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# Intermodal Humanitarian Logistics Model Based on Maritime Transportation in Istanbul

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## Abstract

İstanbul, the economic capital and most populated city of Turkey, is highly prone to earthquakes. When an earthquake occurs, required relief items are expected to be supplied from national and international sources. To alleviate human suffering following an earthquake, in this paper, we propose an intermodal relief-item distribution model for İstanbul involving sea and land transportation with identified road vulnerabilities. The proposed mathematical model utilizes the seaports of İstanbul for maritime transportation and allows for the transportation of relief item between Istanbul's European and Anatolian sides. We also use the seabasing concept for providing supplies to demand areas. The use of maritime transportation and seabasing provides flexibility for humanitarian logistical activities and the proposed model provides an effective and reliable disaster relief system for İstanbul as well as other disaster-prone cities with significant maritime transportation components.



**Keywords:** Humanitarian Logistics, Disaster Relief, Vulnerability, Maritime Transportation, Seaports, Seabasing.


## 1. Introduction

Each year thousands of people are killed and millions are affected by natural and man-made disasters. The International Federation of Red Cross and Red Crescent Societies (IFRC) (IFRC, 2015) defines disaster as 'a sudden, calamitous event that seriously disrupts the functioning of a community or society and causes human, material and economic or environmental losses that exceed the community's or society's ability to cope using its own resources.' Delivering assistance to the victims of disasters is a vital and challenging task that can be addressed by humanitarian logistics. The definition for humanitarian logistics, as given by Thomas and Mizushima (2005), is as follows: 'The process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials as well as related information, from the point of origin to the point of consumption for the purpose of meeting the end beneficiary's requirements.'

Being located on a major seismic belt—the Alpine–Himalayan seismic belt—Turkey is a country prone to natural disasters, especially earthquakes. According to the International Disaster Database (EM-DAT, 2015), the most destructive type of natural disaster in Turkey, in terms of the number of people killed, number of people affected and total financial losses, is the earthquake. On 17 August 1999, an earthquake of magnitude 7.4 struck the Marmara region, the most industrialized region of Turkey, causing 17,479 fatalities, 43,953 injuries and damage to thousands of buildings. In the city of İstanbul, the economic capital and most populated city of Turkey, major losses of life and property also occurred by the 1999 earthquake; 981 people were killed, 7204 were injured, 3073 domiciles and 532 work places were badly damaged and thousands of others sustained moderate damage (Özmen, 2000). After the 1999 earthquake, academic and governmental experts undertook many studies to determine ways to prevent İstanbul from ever again experiencing such destructive effects from an earthquake, the future occurrence of which is highly probable (Parsons *et al*., 2000; Özdamar *et al*., 2004, Görmez *et al*., 2011, Salman and Gül 2014, JICA, 2002).

İstanbul bestrides the Bosphorus, the waterway connecting the Sea of Marmara and the Black Sea. It is a two-sided, transcontinental city; east of the Bosphorus (in Asia) lies the Anatolian Side and west of the Bosphorus (in Europe) lies the European side. As such, there are many seaports located on both sides of the Bosphorus and maritime transportation between these ports is a daily routine. The motivation behind this study was the idea to take advantage of this special geography by converting the daily routine of transporting people to transporting relief items in response to a disaster, particularly an earthquake.

There are a number of benefits associated with utilizing seaways to transport relief items. These benefits are mostly related to the characteristics of maritime transportation. First, massive amounts of relief materials can be transported at one time, much more than is possible by other transportation modes, which require either multiple round trips by fewer land vehicles or fewer trips with greater numbers of land vehicles, before transferring the items to other transportation modes. Second, utilizing sea transportation is much cheaper than land transportation because of the economies of scale, which leads to a reduction in the overall cost of relief efforts. Third, when compared to highways, the risk of collapse is very small for seaways. Disasters pose much greater risk of destruction or congestion and blockage of highways, thus making land vehicles slower than ships following their daily sea routines. Therefore, even though maritime transportation is considered to be much slower than land transportation, this situation is often reversed in the case of disasters. Fourth, arcs and nodes in a transport network are connected and fixed in non-sea-based transportation modes (e.g. a highway or rail terminal cannot be relocated in a day). In maritime transportation, however, while port locations (i.e. nodes) are fixed, the seaways (i.e. arcs) are changeable, requiring the selection of suitable ports as transhipment points among those available. Fifth, in maritime transportation, a container ship located at sea provides great flexibility and resilience with respect to relief efforts. In case of the collapse of all or most of the warehouses located on land, a container ship can provide a vital solution for sourcing relief items. However, all of these characteristics require different modelling techniques than those used for land transportation.

In the mathematical model proposed in our study, we utilise intermodal transportation to distribute relief items. Intermodal transportation can be defined as 'the transportation of a person or a load from its origin to its destination by a sequence of at least two transportation modes, the transfer from one mode to the next being performed at an intermodal terminal' (Crainic and Kim, 2007). The transportation modes we use in this study are maritime and land transportation.

The aim of this paper is to propose a solution for the transportation of relief items from national and international sources (i.e. international nongovernmental organizations and foreign governments) in case of an earthquake in İstanbul. For that purpose, we developed a mathematical model addressing the humanitarian logistics based on intermodal transportation, which takes advantage of the ports of İstanbul and allows for the transportation of relief items between the city's Anatolian and European sides while also considering the road vulnerabilities. Some studies on the distribution of relief items in case of a disaster in İstanbul can be cited, but to the best of our knowledge, no previous study has taken advantage of the use of maritime transportation in İstanbul. The main contribution of this study to the humanitarian logistics literature is that it considers the utilization of seaports and maritime transportation as well as land transportation for the distribution of relief items that may originate from international sources.

The rest of this paper is organized as follows: In the next section, we review related academic work. In section 3, we define the problem characteristics. In section 4, we introduce the mathematical model we developed for a sea-based intermodal relief distribution network. In section 5, we describe the experimental study we conducted and the results obtained. We offer our concluding remarks and suggestions regarding future research in the conclusion section.

## 2. Literature Review

Disasters and ensuing efforts to help disaster victims are as old as humanity, but practically and theoretically, research on humanitarian logistics is a much more recent phenomenon. Studies in the field of humanitarian logistics date back to the 1980s and have gradually intensified since the 2000s. In their review, Altay and Green (2006) found that of the 109 articles on humanitarian logistics published between 1980 and 2004, more than 46% were published after 2000. Also, the 2004 Indian Ocean tsunami, which affected 2.5 million people in 12 countries and resulted in 226,408 fatalities (Duran *et al*., 2013), was a global turning point in our realisation of the significance of logistics in humanitarian relief efforts. As stated by Van Wassenhove (2006): '… what the Indian Ocean tsunami has done is to move logistics to centre stage.'

The main focus of the literature survey in our paper is the delivery of relief items to those in need, in other words, to the end beneficiaries. On the other hand, several studies are worth citing regarding location decisions. A recent study by Nappi and Souza (2015) presents a hierarchical selection criteria for temporary shelter locations. One of the first studies on disaster relief transportation was carried out by Knott who used a routing model developed in 1987 (de la Torre *et al.*, 2012). This study took the form of a single-commodity, single modal network flow problem with the objective of minimising transportation cost.

Haghani and Oh (1996) presented a multi-commodity, multi-modal network flow mixed-integer programming model for minimising total logistics cost. The authors emphasized that their study differs from previous studies in the sense that the model allows transportation mode change and involves more detailed routing and scheduling. Barbarasoğlu and Arda (2004) developed a similar model that considers uncertainty in various model parameters, such as demand and the vulnerability of the arcs. Özdamar *et al.* (2004) proposed a hybrid model that combines a multi-period, multi-commodity network flow problem with a multi-period, multi-modal vehicle routing problem in order to minimise unsatisfied demand. While the authors considered marine transportation as one theoretical mode of transportation in their study, it was not included in the model's application to the Marmara earthquake (1999).

Huang *et al*. (2012) investigated the impact of performance measures on last-mile distribution problem decisions. Their work is distinguished by having combined performance measurement in humanitarian logistics with relief item distribution. In addition, their study is one of the few that have included ethical factors such as equity in humanitarian logistics research, as outlined by Altay and Green (2006) and also pointed out by Galindo and Batta (2013) regarding Balçık *et al*. (2008). de la Torre *et al*. (2012) performed a literature survey on disaster relief routing models in humanitarian logistics and considered distribution models that take into account relief item delivery by air as specialized type relief models. We note that relief item delivery by marine transportation, which would also qualify as a specialized type model, was not addressed. The authors also stated that in several studies decision variables include the number of vehicles making deliveries and the quantity of items delivered, which we have included as decision variables in our proposed model in this study. These types of models are described in the paper by de la Torre et al. (2012) as models with less operational and more strategic detail.

Although there are quite a few humanitarian logistics studies on the intermodal transportation of relief materials, few studies have considered maritime transportation as part of the process. Hsieh (2014) highlighted the importance of ports in today's trade and analysed the risk of port failures with respect to vulnerability. Tatham and Kovacs (2007) introduced the possible application of the military 'seabasing concept' to humanitarian logistics in rapid-onset natural disasters whereby a 'floating warehouse'—a ship stocked with relief items—is established near the risk area. The authors considered the 2005 Pakistan earthquake and discussed the advantages of seabasing over transporting relief items by airfreight, explaining that seabasing, while broadly applied in military activities mostly in providing logistical support to military personnel at the initial stage of intervention in a conflict, is applicable to humanitarian logistics for providing relief items to disaster areas. This study encouraged the utilization of maritime transportation in humanitarian logistics and seabasing for delivery of relief items, as does our paper.

Bemley *et al*. (2013) also consider the utilization of maritime transportation for disaster relief activities. The main concern of their study was to secure port recovery after a natural disaster, such as a hurricane, by repairing navigation aid tools like lighted/unlighted buoys and beacons to ensure waterway safety. The authors proposed a two-stage stochastic facility location model for maximising the number of navigation aid tools repaired to return a port to its full function.

For their master's thesis, Wilberg and Olafsen (2012) developed a simulation model in Microsoft Excel$^{TM}$ to adapt the distribution network of a commercial logistics company to a relief item distribution network for humanitarian aid, utilizing company resources such as vessels and ports/terminals. The IFRC supply chain was taken as an example in which there were three regional logistics units from which relief materials could be airfreighted. In their study, the authors suggested that airfreight transportation be replaced by maritime transportation for the delivery of relief items and to use the 'floating warehouse' concept. These changes were predicted to shorten lead times and also reduce logistics costs as compared to those associated with airfreight transportation.

The studies of Tatham and Kovacs (2007) and of Wilberg and Olafsen (2012) share the views of our paper that maritime transportation constitutes an important part of the supply chain and recognises the merits of utilising the seabasing concept. Table 1 summarises the main characteristics of the studies reviewed above.

**Table 1:** Main characteristics of the studies reviewed.

| Study | Methodology | Performance measures (min. of) | Multi-modal | Maritime transportation | Sea-basing | A real life case study used? |
|---|---|---|---|---|---|---|
| Knott (1987) | Linear programming | Cost/unsatisfied demand | | | | |
| Haghani and Oh (1996) | Linear programming | Cost | X | | | |
| Barbarasoglu and Arda (2004) | Stochastic programming | Cost | X | | | X |
| Özdamar et al. (2004) | Linear/integer programming | Unsatisfied demand | X | | | X |
| Balçık et al. (2008) | Mixed integer programming | Cost/unsatisfied demand | | | | |
| Huang et al. (2012) | Integer programming | Cost/response time | | | | |
| Tatham and Kovacs (2007) | Conceptual comparison | Cost | X | X | X | X |
| Bemley et al. (2013) | Stochastic programming | Unsatisfied demand | | X | | X |
| Wilberg and Olafsen (2012) | Simulation | Cost/response time | X | X | X | X |
| Our study | Integer programming | Response time | X | X | X | X |

As we see in Table 1, while multi-modal relief distribution models are common in humanitarian logistics literature, only a few studies include maritime transportation. Also, only Tatham and Kovacs (2007) and Wilberg and Olafsen (2012) considered multi-modal transportation using maritime transportation. The paper by Tatham and Kovacs (2007) is a conceptual cost analysis of the seabasing concept and concludes that the floating warehouse is a practical concept. Wilberg and Olafsen (2012) used a simulation-based methodology for the seabasing concept in their IFRC case study. Hence, our study is the first to propose an integer programming formulation, based on the seabasing concept, for justifying the use of maritime transportation in humanitarian logistics.

## 3. Problem Description

İstanbul has many seaports, however the two most important are the Ports of Haydarpaşa and Ambarlı. Haydarpaşa is a Turkish State Railways (TCDD) port located in the Anatolian side of İstanbul, in the district of Kadıköy. The Port of Haydarpaşa handles approximately 20% of the total number of containers handled by Turkey's TCDD ports (JICA, 2002). Additionally, the JICA report (2002) stated that while the Port of Haydarpaşa was damaged slightly by the 1999 Marmara earthquake the port functions were not affected. Also, the Port of Haydarpaşa is reported as having facilities for handling containers and being connected to important roads. As such, its surrounding areas were suggested as primary disaster management centres. The Port of Ambarlı is one of the biggest ports in Turkey and is located on the European side of İstanbul, in the Beylikdüzü district. The Port of Ambarlı is a private investment port complex that is used jointly by seven terminals. In this study, we consider the Port of Haydarpaşa and Port of Ambarlı as main supply points as they are the most suitable ports in İstanbul for handling the amount of relief items being delivered from inland and abroad. We refer to them as 'main ports' throughout this paper.

As a third supplier of relief items in this study, we locate a container ship at a certain point in the Marmara Sea. Hence, we use the seabasing concept as part of the relief-items distribution network to meet the demand of the districts of İstanbul following an earthquake. A third source is required because the main ports can be damaged by the earthquake and their capacity may be significantly diminished. In this paper, we refer to the container ship as the third source and to the main ports at Haydarpaşa and Ambarlı as well as the container ship as 'main sources.'

The main waterway transport company in İstanbul is IDO, Inc, which operates 19 seaports in İstanbul, 11 of which are on the Anatolian side: Harem, Kadıköy, Bostancı, Maltepe, Pendik, Kartal, Beykoz, Burgazada, Kınalıada, Heybeliada and Büyükada. Eight IDO seaports are on the European side, including Yenikapı, Bakırköy, Kabataş, İstinye, Sarıyer, Beşiktaş, Sirkeci and Avcılar. The locations of these IDO seaports are available from the IDO website. The relative locations of the main sources and the IDO seaports are illustrated in Figure 1.

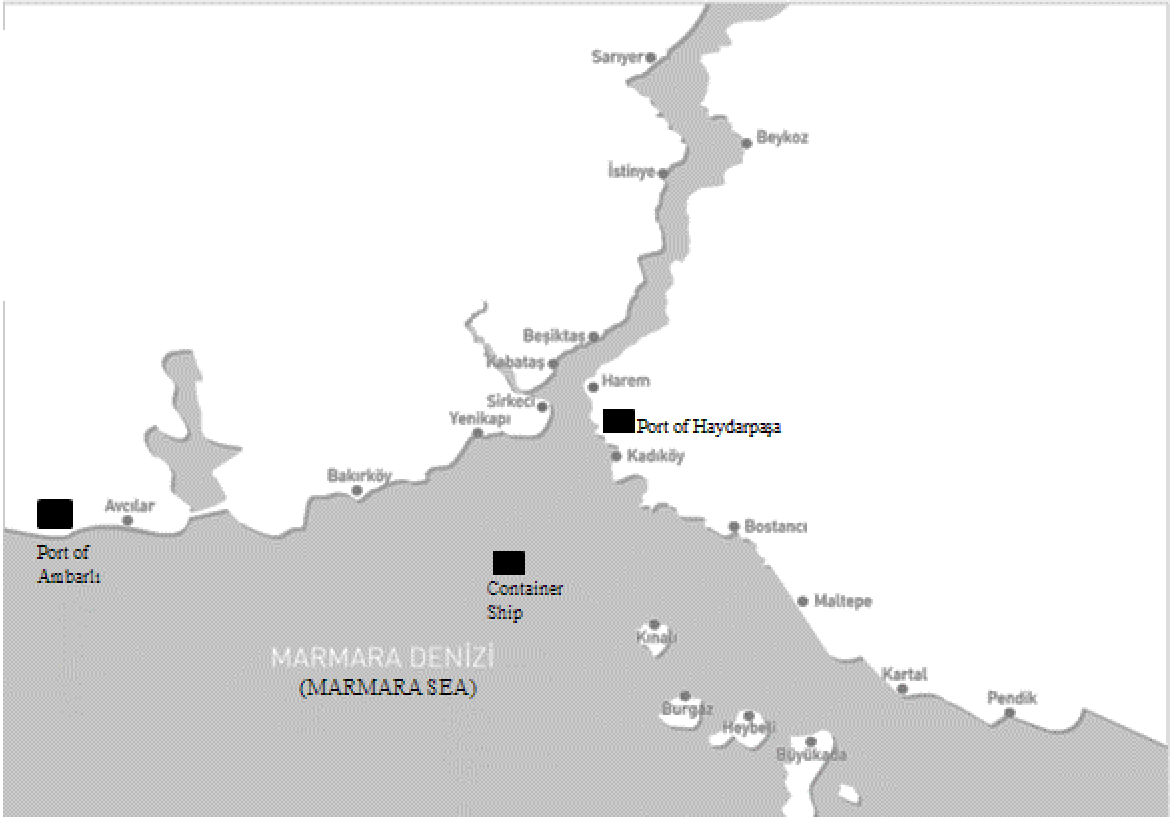


**Fig. 1** Locations of the main sources and IDO seaports (IDO, 2015).

In this study, we considered the IDO seaports of İstanbul as relief-item transhipment points to the demand areas, i.e. the districts of İstanbul. Istanbul has 39 districts, 14 on the Anatolian side and 25 on the European side. A map of the districts is provided in Figure 2.


**Fig. 2** Districts of İstanbul (Wikipedia, 2015).

Humanitarian relief materials from sources abroad (international suppliers such as non-governmental relief organizations and foreign governments) and from sources within the country arrive at the main ports at Haydarpaşa and Ambarlı. From these main ports, the relief materials can be delivered directly to the districts by land vehicles (i.e. via highways) or first to IDO ports by ship (i.e. via seaway) and then from IDO ports to the districts by land vehicles (i.e. via highways). In addition, the container ship anchored in the Marmara Sea supplies relief materials for maritime transport to the IDO ports on both sides. The main difference in this study's application of the seabasing concept from traditional seabasing applications is that the vessel itself does not sail to the IDO ports, as its size prohibits its approach to and unloading of freight at the IDO ports. The position of the container ship is fixed while smaller ships approach it to be loaded with relief materials. After being loaded, these smaller ships sail to the IDO ports to unload. Figure 3 shows a schematic of the routes followed by ships delivering relief materials.

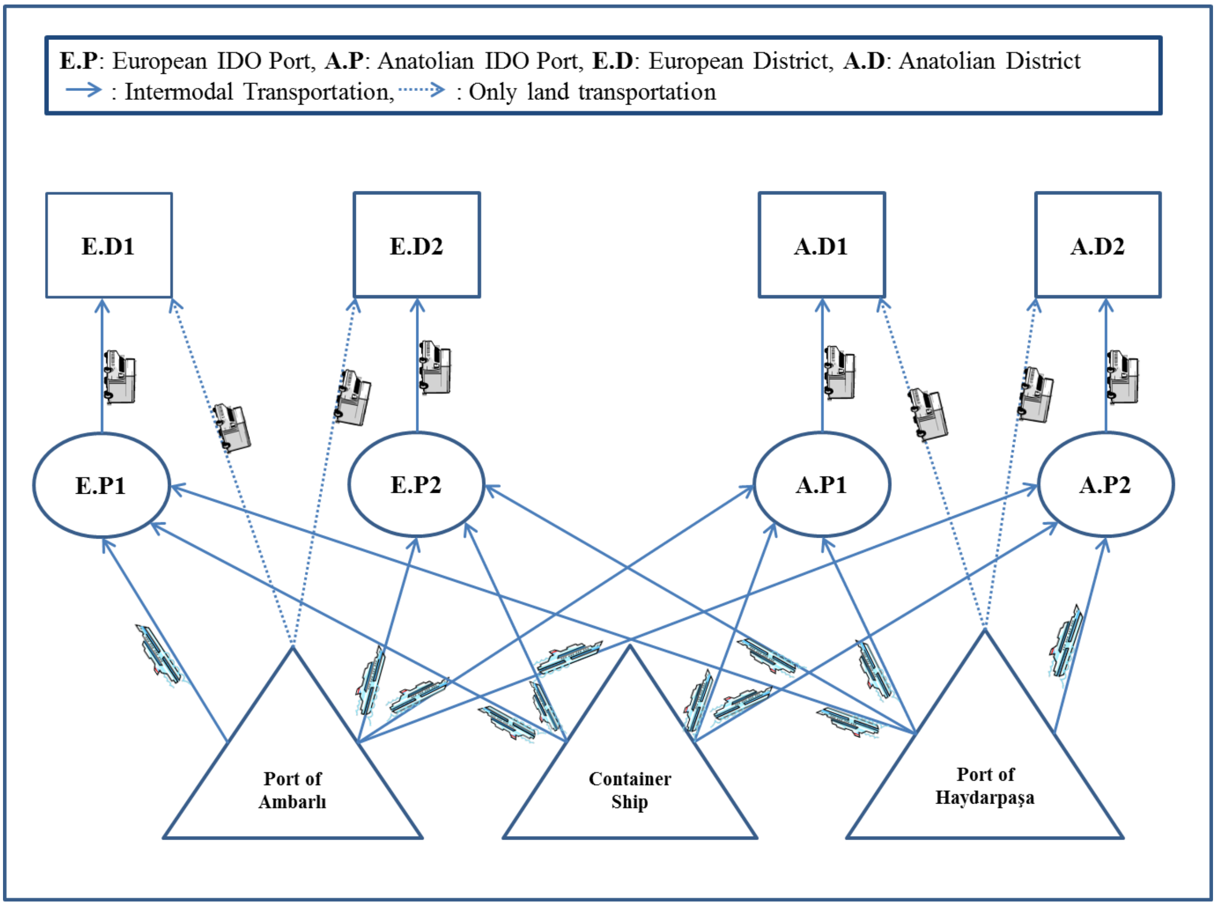


**Fig. 3** Illustration of intermodal relief item transportation network

The assumptions made in this study are as follows: (1) IDO seaports are considered to be transhipment points, districts as demand points, and the container ship and main ports at

Haydarpaşa and Ambarlı as supply points. (2) Of the IDO seaports shown in Figure 1, we have excluded the ports of Kınalı, Burgaz, Heybeli and Büyükada as they are located on islands. (3) Of the districts shown in Figure 2, we exclude Adalar as it is an island. (4) The problem is treated as a single-item type problem. A standard 'relief item package' weighs five kilograms and contains bottles of potable water and boxes of ready-to-eat meals. In the paper, we refer to a 'relief item package' as a 'relief item'. (5) The total demand for relief items is given. (6) The planning period includes one day (24 hours or 1440 min). (7) At transhipment points (i.e. IDO ports), due to space and time limitations, the storage of relief items is not allowed. (8) The maximum quantity of items unloaded by a ship or a land vehicle is the required demand at the IDO port or the district, respectively. (9) In order to avoid the need for the model to make routing decisions, a vehicle will not visit more than one port or district after leaving its point of origin. (10) The flow of relief items is always one-way—from the main sources to the districts. (11) Lateral transhipment between the main ports, between districts and between IDO ports is not allowed.

*Demand.* Demand is determined based on the population of the districts. We obtained Istanbul district population data from the Turkish Statistical Institute's 2012 Address-Based Population Registration System (TSI, 2013). One relief item is delivered per person. In 2015, the total population of İstanbul was 14,657,434. Görmez *et al*. (2011) determined that about three million people would be affected by an earthquake in İstanbul. Considering the projected population increase since the date that figure was determined, we project that the total demand would be 3,424,000 units of relief items.

*Vehicles.* Transportation from the ports to the districts is provided with one type of truck that has a carrying capacity of 500 relief items and an average speed of 50 km/h (Salman and Gül, 2014). Sea transportation from the main sources to the IDO ports is provided by four types of ships, characterized by their carrying capacity for units of relief items and speed (Type 1 capacity: 6286, speed: 30.9 knots or ~57 km/h; Type 2 capacity: 6160, speed: 25 knots or ~46 km/h; Type 3 capacity: 5600, speed: 32 knots or ~59 km/h; Type 4 capacity: 6300, speed: 33.5 knots or ~62 km/h).

*Travel time*. We obtained the travel times from the main or IDO ports to the districts from Google Maps™ and selected the shortest time between two points from the alternatives provided by Google Maps™. Travel times from the main sources to the IDO ports change according to the type of the ship used to carry the relief items. We measured the sea distances in miles between the main sources and IDO ports using Google Earth™ and divided the distances by the speeds of ship types 1, 2, 3 and 4 to calculate the travel time. As we assumed that the ships travel to the IDO ports from the main sources and then return from the IDO ports to the main sources to complete one tour, we calculated the round-trip travel times for maritime transportation by multiplying the travel time by two. In addition, we allowed ten min for the loading/unloading time for vehicles and added this figure to the travel times. All travel times are considered in min.

*Vulnerability*. We determined the vulnerabilities [0.0–1.0 scale] of the roads between the main or IDO ports and the districts based on the JICA report's (2002) road-blockage probabilities for roads 7 to 15 metres wide. To calculate the vulnerabilities between the districts and the ports, we first determined the vulnerability of each district. The vulnerabilities of the ports are considered to be the same as the vulnerability of the district in which the port is located. Then, we determined the vulnerability of the highway between a district and the port by calculating the arithmetic mean of the vulnerabilities of the district and the port in question. We set the vulnerabilities of the sea routes between the main sources and the IDO ports as 0.001. Since the vulnerabilities of the routes affect the travel times, we calculated the vulnerability effect on the travel times using the following formula:

$$Travel\ time = Original\ travel\ time \times \frac{1}{1 - Vulnerability} \tag{0}$$

As indicated in Formula (0), the original travel time of a route is inflated by the degree of vulnerability of that route. Since the vulnerability of the actual network varies between 0.05–0.4, the travel time is thus inflated by at least 5% and at most 66% throughout the network. Horner and Widener (2011) reached a similar conclusion whereby different disruption levels of a network after a hurricane increased the average distance (travel time here) between a neighbourhood and its relief centre. We note that different vulnerability intervals may require different formulas for calculating travel time inflation.

*Supply to the main ports/capacity of the container ship per day*. To determine daily capacity/supply figures for the three main supply sources, we next considered the characteristics of the post-disaster environment. First, the main ports at Haydarpaşa and Ambarlı might not be functioning at full capacity due to a greater degree of damage sustained than initially estimated, or because the availability of port capacity may be reduced by ongoing daily commercial activities. Secondly, accepting a greater supply volume than needed can create problems. For example, when a disaster strikes, a port's wide open areas can be used to provide temporary shelter for people in need, so excess supplies would reduce the serviceable area available. Also, as time is one of the most important factors in humanitarian relief operations, to the greatest extent possible all unnecessary time-consuming activities should be avoided. Therefore, only limited amounts of the supply arriving from national and international sources might be accepted at the main ports due to the constraints of capacity, time or personnel.

For the reasons stated above, we considered the lowest possible total supply from the three main sources. Taking into account that the total demand is 3,424,000 units of relief items and assuming that the total demand is met, and also for calculation convenience, we considered the total supply from the three main sources to be 3,500,000 units of relief items.

*Maximum number of tours/trips of vehicles per day.* In this paper and in general, ships are said to do 'tours', while land vehicles do 'trips.' Ships must return to their points of origin, as the same ships are utilized for relief item distribution, while land vehicles do not necessarily return to their points of origin. The points of origin are always main sources in our case. We calculated the maximum number of tours that a ship can make daily based on the total travel time needed by the ship to make one tour. Hence, we divided the total time interval, which is one day or 1,440 min, by total travel time of the ship and rounded down the results to the nearest integer. The maximum number of trips land vehicles can make, in contrast, is not limited and is considered to be a very big number.

*Maximum daily transhipment capacity of IDO ports.* The maximum daily transhipment capacity of the IDO ports refers to the maximum amount of relief items that can arrive at an IDO port in one day, and this capacity is determined based on the carrying capacity of the ships and the maximum number of tours each ship can make in a day. To calculate the maximum daily transhipment capacity of an IDO port, we multiply the maximum number of tours that each ship can make daily to that port from the main sources by the capacity of the ship.

## 4. Mathematical Model

The integer programming model described in this section minimizes the total transportation time for delivering relief items to the districts, while meeting all of the districts' demands. We chose this objective function to reflect the 'efficacy' (Huang et al., 2012) in our model. Huang et al. (2012) describe three types of objective functions in relief transportation, namely, efficiency, efficacy and equity. Efficacy emphasizes the minimization of the cumulative delivered demand-weighted travel time, which is an objective function similar to the ones in Wilhelm and Srinivasa (1997) for oil spill clean-up operations and in Duran et al. (2011) for pre-positioning of emergency items. Moreover, in reality, transportation time during the response phase of humanitarian logistics is vital to save lives and alleviate the suffering of beneficiaries.

Indices:

$i$ Index for main sources ($i$=1,2,…,$I$)

$j$ Index for IDO ports ($j$=1,2,…,$J$)

$k$ Index for districts ($k$=1,2,…,$K$)

$f$ Index for ship types ($f$= 1,2,….,$F$)

$l$ Index for land vehicle types ($l$=1,2,…,$L$)

Parameters:

$D_k$ Demand for district $k$

$s_i$ Supply of main source $i$

$c_j$ Maximum daily transhipment capacity of IDO port $j$

$capb_f$ Capacity of ship $f$

$capb_l$ Capacity of land vehicle $l$

$t_{ijf}$ Time to travel from main source $i$ to IDO port $j$ by ship $f$

$t_{ikl}$ Time to travel from main source $i$ to district $k$ by land vehicle $l$

$t_{jkl}$ Time to travel from IDO port $j$ to district $k$ by land vehicle $l$

$v_{ijf}$ Vulnerability of the seaway between main source $i$ and IDO port $j$ (when travelled by ship $f$)*

$v_{ikl}$ Vulnerability of the road between main source $i$ and district $k$ (when travelled by land vehicle $l$)*

$v_{jkl}$ Vulnerability of the road between IDO port $j$ and district $k$ (when travelled by land vehicle $l$)*

* Ship type $f$ and land vehicle type $l$ are also included as index for convenience in modelling.

$n_{ijf}$ Maximum number of tours per day ship type $f$ can make from main source $i$ to IDO port $j$

$n_{ikl}$ Maximum number of tours per day land vehicle $l$ can make from main source $i$ to district $k$

$n_{jkl}$ Maximum number of tours per day land vehicle $l$ can make from IDO port $j$ to district $k$

Decision variables:

$x_{ijf}$ Number of relief items transported from main source *i* to IDO port *j* by ship *f*

$x_{ikl}$ Number of relief items transported from main source *i* to district *k* by land vehicle *l*

$x_{jkl}$ Number of relief items transported from IDO port *j* to district *k* by land vehicle *l*

$b_{ijf}$ Number of tours ship *f* makes from main source *i* to IDO port *j*

$b_{ikl}$ Number of tours land vehicle *l* makes from main source *i* to district *k*

$b_{jkl}$ Number of tours land vehicle *l* makes from IDO port *j* to district *k*

Integer Programming Model:

Objective function

$$Minimize \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{f=1}^{F} x_{ijf} * t_{ijf} * \left(\frac{1}{1-v_{ijf}}\right) + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ikl} * t_{ikl} * \left(\frac{1}{1-v_{ikl}}\right) + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{jkl} * t_{jkl} * \left(\frac{1}{1-v_{jkl}}\right) \qquad (1)$$

Constraints

$$\sum_{i=1}^{I}\sum_{l=1}^{L} x_{ikl} + \sum_{j=1}^{J}\sum_{l=1}^{L} x_{jkl} \geq D_k, \qquad \forall k = 1, \dots, K \qquad (2)$$

$$\sum_{j=1}^{J}\sum_{f=1}^{F} x_{ijf} + \sum_{k=1}^{K}\sum_{l=1}^{L} x_{ikl} \leq s_i, \qquad \forall i = 1, \dots, I \qquad (3)$$

$$\sum_{i=1}^{I}\sum_{f=1}^{F} x_{ijf} = \sum_{k=1}^{K}\sum_{l=1}^{L} x_{jkl}, \qquad \forall j = 1, \dots, J \qquad (4)$$

$$\sum_{i=1}^{I}\sum_{f=1}^{F} x_{ijf} \leq c_j, \qquad \forall j = 1, \dots, J \qquad (5)$$

$$b_{ijf} \leq n_{ijf}, \qquad \forall i = 1, \dots, I; \forall j = 1, \dots, J; \forall f = 1, \dots, F \qquad (6)$$

$$b_{ikl} \leq n_{ikl}, \qquad \forall i = 1, \dots, I; \ \forall k = 1, \dots, K; \forall l = 1, \dots, L \qquad (7)$$

$$b_{jkl} \leq n_{jkl}, \qquad \forall j = 1, \dots, J; \forall k = 1, \dots, K; \forall l = 1, \dots, L \qquad (8)$$

$$b_{ijf} * capb_f \geq x_{ijf}, \qquad \forall i = 1, \dots, I; \ \forall j = 1, \dots, J; \forall f = 1, \dots, F \qquad (9)$$

$$b_{ikl} * \ capb_l \geq x_{ikl}, \qquad \forall i = 1, \dots, I; \ \forall k = 1, \dots, K; \ \forall l = 1, \dots, L \qquad (10)$$

$$b_{jkl} * \ capb_l \geq x_{jkl}, \qquad \forall j = 1, \dots, J; \forall k = 1, \dots, K; \forall l = 1, \dots, L \qquad (11)$$

$$b_{ijf} \ \leq x_{ijf}, \qquad \forall i = 1, \dots, I; \forall j = 1, \dots, J; \forall f = 1, \dots, F \qquad (12)$$

$$b_{ikl} \leq x_{ikl}, \qquad \forall i = 1, \dots, I; \ \forall k = 1, \dots, K; \forall l = 1, \dots, L \qquad (13)$$

$$b_{jkl} \leq x_{jkl}, \qquad \forall j = 1, \dots, J; \ \forall k = 1, \dots, K; \forall l = 1, \dots, L \qquad (14)$$

$$x_{ijf}, x_{ikl}, x_{jkl}, b_{ijf}, b_{ikl}, b_{jkl} \qquad integer \qquad (15)$$

Objective (1) is to minimize the total transportation time of relief items. The effect of road vulnerability on transportation time presented in the travel time formula is reflected in the objective function. Constraint set (2) ensures that the demand of each district is met. Constraint set (3) indicates that the total number of relief items delivered from the main sources cannot exceed the total daily supply of the main sources. Constraint set (4) guarantees that the total number of relief items transported from an IDO port to the districts is equal to the total number of relief items transported to that IDO port from the main sources, indicating that relief items are not stocked at IDO ports. Constraint set (5) sees that the total number of relief items transported from the main sources to an IDO port do not exceed the maximum daily transhipment capacity of that IDO port. Constraint set (6) ensures that the number of ship tours per day made from a main source to an IDO port do not exceed the maximum number of ship tours that can be made daily from that main source to that IDO port by that ship type. Constraint sets (7) and (8) indicate that the number of land vehicle tours per day made from a main port or from an IDO port to a district cannot exceed the maximum number of land vehicle tours that can be made daily from that port to that district. Constraint set (9) ensures that a ship travelling from a main source to an IDO port is not required to leave its entire load at the IDO port—partial unloading of the ships is allowed. Likewise, constraint sets (10) and (11) allow for the partial unloading of land vehicles. Constraint sets (12), (13) and (14) guarantee that if there are no relief items transported from a main source to an IDO port or from a port (main or IDO) to a district, then there will be no tours/trips between these points. Constraint set (15) imposes an integrality restriction on the decision variables.

## 5. Experimental Study

The integer programming model is solved by GAMS Distribution 22.6 using alternative supply values for the three main sources. As previously indicated, the combined total supply of the Port of Haydarpaşa, Port of Ambarlı and the container ship is 3,500,000 units of relief items. This total supply was divided between the three main sources in different proportions in each experiment. We conducted ten experiments to consider the supply distribution at proportions of 0.33, 0.67 and 1.00 for the main sources, as presented in Table 2, where proportion 1.00 indicates 3,500,000.

**Table 2:** Supply proportions for the main sources.

| Experiment No | Port of Haydarpaşa | Port of Ambarlı | Container Ship |
|---|---|---|---|
| **1** | 0 | 0 | 1 |
| **2** | 0 | 1 | 0 |
| **3** | 1 | 0 | 0 |
| **4** | 0.33 | 0.33 | 0.34 |
| **5** | 0.33 | 0.67 | 0 |
| **6** | 0.33 | 0 | 0.67 |
| **7** | 0 | 0.33 | 0.67 |
| **8** | 0.67 | 0.33 | 0 |
| **9** | 0.67 | 0 | 0.33 |
| **10** | 0 | 0.67 | 0.33 |

The performance measures obtained in each experiment include the average time spent to send one relief item unit to the demand area, the intermodal transportation percentage and the number of ships used to transport relief items. The formulas used for these three performance measures are given below.

$$Average\ transportation\ time\ per\ unit\ of\ relief\ item = \frac{Objective\ function\ value}{Total\ demand} \quad (16)$$

$$Intermodal\ transportation\ percentage =$$
$$100\,\frac{(Total\ demand - Total\ amount\ transported\ from\ main\ ports\ by\ highways)}{Total\ demand} \quad (17)$$

$$Total\ \#\ of\ ships \begin{cases} if\ b_{ijf} \times t_{ijf}\ \leq 1440\ \ number\ of\ type\ f\ ship\ used = 1 \\ otherwise, number\ of\ type\ f\ ship\ used = \dfrac{Total\ Travelling\ Time}{1{,}440} \end{cases} \quad (18)$$

Table 3 illustrates the results of the three performance measures in each experiment. To better analyse the relationship between the three performance measures, we plotted the graphs in Figures 4 and 5.

**Table 3:** Results of experimental runs.

| Experiment No | Average Transportation Time per Unit Relief Item (min) | Intermodal Transportation Percentage | Total Number of Ships Used |
|---|---|---|---|
| **1** | 72.7 | 100% | 22 |
| **2** | 57.3 | 37% | 13 |
| **3** | 40.7 | 65% | 6 |
| **4** | 38.8 | 37% | 9 |
| **5** | 32.2 | 4% | 2 |
| **6** | 56.8 | 71% | 17 |
| **7** | 54.7 | 66% | 14 |
| **8** | 30.6 | 31% | 5 |
| **9** | 45.4 | 65% | 10 |
| **10** | 47.7 | 37% | 9 |

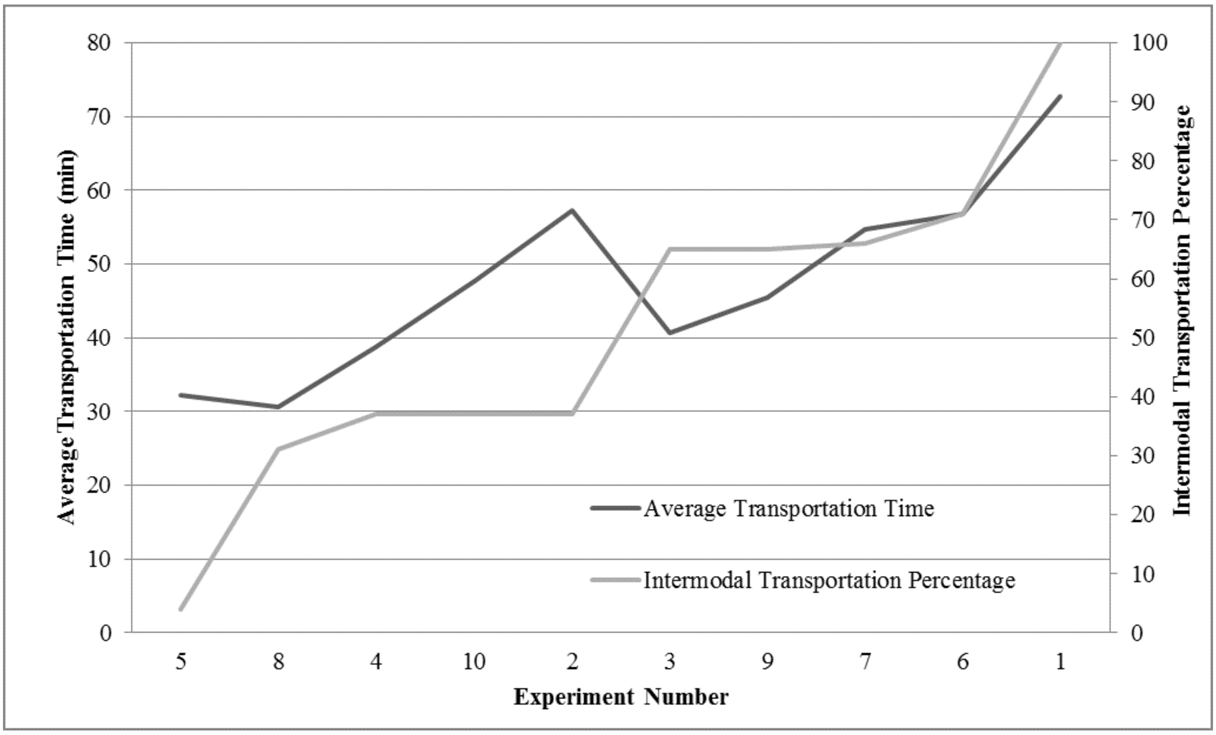


**Fig. 3** Average transportation time vs. intermodal transportation percentage.

Figure 4 shows the relationship between the average transportation time and the intermodal transportation percentage. Generally, as the average transportation time increases, the intermodal transportation percentage also increases. This may be due to the utilisation of two steps for transporting relief items from the main sources to the demand points when using intermodal transportation. The generally direct proportional pattern deviates, however, in experiments three and ten. In experiment three (in which the Port of Haydarpaşa holds 100% of the total supply) the average transportation time decreases as the intermodal transportation percentage increases. In experiment ten (in which the Port of Ambarlı holds 67% and the container ship holds 33% of the total supply), the average transportation time increases and the intermodal transportation percentage stays the same.

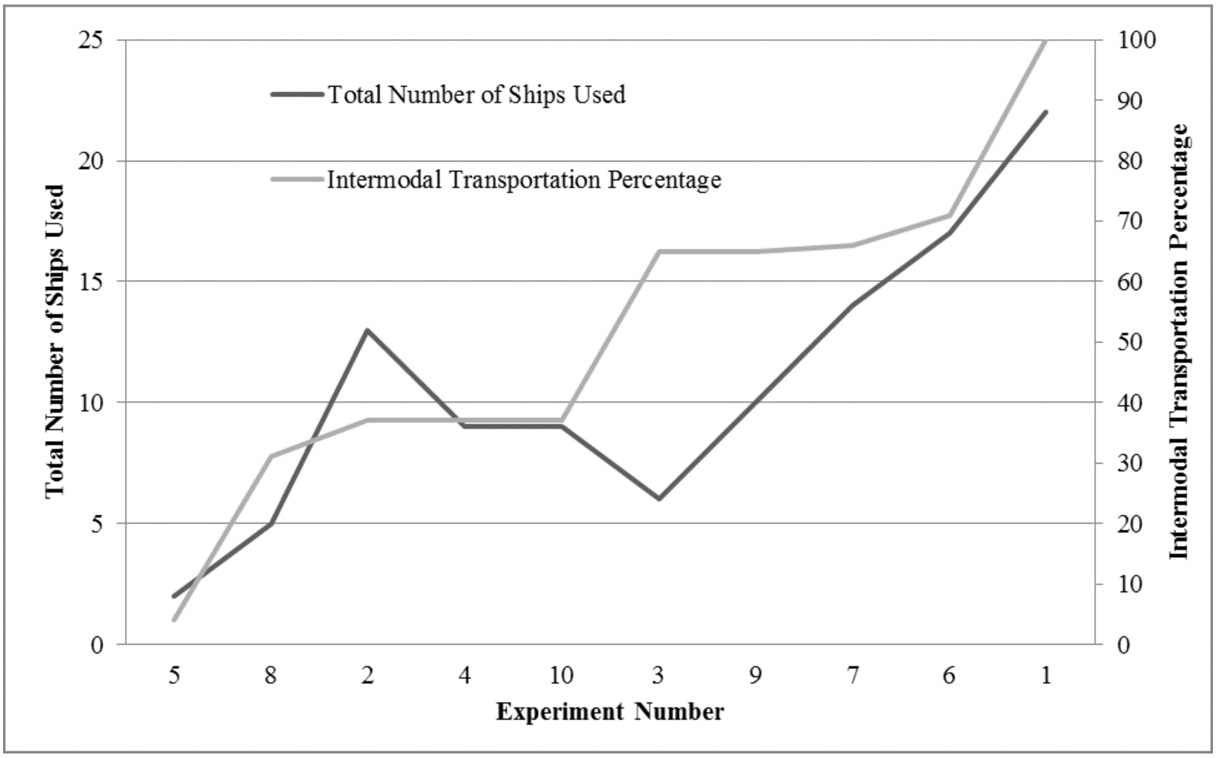


**Fig. 4** Total number of ships used vs. intermodal transportation percentage.

Figure 5 depicts the relationship between the total number of ships used and the intermodal transportation percentage. As we can see, in general, the total number of ships used and the intermodal transportation percentage follow the same pattern, i.e. as the total number of ships increases the intermodal transportation percentage also increases. This can be considered to be a natural result, since the intermodal transportation percentage is directly connected with the utilization of maritime transportation and thus the utilization of ships. However, it cannot be definitely stated that the total number of ships used is directly proportional to the intermodal transportation percentage; it is also related to the type of the ship used (i.e. if higher capacity ships are used, more relief items are distributed with fewer ships, so the total number of ships used decreases). Deviation from the general pattern can be seen in experiments three and four. In experiment three, the total number of ships used decreases while the intermodal transportation percentage increases. In experiment four, the total number of ships used decreases while the intermodal transportation percentage stays the same. By examining Figures 4 and 5 together, we can state that although generally all performance measures are directly proportional, this situation can change depending on the supply distribution of the main sources.

In our study, it would be inaccurate to refer to any one of the scenarios as ‘best case’ or ‘worst case.’ The experiments are designed to take into account real life possibilities and the results of the performance measures show the relative situation in each scenario. Hence, the decision maker can be better prepared to encounter different environments and is guided in making the necessary arrangements with respect to the appropriate ship fleet for each scenario.

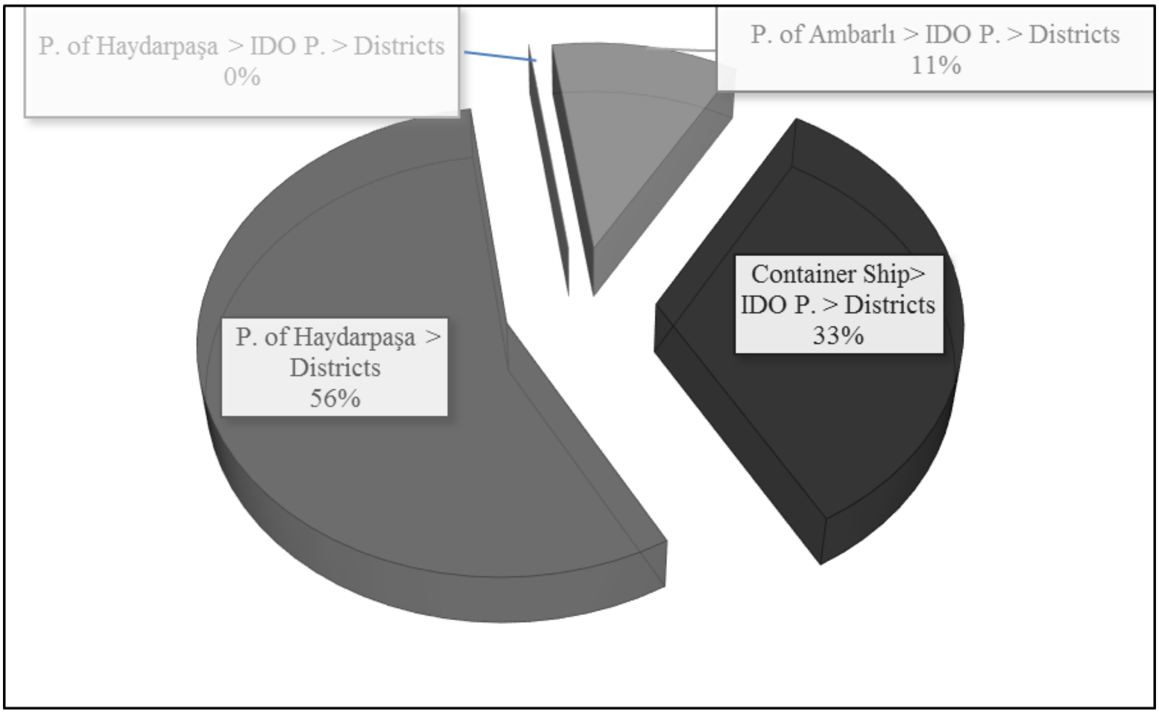


**Fig. 5** Supply distribution for Anatolian districts.

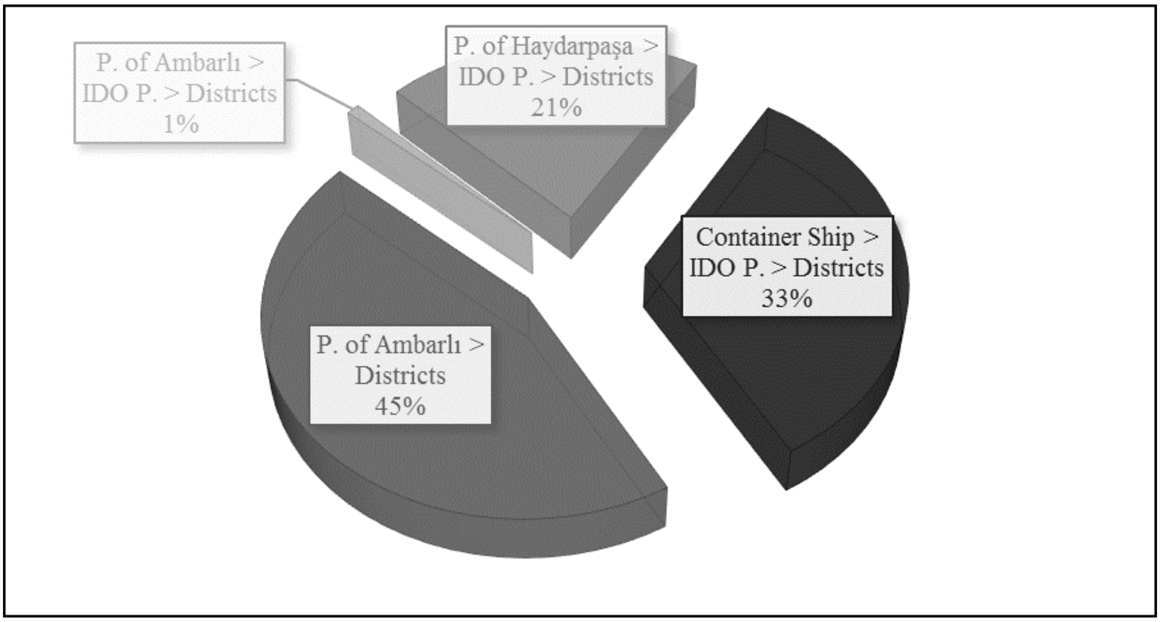


**Fig. 6** Supply distribution for European districts.

Figures 6 and 7 display the average supply distribution for the Anatolian and European districts, respectively. They depict the proportion of demand met by the main sources via intermodal transportation and that met directly via land transportation. The proportions are averages of the values obtained in the ten experiments.

More than half of the demand of Anatolian side is met directly from the Port of Haydarpaşa via highways, and on European side almost half of the demand is met directly from the Port of Ambarlı via highways. We observe that when there is supply from the main ports an important portion of the relief items are distributed to the districts directly from the main ports using only highways. For both sides, exactly the same portion of the demand (33%) is met by the third supply source—the sea-based container ship. When supply is available from the container ship, the model prefers to send relief items from it rather than sending relief items from the opposite side of the Bosphorus. It is significant that, in any case, supply distribution from the main ports to the IDO ports on the same side (i.e. from the Port of Haydarpaşa to Anatolian IDO ports and from the Port of Ambarlı to European IDO ports) is almost zero for both sides. A greater portion of the demand of the European side is met by relief item transportation from the main port on the opposite side than is met for the Anatolian side. For the Anatolian side, supply from the container ship is preferred when there is supply available from both the Port of Ambarlı and the container ship, whereas supply from the Port of Haydarpaşa via highways is preferred when there is supply available from both the Port of Haydarpaşa and the Port of Ambarlı. On the other hand, for the European side, when there is supply available from both the Port of Ambarlı and the Port of Haydarpaşa, almost half of the demand is met by the Port of Ambarlı via highways and half by the Port of Haydarpaşa. In addition, when there is supply available from both the container ship and the Port of Haydarpaşa, again, almost equal portions are met by the two supply points. Therefore, in some cases, the Port of Haydarpaşa (i.e. the opposite side) is an important supply source for the European side.

## 6. Conclusion

In this study, we proposed an intermodal transportation model for humanitarian logistics, using the seabasing concept, for the distribution of national and international relief items to the people in the region of Istanbul in the aftermath of an earthquake. The model is based on maritime transportation and takes advantage of seaports and the unique geography of the city. The main objective was to minimize the demand-weighted transportation time of relief items. The effect of road vulnerability on the transportation times was also taken into account.

The mathematical model was run using different scenarios and the results were analysed with respect to three performance measures—the average transportation time per unit relief item, the intermodal transportation percentage and the number of ships used. The scenarios also took into account different supply proportions for the three main supply sources, one of which could be an international container ship.

We also examined the average supply distribution to the Anatolian and European districts. Although the results indicate that direct transportation from the Port of Ambarlı to the European side and from the Port of Haydarpaşa to the Anatolian side via highways is the preferred method of distributing relief items, a considerable proportion of relief items were transported between the two sides via the utilization of maritime transportation and IDO ports. In addition, the container ship was an important supply source for both the European and Anatolian sides.

These analyses yield valuable insights for the relevant coordinating authorities for the management and planning with respect to the facilities and resources of humanitarian logistics activities. For instance, based on the results of different scenarios, relevant authorities can determine the number and type of ships to dedicate to humanitarian logistics activities, the optimal allocation of incoming supplies to the main ports of Haydarpaşa and Ambarlı, or the necessity of utilizing a container ship. Likewise, time management and the scheduling of distribution activities may be possible based on model results regarding estimated average transportation times for different situations.

The extensive utilization of maritime transportation and seaports for relief-item distribution is the main contribution of this study to the humanitarian logistics literature. Our study establishes a basic foundation for taking advantage of the special geography of İstanbul in the aftermath of an earthquake. The proposed system is open to future development and improvement. For instance, in our study, we considered the loading/unloading time to be ten min. A more complete and detailed time study could be carried out, which takes into account other factors, such as the conjunction of ships at the same port. These kinds of considerations will bring other aspects to the problem, such as scheduling factors and budgetary constraints. By updating the mathematical model in light of these factors, more comprehensive and accurate results can be achieved. Also, the possible inclusion of international airports in the relief item distribution network might be a valuable development. Visiting more than one port in a delivery was not allowed in this study, but routing of ships among ports could be considered in future work.

Overall, since the relief item delivery network developed in this study is based on seaports, earthquake-resistant features of the Istanbul seaports should be improved. Also, port hinterlands should be organized and designed to allow for efficient coordination with seaports in emergencies. For example, roads connecting the seaports to the demand areas, in our case to the districts of Istanbul, should be kept in good condition, infrastructure of the surrounding area should be well maintained and the surrounding facilities and construction projects should be made resistant to earthquakes.

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