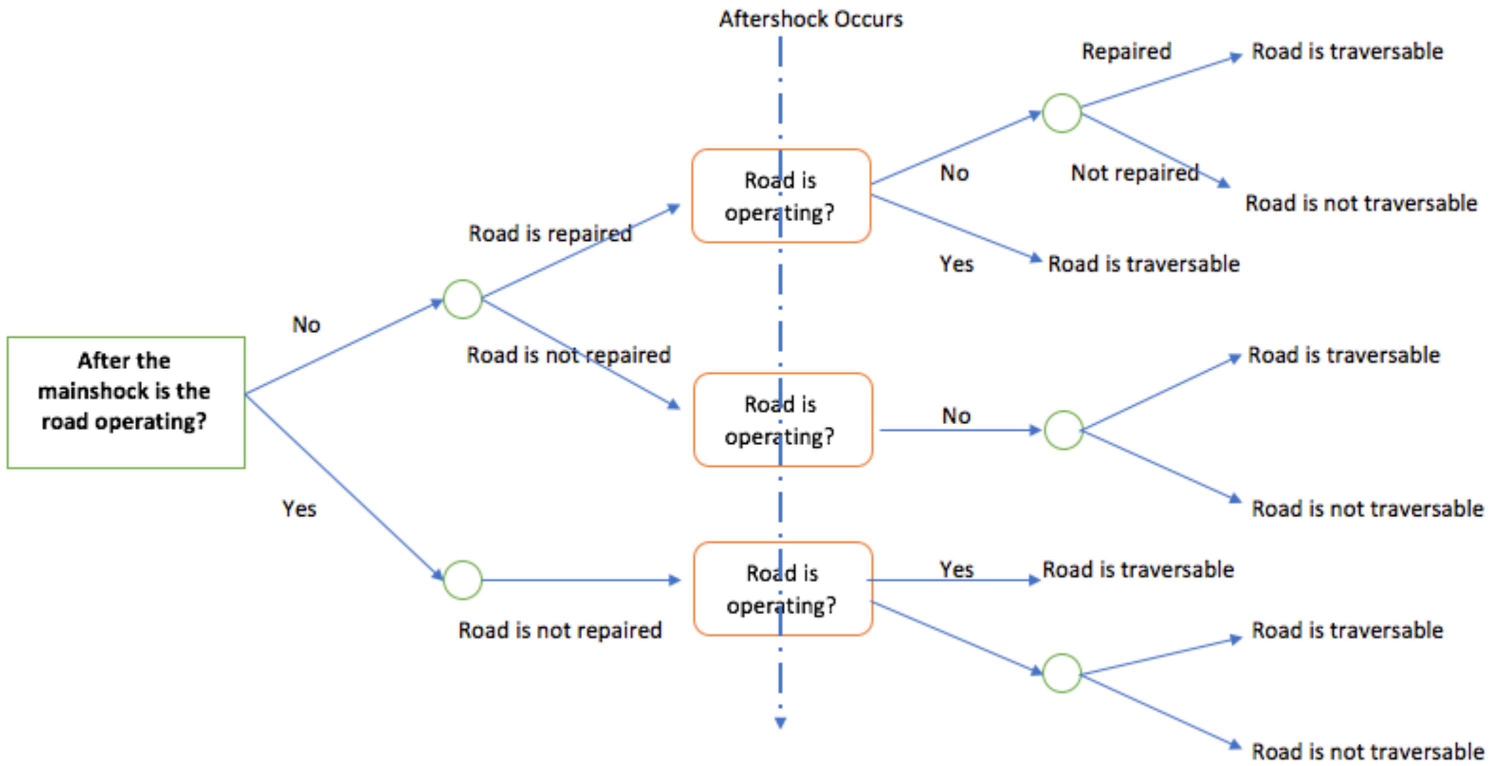


Figure 2: Decision Tree for the Proposed Emergency Roadway Repair Network

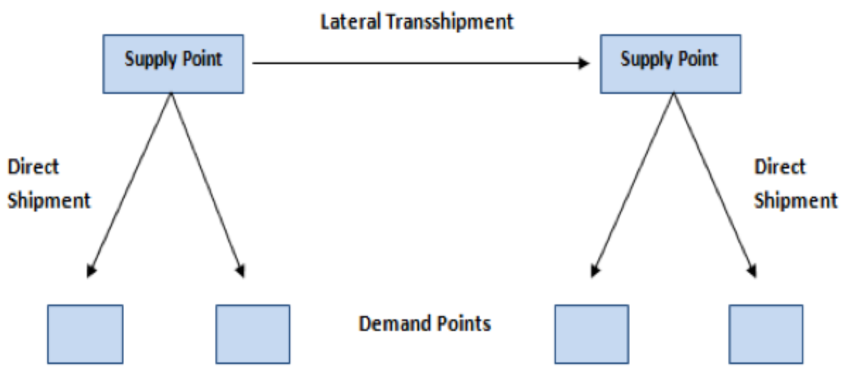


Figure 3: Relief Item Distribution Network

In the following, the basic assumptions that are used to construct the proposed two-stage stochastic mixed-integer programming model are listed. Afterwards, relief item distribution and roadway repair network is detailed.

1. The capacity, number and location of supply and demand points are pre-determined. These decisions are made in the pre-disaster phase of the timeline.

2. The relief items are already pre-positioned in the supply points at the beginning of the response phase. Similarly, these decisions are made in the pre-disaster phase of the timeline.

3. Without loss of generality, warehouses or distribution centers are assumed to be unaffected from main shock or aftershock.

4. Each demand point has the same priority level to balance equity and fairness among the affected people.

5. For simplicity, one type of relief item is taken into consideration. However, as in the study of Rawls and Turnquist [65], this one type of relief item could be

considered as a bundle of relief items such as water, tents, canned goods and first-aid kits.

6. The amount of overall budget is pre-determined and large enough to supply the demand. This available resource is distributed between the first-stage and the second-stage of the problem.
7. A road segment is either fully blocked, or operates at full capacity as a result of the disaster.

3.2. The Proposed Two-Stage Stochastic Programming Model

After defining the problem characteristics properly, a two-stage stochastic mixed integer-programming model is constructed.

The first-stage and second-stage of the problem exhibit deterministic and stochastic nature, respectively. Hereinbefore, the stochastic nature of the proposed model arises from the uncertainty in demand, repair cost, and the nature of damaged roads, which is captured by road vulnerabilities for each road segment. Road vulnerabilities are incorporated into to the model by binary variables for the first-stage and the second-stage of the problem, which will be detailed in Chapter 4 of the thesis.

In this two-stage stochastic programming formulation, the two aforementioned decisions should be made at two different phases in the humanitarian logistics network: after the main shock and after the aftershock. The primary outputs of the proposed mathematical model for both the first-stage and the second-stage of the problem are (i) amount of relief item flow on each road segment via direct shipment, (ii) amount of relief item flow on each road segment via lateral transshipment, (iii) the set of roads that are used in the emergency repair network and (iv) assignment of supply points to demand points, with an objective function that minimizes the total flow-weighted travel time of the relief item for the overall network.

The following notation is used to formulate the proposed model for relief item distribution and emergency roadway repair. Indices, index sets, deterministic and scenario-based parameters and decision variables for both first-stage and second-stage of the problem are defined. Afterwards, objective function and constraints are defined.

Indices and Index Sets

I: demand nodes

J: supply nodes

N: all nodes in the network: N=I∪J

E: edges corresponding to road segments

S: potential aftershock scenarios

Deterministic Parameters

$$b_{ij} = \begin{cases} 1, \text{ if } (i,j) \in E \text{ is still traversable after the main shock} \\ 0, \text{ otherwise} \end{cases}$$

k_{ij}: total capacity of $(i,j) \in E$ for both direct and lateral transshipment

c_{ij}: repair cost of using $(i,j) \in E$ in the emergency repair network

d_i: quantity demanded in node $i \in I$

M: a sufficiently large number

B: total budget for emergency repair for both stages

u_j: available supply in node $j \in J$

t_{ji}: travel time required to transport relief item from supply point $j \in J$ to demand point $i \in I$ for direct shipment

$t_{jj'i}$: travel time required to transport relief item flow from supply point $j \in J$ to demand point $i \in I$ via supply point $j \in J$ for lateral transshipment, $t_{jj'i}=t_{jj'}+t_{ji}$

Scenario-dependent Parameters

$\beta_{ij}^{s} = \begin{cases} 1, \text{if } (i,j) \in E \text{ is not affected by the aftershock under scenario } s \in S \\ 0, \text{otherwise} \end{cases}$

γ_{ij}^{s}: repair cost of using $(i,j) \in E$ in the repair network under aftershock scenario $s \in S$

δ_{i}^{s}: additional quantity demanded in node $i \in I$ at the relief distribution network under aftershock scenario $s \in S$

τ_{ji}^{s}: travel time required to transport relief item from supply point $j \in J$ to demand point $i \in I$ for direct shipment under aftershock scenario $s \in S$

$\tau_{jj'i}^{s}$: travel time required to transport relief item from supply point $j \in J$ to demand $i \in I$ via supply point $j' \in J$ for lateral transshipment under aftershock scenario $s \in S$, $\tau_{jj'i}=\tau_{jj'}^{s}+\tau_{ji}^{s}$

Decision Variables

First-Stage Decision Variables

$m_{ji}= \begin{cases} 1, \text{ if supply point } j \in J \text{ is assigned to demand point } i \in I \text{ for direct shipment} \\ 0, \text{otherwise} \end{cases}$

$m'_{ji}= \begin{cases} 1, \text{ if supply point } j \in J \text{ is assigned to demand point } i \in I \text{ for lateral transshipment} \\ 0, \text{otherwise} \end{cases}$

$y_{ij}= \begin{cases} 1, \text{ if edge } (i,j) \in E \text{ is traversable after repairs in the first-stage} \\ 0, \text{otherwise} \end{cases}$

$x_{ij}= \begin{cases} 1, \text{ if edge } (i,j) \in E \text{ is repaired in the first-stage} \\ 0, \text{otherwise} \end{cases}$

z_{ji}: amount of relief item flow on edge $(i,j) \in E$ via direct shipment

$z_{jj'i}$: amount of relief item flow on edge $(i,j) \in E$ via lateral transshipment

Second-Stage Decision Variables:

$$\mu_{ji}^{s} = \begin{cases} 1, \text{ if supply point } j \in J \text{ is assigned to demand point } i \in I \text{ under scenario } s \in S \text{ for direct shipment} \\ 0, \text{ otherwise} \end{cases}$$

$$\mu'^{s}_{ji} = \begin{cases} 1, \text{ if supply point } j \in J \text{ is assigned to demand point } i \in I \text{ under scenario } s \in S \text{ for lateral transshipment} \\ 0, \text{ otherwise} \end{cases}$$

$$w_{ij}^{s} = \begin{cases} 1, \text{ if edge } (i,j) \in E \text{ is traversable under aftershock scenario } s \in S \text{ after repairs} \\ 0, \text{ otherwise} \end{cases}$$

$$\zeta_{ij}^{s} = \begin{cases} 1, \text{ if edge } (i,j) \in E \text{ is repaired in the second-stage under scenario } s \in S \text{ after repairs} \\ 0, \text{ otherwise} \end{cases}$$

θ_{ji}^{s}: amount of relief item flow on edge $(i,j) \in E$ via direct shipment under scenario $s \in S$

$\theta_{jj'i}^{s}$: amount of relief item flow on edge $(i,j) \in E$ via lateral transshipment under scenario $s \in S$

a_{ij}^{s}: auxiliary variable

To reflect uncertainty in the problem, we define a discrete set of finitely many scenarios $s \in S$ each with probability p_s. In the second stage for each scenario, demand for relief item at the demand points and repair cost of the non-operating roads are different for each scenario. The other parameters remain with the same values. It should be noted that scenarios are generated so as to reflect the all possible outcomes as best as it can. In addition, for simplicity, a single scenario is assumed to occur for the second-stage of the problem.

Objective function

$$\min \sum_{i\in I}\sum_{j\in J} z_{ji} * t_{ji} + \sum_{i\in I}\sum_{j'\in J}\sum_{j\in J} z_{jj'i} * \left(t_{ji} + t_{jj'i} \right) + \sum_{i\in I}\sum_{j\in J}\sum_{s\in S} p_s * \theta_{ji}^{s} * \tau_{ji}^{s} +$$

$$\sum_{i\in I}\sum_{j'\in J}\sum_{J\in j}\sum_{s\in S} p_s * \theta_{Jj'i}^{s} * (\tau_{ji}^{s} + \tau_{jj'i}^{s}) \qquad (1)$$

Objective function (1) can be divided into two parts as that of the first-stage and second-stage problem, respectively. For the first-stage, the objective is the multiplication of amount of flow in each road segment with travel time via either direct shipment or lateral transshipment. For the second-stage, we take an expectation of this flow-weighted distance over all scenarios.

Constraints

$$\sum_{i\in I} z_{li} + \sum_{j\in J}\sum_{i\in I} z_{lji} - \sum_{j\in J}\sum_{i\in I} z_{jli} \le s_l \qquad \forall\, l \in J \qquad (2)$$

$$\sum_{i\in I} z_{ii} = 0 \qquad (3)$$

$$\sum_{(i,j)\in E} c_{ij} x_{ij} + \sum_{(i,j)\in E} \gamma_{ij}^{s} \zeta_{ij}^{s} \le B \qquad \forall\, s \in S \qquad (4)$$

$$\sum_{j\in J} m_{ji} \le 1 \qquad \forall\, i \in I \qquad (5)$$

$$z_{ji} \le M * m_{ji} \qquad \forall\, i \in I ,\, j \in J \qquad (6)$$

$$\sum_{l\in j} z_{lji} \le M * m'_{ji} \qquad \forall\, i \in I ,\, j \in J \qquad (7)$$

$$\sum_{j\in J} m'_{ji} \le 1 \qquad \forall\, i \in I \qquad (8)$$

$$y_{ij} \leq x_{ij} + b_{ij} \qquad \forall\,(i,j) \in E \qquad (9)$$

$$z_{ij} + \sum_{k \in J} z_{kij} + \sum_{k \in I} z_{ijk} + \sum_{k \in I} z_{jik} \leq k_{ij} * y_{ij} \qquad \forall\,(i,j) \in E \qquad (10)$$

$$\sum_{j \in J} z_{jj'i} = 0 \qquad \forall\, i \in I \qquad (11)$$

$$\sum_{i \in I} \theta_{ji}^{s} + \sum_{j \in J} \sum_{i \in I} \theta_{lj'i}^{s} - \sum_{j \in J} \sum_{i \in I} \theta_{jli}^{s} \leq s_l \qquad \forall\, l \in J\,, s \in S \qquad (12)$$

$$\sum_{j \in J} z_{ji} + \sum_{j \in J} \sum_{l \in J} z_{jli} + \sum_{j \in J} \theta_{ji}^{s} + \sum_{j \in J} \sum_{j' \in J} \theta_{jj'i}^{s} \geq d_i + \delta_i^{s} \qquad \forall\, i \in I\,, s \in S \qquad (13)$$

$$\sum_{i \in I} z_{ii}^{s} = 0 \qquad \forall\, s \in S \qquad (14)$$

$$2a_{ij}^{s} \leq \beta_{ij}^{s} + y_{ij} \qquad \forall\,(i,j) \in E\,, s \in S \qquad (15)$$

$$w_{ij}^{s} \leq \zeta_{ij}^{s} + a_{ij}^{s} \qquad \forall\,(i,j) \in E\,, s \in S \qquad (16)$$

$$\zeta_{ij}^{s} \leq 1 - \beta_{ij}^{s} \qquad \forall\,(i,j) \in E\,, s \in S \qquad (17)$$

$$\theta_{ji}^{s} + \sum_{k \in J} \theta_{kji}^{s} + \sum_{k \in I} \theta_{jik}^{s} + \sum_{k \in I} \theta_{ijk}^{s} \leq k_{ij} * w_{ij}^{s} \qquad \forall\,(i,j) \in E\,, s \in S \qquad (18)$$

$$\sum_{j \in J} \mu_{ji}^{s} \leq 1 \qquad \forall\, i \in I\,, s \in S \qquad (19)$$

$$\theta_{ji}^{s} \leq M * \mu_{ji}^{s} \qquad \forall\, i \in I\,, j \in J, s \in S \qquad (20)$$

$$\sum_{l \in J} \theta_{lji}^{s} \leq M * \mu'^{s}_{ji} \qquad \forall\, i \in I\,, j \in J, s \in S \qquad (21)$$

$$\sum_{j \in J} \mu'^{s}_{ij} \leq 1 \qquad \forall\, i \in I\;, s \in S \qquad (22)$$

$$\sum_{j \in J} \theta_{jj'i}^{s} = 0 \qquad \forall\, i \in I\;, s \in S \qquad (23)$$

$$x_{ij} \in \{0,1\} \qquad \forall\, (i,j) \in E \qquad (24)$$

$$\zeta_{ij}^{s} \in \{0,1\} \qquad \forall\, (i,j) \in E\,, s \in S \qquad (25)$$

$$z_{ji} \geq 0 \qquad \forall\, i \in I\;, j \in J \qquad (26)$$

$$\theta_{ji}^{s} \geq 0 \qquad \forall\, i \in I\,, j \in J, s \in S \qquad (27)$$

$$a_{ij}^{s} \in \{0,1\} \qquad \forall\, (i,j) \in E\,, s \in S \qquad (28)$$

$$y_{ij} \in \{0,1\} \qquad \forall\, (i,j) \in E \qquad (29)$$

$$w_{ij}^{s} \in \{0,1\} \qquad \forall\, (i,j) \in E\,, s \in S \qquad (30)$$

$$z_{jj'i} \geq 0 \qquad \forall\, i \in I\;, j, j' \in J \qquad (31)$$

$$\theta_{jj'i}^{s} \geq 0 \qquad \forall\, i \in I\;, j, j' \in J \qquad (32)$$

$$m_{ji} \in \{0,1\} \qquad \forall\, i \in I\;, j \in J \qquad (33)$$

$\mu_{ji}^{s} \in \{0,1\}$ $\forall\, i \in I\,, j \in J, s \in S$ (34)

$m'_{ji} \in \{0,1\}$ $\forall\, i \in I\,, j \in J$ (35)

$\mu'^{s}_{ji} \in \{0,1\}$ $\forall\, i \in I\,, j \in J, s \in S$ (36)

Constraints (2) are the flow conservation equations for every supply point in the relief item distribution network, which state that the difference between outflow from a supply node and inflow to it should be less than or equal to its capacity. These constraints ensure the conservation of relief item flow for supply nodes.

Constraints (3) are defined as an additional flow conservation equation to prevent flow from node i to node i.

Constraints (4) stipulate that the total repair cost in the first-stage (for edges (i, j) where x_{ij}=1) or the second-stage (for edges (i, j) where ζ_{ij}^{s}=1) of the problem) should be less than or equal to the post-disaster budget.

Constraints (5) ensure that each demand point $i \in I$ is assigned to only one supply point $j \in J$ for direct shipment.

Constraints (6) guarantee that relief item flow from supply point $j \in J$ to demand point $i \in I$ can occur if and only if demand point $i \in I$ is assigned to supply point $j \in J$.

Constraints (7) state that relief item flow is allowed from supply points $j \in J$ through $j' \in J$ to demand point $i \in I$ if and only if lateral transshipment is allowed between supply point j and demand point i.

Constraints (8) imply that each demand point $i \in I$ is assigned to only one supply point $j \in J$ through lateral transshipment.

Constraints (9) require that the edge $(i, j) \in E$ is traversable for the first-stage (y_{ij}=1) if and only if the edge (i, j) is not affected by the main shock (b_{ij}=0) or it is repaired (x_{ij}=1).

Constraints (10) ensure the relationship between the amount of relief item flow edge *(i, j)* $\in E$ and traversability condition of the arc (i, j) for both first-stage and second-stage of the problem. Specifically, if the edge is traversable in the first-stage (y_{ij}=1), the total amount of flow on it for both direct shipment and lateral transshipment cannot exceed the pre-determined capacity k_{ij}. If the edge (i, j) is not traversable, then its capacity is zero.

Constraints (11) are defined as an additional flow conservation constraint to prevent flow from supply point $j \in J$ through itself to demand point $i \in I$.

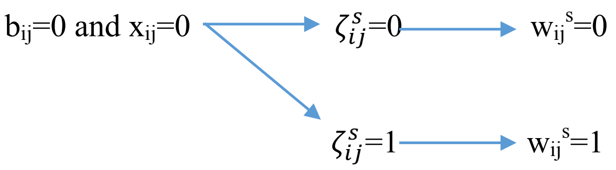
Constraints (12) are the supply capacity constraints for each scenario $s \in S$.

Constraints (13) are the flow conservation constraints for every demand point in the relief item distribution network for both the first-stage and the second-stage. These constraints state that for each demand node, the total relief item flow with direct shipment and lateral transshipment should be greater than or equal to the total quantity demanded in the first-stage and the second-stage.

Constraints (14) is the modified version of the Constraints (3) for each scenario $s \in S$.

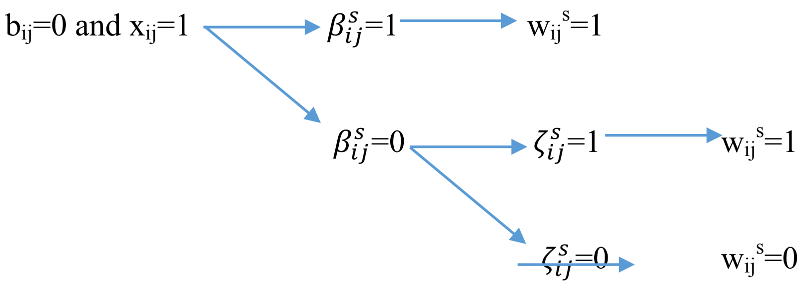
Several constraints should be defined to reflect the relationship between b_{ij}, β_{ij}^{s}, x_{ij}, ζ_{ij}^{s}, y_{ij} and w_{ij}^{s}. The detailed decision tree for emergency roadway repair network can be seen in Figure 2. There are three cases that should be taken into consideration, which are explained in detail below.

Case 1



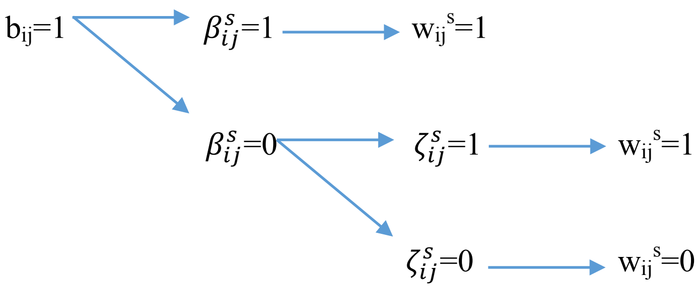
In Case 1, it is assumed that the *edge (i, j)* $\in E$ is not operating after the main disaster (b_{ij}=0) and the edge is not repaired in the first-stage (x_{ij}=0). Consequently, there are two possibilities that can occur after the aftershock: the edge (i, j) is repaired under scenario $s \in S$ (ζ_{ij}^{s}=1), which results in the condition that the edge is traversable under scenario $s \in S$ (w_{ij}^{s}=1), or it is not repaired repair network (ζ_{ij}^{s}=0) which leads to w_{ij}^{s}=0).

Case 2



When the edge $(i, j) \in E$ is blocked after the main disaster (b_{ij}=0) and the arc (i, j) is repaired in the first-stage (x_{ij}=1), two possibilities may follow: if it is operating under scenario s ∈ S (β_{ij}^{s}=1), then it is traversable (w_{ij}^{s}=1). Otherwise, two probable results may occur: if it is repaired (ζ_{ij}^{s}=1), then (w_{ij}^{s}=1). If not, then it is not traversable (w_{ij}^{s}=0).

Case 3



Case 3, considers the case where the edge $(i, j) \in E$ is operating after the main disaster (b_{ij}=1). The possible outcomes in this case is identical to those in Case 2.

To analyze three cases properly in the proposed mathematical model, an auxiliary variable a_{ij}^{s} should be defined.

Constraints (15) force the auxiliary variable a_{ij} to take a value of 1. Only when the edge is operating under scenario s (β_{ij}^{s}=1) and it is traversable in the first-stage of the problem (y_{ij}=1).

Constraints (16) ensure that the edge $(i,j) \in E$ is traversable (w_{ij}^{s}=1) only if it is repaired (ζ_{ij}^{s}=1) or (a_{ij}^{s}=1)

Constraints (17) prevent repairing already traversable roads to avoid alternative optimal.

Constraints (18) modify Constraints (10) for each scenario $s \in S$.

Constraints (19) through (22) are the modified versions of Constraints (5) through (8) for each scenario $s \in S$.

Constraints (23) prevent lateral flow from a supply node to itself each scenario $s \in S$.

Constraint (24) defines the binary road clearance variable in the first-stage of the problem.

3.3. Benchmark Models

Several benchmark models are constructed to analyze the decisions that are made in the proposed humanitarian logistics network. For the remainder of this section, each benchmark model is detailed in terms of objective function, decision variables and constraints. In addition, each benchmark model is also detailed in Chapter 5.

3.3.1. Benchmark Model 1 – No consideration of potential aftershock

Benchmark Model 1 is constructed to analyze the emergency roadway repair and amount of relief item flow only after the main shock. The main difference in the mathematical formulation of base model and benchmark model 1 is that the scenario set $s \in S$ is no longer taken into consideration.

The resulting mathematical model is as follows:

Objective function

$$\min \sum_{i \in I} \sum_{j \in J} z_{ji} * t_{ji} + \sum_{i \in I} \sum_{j' \in J} \sum_{j \in J} z_{jj'i} * (t_{ji} + t_{jj'i}) \tag{37}$$

Constraints

$$\sum_{i \in I} z_{li} + \sum_{j \in J} \sum_{i \in I} z_{lji} - \sum_{j \in J} \sum_{i \in I} z_{jli} \leq s_l \qquad \forall\, l \in J \tag{38}$$

$$\sum_{(i,j) \in E} c_{ij} x_{ij} \leq B \tag{39}$$

$$\sum_{i \in I} z_{ii} = 0 \tag{40}$$

$$\sum_{j \in J} m_{ji} \leq 1 \qquad \forall\, i \in I \tag{41}$$

$$z_{ji} \leq M * m_{ji} \qquad \forall\, i \in I\ , j \in J \tag{42}$$

$$\sum_{l \in j} z_{lji} \leq M * m'_{ji} \qquad \forall\, i \in I\ , j \in J \tag{43}$$

$$\sum_{j \in J} m'_{ji} \leq 1 \qquad \forall\, i \in I \tag{44}$$

$$y_{ij} \leq x_{ij} + b_{ij} \qquad \forall\, (i,j) \in E \tag{45}$$

$$z_{ij} + \sum_{k\in J} z_{kij} + \sum_{k\in I} z_{ijk} + \sum_{k\in I} z_{jik} \leq k_{ij} * y_{ij} \qquad \forall\, (i,j) \in E \qquad (46)$$

$$\sum_{j\in J} z_{jj'i} = 0 \qquad \forall\, i \in I \qquad (47)$$

$$\sum_{j\in J} z_{ji} + \sum_{j\in J}\sum_{i\in I} z_{jli} \geq d_i \qquad \forall\, i \in I \qquad (48)$$

$$x_{ij} \in \{0,1\} \qquad \forall\, (i,j) \in E \qquad (49)$$

$$z_{ji} \geq 0 \qquad \forall\, i \in I\ , j \in J \qquad (50)$$

$$y_{ij} \in \{0,1\} \qquad \forall\, (i,j) \in E \qquad (51)$$

$$z_{jj'i} \geq 0 \qquad \forall\, i \in I\ , j, j' \in J \qquad (52)$$

$$m_{ji} \in \{0,1\} \qquad \forall\, i \in I\ , j \in J \qquad (53)$$

$$m'_{ji} \in \{0,1\} \qquad \forall\, i \in I\ , j \in J \qquad (54)$$

3.3.2. Benchmark Model 2 – No emergency roadway repair

Benchmark Model 2 assumes that the proposed model is implemented for post-disaster optimization decisions only on relief item distribution; there is no emergency roadway repair. Preliminarily, the set of roads that are not operating after the main shock is generated via the approach that is detailed in Chapter 4.1. In frame of this new model, relief item flow can occur in the first-stage and the second-stage of the problem if and only if the edge $(i, j) \in E$ is operating after the main shock and the aftershock, respectively. In other words, In Benchmark Model 2, the roads are traversable (i.e. operating and eligible for relief item distribution) if and only if b_{ij} and β_{ij}^{s} takes a value of 1 in the first-stage and the second-stage of the model, respectively.

The main difference in the mathematical formulation of the base model and Benchmark Model 2 are the following:

(i) The binary road clearance variables x_{ij} and ζ_{ij}^{s} are no longer in consideration.

(ii) Deterministic parameter c_{ij} and scenario-dependent parameter γ_{ij}^{s} are no longer in consideration.

(iii) The binary auxiliary variable a_{ij}^{s}, the binary road traversability variables y_{ij} and w_{ij}^{s} are no longer in consideration.

(iv) Constraints that are related with emergency roadway repair network, namely Constraints (4), (9), (15), and (16) are no longer in consideration.

Constraints (13) and (18) change as follows:

$$z_{ij} + \sum_{k \in J} z_{kij} + \sum_{k \in I} z_{ijk} + \sum_{k \in I} z_{j,i,k} \leq k_{ij} * b_{ij} \qquad \forall\ (i,j) \in E \qquad (55)$$

$$\theta_{ji}^{s} + \sum_{k \in J} \theta_{kji}^{s} + \sum_{k \in I} \theta_{jik}^{s} + \sum_{k \in I} \theta_{ijk}^{s} \leq k_{ji} * \beta_{ij}^{s} \qquad \forall\ (i,j) \in E\ , s \in S \quad (56)$$

Constraints (55) ensure that relief item flow with direct shipment and lateral transshipment can occur if and only if b_{ij} take a value of 1.

Constraints (55) is the modified version of Constrains (56) for each scenario $s \in S$.

3.3.3. Benchmark Model 3 – No lateral transshipment

Benchmark Model 3 assumes that the relief item flow from supply points to demand points is provided by direct shipment; i.e., there is no lateral transshipment.

The main difference in the mathematical formulation of the base model and Benchmark Model 3 are the following:

(i) The decision variables that are related with lateral transshipment variables, namely, $z_{jj'i}$, $\theta^s_{jj'i}$, $m'_{ji,}$ μ'^s_{ij} are no longer in consideration.

(ii) Constraints that are related with lateral transshipment such as Constraints (7), (8), (11), (21), (22), and (23) are no longer in consideration.

The resulting mathematical model is as follows:

Objective function

$$\min \sum_{i \in I} \sum_{j \in J} z_{ji} * t_{ji} + \sum_{i \in I} \sum_{j \in J} \sum_{s \in S} p_s * \theta^s_{ji} * \tau^s_{ji} \quad (57)$$

Constraints

$$\sum_{i \in I} z_{li} \leq s_l \qquad \forall\, l \in J \quad (58)$$

$$\sum_{i \in I} z_{ii} = 0 \quad (59)$$

$$\sum_{(i,j) \in E} c_{ij} x_{ij} + \sum_{(i,j) \in E} \gamma^s_{ij} \zeta^s_{ij} \leq B \qquad \forall\, s \in S \quad (60)$$

$$\sum_{j \in J} m_{ji} \leq 1 \qquad \forall\, i \in I \quad (61)$$

$$z_{ji} \leq M * m_{ji} \qquad \forall\, i \in I\ , j \in J \qquad (62)$$

$$y_{ij} \leq x_{ij}\ + b_{ij} \qquad \forall\, (i,j) \in E \qquad (63)$$

$$z_{ij} \leq k_{ij} * y_{ij} \qquad \forall\, (i,j) \in E \qquad (64)$$

$$\sum_{i \in I} \theta_{ji}^{s} \leq\ s_l \qquad \forall\, l \in J\ , s \in S \qquad (65)$$

$$\sum_{j \in J} z_{ji} + \sum_{j \in J} \theta_{ji}^{s} \geq d_i + \delta_i^{s} \qquad \forall\, i \in I\ , s \in S \qquad (66)$$

$$\sum_{i \in I} z_{ii}^{s} =\ 0 \qquad \forall\, s \in S \qquad (67)$$

$$2a_{ij}^{s} \leq \beta_{ij}^{s} + y_{ij} \qquad \forall\, (i,j) \in E\ , s \in S \qquad (68)$$

$$w_{ij}^{s} \leq \zeta_{ij}^{s} + a_{ij}^{s} \qquad \forall\, (i,j) \in E\ , s \in S \qquad (69)$$

$$\zeta_{ij}^{s} \leq 1 - \beta_{ij}^{s} \qquad \forall\, (i,j) \in E\ , s \in S \qquad (70)$$

$$\theta_{ji}^{s} \leq k_{ji} * w_{ji}^{s} \qquad \forall\, (i,j) \in E\ , s \in S \qquad (71)$$

$$\sum_{j \in J} \mu_{ji}^{s} \leq\ 1 \qquad \forall\, i \in I\ , s \in S \qquad (72)$$

$$\theta_{ji}^{s} \leq M * \mu_{ij}^{s} \qquad \forall\, i \in I\ , j \in J, s \in S \qquad (73)$$

$$x_{ij} \in\ \{0,1\} \qquad \forall\, (i,j) \in E \qquad (74)$$

$$\zeta_{ij}^{s} \in\ \{0,1\} \qquad \forall\, (i,j) \in E\ , s \in S \qquad (75)$$

$z_{ji} \geq 0 \qquad \forall\, i \in I\ , j \in J \qquad (76)$

$\theta_{ji}^{s} \geq 0 \qquad \forall\, i \in I\,, j \in J, s \in S \qquad (77)$

$a_{ij}^{s} \in \{0,1\} \qquad \forall\, (i,j) \in E\,, s \in S \qquad (78)$

$y_{ij} \in \{0,1\} \qquad \forall\, (i,j) \in E \qquad (79)$

$w_{ij}^{s} \in \{0,1\} \qquad \forall\, (i,j) \in E\,, s \in S \qquad (80)$

$m_{ji} \in \{0,1\} \qquad \forall\, i \in I\ , j \in J \qquad (81)$

$\mu_{ji}^{s} \in \{0,1\} \qquad \forall\, i \in I\,, j \in J, s \in S \quad (82)$

3.3.4. Benchmark Model 5 – Minimization of maximum unsatisfied demand

In Benchmark Model 5, the objective function of base model changed from minimization of total travel time to minimization of maximum unsatisfied demand.

The main difference in the mathematical formulation of the base model and Benchmark Model 5 are the following:

(i) A new binary variable uns_i^s is defined which shows the amount of unsatisfied demand in demand point i under scenario $s \in S$.

(ii) A new positive variable w_s is defined to keep track of maximum unsatisfied demand under scenario $s \in S$ which is an auxiliary variable.

The resulting mathematical model is as follows:

Objective function

$$\min \sum_{s} p_s * w_s \tag{83}$$

Right-hand side of Constraint (13) change as follows:

$$\sum_{j\in J} z_{ji} + \sum_{j\in J}\sum_{l\in I} z_{jli} + \sum_{j\in J} \theta_{ji}^{s} + \sum_{j\in J}\sum_{l\in J} \theta_{jj'i}^{s} + uns_i^s \geq (d_i + \delta_i^s) \qquad \forall\, i \in I\;, s \tag{84}$$

Constraints (84) ensure that the total relief item flow with direct shipment and lateral transshipment in the first-stage and the second-stage and amount of unsatisfied demand in each demand point $i \in I$ should be greater than and equal to the summation of the quantity demanded in each demand point $i \in I$ and the additional quantity demanded in each demand point i ∈ I under aftershock scenario $s \epsilon S$.

An additional constraint is defined:

$$w_s \geq uns_i^s \qquad \forall\, i \in I\;, s \in S \tag{85}$$

$$uns_i^s \geq 0 \qquad \forall\, i \in I\;, s \in S \tag{86}$$

3.3.5. Benchmark Model 6 – Incorporating the repair time of non-operating road segments

In Benchmark Model 6, the base model is modified in terms of objective function and constraints by including the repair time of each non-operating road segment.

The main difference in the mathematical formulation of the base model and Benchmark Model 6 are the following:

(i) A new deterministic parameter r_{ji} is defined which shows the repair time of each road segment. For instance, if the road segment is not repaired after the main shock, the total flow-weighted travel time equals to $t_{ji} * z_{ji}$. However, if the road segment is repaired after the main shock, the total flow-weighted travel time includes the repair time which resulted in $(t_{ji} + z_{ji}) * z_{ji}$.

(ii) For direct shipment in the first-stage and the second-stage, a new positive variable ω_{ji} and ω_{ji}^{s} is defined to ensure the relationship between the binary road clearance variable and the repair time.

(iii) Constraints (2) through (36) are still taken into consideration.

The resulting mathematical model is as follows:

Direct Shipment in the First-stage

$$\omega_{ji} \geq r_{ji} * z_{ji} - M * (1 - x_{ij}) \qquad \forall\, i \in I\ , j \in J \qquad (87)$$

Constraints (87) ensure that if the road segment is not repaired after the main shock (x_{ij}=0), there is no repair time of that road segment. On the other hand, if the road segment is repaired after the mainshock (x_{ij}=1), the repair time of the road segment is multiplied with the amount of relief item flow via direct shipment.

Direct Shipment in the Second-stage

$$\omega_{ji}^{s} \geq r_{ji} * \theta_{ji}^{s} - M * (1 - \zeta_{ij}^{s}) \qquad \forall\, i \in I\ , j \in J, s \in S \qquad (88)$$

Constraints (88) modify Constraints (87) for each scenario $s \in S$.

Lateral Transshipment in the First-stage

$$\vartheta_{jj'i} \geq r_{jj'} * \sum_{k \in J} z_{kj'i} - M * \left(1 - x_{ij}\right) \qquad \forall\, i \in I\ , j \in J, k \in J \qquad (89)$$

$$\varphi_{j'i} \geq t_{jj'} * \sum_{k \in J} z_{kj'i} + \vartheta_{jj'i} \qquad \forall\, i \in I\ , j \in J, k \in J \qquad (90)$$

$$\sigma_{j'i} \geq r_{j'i} * \sum_{k \in J} z_{kj'i} - M * (1 - x_{ij}) \qquad \forall\ j' \in J, k \in J \qquad (91)$$

Lateral Transshipment in the Second-stage

$$\vartheta^{s}_{jj'i} \geq r_{jj'} * \sum_{k \in J} \theta^{s}_{jj'i} - M * (1 - \zeta^{s}_{ij}) \qquad \forall\ i \in I\ , j \in J, k \in J, s \in S \quad (92)$$

$$\varphi^{s}_{j'i} \geq t_{jj'} * \sum_{k \in J} \theta^{s}_{jj'i} + \vartheta^{s}_{jj'i} \qquad \forall\ i \in I\ , j \in J, k \in J, s \in S \quad (93)$$

$$\sigma^{s}_{j'i} \geq r_{j'i} * \sum_{k \in J} \theta^{s}_{jj'i} - M * (1 - \zeta^{s}_{ij}) \qquad \forall\ i \in I\ , j \in J, k \in J, s \in S \quad (94)$$

Constraints (92) modify Constraints (89) for each scenario $s \in S$.

Constraints (93) modify Constraints (90) for each scenario $s \in S$.

Constraints (94) modify Constraints (91) for each scenario $s \in S$.

Objective function change as follows:

$$\min \sum_{i \in I} \sum_{j \in J} (z_{ij} * t_{ji} + \omega_{ji}) + \sum_{i \in I} \sum_{j \in J} \sum_{s \in S} p_s * (\theta^{s}_{ji} * t_{ji} + \omega^{s}_{ji}) +$$

$$\sum_{i \in I} \sum_{j \in J} (\varphi_{j'i} + t_{j'i} * (\sum_{k \in J} z_{kj'i}) + \sigma_{j'i}) +$$

$$\sum_{i \in I} \sum_{j \in J} \sum_{s \in S} p_s * (\varphi^{s}_{j'i} + t_{j'i} * (\sum_{k \in J} \theta^{s}_{jj'i}) + \sigma^{s}_{j'i})$$

CHAPTER 4

A CASE STUDY BASED ON A POTENTIAL EARTHQUAKE IN CITY OF ISTANBUL, TURKEY

Istanbul is the largest city in Turkey and fifth largest metropolitan area in the world with a total population of 16.475.190, which is approximately 20% of Turkey's total population. In addition, Istanbul is both located in the Asian and European continents, that resulting in a notable geopolitical importance. Major production and manufacturing companies of Turkey in different industrial areas such as textile, machinery, automotive and construction are in Istanbul and nearby cities. According to a report by Standard & Poor's [66], one of the three biggest credit rating agencies, Istanbul accounts for creating approximately 23% of the GDP and 40% of the national tax revenues of Turkey with an 5.4% growth rate of real GDP. Due to overpopulation and urbanization, Istanbul Metropolitan Municipality continually increases investment on capital expenditures namely infrastructural projects and urban planning.

Moreover, Istanbul is the most migration-receiving city of Turkey from all other regions of the country. An incidence of a potential earthquake in Istanbul would result in severe direct and indirect economic consequences such as loss of lives and production, infrastructural damages, decrease in GDP per capita and decrease in the production demand. To mitigate against these possibilities, after Kocaeli earthquake in 1999, the Turkish government has implemented the Urban Transformation Project to build earthquake-resistant buildings and living areas in Istanbul.

A potential earthquake in Istanbul is unavoidable based on the historical movements of the different segments of the North Anatolian Fault. Several authorities develop scientific and statistical models for different magnitudes of earthquakes to anticipate impacts of a potential earthquake that could occur in the North Anatolian Fault. According to Istanbul Seismic Risk Mitigation and Emergency Preparedness Project [14], the probability of occurrence of an earthquake in Istanbul within 30 years and 10 years are nearly 62 percent and 20 percent, respectively. Furthermore, that there are stupendous shortcomings in disaster management plan and activities in Turkey.

Similarly, the World Bank [67] reports a 4% probability of occurrence of an earthquake in Istanbul with an estimated 80,000 fatalities and 60 billion $ economic losses, which corresponds to nearly 8 percent of Gross Domestic Product of Turkey. According to the same report, a 250-year earthquake event in 2080 with a magnitude of greater than or equal to 7.0 will cause between 1 trillion $ and 2 trillion $ Gross Domestic Product loss. Demircioğlu [68] estimates that a potential earthquake with a magnitude of 7.3 will resulted in 11 billion $ direct economic losses with total 40 billion $ economic losses. In addition, approximately 400,000-800,000 houses will be heavily damaged or destroyed.

In this chapter, to measure effectiveness and efficiency of the proposed mathematical model in Chapter 3, a numerical case study is illustrated for a potential earthquake in Istanbul, Turkey. The relevant data is generated for the European Side of Istanbul. However, the analysis can be easily extended to the Asian side, which can be assumed to be separated from the European side by the disaster.

For the remainder of this chapter, road vulnerabilities, implementation of road vulnerabilities into the scenarios, supply and demand points, amount of relief item that is supplied and demanded, amount of relief item demanded under each scenario, penalty cost for each unit of unsatisfied demand, resource limit, amount of minimum percentage of demand that should be satisfied in each demand point and repair cost for the damaged roads for both first and second-stage of the problem are explained in detail.

4.1. Road Vulnerabilities, Road Damage Scale, and Repair Cost

Earthquakes have several effects on the infrastructural network of a city. In the post-disaster environment, roads have an important role for relief item distribution, commodity flow to the affected areas, and search-and-rescue operations for the dead and injured people. To find the set of roads that are disrupted and need to be repaired for an effective and efficient disaster management, damage scale for each road is defined first. Then, a relationship between road vulnerabilities and the road damage scale is constructed. Damage in the roads can be caused by the cracks, landslides, the damaged/collapsed buildings and facilities and the debris arise from trees, walls and concrete. During the first 72 hours after the disaster, due the complex needs arise from disaster, infrastructural recovery should be made rapidly.

In this study, road vulnerability can be defined as the probability of a blockage in a road due to the collapsed buildings and debris. Aslan [51] studies the road vulnerability between 25 European districts in Istanbul, resulting in a total 625 of pairs of districts. Road vulnerabilities are ranged from 0,00 to 1,1950 for each road segment where 0,00 and 1,1950 [51] which are generated from Baskaya [39]. Then, combinations of two districts are paired up and respected road vulnerability is calculated. Road vulnerability coefficient is divided into three possibilities: low, average and high road vulnerabilities. To find the of roads that are disrupted from the main shock (i.e., in the first-stage of the problem), average road vulnerabilities are used for these 625 pairs of districts. In Table A1 in Appendix A, average road vulnerability value for each road segment can be seen in detail.

Road vulnerabilities are integrated into the first-stage of the proposed mathematical model with a binary parameter which takes value of 0 and 1 when the road is blocked and traversable, respectively. The average road vulnerability for 625 pairs of districts is 0,12 [51]. If the road vulnerability is greater than or equal to 0,08, the parameter takes a value of 0. Otherwise, it takes a value of 1. 0,08 is selected as a threshold value to have sufficient number of disrupted roads both in the first-stage and the second-stage. The incorporation of road vulnerabilities into the scenarios for the second-stage of the problem is detailed in Section 4.6. The values of b_{ij} parameter for each road segment can be seen in Table A2 in Appendix A.

Anbazhagan et al. [69] divide the damage scale of the roads due to the earthquake into five, named as Road Damage Scale (RDS) and proposed as an alternative for the Modified Mercalli Intensity (MMI). Furthermore, the same paper address the fact that there is a strong correlation between the RDS and the magnitude of the earthquake. This segmentation and the respected repair type is detailed in Table 4.1. In terms of the restoring methods, Damage levels 4 and 5 require Rebuild, Damage levels 2 and 3 require Repair, and Damage 1 requires no repair. Since road vulnerabilities do not change for the main shock and aftershock(s), it is assumed that the Road Damage Scale (RDS) for the all 625 pair of districts is the same for both first-stage and second-stage. Erdik [70] conclude that after 1999 Kocaeli earthquake, by-streets and highways were extensively damaged, such as 60 km. of the Ankara-Istanbul highway network. The total cost of infrastructural repair of the damaged roads is approximately 250 million $ [70].

Table 4.1. Road Damage Scale (RDS) and Respected Repair Type [69]

Road Damage Scale	Repair Type
1	Roads are completely accessible and can be used for all post-disaster relief item distribution.
2	Roads are accessible and minor repair works may be needed.
3	Roads are moderately damaged and major repair works may be needed.
4	Roads are highly damaged and major repair or reconstruction in some parts of the roads may be needed.
5	Highest scale and complete reconstruction is needed.

After identifying each road segment in accordance with the Road Damage scale, a straightforward method should be implemented for calculating repair cost for each road segment. According to Furuta et al. [71], an earthquake results in Road Damage Scale 4 and 5 in roadway network of the affected area with percentage of 28, Damage 3 with percentage of 27 and Damage 2 with percentage of 45. Additionally, Furuta et al. [71] calculate the repair cost of roads after earthquake by using life-cycle cost methodology (LCC) with respect to damage scale as represented in Table 4.2. LCC is commonly used in bridge and road networks for measuring and estimating the lifetime and number of repairs that should be required for civil infrastructure. LCC includes user cost, maintenance cost and repair cost over the lifetime of the specified network. Lifetime of road networks is assumed as 100 years. In addition, it should be noted that the topology of the road networks is highly correlated with the repair costs. In the proposed model, it is assumed that repair of a damaged road segment is done in no time; repair time for each RDS is neglected.

Table 4.2. Road Damage Scale (RDS) and Respected Repair Cost

<table>
<tr><th>Road Damage Scale (RDS)</th><th>Repair Cost</th></tr>
<tr><td>1</td><td>0 TL/m^2</td></tr>
<tr><td>2</td><td>(35.000 yen/m^2) 1.08 TL/m^2</td></tr>
<tr><td>3</td><td>(73.000 yen/m^2) 2.25 TL/m^2</td></tr>
<tr><td>4</td><td rowspan="2">120% of the initial construction cost</td></tr>
<tr><td>5</td></tr>
</table>

Up to now, the repair cost for not operating road segments per m^2 could be calculated by using the basic reasoning detailed in Table 4.2. In addition, for Road Damage Scale 4 and 5, initial construction cost for each road segment is calculated to generate their respective repair costs. Öztürk and Öztürk [72] study an approach to Ground Transport Superstructure Costs for Istanbul and calculate the superstructure costs for both highway and railway networks of the Istanbul with a length of 5,585 km and area of 1,118,892 m^2, respectively. This approach is used to determine the initial construction costs in Table 4.2.

The initial construction cost includes labor cost for 5 cm asphalted road (5,60 TL/m^2) and 8 cm asphalted road (8,73 TL/m^2), transportation cost (1,17 TL/m^2), fuel cost (1,17 TL/m^2), depreciation cost (1,17 TL/m2) and material cost (17,16 TL/m^2). Thus, initial construction cost could be calculated by using the given total cost of 33,63 per m^2.

However, our proposed model assumes that the road segments that are not operating after the main shock and/or after shock need to be repaired with a cost greater than zero, Road Damage Scale 1 in which there is no need for repair (i.e. 0 TL/ m^2 repair cost) for the not operating road is omitted. The revised damage scale and respected repair cost is represented in Table 4.3. Finally, if the road is operating after the main shock (b_{ij}=1), the repair cost of the respective road is 0.

Table 4.3. Revised Damage Scale and Respected Repair Cost

Revised Road Damage Scale	Repair Cost
1	(35.000 yen/$m^{2)}$ 1.08 TL/m^2
2	(73.000 yen/m^2) 2.25 TL/m^2
3	120% of the initial construction cost
4	

To determine the repair cost for each road segments, each road vulnerability value is assigned to a Road Damage scale from 1 (lowest) to the 4 (highest). Then, repair cost of each road segment is calculated by multiplying the values in Table 4.2 with the length of each road segment. The road vulnerabilities of each road segment and the respected RDS are shown in Table 4.4. In Table B1 in Appendix B, Road

Damage Scale for each road segment can be seen in detail.

Aslan [51] use 25 districts in the European Side of Istanbul. The distance between each pair of district is the length of that road which is generated via Google Maps for all 625 road pairs. The calculated lengths between each pair of district used to calculate repair cost of each road segment which can be seen in Table B2 in Appendix B.

Table 4.4. Road Vulnerability and Respected Damage Scale

Road Vulnerability	Road Damage Scale
Between 0,00 and 0,199	1
Between 0,2 and 0,399	2
Between 0,4 and 0,599	3
Between 0,6 and 0,799	4

4.2. Supply

As in stated in the Chapter 3, the relief items are pre-positioned in the pre-determined supply points. Supply points and their capacities are retrieved from the baseline results obtained from Stochastic Model 1.1 and Model 3.2. in [51] which aims to minimize expected total demand weighted arrival time with two types of transportation mode: truck and cargo aircraft and to minimize the maximum expected demand weighted arrival time the same two types of transportation mode, respectively.

The uncertainty in Aslan [51], arises from demand uncertainty, road vulnerabilities and facility vulnerabilities which are integrated into the mathematical model by discrete finite set of scenarios. Each scenario reflects a different magnitude of a disaster which results in different amount of quantity demanded for relief item. Eventually, it is proven hard to solve in terms of computational time and number of scenarios. Thus, a sample average approximation heuristic method is performed to obtain the first-stage decisions of facility location, and pre-positioned amounts. These warehouse locations and capacities obtained from Model 1.1 and Model 3.2. are provided in Table 4.5, and used as inputs in this study. Total amount of relief item (tent) that is pre-positioned in the pre-determined six different supply points is 601,682 units.

Table 4.5. Warehouse Locations and Capacities Retrieved from [51]

Warehouse Locations	Capacity
BAĞCILAR	113,513
BAHÇELIEVLER	113,824
BEYLIKDÜZÜ	87,616
ESENLER	104,767
EYÜP	74,845
SULTANGAZI	107,017
TOTAL	601,682

4.3. Scenario Generation

As mentioned earlier, there is a strong correlation between a main shock and sequence of aftershocks. Generally, the main shock is usually followed by several number of aftershocks. It should be noted that the number and magnitude of the aftershocks depend on the characteristics of the main shock. According to Toker [73], after 2011 Van earthquake there were more than 6,000 aftershocks recorded by the Kandilli Observatory and Earthquake Research Institute of Turkey (KOERI) with different magnitudes along the Van Lake Basin. Utkucu et al. [74] listed 4 major aftershocks after the 1999 Düzce earthquake between November 12, 1999 and November 17, 1999 each having a magnitude between 4.4 and 5.5. As mentioned earlier, to have an efficient emergency response planning while reducing the hazards in the disaster area, aftershocks should be taken into consideration.

There are several papers and studies in the literature that aim to forecast the magnitude and location of aftershocks with their respected probabilities. As can be seen in Table 4.6., Japan Meteorological Agency [75] constructs probability of occurrence of aftershocks with different magnitudes.

Table 4.6. Aftershocks and Respected Probabilities [74]

Magnitude of Aftershock	Probability
Probability of occurrence of an aftershock with a magnitude of greater than or equal to 5	0.4 /0.7 = 0.57
Probability of occurrence of an aftershock with a magnitude of greater than or equal to 5.5	0.2 / 0.7 = 0.29
Probability of occurrence of an aftershock with a magnitude of greater than or equal to 6	0.1 / 0.7 = 0.14

Scenario generation is a useful tool to help decision-makers analyze the post-disaster environment with different sets of possible outcomes. To handle uncertainty in the proposed model, a finite number of scenarios is constructed. For each magnitude of aftershock (≥M5.0, ≥M5.5 and ≥M6.0) 10 scenarios are generated which results in total of 30 different scenarios. It must be known that the summation of probability of each scenario should be equal to 1. Hence, probability of each scenario is divided by 0.7. Each scenario generated for each magnitude of aftershock (≥M5.0, ≥M5.5 and ≥M6.0) has a probability of 0.057142857, 0.028571429 and 0.014285714, respectively.

4.4. Demand

In the Study on A Disaster Prevention/Mitigation Basic Plan in Istanbul Including Seismic Microzonation in the Republic of Turkey by Japan International Cooperation Agency (JICA) and Istanbul Metropolitan Municipality (IMM) [14] generate demand for 6 types of relief item: tent, water, energy kit, medical kit, hygiene kit and food kit. Kovács and Spence [76] divide disaster response in to three phases: 7-day, 30-day and 90-day following the disaster onset. The 90-day phase is related with reconstruction and involves rebuilding of houses and infrastructural systems. Tents are used as temporary housing area and shelter for the affected people. In this study, demand for tent is taken into consideration. Demand amounts are generated based on the percentage of people affected by the disaster and the percentage of damaged buildings for the 25 districts. Specifically, total demand for tent is estimated by using 100%, 50% and 10% of the number of survivors in heavily, moderately, and partially damaged buildings, respectively. For the first-stage of the problem, demand data in [51] is generated from the report by JICA which [14] constructs an earthquake analysis by considering four different scenarios A, B, C, and D each having magnitude of 7.5, 7.4, 7.7 and 6.9, respectively. Aslan [51] use the demand of relief item (tent) under two different scenarios: Scenario A and Scenario C which reflect the most probable case and the worst case, respectively. In this study, demand is generated under the worst-case scenario (Scenario C). Hence, base quantities demanded for each district is represented in Table 4.6. Total quantity demanded for relief item (tent) is 487,758 units under Scenario C in [51]. Once and for all, it must not be forgotten that the objective function of the proposed model is to minimize the total demand-weighted arrival time consequentially total amount of supply (601,682) is greater than total amount demand (340,563) to obtain a feasible solution.

The case study covers nineteen demand points and six supply points. In Aslan [51], some districts perform multiple duties. Each supply point (Bağcılar, Beylikdüzü, Esenler, Eyüp, and Sultangazi) serves as both supply point and demand point. In our data, for simplicity, the amount of quantity demanded in these five points is added to available supply in each point and omitted as a demand point.

Table 4.7. Demand Points and Base Quantities Demanded [51]

Demand Point	Amount
AVCILAR	33,424
ARNAVUTKÖY	4,698
BAKIRKÖY	22,089
BAŞAKŞEHİR	20,338
BEYOĞLU	12,560
BEŞİKTAŞ	5,280
BÜYÜKÇEKMECE	14,012
BAYRAMPAŞA	18,142
ESENYURT	41,487
FATİH	36,003
GÜNGOREN	23,978
GAZİOSMANPAŞA	12,326
KAĞITHANE	11,732
KÜÇÜKÇEKMECE	41,172
SARIYER	3,433
ŞİŞLİ	6,751
ZEYTİNBURNU	27,488
ÇATALCA	1,230
SİLİVRİ	4,420
Total	**340,563**

4.5. Capacity of Road Segments

As in any relief item flow optimization problem in humanitarian logistics, maximum relief item flow on any edge is limited by a capacity. Determination of upper bound on relief item flow in 625 pair of district is made by assigning different values to reach a feasible solution. Capacity of each road segment is consequently determined as 32,000 units.

4.6. Incorporation of Road Vulnerabilities into the Scenarios

As stated previously, road vulnerabilities are integrated into the first-stage of the model by defining a binary parameter, b_{ij}. If the road is operating after the main shock, b_{ij} takes a value of 1 and if the road is not operating after the main shock, b_{ij} takes a value of 0. Similarly, a binary parameter β_{ij}^{s} is defined for the second-stage of the problem for each scenario s. If the road is operating after the main shock (i.e. first-stage of the problem), β_{ij}^{s} takes a value of 1 and if the road is not operating after the main shock, β_{ij}^{s} takes a value of 0.

For each pair of district under each scenario, a random number is generated to find road vulnerabilities for the second-stage of the problem and three types of road vulnerabilities are used: low, high and summation of average and high. For occurrence of an aftershock with a magnitude of ≥M5.0 (scenario 1-10), ≥M5.5 (scenario 11-20), and ≥M6.0 (scenario 21-30) low road vulnerabilities, high road vulnerabilities and summation of average and high road vulnerabilities is used, respectively.

4.7. Incorporation of Repair Cost into the Scenarios

As stated previously in Part 4.1, road vulnerabilities, road damage scale and repair cost, distance between each road segment is generated from [51], which is used to calculate repair cost of each road segment for 625 road segments. In the same way as Part 4.1, repair cost is calculated by multiplying the distance between each pair of district with the specified values in Table 4.3. In addition, repair cost of each segment is multiplied by a deviation factor. Repair cost is greater than zero if β_{ij}^s is equal to 0 and equals to zero if β_{ij}^s is equal to 1.

4.8. Incorporation of Demand into the Scenarios

For the second-stage of the problem, we need to generate demand values for each scenario. It should be noted that quantity demanded in the second-stage of the problem is the additional demand that arise because of an aftershock. Noyan et al. [77] used a 94-node network of the October 23, 2011 Van Earthquake with a magnitude of 7.2 and generate the initial demand by clustering the affected area with 94 nodes into 30-node network with regards to three damage intensity levels: destructive, damaging and very strong. Noyan et al. [77] state that under each scenario, demand deviates from their initial level with a deviation factor. To generate demand values for each scenario, base demand value is multiplied by a deviation factor, which is uniformly distributed over [0.75, 1.30], [0.75, 1.20], and [0.75, 1.10] with respect to high, moderate, and low damage intensity levels, respectively. Each deviation factor interval is used to generate demand values for aftershocks with a magnitude of greater than or equal to 5 (scenario 1-10), aftershocks with a magnitude of greater or equal to 5.5 (scenario 11-20) and aftershocks with a magnitude of greater or equal to 6 (scenario 21-30), respectively. Random number generator in Microsoft Excel is used to generate deviation factor over the three-specified intervals.

4.9. Resource Limit (Budget)

The total available resource limit for the model is the distributed between the first-stage and the second-stage. It should be noted that the total available resource limit covers the repair cost of the damaged road segments in first-stage and second-stage of the problem. To obtain a feasible solution to the proposed mathematical model, different values of resource limit (or budget) is tried. Thus, a total budget of 5000 TL is determined for roadway repair.

CHAPTER 5

COMPUTATIONAL EXPERIMENTS

In this chapter, we first aim to conduct preliminary experiments for the base model presented in Chapter 3. The main purpose of these preliminary experiments is to determine the appropriate problem parameters to be used in further experiments. Then, we perform a detailed comparison of the base model with several benchmark models throughout this chapter. We construct the benchmark models to assess the effects of certain assumptions and policies (e.g., the ability to repair the network, consideration of potential aftershocks) and the sensitivity of the model to parameters such as the fraction of blocked roads and supply capacity. For each case, solutions of the deterministic version with where all decisions are made up-front (here-and-now counterpart) and those of the model where all decisions can be made after the uncertainty is revealed (wait-and-see counterpart) are used to calculate the value of stochastic solution (VSS) and the expected value of perfect information (EVPI), respectively. To calculate these, let z_S, z_H, and z_W denote the optimal expected objective values of the two-stage stochastic model, the here-and-now counterpart, and the wait-and-see counterpart, respectively. We report the relative VSS regarding the stochastic solution as $\frac{z_H - z_S}{z_S}$ and the relative EVPI with respect to the wait-and-see solution as $\frac{z_S - z_W}{z_W}$.

The six benchmark models, which were described in detail in Chapter 3, are as follows:

(i) Considering only the main shock when making the relief item distribution and emergency roadway repair decisions. Hence, there is no possibility of occurrence of an aftershock under these settings.

(ii) Ignoring the possibility of emergency roadway repair. Without repairing any road segments, the flow via direct shipment and lateral transshipment is carried out using only the roads that are not affected by the main shock and the aftershock.

(iii) Ignoring the possibility of the lateral transshipment opportunity. Hence, transportation of relief item is only made by means of a direct shipment from supply points to demand points.

(iv) The case where all road segments are blocked after the main shock. Since feasibility becomes an issue in this case, we try different budget levels to achieve a feasible solution make the comparison for cases where both models are feasible.

(v) In the base model, it is assumed that demand at each demand point is fully satisfied from direct shipment and lateral transshipment. However, this is not a realistic assumption in the post-disaster environment with demand uncertainty and asymmetric information. Thus, we modify the base model by assuming a substantial increase in the demand and with an objective function that minimizes the maximum unsatisfied demand as opposed to the total flow-weighted travel time.

(vi) In the base model, repair time of each non-operating road segment is ignored. Thus, we modify the base model by including the repair time of each non-operating road segment.

Apart from these, several sensitivity analyses are constructed in addition to the benchmark models above. Different parameters namely the capacity of each road segment and the total budget are systematically varied.

The proposed two-stage stochastic mixed integer programming models in this chapter are formulated in their extensive form and solved using CPLEX 12.6 through GAMS 23.9.

5.1. Preliminary Experiments to Determine the Number of Scenarios

To represent the inherent uncertainty in our problem environment accurately, it is essential to include as many scenarios as necessary in our model. However, since our models address decisions in the post-disaster stage, it is also crucial to determine the optimal decisions in reasonable time (e.g., within a few hours). In this section of the thesis, we solve the base model by varying the number of scenarios to determine the largest possible number for which we are able to find the optimal solution within reasonable CPU time. For this end, the number of scenarios is varied from 10 to 50 in increments of 10, and a time limit of six hours is used.

Table 5.1. Percentage Optimality Gaps for Different Scenario Sets

Number of Scenarios	Absolute Gap	Relative Gap	Objective Value of the Best Solution	CPU Time
10	0	0	5,779,007.45	10 seconds
20	0	0	5,958,452.03	118 seconds
30	0	0	6,019,969.91	15,060 seconds
40	407.03	Less than 0.01%	6,047,606.55	20,000 seconds
50	660.13	Less than 0.01%	6,066,124.212	20,000 seconds

Table 5.1 represents the percent optimality gaps of the five models over time. As the table also shows, within six hours, it is not possible to solve the base model with a scenario set of 40 or above to optimality. Although the relative gaps are quite small for these cases, this does not hold necessarily true for benchmark instances, therefore we drop the possibility of using more than 30 scenarios. When the optimal solution values are observed from Table 5.1, the conclusion is that after 30 scenarios,the addition of more scenarios does not lead to a significant change in the

objective function; with 40 and 50 scenarios, the value increases by 0.5% and 0.8%, respectively. Due to this stability, we assume that we can safely proceed with 30 scenarios without any concern for the accuracy regarding the optimal objective value.

5.2. Computational Results under the Base Model

In the base model (as well as all stochastic models presented in this chapter), a total of 30 scenarios are generated for each magnitude of aftershock (≥M5.0, ≥M5.5 and ≥M6.0). The model corresponding to this base case can be solved to optimality within 4 hours.

Preliminarily, to attain the condition of the roads after the main shock the rule of thumb method in Chapter 4.1 is used. In Table B1 of the Appendix, the status of each of the 625 road segments is given. As stated previously, there are two types of decisions that is made in the first-stage of the problem: the number of roads that are cleared and the amount of relief item that is transported from the selected roads after the main shock.

As a result of preliminary experiments, a set of 30 representative scenarios are generated for the base model to obtain our preliminary results. Optimal solution statistics for base model are detailed in Table 5.2. Amount of relief item flow with direct shipment and the roads that are cleared after the main shock are presented in Tables C1 and C2 in the Appendix. In addition, amount of relief item flow with lateral transshipment for the first-stage can be seen in Tables 5.3.

Table 5.2. Optimal Solution Statistics for Base Model

Objective Function Value	6,019,969.91
Amount of Lateral Transshipment in the First-Stage	14,493.00
Amount of Direct Shipment in the First-Stage	299,145.86
Percentage of Flow with Lateral Transshipment in the First-Stage	4.62%
Amount of Lateral Transshipment in the Second-Stage	31,345.55
Amount of Direct Shipment in the Second-Stage	328,342.29
Percentage of Flow with Lateral Transshipment in Second-Stage	8.69%

As can be seen from Table 5.2, in the first-stage of the problem 4.62% of the total quantity demanded for all demand points is provided by lateral transshipment. The expectation of the amount of lateral transshipment in the second-stage is 31,345.55. The 8.69% of the additional demand that arise from the aftershock is also met by lateral transshipment. These numbers show that for the base model, consolidation of relief items by lateral transshipment improves travel times to a certain extent in both stages.

Table 5.3. Amount of Relief Item Flow with Lateral Transshipment for Base Model in the First-Stage

From	To	Esenyurt	Büyükçekmece
Bağcılar	Bahçelievler	8,793.96	
Esenler	Bağcılar		5,699.05

As presented in Table 5.3, lateral transshipment policy is effectively used in the first-stage of the problem. 21.20% and 40.67% of the quantity demanded in Esenyurt and Büyükçekmece is carried out by lateral transshipment, respectively.

In the first-stage, quantity demanded in Esenyurt is 41,487. The additional demand that arises from the aftershock in scenario 1 is 42,359.07 which results in a total demand of 83,846.07. In addition, 38.17% and 10.49% of the remaining relief demand is fulfilled by direct shipment and lateral transshipment in the first-stage of the problem. 38.17% and 13.18% of the total demand is satisfied by direct shipment and lateral transshipment under scenario 1, respectively.

In the first-stage, the percentage of the road segments that are repaired is 17.44% of the 344 road segments that are not operating after the main shock. In addition, 2,865.18 TL is used in roadway repair, which corresponds to the 57.30% of the total budget. In the second-stage, all the remaining total budget is not used in all scenarios to repair part of the roads which are not operating after the main shock. The main reason why the budget constraint is not binding is that after the main shock is that the non-operating roads should be repaired in a well-supported way to continue having and effective relief flow. However, after the aftershock, it is aimed to repair the non-operating roads excursively to continue relief item distribution without interruption. As a result, number of roads that that are not operating after the aftershock are relatively less when it is compared to the number of roads that are not operating after the main shock. Herewith, the remaining budget in the second-stage is not totally used.

In the base model, the EVPI is calculated as 6,019,969.913 - 6,019,140.789 = 829,12. In other words, the lack of perfect information results in a less than 0.01% decrease in the objective function value. This is mainly because the second-stage decisions do not differ significantly among the different scenarios, which underlines the robustness of our first-stage solution. On the other hand, the VSS is calculated as 8,186,994.58-6,019,969.92 = 2,167,024.67. Put differently, making use of the easier-to-solve here-and-now counterpart of the proposed model would result in an 35.99% increase in the objective function value. This shows that despite the additional computational burden, solving the stochastic model provides substantial travel time savings for the decision maker.

5.3. Benchmark Models

In this section, we compare the results of the base model that is represented in Chapter 3 in Section 5.2 to the aforementioned six different benchmark models to analyze the effects of (i) the aftershocks, (ii) incorporating emergency roadway repair into the decisions, (iii) potential savings from lateral transshipment opportunities, (iv) assuming that all roads are blocked, (v) considering a more equity-based objective of minimizing maximum unsatisfied demand as opposed to an efficacy-based objective of minimizing total travel time, and (vi) including repair time into the total travel time of each road segment. Then, sensitivity analyses are performed to measure the effect of the parameters such as road vulnerabilities, budget and scenario-dependent parameters.

5.3.1. The Effect of Potential Aftershocks

To understand the effects of an aftershock in sustainable and effective humanitarian relief operations, we make use of Benchmark Model 1, which includes Constraints (2) -(12) and (13) with the first-stage objective function detailed in Chapter 3. It should be obvious that the first-stage of the proposed model is deterministic and there is no uncertainty in the problem environment (i.e., each parameter is known in advance). By comparing the base model with Benchmark Model 1, the difference between the post-disaster humanitarian relief decisions when potential aftershocks are considered and ignored can be better understood within the context of our case study. Amount of relief item flow with direct shipment and the roads that are cleared in Benchmark Model 1 can be seen in Table D1 and D2 in Appendix D. In addition, optimal solution statistics for Benchmark Model 1 and the amount of relief item flow with lateral transshipment is detailed in Tables 5.4. and 5.5, respectively.

Table 5.4. Optimal Solution Statistics for Benchmark Model 1

Objective Function Value	3,118,809.70
Amount of Lateral Transshipment	24,086.00
Percentage of Flow with Lateral Transshipment	7.07%
Amount of Direct Shipment	316,477.00
Total Flow with Direct Shipment and Lateral Transshipment	340,563.00

Table 5.5. Amount of Relief Item Flow with Lateral Transshipment for Benchmark Model 1

From	To	Avcılar	Esenyurt	Fatih	Küçükçekmece
Bağcılar	Bahçelievler	1,424	9,487	4,003	9,172

By comparing the results of Benchmark Model 1 (representing a disaster environment without the possibility of an aftershock) to the base model (represents a disaster environment with the possibility of an aftershock), we observe that the objective function value decreases in the benchmark model from 6,019,969.91 to 3,118,809.70, which corresponds to a 51.81% decrease in the objective function value. Hence, by ignoring the potential effects of the aftershocks, the decision maker would significantly underestimate the resulting relief transportation, which would potentially result in an under allocation of the response budget and would hamper the effectiveness of the decisions.

The number of roads that are cleared after the main shock is 89, which corresponds to 25.87% of the road segments that are not operating. In addition, road segment between Bahçelievler and Avcılar is repaired and then, this road segment is used in lateral transshipment from Bağcılar through Bahçelievler to Avcılar. Likewise, 3,738.36 TL is used for roadway repair, which is 74.76% of the total budget. The increase in the number of road segments repaired compared to the base case is because of the fact that all budget can be allocated to this stage in the benchmark model. Furthermore, as is evident, the budget is still not a binding constraint when aftershocks are ignored.

5.3.2. The Effect of Road Repair

As stated previously, there are two types of decisions that is made in both the first-stage and the second-stage of the problem: road repair and the transport of relief items from the selected roads after the main shock.

In Benchmark Model 2, it is aimed to analyze the proposed model without any emergency roadway repair opportunity. Benchmark Model 2 is detailed in Chapter 3 in terms of decision variables and constraints. Here, the proposed model is forced to carry out the relief item flow through road segments that are unaffected by the disaster in each of the two stages. Optimal solution statistics for Benchmark Model 2 can be seen in Table 5.6.

Table 5.6. Optimal Solution Statistics for Benchmark Model 2

Objective Function Value	7,098,335.96
Amount of Lateral Transshipment in the First-Stage	8,820.95
Amount of Direct Shipment in the First-Stage	187,733.977
Percentage of Flow with Lateral Transshipment in the First-Stage	4.49%
Amount of Lateral Transshipment in the Second-Stage	105,681.97
Amount of Direct Shipment in the Second-Stage	340,462.34
Percentage of Flow with Lateral Transshipment in Second-Stage	23.69%

By eliminating the emergency roadway repair opportunity, the objective function value is increased from 6,019,969.91 to 7,098,335.96 which corresponds to a 17.91% increase when Benchmark Model 2 is compared with the base model. The main reason in the objective function value is without emergency roadway repair opportunity, amount of relief item flow is made by only the roads that are operating after the main shock and the aftershock which are relatively having higher travel times. In addition, amount of relief item flow with lateral transshipment in the first-stage can be seen in Table 5.7. In addition, amount of relief item flow with direct shipment in the first-stage is detailed in Appendix E.

Table 5.7. Amount of Relief Item Flow with Lateral Transshipment in the First-stage of the Problem for Benchmark Model 2

From	To	Esenyurt
Esenler	Bağcılar	8,820.95

By comparing the results of Benchmark Model 2 with the base model, the lateral transshipment in the first-stage is slightly decreased from 4.62% to 4.49%. Similarly, in the second-stage the ratio of lateral transshipment is increased from 8.72% to 22.20%.

In Benchmark Model 2, EVPI is calculated as 7,098,335.96 – 5,933,804.77 = 1,164,531.19, which leads to the conclusion that the value of perfect information is 16.41% of the objective function value. This shows that without road repair, the decisions between scenarios differ more significantly, thus pointing to a less robust solution in terms of uncertainty. Since, here-and-now model is infeasible, the value of the stochastic solution cannot be calculated.

5.3.3. The Effect of Lateral Transshipment

In Benchmark Model 3, relief item flow occurs with only direct shipment policy. Thus, the shipment between supply points is not allowed. When the baseline capacities are used, Benchmark Model 3 returns an infeasible result. To obtain a feasible solution, capacity of each pair of district is increased from 32,000 to 64,000 for both models and the comparison is carried out based on these parameter levels. Objective function value of Benchmark Model 3 is 6,233,985.10. By ignoring the lateral transshipment opportunity, the objective function is increased by 3.56%.

Since the excess amount of relief item in one supply point cannot be transferred to another supply point to ensure the quantity demanded in any demand point, the model is forced to repair more road segments compared to the base model. Amount of relief item flow with direct shipment is detailed in Table F1 in Appendix. As stated previously, an aftershock resulted in an additional demand which is satisfied by relief item flow in the second-stage of the problem. By eliminating the lateral transshipment opportunity, it is observed that the total amount of relief item flow under each scenario is increased from 9,850,268.77 to 11,113,870.13 when it is compared to the base model. To meet relief item requirements for all demand points, number of road segments that are cleared in the first-stage is 54 which is 15.60% of the non-operating roads. Each road segment that is cleared can be seen in detail in Table F2 Appendix.

In Benchmark Model 3, EVPI is calculated as 6,856,164.90 - 6,233,985.10= 622,179.80 which corresponds to 0.001% of the increase in the objective function value. These results are in parallel to those under base model. In addition, here-and-now solution resulted in infeasibility.

5.3.4. The Effect of Assuming All Roads are Blocked

The base model presented in Chapter 3 can also be used as a what-if analysis tool in the pre-disaster stage to assess different potential disaster scenarios. One such possible use is the case where the decision maker may consider the most pessimistic case where all road segments are blocked. In Benchmark Model 4, it is assumed that all 625 road segments are closed both in the first-stage and the second-stage of the problem. Optimal solution statistics for Benchmark Model 4 can be seen in Table 5.8. In addition, amount of relief item flow with direct shipment in the first-stage is detailed in Table G1 in Appendix.

Table 5.8. Optimal Solution Statistics for Benchmark Model 4

Objective Function Value	6,103,740.65
Amount of Lateral Transshipment in the First-Stage	14,493.00
Amount of Direct Shipment in the First-Stage	313,347.28
Percentage of Flow with Lateral Transshipment in the First-Stage	4.63%
Amount of Lateral Transshipment in the Second-Stage	31,345.55
Amount of Direct Shipment in the Second-Stage	312,565.50
Percentage of Flow with Lateral Transshipment in Second-Stage	9.11%

Comparing to the base model, the objective function slightly increases from 6,019,969.91 to 6,103,740.65, which corresponds to a 1.39% increase. This implies that even though all roads are blocked, the repair of a number of critical road segments ensures the efficient flow of relief items to the beneficiaries. Percentage flow of lateral transshipment in the first-stage and the second-stage is 4.63% and 9.11% respectively.

In Benchmark Model 4, EVPI is calculated as 6,103,740.65 - 6,102,911.53 = 829.12, an increase of less than 0.01% in the objective function value. VSS is calculated as 7,495,682.55 - 6,103,740.65 = 1,391,941.90 which corresponds to a 22.80% increase in the objective function value.

Considering the results of this benchmark model, we can conclude that the objective value is quite robust in terms of the set of roads that are blocked as a result of the disaster, due to the availability of repair.

5.3.5. The Effect of Using an Equity-Based Objective Function

In the base model settings, to achieve a feasible solution amount of the total supply is determined to fulfill the total demand at each demand point. Considering a more severe set of demand scenarios, additional demand under each scenario is doubled, since in general it is not possible to meet the total demand of the beneficiaries in the immediate aftermath (e.g., within the first 72 hours) of the disaster. As it can be remembered, the objective function of the base model which is detailed in Chapter 3 is the minimization of the total demand-weighted travel time which is an efficiency-based objective function. Fairness among the affected people can be targeted by an alternative equity-based objective function, which is the minimization of maximum unsatisfied demand. Optimal solution statistics for Benchmark Model 4 can be seen in Table 5.9. Amount of relief item flow with lateral transshipment is detailed in Table 5.10**.** In addition, amount of unsatisfied demand at each demand point in the second-stage can be seen in Table H1 Appendix I.

Table 5.9. Optimal Solution Statistics for Benchmark Model 5

Objective Function Value	2,837.59
Amount of Lateral Transshipment in the First-Stage	313,709.25
Amount of Direct Shipment in the First-Stage	365,665.75
Percentage of Flow with Lateral Transshipment in the First-Stage	46.18%
Amount of Lateral Transshipment in the Second-Stage	12,112.13
Amount of Direct Shipment in the Second-Stage	1,093,035.16
Percentage of Flow with Lateral Transshipment in Second-Stage	1,10%

Table 5.10. Amount of Relief Item Flow with Lateral Transshipment for Benchmark Model 5 for the First-Stage

From	To	Avcılar	Bakırköy	Başakşehir	Beşiktaş
Bağcılar	Eyüp			27,040.814	
Eyüp	Esenler		30,661.628		
Esenler	Bağcılar	31,728.044			271.956
Esenler	Eyüp			4,959.186	

Table 5.10(continued). Amount of Relief Item Flow with Lateral Transshipment for Benchmark Model 5 for the First-Stage

From	To	Bayrampaşa	Esenyurt	Fatih	Güngören
Bağcılar	Esenler				27,443.894
Sultangazi	Eyüp			32,000	
Bahçelievler	Eyüp	2,601.141			
Bahçelievler	Esenler		32,000		
Esenler	Eyüp	27,040.814			

Table 5.10 (continued). Amount of Relief Item Flow with Lateral Transshipment for Benchmark Model 5 for the First-Stage

From	To	Kağıthane	Küçükçekmece	Şişli	Zeytinburnu
Bağcılar	Eyüp			4,959.186	
Bağcılar	Esenler				4,556.106
Eyüp	Sultangazi		32,000		
Sultangazi	Esenler				27,047.62
Bahçelievler	Eyüp	29,398.859			

As can be seen from Table 5.10, except Beylikdüzü all supply points act as a consolidation point that engage with lateral transshipment. The number of roads that are cleared after the main shock is 35 which corresponds to 10.17% of the road segments that are not operating. Likewise, 1,874.97 TL is used for roadway repair which is 37.50% of the total budget.

1n 17 of 30 scenarios, additional quantity demanded as a result of an aftershock is fully satisfied. For instance, additional total quantity demanded in scenario 2 is 645,339.90. Total amount of unsatisfied demand for each demand point in scenario 2 is 71,152.94 which corresponds to 11.03% of the additional demand in scenario 2. The total amount of unsatisfied demand in scenario 17 is 132,309.40. Similarly, 20.30% of the additional demand is unsatisfied in scenario 17. In addition, it should be noted that the additional quantity demanded in Silivri is 9,393.46 and it is fully satisfied in scenario 17.

In the first-stage, quantity demanded in Avcılar is 33,424. The additional demand that arises from the aftershock in scenario 2 is 66,616.89 which results in a total demand of 100,040.89. 4.09% of the total demand in Avcılar is unsatisfied in scenario 2. 31.99% and 31.72% of the total demand is satisfied from Eyüp by direct shipment and from Esenler through Bağcılar by lateral transshipment in the first-stage, respectively. Similarly, 0.22% and 31.99% of the total demand is fulfilled by direct shipment and lateral transshipment from Bağcılar through Eyüp in the second-stage, respectively.

In Table I1, the maximum amount of unsatisfied demand is in Avcılar, Esenyurt, Fatih, and Güngören in scenario 23 with a value of 20,181.957. In order to compare the results of the base model with the equity-based objective function model, an additional constraint is defined to restrict the amount of maximum unsatisfied demand by 20,181.957 in all scenarios. By doing this, we can measure the total demand-weighted travel time by eliminating the assumption that the total amount of demand is fully satisfied. Objective function of the base model with additional constraint that restricts the expectation of the amount of unsatisfied demand in each demand point should be less than or equal to 20,181.957 is increased from 6,019,969.91 to 6,164,133.69 which corresponds to 2.40% increase in the objective function value. Amount of relief item flow with lateral transshipment is detailed in Table 5.11.

Table 5.11. Amount of Relief Item Flow with Lateral Transshipment for Base Model in the First-Stage with Unsatisfied Demand Opportunity

From	To	Esenyurt	Fatih	Küçükçekmece
Bağcılar	Bahçelievler	32,000		
Esenler	Bağcılar		5,805.059	8,023.367

Total quantity demanded in Avcılar is 104,172.16 in scenario 1 after adjusting the model parameters for the base case model. 30.72% and 30.72% of the total demand is satisfied by direct shipment in the first-stage and the second-stage, respectively. In scenario 1, the amount of unsatisfied demand in Avcılar is 40,172.164 which corresponds to 38.56% of the total demand. Furthermore, the expectation of the amount of unsatisfied demand in Avcılar is 19.075.36.

Similarly, total quantity demanded in Fatih is 101,159.718 in scenario 3. 31.63% and 31.00% of the total demand is satisfied with direct shipment in the first-stage and lateral transshipment in the second-stage respectively. Likewise, 5.74% and 31.63% of the total demand is met by lateral transshipment in the first-stage and direct-transshipment in the second-stage. As a result, amount of unsatisfied demand in Fatih is 0.

5.3.6. The Effect of Including Repair Time of each Road Segment

As stated previously, in the base model the repair time of each non-operating road segment is ignored. The repair time of each road segment is generated by multiplying the travel time between each pair of district by 2. For example, travel time from Bağcılar to Esenyurt is 24.9 which resulted in the repair time of that road segment as 49.8 If the road segment is repaired, the travel time include the repair cost of that road segment. Otherwise, repair time takes a value of 0.

Table 5.12. Optimal Solution Statistics for Benchmark Model 6

Objective Function Value	13,280,076.6
Amount of Lateral Transshipment in the First-Stage	14,575.828
Amount of Direct Shipment in the First-Stage	274,612.33
Percentage of Flow with Lateral Transshipment in the First-Stage	5.04%
Amount of Lateral Transshipment in the Second-Stage	33,068.663
Amount of Direct Shipment in the Second-Stage	349,636.79
Percentage of Flow with Lateral Transshipment in Second-Stage	8.64%

Comparing to the base model, the objective function increases from 6,019,969.91 to 13,280,076.6.

As can be seen from Table 5.12, in the first-stage of the problem 5.04% of the total quantity demanded in the overall network is provided by lateral transshipment. In addition, the expectation of the amount of lateral transshipment in the second-stage is 33,068.663. The 8.69% of the additional demand that because of the aftershock is met by lateral transshipment.

In the second-stage, supply points namely Bağcılar, Beylikdüzü, Bahçelievler, and Esenler act as consolidation points that engage in lateral transshipment. For instance, in aftershock scenario 1, 5.89% of the available supply amount in Bağcılar is transferred to other supply points to met relief item requirements in demand points Fatih and Esenyurt.

Similarly, in aftershock scenario 1, 21.17% and 28.19% of the available supply amount in Bağcılar is used to transport relief item to Başakşehir and Küçükçekmece, respecrtively.

Table 5.13. Amount of Relief Item Flow with Lateral Transshipment for Benchmark Model 6 in the First-Stage

From	To	Avcılar	Esenyurt	Fatih	Küçükçekmece
Bağcılar	Beylikdüzü				7,032.349
Bağcılar	Sultangazi	740.757			
Beylikdüzü	Bağcılar		3,401.361	3,401.361	

As presented in Table 5.13, lateral transshipment policy is effectively used in the first-stage of the problem. 8.20% and 17.08% of the quantity demanded in Esenyurt and Küçükçekmece is met by lateral transshipment, respectively.

In the first-stage, quantity demanded in Küçükçekmece is 41,172. The additional demand that arises from the aftershock in scenario 1 is 32,502.43 which results in a total demand of 73,677.43. 43.43% and 17.08% of the relief demand is fulfilled by direct shipment and lateral transshipment in the first-stage of the problem. In addition, the remaining of total demand is satisfied by direct shipment and lateral transshipment under scenario 1, respectively.

Similarly, in the first-stage the number of road segments that are cleared is 81 which corresponds to 23.55% of the non-operating road segments. 3,448.06 TL is used in roadway repair, which corresponds to the 68.96% of the total budget. Likewise, in the second-stage all the remaining budget is not used in emergency roadway repair which is similar to our findings in base model.

5.4. Sensitivity Analysis

As a beginning, in the base model with capacity change, capacity of each road segment is decreased by 20% from 32,000 to 25,600 which results an increase in the objective function from 6,019,969.91 to 6,584,232.38, which corresponds to a 10.93% increase. Amount of relief item flow with lateral transshipment in the first-stage of the problem is detailed in Table 5.14.

Table 5.14. Amount of Relief Item Flow with Lateral Transshipment for Base Model in the First-Stage with Capacity Decrease

From	To	Avcılar	Esenyurt	Fatih	Küçükçekmece
Bağcılar	Bahçelievler	6,033.40	19,566.60		
Esenler	Bağcılar			7,723.02	17,876.98

A 20% decrease in capacity increase results in an increase in the percentage of flow with lateral transshipment in the first-stage from 4.62% to 13.26%. As can be observed from Table A2, the road segment between Esenler and Küçükçekmece is blocked after the main shock. In addition, the road segment between Esenler and Küçükçekmece is not repaired in the first-stage. Since it is not possible to move relief item from Esenler to Küçükçekmece directly, to meet the quantity demanded in Küçükçekmece, relief item is transported by lateral shipment from Esenler through Bağcılar to Küçükçekmece. In Table 5.4, relief flow from Esenler through Bağcılar to Esenyurt is increased from 8,793.96 to 19,566.60, which corresponds to an 122.50% increase. Furthermore, amount of relief item flow with lateral transshipment under each scenario can be seen in Table I1 in Appendix I.

In addition, number of roads that are cleared in the first-stage is increased from 60 to 84 which corresponds to 24.42% of the non-operating road segments. 3,599.37 TL is used in roadway repair which corresponds to the 71.98% of the total budget. Decreasing the capacity of each road segment is forced the model to repair more roads in order to fully satisfy the demand at each demand point.

Similarly, for Base model with 20% capacity decrease EVPI is calculated as 6,584,232.38 - 6,580,272.71=3,959.66, which corresponds to 0.000601% of an increase in the objective function value.

Afterwards, capacity of each road segment in the base model is increased from 32,000 to 38,400 which results in a decrease in the objective function from 6,019,969.91 to 5,695,089.20, a5.40% decrease. It should be noted that CPU time of the base model drastically changed to 20 minutes by increasing the capacity by 20%. The decrease in the objective function value is mainly due to the fact that the lateral transshipment opportunity is not used in the first-stage. Because of the increase in the capacity of each road segment, more demand points are reachable by direct shipment, keeping all other parameters the same.

Total amount of flow in the first-stage is 313,623.11, and demand is fully satisfied by direct shipment. Total flow in the first-stage is increased by 4.84%. In the first-stage, the quantity demanded in Avcılar is 33,424. The additional demand that is arised from the aftershock in scenario 1 is 35,374.09, which results in a total demand of 68,798.082. 54.25% of the total demand is fulfilled by direct shipment in the first-stage. 32.99% and 67.01% of the remaining demand is satisfied by lateral transshipment and direct shipment, respectively. Number of roads that are cleared in the first-stage in increased to 73 which is 21.22% of the non-operating road segments. 3,390.37 TL used in roadway repair which is 67.80% of the total budget.

Once for all, when the capacity of each segment is increased from 32,000 to 64,000, the objective function of the base model in decreased from 6,019,969.91 to 5,601,180.49. Similarly, 77.73% and 22.27% of the total quantity demanded in Avcılar is fulfilled by direct shipment in the first-stage and the second-stage in scenario 1, respectively. Number of roads that are cleared in the first-stage is 32 which is 9.30% of the non-operating roads. 2,256.05 TL is used in roadway repair which corresponds to 45.12% of the total budget.

Capacity of each pair of district is an important parameter that affects Benchmark Model 1. By decreasing the capacity of each pair of district by 10%, keeping all other parameters same, objective function value is increased from 3,118,809.700 to 3,258,230.000 which corresponds to a 4.47% increase in the objective function value. Likewise, amount of relief item flow with lateral transshipment is detailed in Table 7.1. in terms of supply and demand points.

Table 5.15. Amount of Relief Item Flow with Lateral Transshipment in the first-stage for Benchmark Model 1 with 10% Capacity Decrease

From	To	Avcılar	Esenyurt	Fatih	Küçükçekmece
Bağcılar	Bahçelievler	4,624	12,687	7,203	
Bahçelievler	Bağcılar				6,013
Esenler	Bağcılar				6,359

As can be seen from Table 5.15, amount of relief item flow with lateral transshipment increased from 24,086.000 to 36,886.000, which corresponds to a 53.14% increase transshipment by decreasing the capacity of each pair of district by 10%. For instance, quantity demanded in Avcılar met by lateral transshipment is increased from 1,424 to 4,624 which corresponds to a 24.04% increase. Moreover, under Benchmark Model 1 with 10% capacity decrease, lateral transshipment from one supply point to another supply point increased to 3 when it is compared to the base model. Esenler also behaves as consolidation point which engages with lateral transshipment.

In addition, by decreasing the capacity of each pair of district by 20%, keeping all other parameters the same, objective function value is increased from 3,118,809.70 to 3,410,965.50, which corresponds to a 9.37% increase in the objective function value. Similarly, amount of relief item flow with lateral transshipment is detailed in Table 8.1, in terms of supply and demand points with a 20% decrease in the capacity of each pair of district. In addition, amount of relief item flow with lateral transshipment increased from 24,086.000 to 51,566.000. Decrease in the capacity of each pair of district resulted in increase in the lateral transshipment.

In the baseline, when the total budget is decreased by 25% from 5000 to 3250, the objective function value remains the same which is 6,019,969.91. This is reasonable with our findings about budget constraint that is detailed in previous sections. It should be noted that the usage of the budget is related with the number of non-operating roads. In the base model, the budget is decreased by 25% and then it is assumed that each road segment is non-operating for each scenario in the second-stage. The objective function increased from 6,019,969.91 to 6,021,032.19 which corresponds to 0.02%. The number of road segments that are repaired in the first-stage decreased from 60 to 6 when it is compared to the base model. The number of road segments that are repaired in the second-stage is 27. It can be concluded that, the model chooses to transport relief item from road segments with relatively higher travel times rather than repairing more road segments.

In order to analyze and compare the effects of decrease in the budget to the optimal solution, Benchmark Model 4 is solved by decreasing budget from 5000 to 3750. Optimal solution statistics can be seen in Table 5.16.

Table 5.16. Optimal Solution Statistics for Benchmark Model 4 with Budget Decrease

Objective Function Value	6,245,895.17
Amount of Lateral Transshipment in the First-Stage	0
Amount of Direct Shipment in the First-Stage	323,679.484
Amount of Lateral Transshipment in the Second-Stage	45,838.55
Amount of Direct Shipment in the Second-Stage	302,239.00
Percentage of Flow with Lateral Transshipment in Second-Stage	13.17%

The objective function of the Benchmark Model with budget change is increased from 6,103,740.65 to 6.245.895.17 which corresponds to 2.33% change in the objective function value. The number of road segments that are repaired in the first-stage is 13. When it is compared to the base model with budget change, the number of road segments that are repaired is increased from 27 to 39 which corresponds to 44.44% increase.

The computational experiments detailed in this chapter is resulted to need in addressing some important points:

- When the possibility of an aftershock is ignored, the robustness of the proposed model decreased. In other words, the objective function is substantially underestimated.
- By relaxing the assumption of fully satisfying the total demand in each demand point and adopting an equity-based objective, the efficiency-based objective function is slightly increased. Hence, making use of an equity-based model results in a robust solution in terms of efficacy, whereas the opposite is not true.
- When the road repair is no longer taken into consideration, the objective function value increases significantly. In other words, the ability to repair roads provides considerable travel time savings.
- By ignoring the lateral transshipment opportunity, the objective function value is overestimated because the model is forced to transport relief item from road segments with relatively higher travel times.
- Capacity of each road segment is an important parameter on which the relief item flow with direct shipment and lateral transshipment are quite sensitive. Thus, this is an important parameter that needs to be estimated accurately.

In conclusion, the results of each model in terms of objective function value that is detailed in this chapter and the amount of relief item flow in the first-stage with lateral transshipment are summarized in Table 5.15 and Table 5.16, respectively.

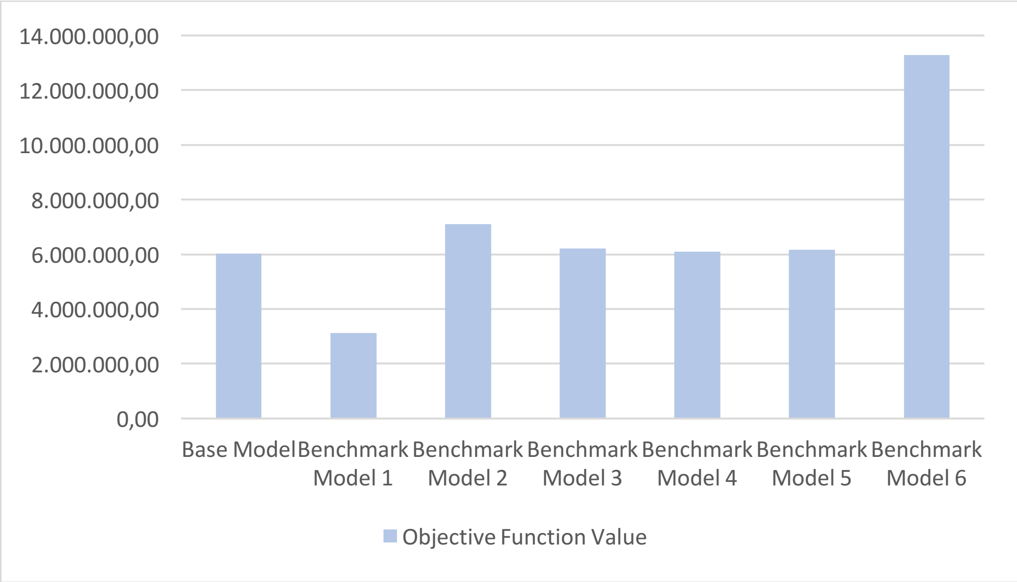


Figure 4. Objective Function Value of each Model

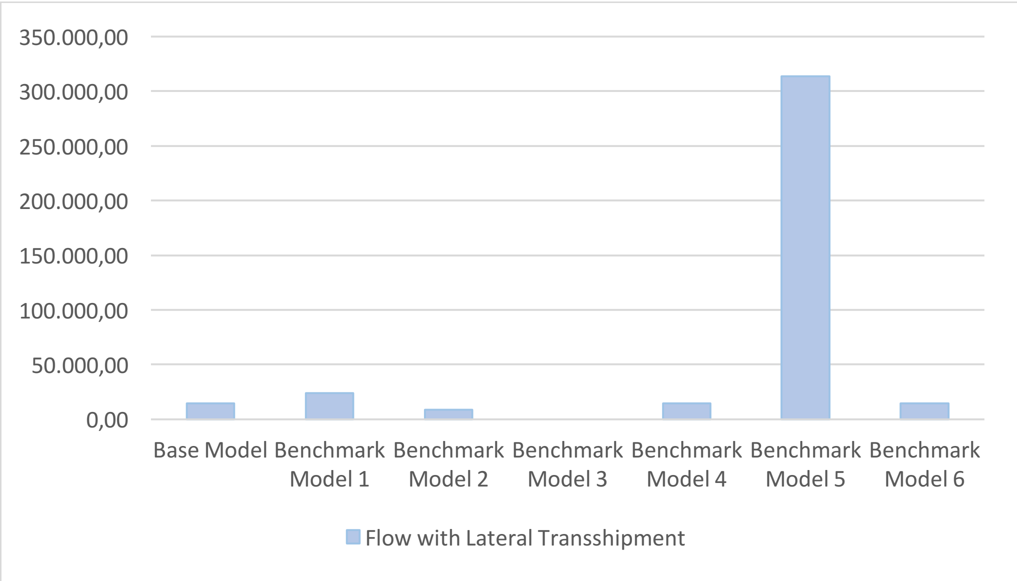


Figure 5. Amount of Relief Item Flow with Lateral Transshipment in the First-stage for each Model

CHAPTER 6

CONCLUSION AND REMARKS

In this thesis, a two-stage mixed-integer stochastic programming model is constructed which considers relief item distribution and emergency roadway repair simultaneously in the aftermath of a large-scale disaster. Both the first-stage and the second-stage of the proposed model are related with post-disaster humanitarian decisions which are (i) relief item distribution with direct shipment, (ii) relief item distribution with lateral transshipment, (iii) emergency roadway repair and, (iv) assignment of supply point to demand points. This thesis differs from the vast majority of the literature on humanitarian logistics in terms of considering the occurrence of an aftershock after the main shock.

The most challenging issue in the disaster response is the uncertainty in the nature such as magnitude and epicenter of the disaster, quantity demanded in the affected areas and asymmetric information. To incorporate uncertainty in the proposed two-stage mixed-integer stochastic programming model, condition of the roads after the main shock and the aftershock, quantity demanded after the aftershock and repair cost of each road segment after the aftershock are treated as stochastic parameters. Condition of each road segment both in the first-stage and the second-stage are defined as binary parameters such that either the road is operating or not after the disaster. Furthermore, the values of these parameters are determined by the road vulnerabilities which are obtained from [51].

The formulation of the two-stage mixed-integer stochastic programming model is detailed in Chapter 3. The objective function is the minimization of total demand-weighted travel time both in the first-stage and the second-stage of the problem. An additional benchmark model is taken into consideration which aimed to minimize the maximum unsatisfied demand. An important contribution of this thesis is incorporating the lateral transshipment opportunity in the overall network while considering the occurrence of an aftershock. The aftershock resulted in additional demand which directly affects the operational decisions after the main shock.

Afterwards, a case study is illustrated for a potential earthquake in Istanbul, Turkey. Road vulnerability for each road segment is generated from [51] as well as supply and demand amounts. Thereafter, these road vulnerabilities are used to obtain Road Damage Scale and respected repair cost of each road segment. Moreover, probability of an aftershock for each magnitude of aftershock (>=M5.0, >=M5.5 and >=M6.0) is generated from Japan Meteorological Agency [75]. Other deterministic parameters such as capacity of each road segment and available budget is determined carefully to obtain a feasible solution. In the preliminary experiments, it is aimed to solve the model that is detailed in Chapter 3 optimally. A scenario set with a size of 30 is determined as a result of these experiments.

To measure the effectiveness of the post-disaster decisions of the proposed model a detailed sensitivity analysis is performed which provides a detailed knowledge about the importance of the parameters. Moreover, a deterministic model is constructed to analyze the proposed humanitarian logistics network only considering the main shock. Additionally, the objective function of Benchmark Model without emergency roadway repair opportunity is much higher than the objective function of Base model.

As a conclusion, this thesis provided a basis model for disaster relief considering the effects of an aftershock. For future research direction, potential effects of an aftershock may be analyzed for pre-disaster decisions such as facility location and pre-positioning of relief items. Also, it is possible to revise the proposed model by

allowing the capacity expansion of supply points. Other potential research directions may include: serving demand points on routes that visit multiple roads.

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APPENDIX A

ROAD VULNERABILITIES FOR EACH PAIR OF DISTRICT

Table A1. Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Arnavutköy	Arnavutköy	0.0000
Arnavutköy	Avcılar	0.0330
Arnavutköy	Bağcılar	0.0300
Arnavutköy	Bahçelievler	0.0820
Arnavutköy	Bakırköy	0.1120
Arnavutköy	Başakşehir	0.0250
Arnavutköy	Bayrampaşa	0.0380
Arnavutköy	Beşiktaş	0.0660
Arnavutköy	Beylikdüzü	0.0250
Arnavutköy	Beyoğlu	0.0280
Arnavutköy	Büyükçekmece	0.0300
Arnavutköy	Çatalca	0.0250
Arnavutköy	Esenler	0.0290
Arnavutköy	Esenyurt	0.0250
Arnavutköy	Eyüp	0.0260
Arnavutköy	Fatih	0.0930
Arnavutköy	Gaziosmanpaşa	0.0250
Arnavutköy	Güngören	0.0830
Arnavutköy	Kağıthane	0.0270
Arnavutköy	Küçükçekmece	0.0320
Arnavutköy	Sarıyer	0.0250
Arnavutköy	Silivri	0.0250
Arnavutköy	Sultangazi	0.0250
Arnavutköy	Şişli	0.0630
Arnavutköy	Zeytinburnu	0.0760
Avcılar	Arnavutköy	0.0330
Avcılar	Bağcılar	0.1090
Avcılar	Bahçelievler	0.1740
Avcılar	Bakırköy	0.1400
Avcılar	Beylikdüzü	0.0510

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Avcılar	Beyoğlu	0.1640
Avcılar	Büyükçekmece	0.0510
Avcılar	Çatalca	0.0410
Avcılar	Esenler	0.0340
Avcılar	Esenyurt	0.0580
Avcılar	Eyüp	0.1320
Avcılar	Fatih	0.1550
Avcılar	Gaziosmanpaşa	0.1420
Avcılar	Güngören	0.1570
Avcılar	Kağıthane	0.1190
Avcılar	Küçükçekmece	0.1980
Avcılar	Sarıyer	0.0970
Avcılar	Silivri	0.0320
Avcılar	Sultangazi	0.0330
Avcılar	Şişli	0.1190
Avcılar	Zeytinburnu	0.1670
Bağcılar	Arnavutköy	0.0300
Bağcılar	Avcılar	0.1090
Bağcılar	Bağcılar	0.0000
Bağcılar	Bahçelievler	0.1250
Bağcılar	Bakırköy	0.2130
Bağcılar	Başakşehir	0.0300
Bağcılar	Bayrampaşa	0.0870
Bağcılar	Beşiktaş	0.1040
Bağcılar	Beylikdüzü	0.0900
Bağcılar	Beyoğlu	0.1350
Bağcılar	Büyükçekmece	0.0840
Bağcılar	Çatalca	0.0280
Bağcılar	Esenler	0.0610
Bağcılar	Esenyurt	0.0280
Bağcılar	Eyüp	0.0640
Bağcılar	Fatih	0.1630
Bağcılar	Gaziosmanpaşa	0.0510
Bağcılar	Güngören	0.2800
Bağcılar	Kağıthane	0.1080
Bağcılar	Küçükçekmece	0.0800
Bağcılar	Sarıyer	0.0300
Bağcılar	Silivri	0.0270
Bağcılar	Sultangazi	0.0420
Bağcılar	Zeytinburnu	0.2810
Bahçelievler	Arnavutköy	0.0820
Bahçelievler	Avcılar	0.1740

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Bahçelievler	Bağcılar	0.1250
Bahçelievler	Bahçelievler	0.0000
Bahçelievler	Bakırköy	0.2960
Bahçelievler	Başakşehir	0.0620
Bahçelievler	Bayrampaşa	0.2850
Bahçelievler	Beşiktaş	0.1270
Bahçelievler	Beylikdüzü	0.1390
Bahçelievler	Beyoğlu	0.2780
Bahçelievler	Büyükçekmece	0.1310
Bahçelievler	Çatalca	0.1000
Bahçelievler	Esenler	0.1270
Bahçelievler	Esenyurt	0.1550
Bahçelievler	Eyüp	0.1220
Bahçelievler	Fatih	0.1650
Bahçelievler	Gaziosmanpaşa	0.1640
Bahçelievler	Güngören	0.2810
Bahçelievler	Kağıthane	0.1540
Bahçelievler	Küçükçekmece	0.1380
Bahçelievler	Sarıyer	0.0830
Bahçelievler	Silivri	0.0780
Bahçelievler	Sultangazi	0.0860
Bahçelievler	Şişli	0.1670
Bahçelievler	Zeytinburnu	0.4030
Bakırköy	Beyoğlu	0.3000
Bakırköy	Büyükçekmece	0.1060
Bakırköy	Çatalca	0.0840
Bakırköy	Esenler	0.2460
Bakırköy	Esenyurt	0.1200
Bakırköy	Eyüp	0.1490
Bakırköy	Fatih	0.3090
Bakırköy	Gaziosmanpaşa	0.1780
Bakırköy	Güngören	0.3690
Bakırköy	Kağıthane	0.1120
Bakırköy	Küçükçekmece	0.0950
Bakırköy	Sarıyer	0.0870
Bakırköy	Silivri	0.0650
Bakırköy	Sultangazi	0.1580
Bakırköy	Şişli	0.2610
Bakırköy	Zeytinburnu	0.3500
Başakşehir	Arnavutköy	0.0250
Başakşehir	Avcılar	0.0380
Başakşehir	Bahçelievler	0.0620

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Başakşehir	Bakırköy	0.0370
Başakşehir	Başakşehir	0.0000
Başakşehir	Bayrampaşa	0.0520
Başakşehir	Beşiktaş	0.0650
Başakşehir	Beylikdüzü	0.0250
Başakşehir	Beyoğlu	0.0710
Başakşehir	Büyükçekmece	0.0290
Başakşehir	Çatalca	0.0250
Başakşehir	Esenler	0.0270
Başakşehir	Esenyurt	0.0250
Başakşehir	Eyüp	0.0260
Başakşehir	Fatih	0.0960
Başakşehir	Gaziosmanpaşa	0.0250
Başakşehir	Güngören	0.0670
Başakşehir	Kağıthane	0.0270
Başakşehir	Küçükçekmece	0.0330
Başakşehir	Sarıyer	0.0250
Başakşehir	Silivri	0.0250
Başakşehir	Sultangazi	0.0250
Başakşehir	Şişli	0.0710
Başakşehir	Zeytinburnu	0.0920
Bayrampaşa	Arnavutköy	0.7043
Bayrampaşa	Avcılar	0.6389
Bayrampaşa	Bağcılar	0.4860
Bayrampaşa	Bahçelievler	0.8986
Bayrampaşa	Bakırköy	0.2143
Bayrampaşa	Başakşehir	0.5252
Bayrampaşa	Bayrampaşa	0.6555
Bayrampaşa	Beşiktaş	0.5038
Bayrampaşa	Beylikdüzü	0.8890
Bayrampaşa	Beyoğlu	0.1985
Bayrampaşa	Büyükçekmece	1.1035
Bayrampaşa	Çatalca	0.0607
Bayrampaşa	Esenler	0.2287
Bayrampaşa	Esenyurt	0.1708
Bayrampaşa	Eyüp	0.5188
Bayrampaşa	Fatih	0.7588

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Bayrampaşa	Gaziosmanpaşa	0.1266
Bayrampaşa	Kağıthane	0.9817
Bayrampaşa	Küçükçekmece	0.5161
Bayrampaşa	Sarıyer	0.4192
Bayrampaşa	Silivri	0.1004
Bayrampaşa	Sultangazi	1.0843
Bayrampaşa	Şişli	1.1105
Bayrampaşa	Zeytinburnu	0.6347
Beşiktaş	Arnavutköy	0.6614
Beşiktaş	Avcılar	0.6500
Beşiktaş	Bağcılar	0.1138
Beşiktaş	Bahçelievler	0.2381
Beşiktaş	Bakırköy	0.4121
Beşiktaş	Başakşehir	0.4886
Beşiktaş	Bayrampaşa	0.0623
Beşiktaş	Beşiktaş	1.1940
Beşiktaş	Beylikdüzü	0.6656
Beşiktaş	Beyoğlu	0.0674
Beşiktaş	Büyükçekmece	0.5392
Beşiktaş	Çatalca	0.4994
Beşiktaş	Esenler	0.0947
Beşiktaş	Esenyurt	0.8857
Beşiktaş	Eyüp	0.2172
Beşiktaş	Fatih	0.1934
Beşiktaş	Gaziosmanpaşa	0.8919
Beşiktaş	Güngören	0.1209
Beşiktaş	Kağıthane	0.1335
Beşiktaş	Küçükçekmece	0.8589
Beşiktaş	Sarıyer	1.0675
Beşiktaş	Silivri	0.8167
Beşiktaş	Sultangazi	0.3122
Beşiktaş	Şişli	0.8739
Beşiktaş	Zeytinburnu	0.5032
Beylikdüzü	Arnavutköy	0.2644
Beylikdüzü	Avcılar	0.8061
Beylikdüzü	Bağcılar	0.6319

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Beylikdüzü	Bahçelievler	0.1545
Beylikdüzü	Bakırköy	0.4837
Beylikdüzü	Başakşehir	0.4265
Beylikdüzü	Bayrampaşa	0.5806
Beylikdüzü	Beşiktaş	0.6125
Beylikdüzü	Beylikdüzü	0.8323
Beylikdüzü	Beyoğlu	0.7095
Beylikdüzü	Büyükçekmece	0.3085
Beylikdüzü	Çatalca	1.1560
Beylikdüzü	Esenler	0.9894
Beylikdüzü	Esenyurt	1.0029
Beylikdüzü	Eyüp	0.1922
Beylikdüzü	Fatih	0.6909
Beylikdüzü	Gaziosmanpaşa	0.4945
Beylikdüzü	Güngören	0.6380
Beylikdüzü	Kağıthane	0.9592
Beylikdüzü	Küçükçekmece	1.1934
Beylikdüzü	Sarıyer	0.3231
Beylikdüzü	Silivri	0.5397
Beylikdüzü	Sultangazi	0.6109
Beylikdüzü	Şişli	0.6364
Beylikdüzü	Zeytinburnu	1.1515
Beyoğlu	Arnavutköy	0.7443
Beyoğlu	Avcılar	1.1200
Beyoğlu	Bağcılar	0.6329
Beyoğlu	Bahçelievler	0.0982
Beyoğlu	Bakırköy	0.4093
Beyoğlu	Başakşehir	0.3426
Beyoğlu	Bayrampaşa	0.0926
Beyoğlu	Beşiktaş	0.2629
Beyoğlu	Beylikdüzü	1.0171
Beyoğlu	Beyoğlu	0.0909
Beyoğlu	Büyükçekmece	1.1345
Beyoğlu	Çatalca	0.4038
Beyoğlu	Esenler	0.3763
Beyoğlu	Esenyurt	0.9411
Beyoğlu	Fatih	0.7402

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Beyoğlu	Eyüp	0.8025
Beyoğlu	Gaziosmanpaşa	0.3568
Beyoğlu	Güngören	0.1906
Beyoğlu	Kağıthane	1.1939
Beyoğlu	Küçükçekmece	0.8589
Beyoğlu	Sarıyer	0.8998
Beyoğlu	Silivri	0.6462
Beyoğlu	Sultangazi	0.1514
Beyoğlu	Şişli	0.9973
Beyoğlu	Zeytinburnu	0.5605
Büyükçekmece	Arnavutköy	0.0300
Büyükçekmece	Avcılar	0.0510
Büyükçekmece	Bağcılar	0.0840
Büyükçekmece	Bahçelievler	0.1310
Büyükçekmece	Bakırköy	0.1060
Büyükçekmece	Başakşehir	0.0290
Büyükçekmece	Bayrampaşa	0.0430
Büyükçekmece	Beşiktaş	0.0950
Büyükçekmece	Beylikdüzü	0.0420
Büyükçekmece	Beyoğlu	0.1000
Büyükçekmece	Büyükçekmece	0.0000
Büyükçekmece	Çatalca	0.0250
Büyükçekmece	Esenler	0.0300
Büyükçekmece	Esenyurt	0.0390
Büyükçekmece	Eyüp	0.0290
Büyükçekmece	Fatih	0.1100
Büyükçekmece	Gaziosmanpaşa	0.0290
Büyükçekmece	Güngören	0.1410
Büyükçekmece	Kağıthane	0.0950
Büyükçekmece	Küçükçekmece	0.1330
Büyükçekmece	Sarıyer	0.0280
Büyükçekmece	Silivri	0.0250
Büyükçekmece	Sultangazi	0.0290
Büyükçekmece	Şişli	0.0970
Büyükçekmece	Zeytinburnu	0.1260
Çatalca	Arnavutköy	0.0250

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Çatalca	Avcılar	0.0410
Çatalca	Bağcılar	0.0280
Çatalca	Bahçelievler	0.1000
Çatalca	Bakırköy	0.0840
Çatalca	Başakşehir	0.0250
Çatalca	Bayrampaşa	0.0370
Çatalca	Beşiktaş	0.0490
Çatalca	Beylikdüzü	0.0310
Çatalca	Beyoğlu	0.0500
Çatalca	Büyükçekmece	0.0250
Çatalca	Çatalca	0.0000
Çatalca	Esenler	0.0260
Çatalca	Esenyurt	0.0310
Çatalca	Eyüp	0.0260
Çatalca	Fatih	0.0580
Çatalca	Gaziosmanpaşa	0.0250
Çatalca	Güngören	0.0520
Çatalca	Kağıthane	0.0270
Çatalca	Küçükçekmece	0.0820
Çatalca	Sarıyer	0.0250
Çatalca	Silivri	0.0250
Çatalca	Sultangazi	0.0250
Çatalca	Şişli	0.0470
Çatalca	Zeytinburnu	0.0760
Esenler	Arnavutköy	0.0290
Esenler	Avcılar	0.0340
Esenler	Bağcılar	0.0610
Esenler	Bahçelievler	0.1270
Esenler	Bakırköy	0.2460
Esenler	Başakşehir	0.0270
Esenler	Bayrampaşa	0.2800
Esenler	Beşiktaş	0.1190
Esenler	Beylikdüzü	0.0430
Esenler	Beyoğlu	0.1430
Esenler	Büyükçekmece	0.0300
Esenler	Çatalca	0.0260
Esenler	Esenler	0.0000

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Esenler	Esenyurt	0.0260
Esenler	Eyüp	0.0660
Esenler	Fatih	0.2110
Esenler	Gaziosmanpaşa	0.0390
Esenler	Güngören	0.2940
Esenler	Kağıthane	0.1280
Esenler	Küçükçekmece	0.0430
Esenler	Sarıyer	0.0300
Esenler	Silivri	0.0280
Esenler	Sultangazi	0.0360
Esenler	Şişli	0.1210
Esenler	Zeytinburnu	0.2310
Esenyurt	Arnavutköy	0.0250
Esenyurt	Avcılar	0.0580
Esenyurt	Bağcılar	0.0280
Esenyurt	Bahçelievler	0.1550
Esenyurt	Bakırköy	0.1200
Esenyurt	Başakşehir	0.0250
Esenyurt	Bayrampaşa	0.0440
Esenyurt	Beşiktaş	0.1020
Esenyurt	Beylikdüzü	0.0250
Esenyurt	Beyoğlu	0.1080
Esenyurt	Büyükçekmece	0.0390
Esenyurt	Çatalca	0.0310
Esenyurt	Esenler	0.0260
Esenyurt	Esenyurt	0.0000
Esenyurt	Eyüp	0.0260
Esenyurt	Fatih	0.1190
Esenyurt	Gaziosmanpaşa	0.0250
Esenyurt	Güngören	0.1590
Esenyurt	Kağıthane	0.0260
Esenyurt	Küçükçekmece	0.1530
Esenyurt	Sarıyer	0.0250
Esenyurt	Silivri	0.0290
Esenyurt	Sultangazi	0.0250
Esenyurt	Şişli	0.1030
Esenyurt	Zeytinburnu	0.0870

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Eyüp	Arnavutköy	0.0260
Eyüp	Avcılar	0.1320
Eyüp	Bağcılar	0.0640
Eyüp	Bahçelievler	0.1220
Eyüp	Bakırköy	0.1490
Eyüp	Başakşehir	0.0260
Eyüp	Bayrampaşa	0.0960
Eyüp	Beşiktaş	0.0400
Eyüp	Beylikdüzü	0.0260
Eyüp	Beyoğlu	0.0650
Eyüp	Büyükçekmece	0.0290
Eyüp	Çatalca	0.0260
Eyüp	Esenler	0.0660
Eyüp	Esenyurt	0.0260
Eyüp	Eyüp	0.0000
Eyüp	Fatih	0.0800
Eyüp	Gaziosmanpaşa	0.0440
Eyüp	Güngören	0.1210
Eyüp	Kağıthane	0.0610
Eyüp	Küçükçekmece	0.0360
Eyüp	Sarıyer	0.0320
Eyüp	Silivri	0.0270
Eyüp	Sultangazi	0.0370
Eyüp	Şişli	0.0320
Eyüp	Zeytinburnu	0.1310
Fatih	Arnavutköy	0.0930
Fatih	Avcılar	0.1550
Fatih	Bağcılar	0.1630
Fatih	Bahçelievler	0.1650
Fatih	Bakırköy	0.3090
Fatih	Başakşehir	0.0960
Fatih	Bayrampaşa	0.3590
Fatih	Beşiktaş	0.0650
Fatih	Beylikdüzü	0.1160
Fatih	Beyoğlu	0.1600
Fatih	Büyükçekmece	0.1100
Fatih	Çatalca	0.0580

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Fatih	Esenler	0.2110
Fatih	Esenyurt	0.1190
Fatih	Eyüp	0.0800
Fatih	Fatih	0.0000
Fatih	Gaziosmanpaşa	0.1650
Fatih	Güngören	0.2510
Fatih	Kağıthane	0.0720
Fatih	Küçükçekmece	0.1090
Fatih	Sarıyer	0.0720
Fatih	Silivri	0.0730
Fatih	Sultangazi	0.1180
Fatih	Şişli	0.1380
Fatih	Zeytinburnu	0.2850
Gaziosmanpaşa	Arnavutköy	0.0250
Gaziosmanpaşa	Avcılar	0.1420
Gaziosmanpaşa	Bağcılar	0.0510
Gaziosmanpaşa	Bahçelievler	0.1640
Gaziosmanpaşa	Bakırköy	0.1780
Gaziosmanpaşa	Bayrampaşa	0.0940
Gaziosmanpaşa	Beşiktaş	0.0430
Gaziosmanpaşa	Beylikdüzü	0.0250
Gaziosmanpaşa	Beyoğlu	0.0480
Gaziosmanpaşa	Büyükçekmece	0.0290
Gaziosmanpaşa	Çatalca	0.0250
Gaziosmanpaşa	Esenler	0.0390
Gaziosmanpaşa	Esenyurt	0.0250
Gaziosmanpaşa	Eyüp	0.0440
Gaziosmanpaşa	Fatih	0.1650
Gaziosmanpaşa	Gaziosmanpaşa	0.0000
Gaziosmanpaşa	Güngören	0.1410
Gaziosmanpaşa	Kağıthane	0.0490
Gaziosmanpaşa	Küçükçekmece	0.0620
Gaziosmanpaşa	Sarıyer	0.0250
Gaziosmanpaşa	Silivri	0.0270
Gaziosmanpaşa	Sultangazi	0.0250
Gaziosmanpaşa	Şişli	0.0530
Gaziosmanpaşa	Zeytinburnu	0.3430

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Güngören	Arnavutköy	0.2050
Güngören	Avcılar	0.3660
Güngören	Bağcılar	0.6480
Güngören	Bahçelievler	0.6410
Güngören	Bakırköy	0.8420
Güngören	Başakşehir	0.1680
Güngören	Bayrampaşa	0.8070
Güngören	Beşiktaş	0.3100
Güngören	Beylikdüzü	0.3590
Güngören	Beyoğlu	0.4310
Güngören	Büyükçekmece	0.3320
Güngören	Çatalca	0.1350
Güngören	Esenler	0.6790
Güngören	Esenyurt	0.3720
Güngören	Eyüp	0.2870
Güngören	Fatih	0.5760
Güngören	Gaziosmanpaşa	0.3320
Güngören	Güngören	0.0000
Güngören	Kağıthane	0.4030
Güngören	Küçükçekmece	0.4110
Güngören	Sarıyer	0.2080
Güngören	Silivri	0.1200
Güngören	Sultangazi	0.2340
Güngören	Şişli	0.3300
Güngören	Zeytinburnu	1.1950
Kağıthane	Arnavutköy	0.0790
Kağıthane	Avcılar	0.2810
Kağıthane	Bağcılar	0.2590
Kağıthane	Bahçelievler	0.3600
Kağıthane	Bakırköy	0.2680
Kağıthane	Başakşehir	0.0790
Kağıthane	Bayrampaşa	0.2000
Kağıthane	Beşiktaş	0.1030
Kağıthane	Beylikdüzü	0.2350
Kağıthane	Beyoğlu	0.0890
Kağıthane	Büyükçekmece	0.2280
Kağıthane	Çatalca	0.0790

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Kağıthane	Esenler	0.3050
Kağıthane	Esenyurt	0.0770
Kağıthane	Eyüp	0.1470
Kağıthane	Fatih	0.1780
Kağıthane	Gaziosmanpaşa	0.1240
Kağıthane	Güngören	0.4030
Kağıthane	Kağıthane	0.0000
Kağıthane	Küçükçekmece	0.1800
Kağıthane	Sarıyer	0.0830
Kağıthane	Silivri	0.0750
Kağıthane	Sultangazi	0.0910
Kağıthane	Şişli	0.0870
Kağıthane	Zeytinburnu	0.3420
Küçükçekmece	Arnavutköy	0.0890
Küçükçekmece	Avcılar	0.4550
Küçükçekmece	Bağcılar	0.1910
Küçükçekmece	Bahçelievler	0.3170
Küçükçekmece	Bakırköy	0.2230
Küçükçekmece	Başakşehir	0.0920
Küçükçekmece	Bayrampaşa	0.1150
Küçükçekmece	Beşiktaş	0.1650
Küçükçekmece	Beylikdüzü	0.3450
Küçükçekmece	Beyoğlu	0.1760
Küçükçekmece	Büyükçekmece	0.3150
Küçükçekmece	Çatalca	0.2020
Küçükçekmece	Esenler	0.1130
Küçükçekmece	Esenyurt	0.3590
Küçükçekmece	Eyüp	0.0980
Küçükçekmece	Fatih	0.2560
Küçükçekmece	Gaziosmanpaşa	0.1530
Küçükçekmece	Güngören	0.4110
Küçükçekmece	Kağıthane	0.1800
Küçükçekmece	Küçükçekmece	0.0000
Küçükçekmece	Sarıyer	0.0910
Küçükçekmece	Silivri	0.1920
Küçükçekmece	Sultangazi	0.1020
Küçükçekmece	Şişli	0.1690

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Küçükçekmece	Zeytinburnu	0.3560
Sarıyer	Arnavutköy	0.0750
Sarıyer	Avcılar	0.2320
Sarıyer	Bağcılar	0.0850
Sarıyer	Bahçelievler	0.2030
Sarıyer	Bakırköy	0.2130
Sarıyer	Başakşehir	0.0750
Sarıyer	Bayrampaşa	0.1400
Sarıyer	Beşiktaş	0.0750
Sarıyer	Beylikdüzü	0.0750
Sarıyer	Beyoğlu	0.0750
Sarıyer	Büyükçekmece	0.0810
Sarıyer	Çatalca	0.0750
Sarıyer	Esenler	0.0850
Sarıyer	Esenyurt	0.0750
Sarıyer	Eyüp	0.0890
Sarıyer	Fatih	0.1780
Sarıyer	Gaziosmanpaşa	0.0750
Sarıyer	Güngören	0.2080
Sarıyer	Kağıthane	0.0830
Sarıyer	Küçükçekmece	0.0910
Sarıyer	Sarıyer	0.0000
Sarıyer	Silivri	0.0750
Sarıyer	Sultangazi	0.0750
Sarıyer	Şişli	0.0750
Sarıyer	Zeytinburnu	0.2130
Silivri	Arnavutköy	0.0750
Silivri	Avcılar	0.0900
Silivri	Bağcılar	0.0790
Silivri	Bahçelievler	0.1920
Silivri	Bakırköy	0.1630
Silivri	Başakşehir	0.0750
Silivri	Bayrampaşa	0.0940
Silivri	Beşiktaş	0.1230
Silivri	Beylikdüzü	0.0840
Silivri	Beyoğlu	0.1250
Silivri	Büyükçekmece	0.0750

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Silivri	Çatalca	0.0750
Silivri	Esenler	0.0810
Silivri	Esenyurt	0.0840
Silivri	Eyüp	0.0790
Silivri	Fatih	0.1810
Silivri	Gaziosmanpaşa	0.0790
Silivri	Güngören	0.1200
Silivri	Kağıthane	0.0750
Silivri	Küçükçekmece	0.1920
Silivri	Sarıyer	0.0750
Silivri	Silivri	0.0000
Silivri	Sultangazi	0.0800
Silivri	Şişli	0.1710
Silivri	Zeytinburnu	0.2050
Sultangazi	Arnavutköy	0.0750
Sultangazi	Avcılar	0.0920
Sultangazi	Bağcılar	0.1100
Sultangazi	Bahçelievler	0.2070
Sultangazi	Bakırköy	0.3680
Sultangazi	Başakşehir	0.0750
Sultangazi	Bayrampaşa	0.1520
Sultangazi	Beşiktaş	0.0930
Sultangazi	Beylikdüzü	0.0750
Sultangazi	Beyoğlu	0.0770
Sultangazi	Büyükçekmece	0.0830
Sultangazi	Çatalca	0.0750
Sultangazi	Esenler	0.0970
Sultangazi	Esenyurt	0.0750
Sultangazi	Eyüp	0.1000
Sultangazi	Fatih	0.2810
Sultangazi	Gaziosmanpaşa	0.0750
Sultangazi	Güngören	0.2340
Sultangazi	Kağıthane	0.0910
Sultangazi	Küçükçekmece	0.1020
Sultangazi	Sarıyer	0.0750
Sultangazi	Silivri	0.0800
Sultangazi	Sultangazi	0.0000

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Sultangazi	Şişli	0.0770
Sultangazi	Zeytinburnu	0.3650
Şişli	Arnavutköy	0.1610
Şişli	Avcılar	0.2810
Şişli	Bağcılar	0.2830
Şişli	Bahçelievler	0.3910
Şişli	Bakırköy	0.6040
Şişli	Başakşehir	0.1780
Şişli	Bayrampaşa	0.1950
Şişli	Beşiktaş	0.0750
Şişli	Beylikdüzü	0.2400
Şişli	Beyoğlu	0.1820
Şişli	Büyükçekmece	0.2320
Şişli	Çatalca	0.1250
Şişli	Esenler	0.2900
Şişli	Esenyurt	0.2450
Şişli	Eyüp	0.0890
Şişli	Fatih	0.3180
Şişli	Gaziosmanpaşa	0.1340
Şişli	Güngören	0.3300
Şişli	Kağıthane	0.0870
Şişli	Küçükçekmece	0.1690
Şişli	Sarıyer	0.0750
Şişli	Silivri	0.1710
Şişli	Sultangazi	0.0770
Şişli	Şişli	0.0000
Şişli	Zeytinburnu	0.3110
Zeytinburnu	Arnavutköy	0.1890
Zeytinburnu	Avcılar	0.3880
Zeytinburnu	Bağcılar	0.6420
Zeytinburnu	Bahçelievler	0.9140
Zeytinburnu	Bakırköy	0.8150
Zeytinburnu	Başakşehir	0.2240
Zeytinburnu	Bayrampaşa	0.6680
Zeytinburnu	Beşiktaş	0.2890
Zeytinburnu	Beylikdüzü	0.3130

Table A1 (continued). Average Road Vulnerabilities

From	To	Average Road Vulnerabilities
Zeytinburnu	Büyükçekmece	0.2970
Zeytinburnu	Çatalca	0.1890
Zeytinburnu	Esenler	0.5330
Zeytinburnu	Esenyurt	0.2130
Zeytinburnu	Eyüp	0.3110
Zeytinburnu	Fatih	0.6540
Zeytinburnu	Gaziosmanpaşa	0.3430
Zeytinburnu	Güngören	1.1950
Zeytinburnu	Kağıthane	0.3420
Zeytinburnu	Küçükçekmece	0.3560
Zeytinburnu	Sarıyer	0.2130
Zeytinburnu	Silivri	0.2050
Zeytinburnu	Sultangazi	0.3650
Zeytinburnu	Şişli	0.3110

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating. b_{ij}=1 operating)

From	To	b_{ij}
Arnavutköy	Arnavutköy	1
Arnavutköy	Avcılar	1
Arnavutköy	Bağcılar	1
Arnavutköy	Bahçelievler	0
Arnavutköy	Bakırköy	0
Arnavutköy	Başakşehir	1
Arnavutköy	Bayrampaşa	1
Arnavutköy	Beşiktaş	1
Arnavutköy	Beylikdüzü	1
Arnavutköy	Beyoğlu	1
Arnavutköy	Büyükçekmece	1
Arnavutköy	Çatalca	1
Arnavutköy	Esenler	1
Arnavutköy	Esenyurt	1
Arnavutköy	Eyüp	1
Arnavutköy	Fatih	0
Arnavutköy	Gaziosmanpaşa	1
Arnavutköy	Kağıthane	1
Arnavutköy	Küçükçekmece	1
Arnavutköy	Sarıyer	1
Arnavutköy	Silivri	1
Arnavutköy	Sultangazi	1
Arnavutköy	Şişli	1
Arnavutköy	Zeytinburnu	1
Avcılar	Arnavutköy	1
Avcılar	Avcılar	1
Avcılar	Bağcılar	0
Avcılar	Bahçelievler	0
Avcılar	Bakırköy	0
Avcılar	Başakşehir	1
Avcılar	Bayrampaşa	0
Avcılar	Beşiktaş	0
Avcılar	Beylikdüzü	1
Avcılar	Beyoğlu	0
Avcılar	Büyükçekmece	1
Avcılar	Çatalca	1

Table A2 (continued). Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Avcılar	Esenler	1
Avcılar	Esenyurt	1
Avcılar	Eyüp	0
Avcılar	Fatih	0
Avcılar	Gaziosmanpaşa	0
Avcılar	Güngören	0
Avcılar	Kağıthane	0
Avcılar	Küçükçekmece	0
Avcılar	Sarıyer	0
Avcılar	Silivri	1
Avcılar	Sultangazi	1
Avcılar	Şişli	0
Avcılar	Zeytinburnu	0
Bağcılar	Arnavutköy	1
Bağcılar	Avcılar	0
Bağcılar	Bağcılar	1
Bağcılar	Bahçelievler	0
Bağcılar	Bakırköy	0
Bağcılar	Başakşehir	1
Bağcılar	Bayrampaşa	0
Bağcılar	Beşiktaş	0
Bağcılar	Beylikdüzü	0
Bağcılar	Beyoğlu	0
Bağcılar	Büyükçekmece	0
Bağcılar	Çatalca	1
Bağcılar	Esenler	1
Bağcılar	Esenyurt	1
Bağcılar	Eyüp	1
Bağcılar	Fatih	0
Bağcılar	Gaziosmanpaşa	1
Bağcılar	Güngören	0
Bağcılar	Kağıthane	0
Bağcılar	Küçükçekmece	0
Bağcılar	Sarıyer	1
Bağcılar	Silivri	1
Bağcılar	Sultangazi	1

Table A2 (continued). Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Bağcılar	Şişli	1
Bağcılar	Zeytinburnu	0
Bahçelievler	Arnavutköy	0
Bahçelievler	Avcılar	0
Bahçelievler	Bağcılar	0
Bahçelievler	Bahçelievler	1
Bahçelievler	Bakırköy	0
Bahçelievler	Başakşehir	1
Bahçelievler	Bayrampaşa	0
Bahçelievler	Beşiktaş	0
Bahçelievler	Beylikdüzü	0
Bahçelievler	Beyoğlu	0
Bahçelievler	Büyükçekmece	0
Bahçelievler	Çatalca	0
Bahçelievler	Esenler	0
Bahçelievler	Esenyurt	0
Bahçelievler	Eyüp	0
Bahçelievler	Fatih	0
Bahçelievler	Gaziosmanpaşa	0
Bahçelievler	Güngören	0
Bahçelievler	Kağıthane	0
Bahçelievler	Küçükçekmece	0
Bahçelievler	Sarıyer	0
Bahçelievler	Silivri	1
Bahçelievler	Sultangazi	0
Bahçelievler	Şişli	0
Bahçelievler	Zeytinburnu	0
Bakırköy	Arnavutköy	0
Bakırköy	Avcılar	0
Bakırköy	Bağcılar	0
Bakırköy	Bahçelievler	0
Bakırköy	Bakırköy	1
Bakırköy	Başakşehir	1
Bakırköy	Bayrampaşa	0
Bakırköy	Beşiktaş	0
Bakırköy	Beylikdüzü	0

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Bakırköy	Beyoğlu	0
Bakırköy	Büyükçekmece	0
Bakırköy	Çatalca	0
Bakırköy	Esenler	0
Bakırköy	Esenyurt	0
Bakırköy	Eyüp	0
Bakırköy	Fatih	0
Bakırköy	Gaziosmanpaşa	0
Bakırköy	Güngören	0
Bakırköy	Kağıthane	0
Bakırköy	Küçükçekmece	0
Bakırköy	Sarıyer	0
Bakırköy	Silivri	1
Bakırköy	Sultangazi	0
Bakırköy	Şişli	0
Bakırköy	Zeytinburnu	0
Başakşehir	Arnavutköy	1
Başakşehir	Avcılar	1
Başakşehir	Bağcılar	1
Başakşehir	Bahçelievler	1
Başakşehir	Bakırköy	1
Başakşehir	Başakşehir	1
Başakşehir	Bayrampaşa	1
Başakşehir	Beşiktaş	1
Başakşehir	Beylikdüzü	1
Başakşehir	Beyoğlu	1
Başakşehir	Büyükçekmece	1
Başakşehir	Çatalca	1
Başakşehir	Esenler	1
Başakşehir	Esenyurt	1
Başakşehir	Eyüp	1
Başakşehir	Fatih	0
Başakşehir	Gaziosmanpaşa	1
Başakşehir	Güngören	1
Başakşehir	Kağıthane	1
Başakşehir	Küçükçekmece	1

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Başakşehir	Sarıyer	1
Başakşehir	Silivri	1
Başakşehir	Sultangazi	1
Başakşehir	Şişli	1
Bayrampaşa	Arnavutköy	0
Bayrampaşa	Avcılar	0
Bayrampaşa	Bağcılar	0
Bayrampaşa	Bahçelievler	0
Bayrampaşa	Bakırköy	0
Bayrampaşa	Başakşehir	0
Bayrampaşa	Bayrampaşa	1
Bayrampaşa	Beşiktaş	0
Bayrampaşa	Beylikdüzü	0
Bayrampaşa	Beyoğlu	0
Bayrampaşa	Büyükçekmece	0
Bayrampaşa	Çatalca	1
Bayrampaşa	Esenler	0
Bayrampaşa	Esenyurt	0
Bayrampaşa	Eyüp	0
Bayrampaşa	Fatih	0
Bayrampaşa	Gaziosmanpaşa	0
Bayrampaşa	Güngören	0
Bayrampaşa	Kağıthane	0
Bayrampaşa	Küçükçekmece	0
Bayrampaşa	Sarıyer	0
Bayrampaşa	Silivri	0
Bayrampaşa	Sultangazi	0
Bayrampaşa	Şişli	0
Bayrampaşa	Zeytinburnu	0
Beşiktaş	Arnavutköy	0
Beşiktaş	Avcılar	0
Beşiktaş	Bağcılar	0
Beşiktaş	Bahçelievler	0
Beşiktaş	Bakırköy	0
Beşiktaş	Başakşehir	0
Beşiktaş	Bayrampaşa	1

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Beşiktaş	Beylikdüzü	0
Beşiktaş	Beşiktaş	1
Beşiktaş	Beyoğlu	1
Beşiktaş	Büyükçekmece	0
Beşiktaş	Çatalca	0
Beşiktaş	Esenler	0
Beşiktaş	Esenyurt	0
Beşiktaş	Eyüp	0
Beşiktaş	Fatih	0
Beşiktaş	Gaziosmanpaşa	0
Beşiktaş	Güngören	0
Beşiktaş	Kağıthane	0
Beşiktaş	Küçükçekmece	0
Beşiktaş	Sarıyer	0
Beşiktaş	Silivri	0
Beşiktaş	Sultangazi	0
Beşiktaş	Şişli	0
Beşiktaş	Zeytinburnu	0
Beylikdüzü	Arnavutköy	0
Beylikdüzü	Avcılar	0
Beylikdüzü	Bağcılar	0
Beylikdüzü	Bahçelievler	0
Beylikdüzü	Bakırköy	0
Beylikdüzü	Başakşehir	0
Beylikdüzü	Bayrampaşa	0
Beylikdüzü	Beşiktaş	0
Beylikdüzü	Beylikdüzü	1
Beylikdüzü	Beyoğlu	0
Beylikdüzü	Büyükçekmece	0
Beylikdüzü	Çatalca	0
Beylikdüzü	Esenler	0
Beylikdüzü	Esenyurt	0
Beylikdüzü	Eyüp	0
Beylikdüzü	Fatih	0
Beylikdüzü	Gaziosmanpaşa	0
Beylikdüzü	Güngören	0

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Beylikdüzü	Kağıthane	0
Beylikdüzü	Küçükçekmece	0
Beylikdüzü	Silivri	0
Beylikdüzü	Sultangazi	0
Beylikdüzü	Şişli	0
Beylikdüzü	Zeytinburnu	0
Beylikdüzü	Sarıyer	0
Beyoğlu	Arnavutköy	0
Beyoğlu	Avcılar	0
Beyoğlu	Bağcılar	0
Beyoğlu	Bahçelievler	0
Beyoğlu	Bakırköy	0
Beyoğlu	Başakşehir	0
Beyoğlu	Bayrampaşa	0
Beyoğlu	Beşiktaş	0
Beyoğlu	Beylikdüzü	0
Beyoğlu	Beyoğlu	1
Beyoğlu	Büyükçekmece	0
Beyoğlu	Çatalca	0
Beyoğlu	Esenler	0
Beyoğlu	Esenyurt	0
Beyoğlu	Eyüp	0
Beyoğlu	Fatih	0
Beyoğlu	Gaziosmanpaşa	0
Beyoğlu	Güngören	0
Beyoğlu	Kağıthane	0
Beyoğlu	Küçükçekmece	0
Beyoğlu	Sarıyer	0
Beyoğlu	Silivri	0
Beyoğlu	Sultangazi	0
Beyoğlu	Şişli	0
Beyoğlu	Zeytinburnu	0
Büyükçekmece	Arnavutköy	1
Büyükçekmece	Avcılar	1
Büyükçekmece	Bağcılar	0
Büyükçekmece	Bahçelievler	0

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Büyükçekmece	Bakırköy	0
Büyükçekmece	Başakşehir	1
Büyükçekmece	Bayrampaşa	1
Büyükçekmece	Beşiktaş	0
Büyükçekmece	Beylikdüzü	1
Büyükçekmece	Beyoğlu	0
Büyükçekmece	Büyükçekmece	1
Büyükçekmece	Çatalca	1
Büyükçekmece	Esenler	1
Büyükçekmece	Esenyurt	1
Büyükçekmece	Eyüp	1
Büyükçekmece	Fatih	0
Büyükçekmece	Gaziosmanpaşa	1
Büyükçekmece	Güngören	0
Büyükçekmece	Kağıthane	0
Büyükçekmece	Küçükçekmece	0
Büyükçekmece	Sarıyer	1
Büyükçekmece	Silivri	1
Büyükçekmece	Sultangazi	1
Büyükçekmece	Şişli	0
Büyükçekmece	Zeytinburnu	0
Çatalca	Arnavutköy	1
Çatalca	Avcılar	1
Çatalca	Bağcılar	1
Çatalca	Bahçelievler	0
Çatalca	Bakırköy	0
Çatalca	Başakşehir	1
Çatalca	Bayrampaşa	1
Çatalca	Beşiktaş	1
Çatalca	Beylikdüzü	1
Çatalca	Beyoğlu	1
Çatalca	Büyükçekmece	1
Çatalca	Çatalca	1
Çatalca	Esenler	1
Çatalca	Esenyurt	1
Çatalca	Eyüp	1

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Çatalca	Fatih	1
Çatalca	Gaziosmanpaşa	1
Çatalca	Güngören	1
Çatalca	Kağıthane	1
Çatalca	Küçükçekmece	0
Çatalca	Sarıyer	1
Çatalca	Silivri	1
Çatalca	Sultangazi	1
Çatalca	Şişli	1
Çatalca	Zeytinburnu	1
Esenler	Arnavutköy	1
Esenler	Avcılar	1
Esenler	Bağcılar	1
Esenler	Bahçelievler	0
Esenler	Bakırköy	0
Esenler	Başakşehir	1
Esenler	Bayrampaşa	0
Esenler	Beşiktaş	0
Esenler	Beylikdüzü	1
Esenler	Beyoğlu	0
Esenler	Büyükçekmece	1
Esenler	Çatalca	1
Esenler	Esenler	1
Esenler	Esenyurt	1
Esenler	Eyüp	1
Esenler	Fatih	0
Esenler	Gaziosmanpaşa	1
Esenler	Güngören	0
Esenler	Kağıthane	0
Esenler	Küçükçekmece	1
Esenler	Sarıyer	1
Esenler	Silivri	1
Esenler	Sultangazi	1
Esenler	Şişli	0
Esenler	Zeytinburnu	0
Esenyurt	Arnavutköy	1

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Esenyurt	Avcılar	1
Esenyurt	Bağcılar	1
Esenyurt	Bahçelievler	0
Esenyurt	Bakırköy	0
Esenyurt	Başakşehir	1
Esenyurt	Bayrampaşa	1
Esenyurt	Beşiktaş	0
Esenyurt	Beylikdüzü	1
Esenyurt	Beyoğlu	0
Esenyurt	Büyükçekmece	1
Esenyurt	Çatalca	1
Esenyurt	Esenler	1
Esenyurt	Esenyurt	1
Esenyurt	Eyüp	1
Esenyurt	Fatih	0
Esenyurt	Gaziosmanpaşa	1
Esenyurt	Güngören	0
Esenyurt	Kağıthane	1
Esenyurt	Küçükçekmece	0
Esenyurt	Sarıyer	1
Esenyurt	Silivri	1
Esenyurt	Sultangazi	0
Esenyurt	Şişli	1
Esenyurt	Zeytinburnu	0
Eyüp	Arnavutköy	1
Eyüp	Avcılar	0
Eyüp	Bağcılar	1
Eyüp	Bahçelievler	0
Eyüp	Bakırköy	0
Eyüp	Başakşehir	1
Eyüp	Bayrampaşa	0
Eyüp	Beşiktaş	1
Eyüp	Beylikdüzü	1
Eyüp	Beyoğlu	1
Eyüp	Büyükçekmece	1
Eyüp	Çatalca	1

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Eyüp	Esenler	1
Eyüp	Esenyurt	1
Eyüp	Eyüp	1
Eyüp	Fatih	0
Eyüp	Gaziosmanpaşa	1
Eyüp	Güngören	0
Eyüp	Kağıthane	1
Eyüp	Küçükçekmece	1
Eyüp	Sarıyer	1
Eyüp	Silivri	1
Eyüp	Sultangazi	1
Eyüp	Şişli	1
Eyüp	Zeytinburnu	0
Fatih	Arnavutköy	0
Fatih	Avcılar	0
Fatih	Bağcılar	0
Fatih	Bahçelievler	0
Fatih	Bakırköy	0
Fatih	Başakşehir	0
Fatih	Bayrampaşa	0
Fatih	Beşiktaş	1
Fatih	Beylikdüzü	0
Fatih	Beyoğlu	0
Fatih	Büyükçekmece	0
Fatih	Çatalca	1
Fatih	Esenler	0
Fatih	Esenyurt	0
Fatih	Eyüp	0
Fatih	Fatih	1
Fatih	Gaziosmanpaşa	0
Fatih	Güngören	0
Fatih	Kağıthane	1
Fatih	Küçükçekmece	0
Fatih	Sarıyer	1
Fatih	Silivri	1
Fatih	Sultangazi	0

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Fatih	Şişli	0
Fatih	Zeytinburnu	0
Gaziosmanpaşa	Arnavutköy	1
Gaziosmanpaşa	Avcılar	0
Gaziosmanpaşa	Bağcılar	1
Gaziosmanpaşa	Bahçelievler	0
Gaziosmanpaşa	Bakırköy	0
Gaziosmanpaşa	Başakşehir	1
Gaziosmanpaşa	Bayrampaşa	0
Gaziosmanpaşa	Beylikdüzü	1
Gaziosmanpaşa	Beyoğlu	1
Gaziosmanpaşa	Büyükçekmece	1
Gaziosmanpaşa	Çatalca	1
Gaziosmanpaşa	Esenler	1
Gaziosmanpaşa	Esenyurt	1
Gaziosmanpaşa	Eyüp	1
Gaziosmanpaşa	Fatih	0
Gaziosmanpaşa	Gaziosmanpaşa	1
Gaziosmanpaşa	Güngören	0
Gaziosmanpaşa	Kağıthane	1
Gaziosmanpaşa	Küçükçekmece	1
Gaziosmanpaşa	Sarıyer	1
Gaziosmanpaşa	Silivri	1
Gaziosmanpaşa	Sultangazi	1
Gaziosmanpaşa	Şişli	1
Gaziosmanpaşa	Zeytinburnu	0
Güngören	Arnavutköy	0
Güngören	Avcılar	0
Güngören	Bağcılar	0
Güngören	Bahçelievler	0
Güngören	Bakırköy	0
Güngören	Başakşehir	0
Güngören	Bayrampaşa	0
Güngören	Beşiktaş	0
Güngören	Beylikdüzü	0
Güngören	Beyoğlu	0

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Güngören	Büyükçekmece	0
Güngören	Çatalca	0
Güngören	Esenler	0
Güngören	Esenyurt	0
Güngören	Eyüp	0
Güngören	Fatih	0
Güngören	Gaziosmanpaşa	0
Güngören	Güngören	1
Güngören	Kağıthane	0
Güngören	Küçükçekmece	0
Güngören	Sarıyer	0
Güngören	Silivri	0
Güngören	Sultangazi	0
Güngören	Şişli	0
Güngören	Zeytinburnu	0
Kağıthane	Arnavutköy	1
Kağıthane	Avcılar	0
Kağıthane	Bağcılar	0
Kağıthane	Bahçelievler	0
Kağıthane	Bakırköy	0
Kağıthane	Başakşehir	1
Kağıthane	Bayrampaşa	0
Kağıthane	Beşiktaş	0
Kağıthane	Beylikdüzü	0
Kağıthane	Beyoğlu	0
Kağıthane	Büyükçekmece	0
Kağıthane	Çatalca	1
Kağıthane	Esenler	0
Kağıthane	Esenyurt	1
Kağıthane	Eyüp	0
Kağıthane	Fatih	0
Kağıthane	Gaziosmanpaşa	0
Kağıthane	Güngören	0
Kağıthane	Kağıthane	1
Kağıthane	Küçükçekmece	0
Kağıthane	Sarıyer	0

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Kağıthane	Silivri	1
Kağıthane	Sultangazi	0
Kağıthane	Şişli	0
Kağıthane	Zeytinburnu	0
Küçükçekmece	Arnavutköy	0
Küçükçekmece	Avcılar	0
Küçükçekmece	Bağcılar	0
Küçükçekmece	Bahçelievler	0
Küçükçekmece	Bakırköy	0
Küçükçekmece	Başakşehir	0
Küçükçekmece	Bayrampaşa	0
Küçükçekmece	Beşiktaş	0
Küçükçekmece	Beylikdüzü	0
Küçükçekmece	Beyoğlu	0
Küçükçekmece	Büyükçekmece	0
Küçükçekmece	Çatalca	0
Küçükçekmece	Esenler	0
Küçükçekmece	Esenyurt	0
Küçükçekmece	Eyüp	0
Küçükçekmece	Fatih	0
Küçükçekmece	Gaziosmanpaşa	0
Küçükçekmece	Güngören	0
Küçükçekmece	Kağıthane	0
Küçükçekmece	Küçükçekmece	1
Küçükçekmece	Sarıyer	0
Küçükçekmece	Silivri	0
Küçükçekmece	Sultangazi	0
Küçükçekmece	Şişli	0
Küçükçekmece	Zeytinburnu	0
Sarıyer	Arnavutköy	1
Sarıyer	Avcılar	0
Sarıyer	Bağcılar	0
Sarıyer	Bahçelievler	0
Sarıyer	Bakırköy	0
Sarıyer	Başakşehir	1
Sarıyer	Bayrampaşa	0

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Sarıyer	Beşiktaş	1
Sarıyer	Beylikdüzü	1
Sarıyer	Beyoğlu	1
Sarıyer	Büyükçekmece	0
Sarıyer	Çatalca	1
Sarıyer	Esenler	0
Sarıyer	Esenyurt	1
Sarıyer	Eyüp	0
Sarıyer	Fatih	0
Sarıyer	Gaziosmanpaşa	1
Sarıyer	Güngören	0
Sarıyer	Kağıthane	0
Sarıyer	Küçükçekmece	0
Sarıyer	Sarıyer	1
Sarıyer	Silivri	1
Sarıyer	Sultangazi	1
Sarıyer	Şişli	1
Sarıyer	Zeytinburnu	0
Silivri	Arnavutköy	1
Silivri	Avcılar	0
Silivri	Bağcılar	1
Silivri	Bahçelievler	0
Silivri	Bakırköy	0
Silivri	Başakşehir	1
Silivri	Bayrampaşa	0
Silivri	Beşiktaş	0
Silivri	Beylikdüzü	0
Silivri	Beyoğlu	0
Silivri	Büyükçekmece	1
Silivri	Çatalca	1
Silivri	Esenler	0
Silivri	Esenyurt	0
Silivri	Eyüp	1
Silivri	Fatih	0
Silivri	Gaziosmanpaşa	1
Silivri	Güngören	0

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Silivri	Kağıthane	1
Silivri	Küçükçekmece	0
Silivri	Sarıyer	1
Silivri	Silivri	1
Silivri	Sultangazi	0
Silivri	Şişli	0
Silivri	Zeytinburnu	0
Sultangazi	Arnavutköy	1
Sultangazi	Avcılar	0
Sultangazi	Bağcılar	0
Sultangazi	Bahçelievler	0
Sultangazi	Bakırköy	0
Sultangazi	Başakşehir	1
Sultangazi	Bayrampaşa	0
Sultangazi	Beşiktaş	0
Sultangazi	Beylikdüzü	1
Sultangazi	Beyoğlu	1
Sultangazi	Büyükçekmece	0
Sultangazi	Çatalca	1
Sultangazi	Esenler	0
Sultangazi	Esenyurt	1
Sultangazi	Eyüp	0
Sultangazi	Fatih	0
Sultangazi	Gaziosmanpaşa	1
Sultangazi	Güngören	0
Sultangazi	Kağıthane	0
Sultangazi	Küçükçekmece	0
Sultangazi	Sarıyer	1
Sultangazi	Silivri	0
Sultangazi	Sultangazi	1
Sultangazi	Şişli	1
Sultangazi	Zeytinburnu	0
Şişli	Arnavutköy	0
Şişli	Avcılar	0
Şişli	Bağcılar	0
Şişli	Bahçelievler	0

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Şişli	Bakırköy	0
Şişli	Başakşehir	0
Şişli	Bayrampaşa	0
Şişli	Beşiktaş	1
Şişli	Beylikdüzü	0
Şişli	Beyoğlu	0
Şişli	Büyükçekmece	0
Şişli	Çatalca	0
Şişli	Esenler	0
Şişli	Esenyurt	0
Şişli	Eyüp	0
Şişli	Fatih	0
Şişli	Gaziosmanpaşa	0
Şişli	Güngören	0
Şişli	Kağıthane	0
Şişli	Küçükçekmece	1
Şişli	Sarıyer	0
Şişli	Silivri	1
Şişli	Sultangazi	1
Şişli	Şişli	1
Şişli	Zeytinburnu	0
Zeytinburnu	Arnavutköy	0
Zeytinburnu	Avcılar	0
Zeytinburnu	Bağcılar	0
Zeytinburnu	Bahçelievler	0
Zeytinburnu	Bakırköy	0
Zeytinburnu	Başakşehir	0
Zeytinburnu	Bayrampaşa	0
Zeytinburnu	Beşiktaş	0
Zeytinburnu	Beylikdüzü	0
Zeytinburnu	Beyoğlu	0
Zeytinburnu	Büyükçekmece	0
Zeytinburnu	Çatalca	0
Zeytinburnu	Esenler	0
Zeytinburnu	Esenyurt	0
Zeytinburnu	Eyüp	0

Table A2. Condition of the Road Segment after the main shock (b_{ij}=0 not operating, b_{ij}=1 operating)

From	To	b_{ij}
Zeytinburnu	Fatih	0
Zeytinburnu	Gaziosmanpaşa	0
Zeytinburnu	Güngören	0
Zeytinburnu	Kağıthane	0
Zeytinburnu	Küçükçekmece	0
Zeytinburnu	Sarıyer	0
Zeytinburnu	Silivri	0
Zeytinburnu	Sultangazi	0
Zeytinburnu	Şişli	0
Zeytinburnu	Zeytinburnu	1

APPENDIX B

ROAD DAMAGE SCALE, DISTANCE BETWEEN EACH ROAD SEGMENT AND RESPECTIVE REPAIR COST

Table B1. Road Damage Scale for Each Road Segment

From	To	Revised Road Damage Scale
Arnavutköy	Arnavutköy	1
Arnavutköy	Avcılar	1
Arnavutköy	Bağcılar	1
Arnavutköy	Bahçelievler	1
Arnavutköy	Bakırköy	1
Arnavutköy	Başakşehir	1
Arnavutköy	Bayrampaşa	1
Arnavutköy	Beşiktaş	1
Arnavutköy	Beylikdüzü	1
Arnavutköy	Beyoğlu	1
Arnavutköy	Büyükçekmece	1
Arnavutköy	Çatalca	1
Arnavutköy	Esenler	1
Arnavutköy	Esenyurt	1
Arnavutköy	Eyüp	1
Arnavutköy	Fatih	1
Arnavutköy	Gaziosmanpaşa	1
Arnavutköy	Güngören	1
Arnavutköy	Kağıthane	1
Arnavutköy	Küçükçekmece	1
Arnavutköy	Sarıyer	1
Arnavutköy	Silivri	1
Arnavutköy	Sultangazi	1
Arnavutköy	Şişli	1
Arnavutköy	Zeytinburnu	1

Table B1 (continued). Road Damage Scale for Each Road Segment

From	To	Revised Road Damage Scale
Avcılar	Arnavutköy	1
Avcılar	Avcılar	1
Avcılar	Bağcılar	1
Avcılar	Bahçelievler	1
Avcılar	Bakırköy	1
Avcılar	Başakşehir	1
Avcılar	Bayrampaşa	1
Avcılar	Beşiktaş	1
Avcılar	Beşiktaş	1
Avcılar	Beylikdüzü	1
Avcılar	Beyoğlu	1
Avcılar	Büyükçekmece	1
Avcılar	Çatalca	1
Avcılar	Esenler	1
Avcılar	Esenyurt	1
Avcılar	Eyüp	1
Avcılar	Fatih	1
Avcılar	Gaziosmanpaşa	1
Avcılar	Güngören	1
Avcılar	Kağıthane	1
Avcılar	Küçükçekmece	1
Avcılar	Sarıyer	1
Avcılar	Silivri	1
Avcılar	Sultangazi	1
Avcılar	Şişli	1
Avcılar	Zeytinburnu	1
Bağcılar	Arnavutköy	1
Bağcılar	Avcılar	1
Bağcılar	Bağcılar	1
Bağcılar	Bahçelievler	1
Bağcılar	Bakırköy	2
Bağcılar	Başakşehir	1
Bağcılar	Bayrampaşa	1
Bağcılar	Beşiktaş	1
Bağcılar	Beylikdüzü	1
Bağcılar	Beyoğlu	1

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Bağcılar	Büyükçekmece	1
Bağcılar	Çatalca	1
Bağcılar	Esenler	1
Bağcılar	Esenyurt	1
Bağcılar	Eyüp	1
Bağcılar	Fatih	1
Bağcılar	Gaziosmanpaşa	1
Bağcılar	Güngören	2
Bağcılar	Kağıthane	1
Bağcılar	Sarıyer	1
Bağcılar	Silivri	1
Bağcılar	Sultangazi	1
Bağcılar	Şişli	1
Bağcılar	Zeytinburnu	2
Bahçelievler	Arnavutköy	1
Bahçelievler	Avcılar	1
Bahçelievler	Bağcılar	1
Bahçelievler	Bahçelievler	1
Bahçelievler	Bakırköy	2
Bahçelievler	Başakşehir	1
Bahçelievler	Bayrampaşa	2
Bahçelievler	Beşiktaş	1
Bahçelievler	Beylikdüzü	1
Bahçelievler	Beyoğlu	2
Bahçelievler	Büyükçekmece	1
Bahçelievler	Çatalca	1
Bahçelievler	Esenler	1
Bahçelievler	Esenyurt	1
Bahçelievler	Eyüp	1
Bahçelievler	Fatih	1
Bahçelievler	Gaziosmanpaşa	1
Bahçelievler	Güngören	2
Bahçelievler	Kağıthane	1
Bahçelievler	Küçükçekmece	1
Bahçelievler	Sarıyer	1
Bahçelievler	Silivri	1

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Bahçelievler	Sultangazi	1
Bahçelievler	Şişli	1
Bahçelievler	Zeytinburnu	3
Bakırköy	Arnavutköy	1
Bakırköy	Avcılar	1
Bakırköy	Bağcılar	2
Bakırköy	Bahçelievler	2
Bakırköy	Bakırköy	1
Bakırköy	Başakşehir	1
Bakırköy	Bayrampaşa	2
Bakırköy	Beşiktaş	1
Bakırköy	Beylikdüzü	1
Bakırköy	Beyoğlu	2
Bakırköy	Büyükçekmece	1
Bakırköy	Çatalca	1
Bakırköy	Esenler	2
Bakırköy	Esenyurt	1
Bakırköy	Eyüp	1
Bakırköy	Fatih	2
Bakırköy	Gaziosmanpaşa	1
Bakırköy	Güngören	2
Bakırköy	Kağıthane	1
Bakırköy	Küçükçekmece	1
Bakırköy	Sarıyer	1
Bakırköy	Silivri	1
Bakırköy	Sultangazi	1
Bakırköy	Şişli	2
Bakırköy	Zeytinburnu	2
Başakşehir	Arnavutköy	1
Başakşehir	Avcılar	1
Başakşehir	Bağcılar	1
Başakşehir	Bahçelievler	1
Başakşehir	Bakırköy	1
Başakşehir	Başakşehir	1
Başakşehir	Bayrampaşa	1
Başakşehir	Beşiktaş	1

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Başakşehir	Beylikdüzü	1
Başakşehir	Beyoğlu	1
Başakşehir	Büyükçekmece	1
Başakşehir	Çatalca	1
Başakşehir	Esenler	1
Başakşehir	Esenyurt	1
Başakşehir	Eyüp	1
Başakşehir	Fatih	1
Başakşehir	Gaziosmanpaşa	1
Başakşehir	Güngören	1
Başakşehir	Kağıthane	1
Başakşehir	Küçükçekmece	1
Başakşehir	Sarıyer	1
Başakşehir	Silivri	1
Başakşehir	Sultangazi	1
Başakşehir	Şişli	1
Başakşehir	Zeytinburnu	1
Bayrampaşa	Arnavutköy	4
Bayrampaşa	Avcılar	4
Bayrampaşa	Bağcılar	3
Bayrampaşa	Bahçelievler	4
Bayrampaşa	Bakırköy	2
Bayrampaşa	Başakşehir	3
Bayrampaşa	Bayrampaşa	4
Bayrampaşa	Beşiktaş	3
Bayrampaşa	Beylikdüzü	4
Bayrampaşa	Beyoğlu	1
Bayrampaşa	Büyükçekmece	4
Bayrampaşa	Çatalca	1
Bayrampaşa	Esenler	2
Bayrampaşa	Esenyurt	1
Bayrampaşa	Eyüp	3
Bayrampaşa	Fatih	4
Bayrampaşa	Gaziosmanpaşa	1
Bayrampaşa	Güngören	1
Bayrampaşa	Kağıthane	4

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Bayrampaşa	Küçükçekmece	3
Bayrampaşa	Sarıyer	3
Bayrampaşa	Silivri	1
Bayrampaşa	Sultangazi	4
Bayrampaşa	Şişli	4
Bayrampaşa	Zeytinburnu	4
Beşiktaş	Arnavutköy	4
Beşiktaş	Avcılar	4
Beşiktaş	Bağcılar	1
Beşiktaş	Bahçelievler	2
Beşiktaş	Bakırköy	3
Beşiktaş	Başakşehir	3
Beşiktaş	Bayrampaşa	1
Beşiktaş	Beşiktaş	4
Beşiktaş	Beylikdüzü	4
Beşiktaş	Beyoğlu	1
Beşiktaş	Büyükçekmece	3
Beşiktaş	Çatalca	3
Beşiktaş	Esenler	1
Beşiktaş	Esenyurt	4
Beşiktaş	Eyüp	2
Beşiktaş	Fatih	1
Beşiktaş	Gaziosmanpaşa	4
Beşiktaş	Güngören	1
Beşiktaş	Kağıthane	1
Beşiktaş	Küçükçekmece	4
Beşiktaş	Sarıyer	4
Beşiktaş	Silivri	4
Beşiktaş	Sultangazi	2
Beşiktaş	Şişli	4
Beşiktaş	Zeytinburnu	3
Beylikdüzü	Arnavutköy	2
Beylikdüzü	Avcılar	4
Beylikdüzü	Bağcılar	4
Beylikdüzü	Bahçelievler	1
Beylikdüzü	Bakırköy	3

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Beylikdüzü	Başakşehir	3
Beylikdüzü	Bayrampaşa	3
Beylikdüzü	Beşiktaş	4
Beylikdüzü	Beylikdüzü	4
Beylikdüzü	Beyoğlu	4
Beylikdüzü	Büyükçekmece	2
Beylikdüzü	Çatalca	4
Beylikdüzü	Esenler	4
Beylikdüzü	Esenyurt	4
Beylikdüzü	Eyüp	1
Beylikdüzü	Fatih	4
Beylikdüzü	Gaziosmanpaşa	3
Beylikdüzü	Güngören	4
Beylikdüzü	Kağıthane	4
Beylikdüzü	Küçükçekmece	4
Beylikdüzü	Sarıyer	2
Beylikdüzü	Silivri	3
Beylikdüzü	Sultangazi	4
Beylikdüzü	Şişli	4
Beylikdüzü	Zeytinburnu	4
Beyoğlu	Arnavutköy	4
Beyoğlu	Avcılar	4
Beyoğlu	Bağcılar	4
Beyoğlu	Bahçelievler	1
Beyoğlu	Bakırköy	3
Beyoğlu	Başakşehir	2
Beyoğlu	Bayrampaşa	1
Beyoğlu	Beşiktaş	2
Beyoğlu	Beylikdüzü	4
Beyoğlu	Beyoğlu	1
Beyoğlu	Büyükçekmece	4
Beyoğlu	Çatalca	3
Beyoğlu	Esenler	2
Beyoğlu	Esenyurt	4
Beyoğlu	Eyüp	4
Beyoğlu	Fatih	4

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Beyoğlu	Gaziosmanpaşa	2
Beyoğlu	Güngören	1
Beyoğlu	Kağıthane	4
Beyoğlu	Küçükçekmece	4
Beyoğlu	Sarıyer	4
Beyoğlu	Silivri	4
Beyoğlu	Sultangazi	1
Beyoğlu	Şişli	4
Beyoğlu	Zeytinburnu	3
Büyükçekmece	Arnavutköy	1
Büyükçekmece	Avcılar	1
Büyükçekmece	Bağcılar	1
Büyükçekmece	Bahçelievler	1
Büyükçekmece	Bakırköy	1
Büyükçekmece	Başakşehir	1
Büyükçekmece	Bayrampaşa	1
Büyükçekmece	Beşiktaş	1
Büyükçekmece	Beylikdüzü	1
Büyükçekmece	Beyoğlu	1
Büyükçekmece	Büyükçekmece	1
Büyükçekmece	Çatalca	1
Büyükçekmece	Esenler	1
Büyükçekmece	Esenyurt	1
Büyükçekmece	Eyüp	1
Büyükçekmece	Fatih	1
Büyükçekmece	Gaziosmanpaşa	1
Büyükçekmece	Güngören	1
Büyükçekmece	Kağıthane	1
Büyükçekmece	Küçükçekmece	1
Büyükçekmece	Sarıyer	1
Büyükçekmece	Silivri	1
Büyükçekmece	Sultangazi	1
Büyükçekmece	Şişli	1
Büyükçekmece	Zeytinburnu	1
Çatalca	Arnavutköy	1
Çatalca	Avcılar	1

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Çatalca	Bağcılar	1
Çatalca	Bahçelievler	1
Çatalca	Bakırköy	1
Çatalca	Başakşehir	1
Çatalca	Bayrampaşa	1
Çatalca	Beşiktaş	1
Çatalca	Beylikdüzü	1
Çatalca	Beyoğlu	1
Çatalca	Büyükçekmece	1
Çatalca	Çatalca	1
Çatalca	Esenler	1
Çatalca	Esenyurt	1
Çatalca	Eyüp	1
Çatalca	Fatih	1
Çatalca	Gaziosmanpaşa	1
Çatalca	Güngören	1
Çatalca	Kağıthane	1
Çatalca	Küçükçekmece	1
Çatalca	Sarıyer	1
Çatalca	Silivri	1
Çatalca	Sultangazi	1
Çatalca	Şişli	1
Çatalca	Zeytinburnu	1
Esenler	Arnavutköy	1
Esenler	Avcılar	1
Esenler	Bağcılar	1
Esenler	Bahçelievler	1
Esenler	Bakırköy	2
Esenler	Başakşehir	1
Esenler	Bayrampaşa	2
Esenler	Beşiktaş	1
Esenler	Beylikdüzü	1
Esenler	Beyoğlu	1
Esenler	Büyükçekmece	1
Esenler	Çatalca	1
Esenler	Esenler	1

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Esenler	Esenyurt	1
Esenler	Eyüp	1
Esenler	Fatih	2
Esenler	Gaziosmanpaşa	1
Esenler	Güngören	2
Esenler	Kağıthane	1
Esenler	Küçükçekmece	1
Esenler	Sarıyer	1
Esenler	Silivri	1
Esenler	Sultangazi	1
Esenler	Şişli	1
Esenler	Zeytinburnu	2
Esenyurt	Arnavutköy	1
Esenyurt	Avcılar	1
Esenyurt	Bağcılar	1
Esenyurt	Bahçelievler	1
Esenyurt	Bakırköy	1
Esenyurt	Başakşehir	1
Esenyurt	Bayrampaşa	1
Esenyurt	Beşiktaş	1
Esenyurt	Beylikdüzü	1
Esenyurt	Beyoğlu	1
Esenyurt	Büyükçekmece	1
Esenyurt	Çatalca	1
Esenyurt	Esenler	1
Esenyurt	Esenyurt	1
Esenyurt	Eyüp	1
Esenyurt	Fatih	1
Esenyurt	Gaziosmanpaşa	1
Esenyurt	Güngören	1
Esenyurt	Kağıthane	1
Esenyurt	Küçükçekmece	1
Esenyurt	Sarıyer	1
Esenyurt	Silivri	1
Esenyurt	Sultangazi	1
Esenyurt	Şişli	1

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Esenyurt	Zeytinburnu	1
Eyüp	Arnavutköy	1
Eyüp	Avcılar	1
Eyüp	Bağcılar	1
Eyüp	Bahçelievler	1
Eyüp	Bakırköy	1
Eyüp	Başakşehir	1
Eyüp	Bayrampaşa	1
Eyüp	Beşiktaş	1
Eyüp	Beylikdüzü	1
Eyüp	Beyoğlu	1
Eyüp	Büyükçekmece	1
Eyüp	Çatalca	1
Eyüp	Esenler	1
Eyüp	Esenyurt	1
Eyüp	Eyüp	1
Eyüp	Fatih	1
Eyüp	Gaziosmanpaşa	1
Eyüp	Güngören	1
Eyüp	Kağıthane	1
Eyüp	Küçükçekmece	1
Eyüp	Silivri	1
Eyüp	Sultangazi	1
Eyüp	Şişli	1
Eyüp	Zeytinburnu	1
Fatih	Arnavutköy	1
Fatih	Avcılar	1
Fatih	Bağcılar	1
Fatih	Bahçelievler	1
Fatih	Bakırköy	2
Fatih	Başakşehir	1
Fatih	Bayrampaşa	2
Fatih	Beşiktaş	1
Fatih	Beylikdüzü	1
Fatih	Beyoğlu	1
Fatih	Büyükçekmece	1

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Fatih	Çatalca	1
Fatih	Esenler	2
Fatih	Esenyurt	1
Fatih	Eyüp	1
Fatih	Fatih	1
Fatih	Gaziosmanpaşa	1
Fatih	Güngören	2
Fatih	Kağıthane	1
Fatih	Küçükçekmece	1
Fatih	Sarıyer	1
Fatih	Silivri	1
Fatih	Sultangazi	1
Fatih	Şişli	1
Fatih	Zeytinburnu	2
Gaziosmanpaşa	Arnavutköy	1
Gaziosmanpaşa	Avcılar	1
Gaziosmanpaşa	Bağcılar	1
Gaziosmanpaşa	Bahçelievler	1
Gaziosmanpaşa	Bakırköy	1
Gaziosmanpaşa	Başakşehir	1
Gaziosmanpaşa	Bayrampaşa	1
Gaziosmanpaşa	Beşiktaş	1
Güngören	Arnavutköy	2
Güngören	Avcılar	2
Güngören	Bağcılar	4
Güngören	Bahçelievler	4
Güngören	Bakırköy	4
Güngören	Başakşehir	1
Güngören	Bayrampaşa	4
Güngören	Beşiktaş	2
Güngören	Beylikdüzü	2
Güngören	Beyoğlu	3
Güngören	Büyükçekmece	2
Güngören	Çatalca	1
Güngören	Esenler	4
Güngören	Esenyurt	2

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Güngören	Eyüp	2
Güngören	Fatih	3
Güngören	Gaziosmanpaşa	2
Güngören	Güngören	1
Güngören	Kağıthane	3
Güngören	Küçükçekmece	3
Güngören	Sarıyer	2
Güngören	Silivri	1
Güngören	Sultangazi	2
Güngören	Şişli	2
Güngören	Zeytinburnu	4
Kağıthane	Arnavutköy	1
Kağıthane	Avcılar	2
Kağıthane	Bağcılar	2
Kağıthane	Bahçelievler	2
Kağıthane	Bakırköy	2
Kağıthane	Başakşehir	1
Kağıthane	Bayrampaşa	2
Kağıthane	Beşiktaş	1
Kağıthane	Beylikdüzü	2
Kağıthane	Beyoğlu	1
Kağıthane	Çatalca	1
Kağıthane	Esenler	2
Kağıthane	Esenyurt	1
Kağıthane	Eyüp	1
Kağıthane	Fatih	1
Kağıthane	Gaziosmanpaşa	1
Kağıthane	Güngören	3
Kağıthane	Kağıthane	1
Kağıthane	Küçükçekmece	1
Kağıthane	Sarıyer	1
Kağıthane	Silivri	1
Kağıthane	Sultangazi	1
Kağıthane	Şişli	1
Kağıthane	Zeytinburnu	2
Küçükçekmece	Arnavutköy	1

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Küçükçekmece	Avcılar	3
Küçükçekmece	Bağcılar	1
Küçükçekmece	Bahçelievler	2
Küçükçekmece	Bakırköy	2
Küçükçekmece	Başakşehir	1
Küçükçekmece	Bayrampaşa	1
Küçükçekmece	Bayrampaşa	1
Küçükçekmece	Beşiktaş	1
Küçükçekmece	Beylikdüzü	2
Küçükçekmece	Beyoğlu	1
Küçükçekmece	Büyükçekmece	2
Küçükçekmece	Çatalca	2
Küçükçekmece	Esenler	1
Küçükçekmece	Esenyurt	2
Küçükçekmece	Eyüp	1
Küçükçekmece	Fatih	2
Küçükçekmece	Gaziosmanpaşa	1
Küçükçekmece	Güngören	3
Küçükçekmece	Kağıthane	1
Küçükçekmece	Küçükçekmece	1
Küçükçekmece	Sarıyer	1
Küçükçekmece	Silivri	1
Küçükçekmece	Sultangazi	1
Küçükçekmece	Şişli	1
Küçükçekmece	Zeytinburnu	2
Sarıyer	Arnavutköy	1
Sarıyer	Avcılar	2
Sarıyer	Bağcılar	1
Sarıyer	Bahçelievler	2
Sarıyer	Bakırköy	2
Sarıyer	Başakşehir	1
Sarıyer	Bayrampaşa	1
Sarıyer	Beşiktaş	1
Sarıyer	Beylikdüzü	1
Sarıyer	Beyoğlu	1
Sarıyer	Büyükçekmece	1

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Sarıyer	Çatalca	1
Sarıyer	Esenler	1
Sarıyer	Esenyurt	1
Sarıyer	Eyüp	1
Sarıyer	Fatih	1
Sarıyer	Gaziosmanpaşa	1
Sarıyer	Güngören	2
Sarıyer	Kağıthane	1
Sarıyer	Küçükçekmece	1
Sarıyer	Sarıyer	1
Sarıyer	Silivri	1
Sarıyer	Sultangazi	1
Sarıyer	Şişli	1
Sarıyer	Zeytinburnu	2
Silivri	Arnavutköy	1
Silivri	Avcılar	1
Silivri	Bağcılar	1
Silivri	Bahçelievler	1
Silivri	Bakırköy	1
Silivri	Başakşehir	1
Silivri	Bayrampaşa	1
Silivri	Beşiktaş	1
Silivri	Beylikdüzü	1
Silivri	Beyoğlu	1
Silivri	Büyükçekmece	1
Silivri	Çatalca	1
Silivri	Esenler	1
Silivri	Esenyurt	1
Silivri	Eyüp	1
Silivri	Fatih	1
Silivri	Gaziosmanpaşa	1
Silivri	Güngören	1
Silivri	Kağıthane	1
Silivri	Küçükçekmece	1
Silivri	Sarıyer	1
Silivri	Silivri	1

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Silivri	Sultangazi	1
Silivri	Şişli	1
Silivri	Zeytinburnu	2
Sultangazi	Arnavutköy	1
Sultangazi	Avcılar	1
Sultangazi	Bağcılar	1
Sultangazi	Bahçelievler	2
Sultangazi	Bakırköy	2
Sultangazi	Başakşehir	1
Sultangazi	Bayrampaşa	1
Sultangazi	Beşiktaş	1
Sultangazi	Beylikdüzü	1
Sultangazi	Beyoğlu	1
Sultangazi	Büyükçekmece	1
Sultangazi	Çatalca	1
Sultangazi	Esenler	1
Sultangazi	Esenyurt	1
Sultangazi	Eyüp	1
Sultangazi	Fatih	2
Sultangazi	Gaziosmanpaşa	1
Sultangazi	Güngören	2
Sultangazi	Kağıthane	1
Sultangazi	Küçükçekmece	1
Sultangazi	Sarıyer	1
Sultangazi	Silivri	1
Sultangazi	Sultangazi	1
Sultangazi	Şişli	1
Sultangazi	Zeytinburnu	2
Şişli	Arnavutköy	1
Şişli	Avcılar	2
Şişli	Bağcılar	2
Şişli	Bahçelievler	2
Şişli	Bakırköy	4
Şişli	Başakşehir	1
Şişli	Bayrampaşa	1
Şişli	Beşiktaş	1

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Şişli	Beylikdüzü	2
Şişli	Beyoğlu	1
Şişli	Büyükçekmece	2
Şişli	Çatalca	1
Şişli	Esenler	2
Şişli	Esenyurt	2
Şişli	Eyüp	1
Şişli	Fatih	2
Şişli	Gaziosmanpaşa	1
Şişli	Güngören	2
Şişli	Kağıthane	1
Şişli	Küçükçekmece	1
Şişli	Sarıyer	1
Şişli	Silivri	1
Şişli	Sultangazi	1
Şişli	Şişli	1
Şişli	Zeytinburnu	2
Zeytinburnu	Arnavutköy	1
Zeytinburnu	Avcılar	2
Zeytinburnu	Bağcılar	4
Zeytinburnu	Bahçelievler	4
Zeytinburnu	Bakırköy	4
Zeytinburnu	Başakşehir	2
Zeytinburnu	Bayrampaşa	4
Zeytinburnu	Beşiktaş	2
Zeytinburnu	Beylikdüzü	2
Zeytinburnu	Beyoğlu	4
Zeytinburnu	Büyükçekmece	2
Zeytinburnu	Çatalca	1
Zeytinburnu	Esenler	3
Zeytinburnu	Esenyurt	2
Zeytinburnu	Eyüp	2
Zeytinburnu	Fatih	4
Zeytinburnu	Gaziosmanpaşa	2
Zeytinburnu	Güngören	4
Zeytinburnu	Kağıthane	2

Table B1 (continued). Road Damage Scale for Each Road segment

From	To	Revised Road Damage Scale
Zeytinburnu	Küçükçekmece	2
Zeytinburnu	Sarıyer	2
Zeytinburnu	Silivri	2
Zeytinburnu	Sultangazi	2
Zeytinburnu	Şişli	2
Zeytinburnu	Zeytinburnu	1

Table B2. Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Arnavutköy	Arnavutköy	0	0
Arnavutköy	Avcılar	36.6	39.528
Arnavutköy	Bağcılar	24.9	26.892
Arnavutköy	Bahçelievler	29.1	31.428
Arnavutköy	Bakırköy	38.2	41.256
Arnavutköy	Başakşehir	19	20.52
Arnavutköy	Bayrampaşa	25.2	27.216
Arnavutköy	Beşiktaş	39.7	42.876
Arnavutköy	Beylikdüzü	33.4	36.072
Arnavutköy	Beyoğlu	36.6	39.528
Arnavutköy	Büyükçekmece	34.2	36.936
Arnavutköy	Çatalca	38.1	41.148
Arnavutköy	Esenler	25.4	27.432
Arnavutköy	Esenyurt	29.3	31.644
Arnavutköy	Eyüp	23.8	25.704
Arnavutköy	Fatih	30.9	33.372
Arnavutköy	Gaziosmanpaşa	23.1	24.948
Arnavutköy	Güngören	30	32.4
Arnavutköy	Kağıthane	32.1	34.668
Arnavutköy	Küçükçekmece	27.8	30.024
Arnavutköy	Sarıyer	38.6	41.688
Arnavutköy	Silivri	66.8	72.144
Arnavutköy	Sultangazi	18.7	20.196
Arnavutköy	Şişli	37.3	40.284
Arnavutköy	Zeytinburnu	31.2	33.696
Avcılar	Arnavutköy	38.5	41.58
Avcılar	Avcılar	0	0
Avcılar	Bağcılar	21.6	23.328
Avcılar	Bahçelievler	21	22.68
Avcılar	Bakırköy	18.4	19.872
Avcılar	Başakşehir	22.5	24.3
Avcılar	Bayrampaşa	26.4	28.512
Avcılar	Beşiktaş	33.1	35.748
Avcılar	Beylikdüzü	10.3	11.124
Avcılar	Beyoğlu	29.2	31.536

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Avcılar	Büyükçekmece	14.7	15.876
Avcılar	Çatalca	35.9	38.772
Avcılar	Esenler	26.9	29.052
Avcılar	Esenyurt	7.4	7.992
Avcılar	Eyüp	32.2	34.776
Avcılar	Fatih	24.4	26.352
Avcılar	Gaziosmanpaşa	31.5	34.02
Avcılar	Güngören	29	31.32
Avcılar	Kağıthane	31.6	34.128
Avcılar	Küçükçekmece	12.9	13.932
Avcılar	Sarıyer	44.3	47.844
Avcılar	Silivri	49.3	53.244
Avcılar	Sultangazi	30.7	33.156
Avcılar	Şişli	30.5	32.94
Avcılar	Zeytinburnu	26.4	28.512
Bağcılar	Arnavutköy	25	27
Bağcılar	Avcılar	19.4	20.952
Bağcılar	Bağcılar	0	0
Bağcılar	Bahçelievler	4.4	4.752
Bağcılar	Bakırköy	8.2	18.45
Bağcılar	Başakşehir	14.9	16.092
Bağcılar	Bayrampaşa	8.9	9.612
Bağcılar	Beşiktaş	20.8	22.464
Bağcılar	Beylikdüzü	28.1	30.348
Bağcılar	Beyoğlu	16.9	18.252
Bağcılar	Büyükçekmece	32.5	35.1
Bağcılar	Çatalca	48.7	52.596
Bağcılar	Esenler	5.4	5.832
Bağcılar	Esenyurt	24.9	26.892
Bağcılar	Eyüp	13.4	14.472
Bağcılar	Fatih	12.1	13.068
Bağcılar	Gaziosmanpaşa	11.1	11.988
Bağcılar	Güngören	4.9	11.025
Bağcılar	Kağıthane	19.3	20.844
Bağcılar	Küçükçekmece	7.1	7.668

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Bağcılar	Sarıyer	26.5	28.62
Bağcılar	Silivri	67.1	72.468
Bağcılar	Sultangazi	12.9	13.932
Bağcılar	Şişli	18.2	19.656
Bağcılar	Zeytinburnu	10.9	24.525
Bahçelievler	Arnavutköy	27.8	30.024
Bahçelievler	Avcılar	16.7	18.036
Bahçelievler	Bağcılar	4.7	5.076
Bahçelievler	Bahçelievler	0	0
Bahçelievler	Bakırköy	4.6	10.35
Bahçelievler	Başakşehir	17.6	19.008
Bahçelievler	Bayrampaşa	10.2	22.95
Bahçelievler	Beşiktaş	24.9	26.892
Bahçelievler	Beylikdüzü	25.4	27.432
Bahçelievler	Beyoğlu	21	47.25
Bahçelievler	Büyükçekmece	29.9	32.292
Bahçelievler	Çatalca	51.4	55.512
Bahçelievler	Esenler	7	7.56
Bahçelievler	Esenyurt	23.2	25.056
Bahçelievler	Eyüp	20.2	21.816
Bahçelievler	Fatih	11.8	12.744
Bahçelievler	Gaziosmanpaşa	15.2	16.416
Bahçelievler	Güngören	4.3	9.675
Bahçelievler	Kağıthane	23.4	25.272
Bahçelievler	Küçükçekmece	7.1	7.668
Bahçelievler	Sarıyer	32.3	34.884
Bahçelievler	Silivri	64.5	69.66
Bahçelievler	Sultangazi	16.7	18.036
Bahçelievler	Şişli	22.3	24.084
Bahçelievler	Zeytinburnu	8.1	326.8836
Bakırköy	Arnavutköy	37.3	40.284
Bakırköy	Avcılar	16.6	17.928
Bakırköy	Bağcılar	8.3	18.675
Bakırköy	Bahçelievler	4.7	10.575
Bakırköy	Bakırköy	0	0

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Bakırköy	Başakşehir	21.7	23.436
Bakırköy	Bayrampaşa	11.8	26.55
Bakırköy	Beşiktaş	23.7	25.596
Bakırköy	Beylikdüzü	25.3	27.324
Bakırköy	Beyoğlu	17.1	38.475
Bakırköy	Büyükçekmece	29.8	32.184
Bakırköy	Çatalca	51	55.08
Bakırköy	Esenler	10.5	23.625
Bakırköy	Esenyurt	23.1	24.948
Bakırköy	Eyüp	20.9	22.572
Bakırköy	Fatih	12.1	27.225
Bakırköy	Gaziosmanpaşa	16.5	17.82
Bakırköy	Güngören	6.5	14.625
Bakırköy	Kağıthane	22.1	23.868
Bakırköy	Küçükçekmece	10.3	11.124
Bakırköy	Sarıyer	32	34.56
Bakırköy	Silivri	64.4	69.552
Bakırköy	Sultangazi	20	21.6
Bakırköy	Şişli	19	42.75
Bakırköy	Zeytinburnu	7.8	17.55
Başakşehir	Arnavutköy	18.4	19.872
Başakşehir	Avcılar	21	22.68
Başakşehir	Bağcılar	13.5	14.58
Başakşehir	Bahçelievler	18.3	19.764
Başakşehir	Bakırköy	25.5	27.54
Başakşehir	Başakşehir	0	0
Başakşehir	Bayrampaşa	19.9	21.492
Başakşehir	Beşiktaş	31.6	34.128
Başakşehir	Beylikdüzü	31.9	34.452
Başakşehir	Beyoğlu	27.7	29.916
Başakşehir	Büyükçekmece	36.6	39.528
Başakşehir	Çatalca	51.5	55.62
Başakşehir	Esenler	16.1	17.388
Başakşehir	Esenyurt	27.7	29.916
Başakşehir	Eyüp	21.8	23.544

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Başakşehir	Fatih	22.8	24.624
Başakşehir	Gaziosmanpaşa	21	22.68
Başakşehir	Güngören	19	20.52
Başakşehir	Kağıthane	28.7	30.996
Başakşehir	Küçükçekmece	12.1	13.068
Başakşehir	Sarıyer	33.9	36.612
Başakşehir	Silivri	69.9	75.492
Başakşehir	Sultangazi	20.2	21.816
Başakşehir	Şişli	29	31.32
Başakşehir	Zeytinburnu	23.3	25.164
Bayrampaşa	Arnavutköy	24.4	984.68
Bayrampaşa	Avcılar	25.4	1,025.04
Bayrampaşa	Bağcılar	9.6	387.41
Bayrampaşa	Bahçelievler	14.3	577.09
Bayrampaşa	Bakırköy	13.5	544.80
Bayrampaşa	Başakşehir	19.7	795.01
Bayrampaşa	Bayrampaşa	0	0
Bayrampaşa	Beşiktaş	14.9	601.30
Bayrampaşa	Beylikdüzü	33.9	1,368.06
Bayrampaşa	Beyoğlu	9.9	399.52
Bayrampaşa	Büyükçekmece	38.6	1,557.74
Bayrampaşa	Çatalca	53.5	2159.04
Bayrampaşa	Esenler	4.9	197.74
Bayrampaşa	Esenyurt	29.7	1,198.57
Bayrampaşa	Eyüp	6.8	274.42
Bayrampaşa	Fatih	6.2	250.20
Bayrampaşa	Gaziosmanpaşa	4	161.42
Bayrampaşa	Güngören	7.1	286.52
Bayrampaşa	Kağıthane	12.2	492.34
Bayrampaşa	Küçükçekmece	18.3	738.51
Bayrampaşa	Sarıyer	23.2	936.25
Bayrampaşa	Silivri	71.9	2,901.59
Bayrampaşa	Sultangazi	8.2	330.91
Bayrampaşa	Şişli	11.2	451.98
Bayrampaşa	Zeytinburnu	8.3	334.95

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Beşiktaş	Arnavutköy	34.2	1,380.17
Beşiktaş	Avcılar	32.6	1,315.60
Beşiktaş	Bağcılar	20.7	835.36
Beşiktaş	Bahçelievler	20.9	843.44
Beşiktaş	Bakırköy	20.6	831.33
Beşiktaş	Başakşehir	30	1,210.68
Beşiktaş	Bayrampaşa	13.6	548.84
Beşiktaş	Beşiktaş	0	0
Beşiktaş	Beylikdüzü	41.3	1,666.70
Beşiktaş	Beyoğlu	8.3	334.95
Beşiktaş	Büyükçekmece	45.8	1,848.30
Beşiktaş	Çatalca	63.8	2,574.71
Beşiktaş	Esenler	16	645.69
Beşiktaş	Esenyurt	39.1	1,577.91
Beşiktaş	Eyüp	14.3	577.09
Beşiktaş	Fatih	13.5	544.80
Beşiktaş	Gaziosmanpaşa	15.7	633.58
Beşiktaş	Güngören	16.5	665.87
Beşiktaş	Kağıthane	4.8	193.70
Beşiktaş	Küçükçekmece	26.3	1,061.36
Beşiktaş	Sarıyer	10.5	423.73
Beşiktaş	Silivri	80.4	3,244.62
Beşiktaş	Sultangazi	17.7	714.30
Beşiktaş	Şişli	4.2	169.49
Beşiktaş	Zeytinburnu	15.8	637.62
Beylikdüzü	Arnavutköy	34	1,372.10
Beylikdüzü	Avcılar	10.6	427.77
Beylikdüzü	Bağcılar	28.1	1,134.00
Beylikdüzü	Bahçelievler	27.5	1,109.79
Beylikdüzü	Bakırköy	24.9	1,004.86
Beylikdüzü	Başakşehir	23.9	964.50
Beylikdüzü	Bayrampaşa	32.9	1,327.71
Beylikdüzü	Beşiktaş	39.6	1,598.09
Beylikdüzü	Beylikdüzü	0	0
Beylikdüzü	Beyoğlu	35.7	1,440.70

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Beylikdüzü	Büyükçekmece	10.8	435.84
Beylikdüzü	Çatalca	32.1	1,295.42
Beylikdüzü	Esenler	29.3	1,182.43
Beylikdüzü	Esenyurt	6.8	274.42
Beylikdüzü	Eyüp	35	1,412.46
Beylikdüzü	Fatih	30.9	1,247.00
Beylikdüzü	Gaziosmanpaşa	34.2	1,380.17
Beylikdüzü	Güngören	27	1089.61
Beylikdüzü	Kağıthane	38.1	1,537.56
Beylikdüzü	Küçükçekmece	19.4	782.90
Beylikdüzü	Sarıyer	47.1	1,900.76
Beylikdüzü	Silivri	45.4	1,832.16
Beylikdüzü	Sultangazi	33.4	1,347.89
Beylikdüzü	Şişli	37	1,493.17
Beylikdüzü	Zeytinburnu	33.7	1,359.99
Beyoğlu	Arnavutköy	33.6	1,355.96
Beyoğlu	Avcılar	29.5	1,190.50
Beyoğlu	Bağcılar	16.4	661.83
Beyoğlu	Bahçelievler	16.6	669.90
Beyoğlu	Bakırköy	16.4	661.83
Beyoğlu	Başakşehir	26.9	1,085.57
Beyoğlu	Bayrampaşa	9.9	399.52
Beyoğlu	Beşiktaş	7.8	314.7
Beyoğlu	Beylikdüzü	38.2	1,541.59
Beyoğlu	Beyoğlu	0	0
Beyoğlu	Büyükçekmece	42.6	1,719.16
Beyoğlu	Çatalca	60.7	2,449.60
Beyoğlu	Esenler	11.7	472.16
Beyoğlu	Esenyurt	36	1,452.81
Beyoğlu	Eyüp	8.3	334.95
Beyoğlu	Fatih	6.2	250.20
Beyoğlu	Gaziosmanpaşa	10.7	431.80
Beyoğlu	Güngören	12.2	492.34
Beyoğlu	Kağıthane	6.1	246.17
Beyoğlu	Küçükçekmece	23.1	932.22

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Beyoğlu	Sarıyer	16.5	665.87
Beyoğlu	Silivri	77.2	3,115.48
Beyoğlu	Sultangazi	17	686.05
Beyoğlu	Şişli	4.1	165.45
Beyoğlu	Zeytinburnu	11.4	460.05
Büyükçekmece	Arnavutköy	36.3	39.204
Büyükçekmece	Avcılar	17.9	19.332
Büyükçekmece	Bağcılar	34.3	37.044
Büyükçekmece	Bahçelievler	38.7	41.796
Büyükçekmece	Bakırköy	32.3	34.884
Büyükçekmece	Başakşehir	30.2	32.616
Büyükçekmece	Bayrampaşa	40.1	43.308
Büyükçekmece	Beşiktaş	47	50.76
Büyükçekmece	Beylikdüzü	11.2	12.096
Büyükçekmece	Beyoğlu	43.1	46.548
Büyükçekmece	Büyükçekmece	0	0
Büyükçekmece	Çatalca	21.3	23.004
Büyükçekmece	Esenler	35.6	38.448
Büyükçekmece	Esenyurt	12.4	13.392
Büyükçekmece	Eyüp	41.2	44.496
Büyükçekmece	Fatih	38.3	41.364
Büyükçekmece	Gaziosmanpaşa	40.5	43.74
Büyükçekmece	Güngören	41.5	44.82
Büyükçekmece	Kağıthane	45.5	49.14
Büyükçekmece	Küçükçekmece	27.3	29.484
Büyükçekmece	Sarıyer	53.3	57.564
Büyükçekmece	Silivri	35.1	37.908
Büyükçekmece	Sultangazi	39.7	42.876
Büyükçekmece	Şişli	44.4	47.952
Büyükçekmece	Zeytinburnu	42.7	46.116
Çatalca	Arnavutköy	36.6	39.528
Çatalca	Avcılar	38.7	41.796
Çatalca	Bağcılar	47.6	51.408
Çatalca	Bahçelievler	52	56.16
Çatalca	Bakırköy	58	62.64

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Çatalca	Başakşehir	43.4	46.872
Çatalca	Bayrampaşa	53.3	57.564
Çatalca	Beşiktaş	64.3	69.444
Çatalca	Beylikdüzü	32	34.56
Çatalca	Beyoğlu	60.4	65.232
Çatalca	Büyükçekmece	21.5	23.22
Çatalca	Çatalca	0	0
Çatalca	Esenler	48.8	52.704
Çatalca	Esenyurt	33.1	35.748
Çatalca	Eyüp	54.5	58.86
Çatalca	Fatih	55.5	59.94
Çatalca	Gaziosmanpaşa	53.7	57.996
Çatalca	Güngören	54.7	59.076
Çatalca	Kağıthane	61.4	66.312
Çatalca	Küçükçekmece	46.1	49.788
Çatalca	Sarıyer	66.6	71.928
Çatalca	Silivri	33.2	35.856
Çatalca	Sultangazi	52.9	57.132
Çatalca	Şişli	61.7	66.636
Çatalca	Zeytinburnu	56	60.48
Esenler	Arnavutköy	25.3	27.324
Esenler	Avcılar	26.3	28.404
Esenler	Bağcılar	4	4.32
Esenler	Bahçelievler	6.8	7.344
Esenler	Bakırköy	9.8	22.05
Esenler	Başakşehir	15.6	16.848
Esenler	Bayrampaşa	4.2	9.45
Esenler	Beşiktaş	16.8	18.144
Esenler	Beylikdüzü	29.8	32.184
Esenler	Beyoğlu	12.9	13.932
Esenler	Büyükçekmece	34.5	37.26
Esenler	Çatalca	49.4	53.352
Esenler	Esenler	0	0
Esenler	Esenyurt	25.6	27.648
Esenler	Eyüp	10.7	11.556

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Esenler	Fatih	8.1	18.225
Esenler	Gaziosmanpaşa	6.7	7.236
Esenler	Güngören	3.9	8.775
Esenler	Kağıthane	15.3	16.524
Esenler	Küçükçekmece	14.2	15.336
Esenler	Sarıyer	24.2	26.136
Esenler	Silivri	67.8	73.224
Esenler	Sultangazi	10.1	10.908
Esenler	Şişli	14.2	15.336
Esenler	Zeytinburnu	7.6	17.1
Esenyurt	Arnavutköy	29.9	32.292
Esenyurt	Avcılar	7.5	8.1
Esenyurt	Bağcılar	24.2	26.136
Esenyurt	Bahçelievler	24.9	26.892
Esenyurt	Bakırköy	25.2	27.216
Esenyurt	Başakşehir	20	21.6
Esenyurt	Bayrampaşa	29.2	31.536
Esenyurt	Beşiktaş	40	43.2
Esenyurt	Beylikdüzü	6.6	7.128
Esenyurt	Beyoğlu	36.1	38.988
Esenyurt	Büyükçekmece	10.1	10.908
Esenyurt	Çatalca	31.3	33.804
Esenyurt	Esenler	25.4	27.432
Esenyurt	Esenyurt	0	0
Esenyurt	Eyüp	31.1	33.588
Esenyurt	Fatih	31.3	33.804
Esenyurt	Gaziosmanpaşa	30.3	32.724
Esenyurt	Güngören	27.3	29.484
Esenyurt	Kağıthane	38	41.04
Esenyurt	Küçükçekmece	19.8	21.384
Esenyurt	Sarıyer	43.2	46.656
Esenyurt	Silivri	44.6	48.168
Esenyurt	Sultangazi	29.5	31.86
Esenyurt	Şişli	37.4	40.392
Esenyurt	Zeytinburnu	32.6	35.208

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Eyüp	Arnavutköy	22.7	24.516
Eyüp	Avcılar	30.9	33.372
Eyüp	Bağcılar	15.6	16.848
Eyüp	Bahçelievler	19.1	20.628
Eyüp	Bakırköy	18.9	20.412
Eyüp	Başakşehir	21.6	23.328
Eyüp	Bayrampaşa	7.1	7.668
Eyüp	Beşiktaş	13.4	14.472
Eyüp	Beylikdüzü	35.8	38.664
Eyüp	Beyoğlu	8.4	9.072
Eyüp	Büyükçekmece	40.5	43.74
Eyüp	Çatalca	55.4	59.832
Eyüp	Esenler	9	9.72
Eyüp	Esenyurt	31.5	34.02
Eyüp	Eyüp	0	0
Eyüp	Fatih	11.8	12.744
Eyüp	Gaziosmanpaşa	3.6	3.888
Eyüp	Güngören	13.6	14.688
Eyüp	Kağıthane	7	7.56
Eyüp	Küçükçekmece	20.2	21.816
Eyüp	Sarıyer	15.5	16.74
Eyüp	Silivri	73.8	79.704
Eyüp	Sultangazi	6.3	6.804
Eyüp	Şişli	8.4	9.072
Eyüp	Zeytinburnu	14.1	15.228
Fatih	Arnavutköy	29.9	32.292
Fatih	Avcılar	25	27
Fatih	Bağcılar	12.8	13.824
Fatih	Bahçelievler	10.4	11.232
Fatih	Bakırköy	11.4	25.65
Fatih	Başakşehir	22.1	23.868
Fatih	Bayrampaşa	6.1	13.725
Fatih	Beşiktaş	13.3	14.364
Fatih	Beylikdüzü	33.7	36.396
Fatih	Beyoğlu	6.4	6.912

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Fatih	Büyükçekmece	41	44.28
Fatih	Çatalca	55.9	60.372
Fatih	Esenler	8.1	18.225
Fatih	Esenyurt	31.5	34.02
Fatih	Eyüp	11.1	11.988
Fatih	Fatih	0	0
Fatih	Gaziosmanpaşa	9	9.72
Fatih	Güngören	6.6	14.85
Fatih	Kağıthane	11.8	12.744
Fatih	Küçükçekmece	20.7	22.356
Fatih	Sarıyer	21.6	23.328
Fatih	Silivri	72.7	78.516
Fatih	Sultangazi	13.1	14.148
Fatih	Şişli	8.6	9.288
Fatih	Zeytinburnu	5.5	12.375
Gaziosmanpaşa	Arnavutköy	22.2	23.976
Gaziosmanpaşa	Avcılar	28.6	30.888
Gaziosmanpaşa	Bağcılar	9.3	10.044
Gaziosmanpaşa	Bahçelievler	15	16.2
Gaziosmanpaşa	Bakırköy	16.7	18.036
Gaziosmanpaşa	Başakşehir	20.5	22.14
Gaziosmanpaşa	Bayrampaşa	3.8	4.104
Gaziosmanpaşa	Beşiktaş	15.4	16.632
Gaziosmanpaşa	Beylikdüzü	34.6	37.368
Gaziosmanpaşa	Beyoğlu	10.4	11.232
Gaziosmanpaşa	Büyükçekmece	39.4	42.552
Gaziosmanpaşa	Çatalca	55.1	59.508
Gaziosmanpaşa	Esenler	6.4	6.912
Gaziosmanpaşa	Esenyurt	30.4	32.832
Gaziosmanpaşa	Eyüp	3.1	3.348
Gaziosmanpaşa	Fatih	9.4	10.152
Gaziosmanpaşa	Gaziosmanpaşa	0	0
Gaziosmanpaşa	Güngören	11	11.88
Gaziosmanpaşa	Kağıthane	10.9	11.772
Gaziosmanpaşa	Küçükçekmece	19.8	21.384

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Gaziosmanpaşa	Sarıyer	16.9	18.252
Gaziosmanpaşa	Silivri	73.5	79.38
Gaziosmanpaşa	Sultangazi	4.4	4.752
Gaziosmanpaşa	Şişli	10.9	11.772
Gaziosmanpaşa	Zeytinburnu	12.3	27.675
Güngören	Arnavutköy	28.9	65.025
Güngören	Avcılar	18.3	41.175
Güngören	Bağcılar	5	201.78
Güngören	Bahçelievler	3.8	153.3528
Güngören	Bakırköy	6.2	250.2072
Güngören	Başakşehir	18.6	20.088
Güngören	Bayrampaşa	6	242.136
Güngören	Beşiktaş	20.3	45.675
Güngören	Beylikdüzü	27	60.75
Güngören	Beyoğlu	13.1	528.6636
Güngören	Büyükçekmece	31.5	70.875
Güngören	Çatalca	52.4	56.592
Güngören	Esenler	3.7	149.3172
Güngören	Esenyurt	24.8	55.8
Güngören	Eyüp	13.8	31.05
Güngören	Fatih	7.4	298.6344
Güngören	Gaziosmanpaşa	10.2	22.95
Güngören	Güngören	0	0
Güngören	Kağıthane	15.7	633.5892
Güngören	Küçükçekmece	9.2	371.2752
Güngören	Sarıyer	28.5	64.125
Güngören	Silivri	70.8	76.464
Güngören	Sultangazi	14.9	33.525
Güngören	Şişli	15	33.75
Güngören	Zeytinburnu	5.1	205.8156
Kağıthane	Arnavutköy	30.1	32.508
Kağıthane	Avcılar	30.4	68.4
Kağıthane	Bağcılar	18.4	41.4
Kağıthane	Bahçelievler	18.6	41.85
Kağıthane	Bakırköy	18.4	41.4

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Kağıthane	Başakşehir	27.7	29.916
Kağıthane	Bayrampaşa	11.9	26.775
Kağıthane	Beşiktaş	5.3	5.724
Kağıthane	Beylikdüzü	42	94.5
Kağıthane	Beyoğlu	5.8	6.264
Kağıthane	Büyükçekmece	46.8	105.3
Kağıthane	Çatalca	61.7	66.636
Kağıthane	Esenler	13.7	30.825
Kağıthane	Esenyurt	37.8	40.824
Kağıthane	Eyüp	6.6	7.128
Kağıthane	Fatih	11.2	12.096
Kağıthane	Gaziosmanpaşa	10.4	11.232
Kağıthane	Güngören	14.3	577.0908
Kağıthane	Kağıthane	0	0
Kağıthane	Küçükçekmece	24	25.92
Kağıthane	Sarıyer	11.3	12.204
Kağıthane	Silivri	80.1	86.508
Kağıthane	Sultangazi	13.1	14.148
Kağıthane	Şişli	3.1	3.348
Kağıthane	Zeytinburnu	13.5	30.375
Küçükçekmece	Arnavutköy	27.5	29.7
Küçükçekmece	Avcılar	12	484.272
Küçükçekmece	Bağcılar	8	8.64
Küçükçekmece	Bahçelievler	7.2	16.2
Küçükçekmece	Bakırköy	11.4	25.65
Küçükçekmece	Başakşehir	12.1	13.068
Küçükçekmece	Bayrampaşa	16.1	17.388
Küçükçekmece	Beşiktaş	29	31.32
Küçükçekmece	Beylikdüzü	20.7	46.575
Küçükçekmece	Beyoğlu	25.1	27.108
Küçükçekmece	Büyükçekmece	25.2	56.7
Küçükçekmece	Çatalca	46.4	104.4
Küçükçekmece	Esenler	12.8	13.824
Küçükçekmece	Esenyurt	18.5	41.625
Küçükçekmece	Eyüp	19.3	20.844

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Küçükçekmece	Fatih	20.3	45.675
Küçükçekmece	Gaziosmanpaşa	17.3	18.684
Küçükçekmece	Güngören	9.7	391.4532
Küçükçekmece	Kağıthane	26.2	28.296
Küçükçekmece	Küçükçekmece	0	0
Küçükçekmece	Sarıyer	31.3	33.804
Küçükçekmece	Silivri	59.8	64.584
Küçükçekmece	Sultangazi	17.7	19.116
Küçükçekmece	Şişli	26.4	28.512
Küçükçekmece	Zeytinburnu	16.1	36.225
Sarıyer	Arnavutköy	34.5	37.26
Sarıyer	Avcılar	40	90
Sarıyer	Bağcılar	26.3	28.404
Sarıyer	Bahçelievler	28.3	63.675
Sarıyer	Bakırköy	28	63
Sarıyer	Başakşehir	32.3	34.884
Sarıyer	Bayrampaşa	21.5	23.22
Sarıyer	Beşiktaş	11	11.88
Sarıyer	Beylikdüzü	46.5	50.22
Sarıyer	Beyoğlu	16.1	17.388
Sarıyer	Büyükçekmece	51.2	55.296
Sarıyer	Çatalca	66.1	71.388
Sarıyer	Esenler	23	24.84
Sarıyer	Esenyurt	42.2	45.576
Sarıyer	Eyüp	14.6	15.768
Sarıyer	Fatih	20.9	22.572
Sarıyer	Gaziosmanpaşa	16.7	18.036
Sarıyer	Güngören	23.9	53.775
Sarıyer	Kağıthane	10	10.8
Sarıyer	Küçükçekmece	33.7	36.396
Sarıyer	Sarıyer	0	0
Sarıyer	Silivri	84.5	91.26
Sarıyer	Sultangazi	18	19.44
Sarıyer	Şişli	11.8	12.744
Sarıyer	Zeytinburnu	23.2	52.2

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Silivri	Arnavutköy	73	78.84
Silivri	Avcılar	58.5	63.18
Silivri	Bağcılar	73.5	79.38
Silivri	Bahçelievler	77.9	84.132
Silivri	Bakırköy	72.8	78.624
Silivri	Başakşehir	69.3	74.844
Silivri	Bayrampaşa	79.2	85.536
Silivri	Beşiktaş	87.6	94.608
Silivri	Beylikdüzü	51.8	55.944
Silivri	Beyoğlu	83.7	90.396
Silivri	Büyükçekmece	42.1	45.468
Silivri	Çatalca	33.2	35.856
Silivri	Esenler	74.8	80.784
Silivri	Esenyurt	82.9	89.532
Silivri	Eyüp	80.4	86.832
Silivri	Fatih	78.9	85.212
Silivri	Gaziosmanpaşa	79.7	86.076
Silivri	Güngören	80.7	87.156
Silivri	Kağıthane	86	92.88
Silivri	Küçükçekmece	67.4	72.792
Silivri	Sarıyer	92.5	99.9
Silivri	Silivri	0	0
Silivri	Sultangazi	78.9	85.212
Silivri	Şişli	85	91.8
Silivri	Zeytinburnu	81.6	183.6
Sultangazi	Arnavutköy	17.6	19.008
Sultangazi	Avcılar	34.8	37.584
Sultangazi	Bağcılar	13.4	14.472
Sultangazi	Bahçelievler	17.3	38.925
Sultangazi	Bakırköy	21.1	47.475
Sultangazi	Başakşehir	22.1	23.868
Sultangazi	Bayrampaşa	8	8.64
Sultangazi	Beşiktaş	20.4	22.032
Sultangazi	Beylikdüzü	34.9	37.692
Sultangazi	Beyoğlu	17.8	19.224

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Sultangazi	Büyükçekmece	39.6	42.768
Sultangazi	Çatalca	54.6	58.968
Sultangazi	Esenler	10.9	11.772
Sultangazi	Esenyurt	30.7	33.156
Sultangazi	Eyüp	6.3	6.804
Sultangazi	Fatih	16.4	36.9
Sultangazi	Gaziosmanpaşa	5.2	5.616
Sultangazi	Güngören	15.5	34.875
Sultangazi	Kağıthane	13.2	14.256
Sultangazi	Küçükçekmece	17.7	19.116
Sultangazi	Sarıyer	19.8	21.384
Sultangazi	Silivri	77.2	83.376
Sultangazi	Sultangazi	0	0
Sultangazi	Şişli	19.4	20.952
Sultangazi	Zeytinburnu	16.7	37.575
Şişli	Arnavutköy	34.9	37.692
Şişli	Avcılar	30.5	68.625
Şişli	Bağcılar	18.6	41.85
Şişli	Bahçelievler	18.7	42.075
Şişli	Bakırköy	18.5	746.586
Şişli	Başakşehir	27.9	30.132
Şişli	Bayrampaşa	12	12.96
Şişli	Beşiktaş	4.2	4.536
Şişli	Beylikdüzü	39.2	88.2
Şişli	Beyoğlu	4.1	4.428
Şişli	Büyükçekmece	43.6	98.1
Şişli	Çatalca	61.7	66.636
Şişli	Esenler	13.6	30.6
Şişli	Esenyurt	37	83.25
Şişli	Eyüp	8.1	8.748
Şişli	Fatih	8.9	20.025
Şişli	Gaziosmanpaşa	10.5	11.34
Şişli	Güngören	14.4	32.4
Şişli	Kağıthane	3.3	3.564
Şişli	Küçükçekmece	24.1	26.028

Table B2 (continued). Distance (km) Between Each Pair of District and Corresponding Repair Cost (TL)

From	To	Distance (km)	Repair Cost (TL)
Şişli	Sarıyer	12.2	13.176
Şişli	Silivri	78.2	84.456
Şişli	Sultangazi	17.7	19.116
Şişli	Şişli	0	0
Şişli	Zeytinburnu	13.6	30.6
Zeytinburnu	Arnavutköy	36	38.88
Zeytinburnu	Avcılar	23.5	52.875
Zeytinburnu	Bağcılar	10.3	415.6668
Zeytinburnu	Bahçelievler	8.8	355.1328
Zeytinburnu	Bakırköy	7.4	298.6344
Zeytinburnu	Başakşehir	25.7	57.825
Zeytinburnu	Bayrampaşa	9.9	399.5244
Zeytinburnu	Beşiktaş	17	38.25
Zeytinburnu	Beylikdüzü	32.3	72.675
Zeytinburnu	Beyoğlu	11.9	480.2364
Zeytinburnu	Büyükçekmece	36.7	82.575
Zeytinburnu	Çatalca	59.5	64.26
Zeytinburnu	Esenler	9.3	375.3108
Zeytinburnu	Esenyurt	30	67.5
Zeytinburnu	Eyüp	14.2	31.95
Zeytinburnu	Fatih	6.7	270.3852
Zeytinburnu	Gaziosmanpaşa	12.5	28.125
Zeytinburnu	Güngören	5.5	221.958
Zeytinburnu	Kağıthane	15.4	34.65
Zeytinburnu	Küçükçekmece	15.5	34.875
Zeytinburnu	Sarıyer	25.3	56.925
Zeytinburnu	Silivri	77.9	175.275
Zeytinburnu	Sultangazi	17.1	38.475
Zeytinburnu	Şişli	13.8	31.05
Zeytinburnu	Zeytinburnu	0	0

APPENDIX C

COMPUTATIONAL RESULTS FOR BASE MODEL

Table C1. Relief Item Flow with Direct Shipment in the First-stage of the Problem

	Avcılar	Bakırköy	Başakşehir	Beyoğlu	Büyükçekmece
Bağcılar			32,000		
Beylikdüzü	32,000				18,372.778
Eyüp				22,022.313	
Bahçelievler		16,589.556			

Table C1 (continued). Relief Item Flow with Direct Shipment in the First-stage of the Problem

	Bayrampaşa	Esenyurt	Fatih	Güngören	Küçükçekmece
Beylikdüzü		32,000			
Bahçelievler					32.000
Esenler	9,129.369		32,000	27,236.651	

Table C1 (continued). Relief Item Flow with Direct Shipment in the First-stage of the Problem

	Şişli	Zeytinburnu
Sultangazi	15,093.254	
Esenler		30,701.935

Table C2. Road Segments that are Cleared ($x_{ij}=1$) in the First-stage of the Problem

From	To
Bağcılar	Beylikdüzü
Bağcılar	Sultangazi
Bağcılar	Avcılar
Beylikdüzü	Eyüp
Eyüp	Bağcılar
Eyüp	Beylikdüzü
Eyüp	Sultangazi
Sultangazi	Beylikdüzü
Bahçelievler	Bağcılar
Bahçelievler	Beylikdüzü
Bahçelievler	Eyüp
Bahçelievler	Sultangazi
Bahçelievler	Avcılar
Esenler	Beylikdüzü
Esenler	Eyüp
Esenler	Sultangazi
Bağcılar	Bahçelievler
Bağcılar	Bakırköy
Bağcılar	Beyoğlu
Bağcılar	Beşiktaş
Eyüp	Arnavutköy
Eyüp	Bahçelievler
Eyüp	Bakırköy
Eyüp	Beyoğlu
Eyüp	Beşiktaş
Sultangazi	Arnavutköy
Sultangazi	Bahçelievler
Bahçelievler	Bakırköy
Esenler	Arnavutköy
Esenler	Bahçelievler
Esenler	Beyoğlu
Bağcılar	Büyükçekmece
Bağcılar	Bayrampaşa
Bağcılar	Fatih

Table C2 (continued). Road Segments that are Cleared (x_{ij}=1) in the First-stage of the Problem

From	To
Bağcılar	Güngören
Eyüp	Esenyurt
Eyüp	Fatih
Eyüp	Güngören
Bahçelievler	Esenyurt
Bahçelievler	Fatih
Bahçelievler	Güngören
Esenler	Güngören
Bağcılar	Kağıthane
Bağcılar	Küçükçekmece
Bağcılar	Zeytinburnu
Eyüp	Gaziosmanpaşa
Eyüp	Kağıthane
Sultangazi	Gaziosmanpaşa
Bahçelievler	Kağıthane
Bahçelievler	Küçükçekmece
Bahçelievler	Şişli
Bahçelievler	Zeytinburnu
Esenler	Kağıthane
Eyüp	Çatalca
Eyüp	Silivri
Sultangazi	Esenler
Sultangazi	Silivri
Bahçelievler	Esenler
Esenler	Silivri

Table C3. Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			1	2	3	4
Bağcılar	Bahçelievler	Avcılar	4,798.082	2,732.444	5,019.275	4,142.117
Bağcılar	Bahçelievler	Esenyurt	11,052.115	13,995.255	7,233.324	7,421.635
Bağcılar	Bahçelievler	Fatih			4,581.359	
Bağcılar	Bahçelievler	Küçükçekmece		14,819.176	13,740.956	

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			5	6	7	8
Bağcılar	Bahçelievler	Avcılar	3,062.598			4,209.864
Bağcılar	Bahçelievler	Esenyurt	26.995	10,512.899	13,015.751	10,297.14
Bağcılar	Bahçelievler	Fatih	7,128.37		7,365.326	10,950.095

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			9	10	11	12
Bağcılar	Bahçelievler	Esenyurt	6,429.835	1,317.362	735.239	1,091.189
Bağcılar	Bahçelievler	Fatih	7,802.634	10,437.939	9,433.258	14,848.34
Bağcılar	Bahçelievler	Küçükçekmece			3,422.671	

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			13	14	15	16
Bağcılar	Bahçelievler	Avcılar	4,975.499			4,300.352
Bağcılar	Bahçelievler	Esenyurt		2,722.993	3,923.113	11,031.437
Bağcılar	Bahçelievler	Fatih		5,544.539	11,509.13	6,064.911
Bağcılar	Bahçelievler	Küçükçekmece		7,267.706		

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			21	22	23	24
Bağcılar	Bahçelievler	Avcılar	5,711.108	668.929	7,421.239	4,624.587
Bağcılar	Bahçelievler	Esenyurt	8,905.05	2,233.529	2,949.194	19,102.793
Bağcılar	Bahçelievler	Fatih	3,244.832	11,495.777	3,817.066	

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			25	26	27	28
Bağcılar	Bahçelievler	Avcılar		7,347.012	6,854.987	12,171.256
Bağcılar	Bahçelievler	Esenyurt	19,961.833	9,351.133	12,442.441	4,907.925
Bağcılar	Bahçelievler	Fatih	8,504.703	13,097.519	6,265.319	14,727.512

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			29	30
Bağcılar	Bahçelievler	Avcılar	6,865.446	331.79
Bağcılar	Bahçelievler	Esenyurt	8,332.293	470.204
Bağcılar	Bahçelievler	Fatih	16,784.657	10,274.269

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			4	5	8	10
Bahçelievler	Bağcılar	Küçükçekmce	331.33	1,636.866	2,461.037	1,399.343

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			13	15	16	17
Bahçelievler	Bağcılar	Fatih	610.755			
Bahçelievler	Bağcılar	Küçükçekmce		354.987	1,324.872	295.585

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			13	15	16	17
Bahçelievler	Bağcılar	Fatih	610.755			
Bahçelievler	Bağcılar	Küçükçekmce		354.987	1,324.872	295.585

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			21	24	26	27
Bahçelievler	Bağcılar	Fatih		6,095.896		
Bahçelievler	Bağcılar	Küçükçekmce	7,381.072		4,913.749	3,941.817

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			28	29
Bahçelievler	Bağcılar	Küçükçekmce	5,601.936	7,070.988

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			1	4	5	6
Esenler	Bağcılar	Fatih	7,442.704			
Esenler	Bağcılar	Küçükçekmce	3,975.386	9,354.5	3,673.165	3,866.924

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			7	8	9	10
Esenler	Bağcılar	Küçükçekmce	9,090.489	8,078.968	6,929.943	8,412.061

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			12	13	15	16
Esenler	Bağcılar	Fatih		7,666.842		
Esenler	Bağcılar	Küçükçekmce	5,872.958	20,025.539	3,744.05	16,244.456

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			17	18	19	20
Esenler	Bağcılar	Fatih				2,564.469
Esenler	Bağcılar	Küçükçekmce	20,235.229	19,479.215	20,229.214	
Esenler	Bağcılar	Esenyurt			207.449	

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			21	22	23	24
Esenler	Bağcılar	Fatih				7,306.193
Esenler	Bağcılar	Küçükçekmce	12,640.968	19,161.824	24,977.933	13,949.444

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			25	26	27	28
Esenler	Bağcılar	Küçükçekmce	20,380.026	1,872.571	16,347.8	8,635.484

Table C3 (continued). Relief Item Flow with Direct Shipment in the Second-stage of the Problem

			29	30
Esenler	Bağcılar	Küçükçekmce	4,920.112	14,029.522

APPENDIX D

COMPUTATIONAL RESULTS FOR BENCHMARK MODEL 1

Table D1. Relief Item Flow with Direct Shipment

	Avcılar	Arnavutköy	Bakırköy	Başakşehir	Beyoğlu
Bağcılar				20,288	
Beylikdüzü	32,000				
Eyüp					12,560
Sultangazi		4,698			
Bahçelievler			22,089		

Table D1 (continued). Relief Item Flow with Direct Shipment

	Beşiktaş	Büyükçekmece	Bayrampaşa	Esenyurt	Fatih
Beylikdüzü		14,012		32,000	
Eyüp	5,280				
Esenler			18,142		32,000

Table D1 (continued). Relief Item Flow with Direct Shipment

	Şişli	Zeytinburnu	Çatalca	Silivri
Beylikdüzü			1,230	4,420
Sultangazi	6,751			
Esenler		27,488		

Table D1 (continued). Relief Item Flow with Direct Shipment

	Güngören	Gaziosmanpaşa	Kağıthane	Küçükçekmece	Sarıyer
Bağcılar				32,000	
Eyüp		12,326	11,732		3,433

Table D2. Pair of Roads that are Cleared (x_{ij}=1) in the First-stage of the Problem

From	To
Bağcılar	Beylikdüzü
Bağcılar	Sultangazi
Bağcılar	Avcılar
Beylikdüzü	Eyüp
Beylikdüzü	Sultangazi
Eyüp	Bağcılar
Eyüp	Beylikdüzü
Eyüp	Sultangazi
Eyüp	Avcılar
Sultangazi	Beylikdüzü
Bahçelievler	Bağcılar
Bahçelievler	Beylikdüzü
Bahçelievler	Eyüp
Bahçelievler	Sultangazi
Bahçelievler	Avcılar
Esenler	Bağcılar
Esenler	Beylikdüzü
Esenler	Eyüp
Esenler	Sultangazi
Esenler	Avcılar
Bağcılar	Bahçelievler
Bağcılar	Bakırköy
Bağcılar	Beyoğlu
Eyüp	Arnavutköy
Eyüp	Bahçelievler
Eyüp	Bakırköy
Eyüp	Başakşehir
Eyüp	Beyoğlu
Sultangazi	Arnavutköy
Sultangazi	Bahçelievler
Bahçelievler	Arnavutköy
Bahçelievler	Bakırköy
Bahçelievler	Beyoğlu
Esenler	Bağcılar
From	**To**
Esenler	Beylikdüzü
Esenler	Eyüp
Esenler	Sultangazi
Esenler	Avcılar
Bağcılar	Beşiktaş
Bağcılar	Büyükçekmece

Table D2 (continued). Pair of Roads that are Cleared (x_{ij}=1) in the First-stage of the Problem

Bağcılar	Bayrampaşa
Bağcılar	Fatih
Eyüp	Beşiktaş
Eyüp	Büyükçekmece
Eyüp	Bayrampaşa
Eyüp	Esenyurt
Eyüp	Fatih
Sultangazi	Büyükçekmece
Sultangazi	Fatih
Bahçelievler	Beşiktaş
Bahçelievler	Büyükçekmece
Bahçelievler	Bayrampaşa
Bahçelievler	Esenyurt
Bahçelievler	Fatih
Esenler	Beşiktaş
Bağcılar	Güngören
Bağcılar	Kağıthane
Bağcılar	Küçükçekmece
Eyüp	Güngören
Eyüp	Gaziosmanpaşa
Eyüp	Kağıthane
Eyüp	Küçükçekmece
Sultangazi	Gaziosmanpaşa
Sultangazi	Kağıthane
Sultangazi	Küçükçekmece
Bahçelievler	Güngören
Bahçelievler	Gaziosmanpaşa
Bahçelievler	Kağıthane
Bahçelievler	Küçükçekmece
Bahçelievler	Sarıyer
Esenler	Güngören
Esenler	Kağıthane
Esenler	Küçükçekmece
Bağcılar	Zeytinburnu
Beylikdüzü	Zeytinburnu
Eyüp	Şişli
Eyüp	Zeytinburnu
Eyüp	Silivri
Sultangazi	Zeytinburnu
Sultangazi	Esenler
Sultangazi	Çatalca
Sultangazi	Silivri

Table D2 (continued). Pair of Roads that are Cleared (x_{ij}=1) in the First-stage of the Problem

From	To
Bahçelievler	Şişli
Bahçelievler	Zeytinburnu
Bahçelievler	Silivri
Bahçelievler	Çatalca
Esenler	Silivri

APPENDIX E

COMPUTATIONAL RESULTS FOR BENCHMARK MODEL 2

Table E1. Relief Item Flow with Direct Shipment

	Avcılar	Başakşehir	Başakşehir	Bayrampaşa	Esenyurt
Bağcılar		14,640.956			
Beylikdüzü	24,939.021			32,000	
Esenler			32,000		32,000

Table E1. Relief Item Flow with Direct Shipment

	Küçükçekmece	Sarıyer	Şişli
Beylikdüzü	30,676.979		
Eyüp		6,197.868	
Sultangazi			15,279.153

APPENDIX F

COMPUTATIONAL RESULTS FOR BENCHMARK MODEL 3

Table F1. Relief Item Flow with Direct Shipment in the First-stage

	Avcılar	Başakşehir	Bayrampaşa	Esenyurt	Fatih
Bağcılar		35,954.579			
Beylikdüzü	22,594.399			30,370.66	
Esenler			33,143.451		63,904.556

Table F1 (continued). Relief Item Flow with Direct Shipment in the First-stage

	Küçükçekmece	Sarıyer	Şişli	Çatalca	Silivri
Beylikdüzü	30,676.979			80,64	3,893.322
Eyüp		6,145.016			
Sultangazi			15,279.153		

Table F2. Pair of Roads that are Cleared (x_{ij}=1) in the First-stage of the Problem

From	To
Bağcılar	Avcılar
Bağcılar	Bakırköy
Eyüp	Avcılar
Eyüp	Arnavutköy
Eyüp	Başakşehir
Eyüp	Beyoğlu
Sultangazi	Arnavutköy
Bahçelievler	Avcılar
Bahçelievler	Arnavutköy
Bahçelievler	Beyoğlu
Esenler	Avcılar
Esenler	Arnavutköy

Table F2 (continued). Pair of Roads that are Cleared (x_{ij}=1) in the First-stage of the Problem

From	To
Esenler	Bakırköy
Esenler	Başakşehir
Esenler	Beyoğlu
Bağcılar	Bayrampaşa
Bağcılar	Fatih
Eyüp	Beşiktaş
Eyüp	Büyükçekmece
Eyüp	Bayrampaşa
Eyüp	Esenyurt
Eyüp	Fatih
Sultangazi	Büyükçekmece
Sultangazi	Fatih
Bahçelievler	Beşiktaş
Bahçelievler	Büyükçekmece
Bahçelievler	Bayrampaşa
Bahçelievler	Fatih
Esenler	Beşiktaş
Bağcılar	Güngören
Bağcılar	Küçükçekmece
Eyüp	Güngören
Eyüp	Gaziosmanpaşa
Eyüp	Kağıthane
Eyüp	Küçükçekmece
Sultangazi	Gaziosmanpaşa
Sultangazi	Kağıthane
Sultangazi	Küçükçekmece
Bahçelievler	Güngören
Bahçelievler	Gaziosmanpaşa
Bahçelievler	Kağıthane
Bahçelievler	Küçükçekmece
Bahçelievler	Sarıyer
Esenler	Güngören
Esenler	Kağıthane
Esenler	Küçükçekmece
Bağcılar	Zeytinburnu
Eyüp	Şişli
Eyüp	Çatalca
Bahçelievler	Şişli
Esenler	Zeytinburnu
Esenler	Çatalca
Esenler	Silivri

APPENDIX G

COMPUTATIONAL RESULTS FOR BENCHMARK MODEL 4

Table G1. Relief Item Flow with Direct Shipment in the First-stage

	Avcılar	Bakırköy	Başakşehir	Beyoğlu	Büyükçekmece
Bağcılar			32,000		
Beylikdüzü	32,000				18,372.778
Eyüp				22,216.051	
Bahçelievler		32,000			

Table G1 (continued). Relief Item Flow with Direct Shipment in the First-stage

	Bayrampaşa	Esenyurt	Fatih	Güngören	Kağıthane
Beylikdüzü		32,000			
Eyüp					13,690.491
Esenler	9,129.369		32,000	27,236.651	

APPENDIX H

COMPUTATIONAL RESULTS FOR BENCHMARK MODEL 5

Table H1. Amount of Unsatisfied Demand at Each Demand Point in the Second-stage

	2	7	13	16	17
Avcılar	4,091.420	2,132.411	10,277.170	5,364.747	11,287.720
Arnavutköy	4,091.420	2,132.411			
Bakırköy	4,091.420	2,132.411	10,277.170	5,364.747	2,966.849
Başakşehir	2,286.434	2,132.411	10,277.170	1,380.896	5,531.413
Beyoğlu	4,091.420	2,132.411	10,094.791	5,364.747	11,287.720
Beşiktaş	4,091.420	1,483.319	2,774.390	2,343.494	4,447.877
Büyükçekmece	4,091.420	2,132.411	10,277.170	5,364.747	10,374.972
Bayrampaşa	1,565.948	2,132.411	1,894.675	5,364.747	10,479.215
Esenyurt	4,091.420	2,132.411	10,277.170	5,364.747	10,360.665
Fatih	4,091.420	2,132.411	10,277.170	5,364.747	11,287.720
Güngören	4,091.420	2,132.411	10,277.170		7,042.832
Gaziosmanpaşa	2,666.421	2,132.411	3,549.617	5,364.747	4,396.406
Kağıthane	4,091.420	2,132.411		5,364.747	5,832.139
Küçükçekmece	4,091.420	2,132.411	10,277.170	5,364.747	11,287.720
Sarıyer	4,091.420	2,132.411	9,568.645		8,890.013
Şişli	4,039.778	1,404.048	5,455.739	5,364.747	1,787.701
Zeytinburnu	4,091.420	2,132.411	10,277.170		1,.287.720
Çatalca	3,314.033		3,379.218	3,286.622	3,760.713
Silivri	4,091.420				

Table H1 (continued). Amount of Unsatisfied Demand at Each Demand Point in the Second-stage

	18	19	21	22	23
Avcılar	9,184.522	10,684.520	10,270.172	8,549.740	20,181.957
Arnavutköy	9,184.522		10,270.172	8,549.740	13,519.308
Bakırköy	9,184.522	9,168.163	7,728.182	2,178.902	6,283.403
Başakşehir	9,184.522	5,478.471	3,652.680	6,923.748	20,181.957
Beyoğlu	9,184.522	10,684.520	8,761.535	7,878.800	16,502.393
Beşiktaş	4,636.418	4,136.566	1,731.565	4,791.666	5,737.569

Table H1 (continued). Amount of Unsatisfied Demand at Each Demand Point in the Second-stage

	18	19	21	22	23
Büyükçekmece	9,184.522	7,812.019	10270.172	8,549.740	11,787.409
Bayrampaşa	3,668.675	8,540.919	10,270.172	6,781.623	5,189.700
Esenyurt	9,184.522	10,684.520	10,270.172	8,549.740	20,181.957
Fatih	9,184.522	10,684.520	10.270.172	8,549.740	20,181.957
Güngören	9,184.522	10,684.520		8,549.740	20,181.957
Gaziosmanpaşa	3,326.657	2,303.443	1,666.323	8,549.740	11,440.013
Kağıthane	5,235.402	5,912.214	1,512.676	7,490.643	467.121
Küçükçekmece	9,184.522	10,684.520	10,270.172	8,549.740	20,181.957
Sarıyer	8,990.101	10,179.249	10,250.515		9,870.550
Şişli	5,608.158	3,380.061	2,964.823	2,386.072	3,030.808
Zeytinburnu	9,184.522	10,684.520	10,270.172	8,549.740	9,259.053
Çatalca	3,223.694	4,096.871	4,086.368	3,826.157	4,100.257
Silivri			10,270.172	8,549.740	11,504.597

Table H1 (continued). Amount of Unsatisfied Demand at Each Demand Point in the Second-stage

	24	25	26
Avcılar	8,097.130	16,024.575	10,805.326
Arnavutköy	12,319.306	11,879.123	10,805.326
Bakırköy	14,306.495	8,117.056	10,805.326
Başakşehir	1,504.695	16,024.575	4,572.763
Beyoğlu	14,306.495	9,207.461	10,805.326
Beşiktaş	1,905.085	5,189.240	3,313.021
Büyükçekmece	6,167.825	4,027.705	10,482.609
Bayrampaşa	14,306.495	9,973.670	2,586.625
Esenyurt	14,306.495	16,024.575	10,805.326
Fatih	14,306.495	16,024.575	10,805.326
Güngören	174.134	4,716.665	1,091.311
Gaziosmanpaşa	2,910.861	9,872.035	
Kağıthane	7,429.376	4,693.512	2,539.134
Küçükçekmece	14,306.495	16,024.575	10,805.326
Sarıyer	11,155.812	10,903.012	10,805.326
Şişli	6,292.950	6,664.749	1,244.472
Zeytinburnu	14,306.495	16,024.575	10,805.326
Silivri	13,086.504	3,593.122	3,684.612

APPENDIX I

COMPUTATIONAL RESULTS FOR BASE MODEL WITH CAPACITY DECREASE

Table I1. Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			1	2	3	4
Bağcılar	Bahçelievler	Avcılar	11,564.678	9,499.04	11,785.871	10,908.713
Bağcılar	Bahçelievler	Esenyurt	13,079.473	15,545.399	9,260.682	9,448.993
Bağcılar	Bahçelievler	Zeytinburnu		555.561		226.608

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			5	6	7	8
Bağcılar	Bahçelievler	Avcılar	9,829.194	3,214.419	5,542.043	10,976.46
Bağcılar	Bahçelievler	Esenyurt	2,054.354	1,2540.258	15,043.109	12,301.231
Bağcılar	Bahçelievler	Zeytinburnu	3,770.511			2,322.309

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			9	10	11	12
Bağcılar	Bahçelievler	Avcılar	6,751.175	1,538.584	1,289.285	1,263.086
Bağcılar	Bahçelievler	Esenyurt	8,457.193	3,344.721	2,762.597	3,118.548
Bağcılar	Bahçelievler	Fatih			14,510.237	
Bağcılar	Bahçelievler	Zeytinburnu				3,069.281

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			9	10	11	12
Bağcılar	Bahçelievler	Avcılar	6,751.175	1,538.584	1,289.285	1,263.086
Bağcılar	Bahçelievler	Esenyurt	8,457.193	3,344.721	2,762.597	3,118.548
Bağcılar	Bahçelievler	Fatih			14,510.237	
Bağcılar	Bahçelievler	Zeytinburnu				3,069.281

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			13	14	15	16
Bağcılar	Bahçelievler	Avcılar	11,742.096	2,836.265	3,018.426	11,066.948
Bağcılar	Bahçelievler	Esenyurt		4,750.352	5,950.472	13,058.796
Bağcılar	Bahçelievler	Fatih	13,354.576			
Bağcılar	Bahçelievler	Zeytinburnu	503.329	8,882.27	4,002.788	
Esenler	Bahçelievler	Zeytinburnu				7,993.738

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			17	18	19	20
Bağcılar	Bahçelievler	Avcılar	6,883.975	9,881.716	6,171.139	11,966.78
Bağcılar	Bahçelievler	Esenyurt	3,157.236	7,750.993	16,904.723	8,760.344
Bağcılar	Bahçelievler	Fatih	9,572.359			
Bağcılar	Bahçelievler	Zeytinburnu	3,668.211	5,968.454	2,524.138	4,872.875

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			21	22	23	24
Bağcılar	Bahçelievler	Avcılar	12,477.704	7,435.525	14,187.835	4,469.848
Bağcılar	Bahçelievler	Esenyurt	10,932.409	4,260.887	4,976.552	21,130.152
Bağcılar	Bahçelievler	Güngören		235.654	1,301.704	
Bağcılar	Bahçelievler	Zeytinburnu		2,393.475		
Esenler	Bahçelievler	Zeytinburnu	8,031.909			10,768.883

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			29	30
Bağcılar	Bahçelievler	Avcılar	13,632.042	7,098.386
Bağcılar	Bahçelievler	Esenyurt	5,808.467	2,497.563
Bağcılar	Bahçelievler	Zeytinburnu	6,159.49	9,452.339

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			3	8	10	12
Bahçelievler	Bağcılar	Fatih	4,804.237	1,589.145	1,490.777	820.344

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			13	16	18	19
Bahçelievler	Bağcılar	Fatih		3,733.285	8,737.818	19,278.784
Bahçelievler	Bağcılar	Küçükçekmece	57.131			4,202

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			21	22	23	24
Bahçelievler	Bağcılar	Fatih	3,365.918	16,572.755	8,894.045	7,450.579
Bahçelievler	Bağcılar	Küçükçekmece		1,862.959	5,858.496	

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			25	27	28	29
Bahçelievler	Bağcılar	Fatih	12,609.224	6,653.983	10,256.079	11,900.835

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			30
Bahçelievler	Bağcılar	Fatih	5,070.245

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			1	2	3	4
Esenler	Bağcılar	Fatih	12,519.683	4,981.535	4,854.101	4,693.687
Esenler	Bağcılar	Küçükçekmece	4,597.453	15,441.243	14,363.024	10,307.897
Esenler	Bağcılar	Esenyurt		477.215		

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			5	6	7	8
Esenler	Bağcılar	Fatih	12,205.348	4,476.828	12,442.304	14,437.928
Esenler	Bağcılar	Küçükçekmece	5,932.098	4,488.991	9,712.556	11,162.072
Esenler	Bağcılar	Esenyurt				23.267

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			9	10	11	12
Esenler	Bağcılar	Fatih	12,879.613	14,024.14		19,104.975
Esenler	Bağcılar	Küçükçekmece	7,552.01	10,433.472	4,044.739	6,495.025

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			13	14	15	16
Esenler	Bağcılar	Esenyurt	2,027.359			
Esenler	Bağcılar	Fatih		10,621.517	16,586.109	7,408.605
Esenler	Bağcılar	Küçükçekmece	20,590.475	7,889.773	4,721.104	18,191.395

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			17	18	19	20
Esenler	Bağcılar	Fatih		4,186.421		7,641.448
Esenler	Bağcılar	Küçükçekmece	21,152.881	20,101.282	16,649.281	10,920.109
Esenler	Bağcılar	Avcılar			3,723.736	

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			21	22	23	24
Esenler	Bağcılar	Fatih	4,955.893			11,028.489
Esenler	Bağcılar	Küçükçekmece	20,644.107	17,920.932	19,741.504	14,571.511
Esenler	Bağcılar	Avcılar				6,921.334

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			25	26	27	28
Esenler	Bağcılar	Fatih	972.458	18,174.498	4,688.316	9,548.412
Esenler	Bağcılar	Küçükçekmece	21,002.093	7,408.387	20,911.684	14,859.488
Esenler	Bağcılar	Avcılar	1,394.583			
Esenler	Bağcılar	Esenyurt			2,491.383	1,882.063

Table I1 (continued). Relief Item Flow with Lateral Transshipment in the Second-stage of the Problem

			29	30
Esenler	Bağcılar	Fatih	9,960.801	10,281.003
Esenler	Bağcılar	Küçükçekmece	12,613.167	14,651.589
Esenler	Bağcılar	Esenyurt	4,551.184	