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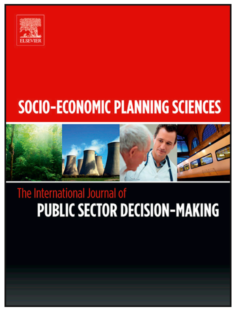

Pre-positioning of relief items in humanitarian logistics considering lateral transhipment opportunities

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Pre-positioning of Relief Items in Humanitarian Logistics Considering Lateral Transhipment Opportunities

The main objective of this study is to investigate the inclusion of lateral transhipment opportunities into the humanitarian relief chain and to examine the effect of different parameters on minimizing the average distance travelled per item while serving the beneficiaries. Direct shipment model (DT), lateral transhipment model (LTSP) and maritime lateral transhipment model (MLTSP) are developed and compared between each other by using a real life earthquake scenario prepared for the city of Istanbul by JICA (Japanese International Cooperation Agency). Developed mathematical models decide on the locations and number of disaster relief facilities, quantity of relief items to hold at those facilities, and quantity of lateral transhipment between the facilities. Vulnerability of the roads and heterogeneous capacitated facilities are also considered. It can be concluded that both LTSP and MLTSP models gave better results than DT model and lateral transhipment option helps beneficiaries to obtain relief items faster and with higher service level.

Key Words: Freight transportation, maritime transportation, relief chain, capacitated facility location, vulnerability

1. Introduction

From 2003 to 2012, annual average of 106,654 people were reported dead, more than 216 million people were reported to be affected by disasters, and close to $157 billion worth of economic damage was reported (Guha-Sapir et al., 2014). These facts reveal the importance of disaster management in mitigating the negative effects of the disaster. Humanitarian logistics, which plays a key role in every stage of disaster relief operations, is defined as "the process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from point of origin to point of consumption for the purpose of meeting the end beneficiary's requirements" (Thomas and Mizushima, 2005). When a state of emergency is declared and aid is appealed, resources such as relief personnel, relief goods and equipment are mobilized to the disaster location. By its definition, mobilization of resources as well as its predecessor and successor operations in a relief chain (Duran et al., 2013) can be categorized as humanitarian logistics, which contribute to more than 80% of the total relief costs (Van Wassenhove, 2006). Although local government of the disaster location is mainly responsible to alleviate the suffering of its people (Thomas and Fritz, 2006), non-governmental organizations (NGOs) as well as other relief aid agencies offer their help to transport the right number of relief goods on time to the right place (Tatham and Pettit, 2010).

Supply chains are usually considered to be consisting of vertical transportation through several echelons (i.e. levels) such as manufacturer, warehouse, retailer, customer etc. The practice of allowing horizontal transportation within the same echelon is called lateral transhipment (Axsater, 2006) and is mostly used for low demand, high value items where emergency orders are allowed (Wong et al., 2006; Kutanoglu and Mohajan, 2009). In settings where lateral transhipment is observed, retailers might keep only certain types of items and replenish those items from the warehouses. As a cure to the burden of waiting for next regular warehouse shipment or placing emergency orders with high cost to the warehouse, transhipments from other retailers with adequate inventory is utilized. Thus, retailers face two sources of demand (from customers and other retailers) and two sources of supply (from warehouses and other retailers) (Axsater, 2006).

Inspired from the emergency nature of lateral transhipment decisions in commercial logistics, lateral transhipment in humanitarian logistics can also be a viable alternative to alleviate the suffering of beneficiaries within the shortest time possible. Lateral transhipment in humanitarian logistics is observed when aid distribution centres transfer relief items among themselves when they cannot satisfy the immediate need of beneficiaries from their own inventory. To the best of our knowledge, lateral transhipment in humanitarian logistics has not been analysed thoroughly in the literature. The objective of this study is addressing this literature gap and proposing an integrated model for facility location and transportation decisions including lateral transhipments.

The rest of the paper is organized as follows. In the second section, we present the related literature. The problem is defined and the related systems are described in the third section. Proposed mathematical formulations are presented in the fourth section. The fifth section provides the results of experimental studies conducted for the city of Istanbul with the real life data. Finally, we conclude with our major findings and possible future research directions.

2. Literature Review

Disaster management can be analyzed in four phases, namely, mitigation, preparedness, response and recovery (Altay and Green, 2006). Most of the studies in humanitarian logistics have focused on the preparedness and response phases (Altay and Green, 2006). In their review study, Caunhye et al. (2012) state that inventory pre-positioning, evacuation and relief distribution aims are brought together in location analysis in most of the facility location optimization models in humanitarian logistics. The decisions are varied such as commodity pre-positioning, facility selection among potential local and global distribution centres, and optimizing facility size. In the pre-positioning literature, the most frequent objectives are minimizing costs of setting up relief centres, transportation (Galindo and Batta 2013, Lin et al. 2012, Khayal et al. 2015) and commodity procurement costs, average (Duran et al., 2011) or maximum response time, unfilled demand (Afshar and Haghani, 2012) and expected number of casualties left behind or maximizing beneficiaries' coverage. Huang et al. (2012) describe efficiency, efficacy and equity types of objective functions for relief routing. Facility location problem can also be solved together with the routing of vehicles as in Ukkusuri and Yushimito (2008).

Two stage stochastic models are utilized in some pre-positioning studies. Barbarosoglu and Arda (2004) propose a two-stage stochastic programming model to plan the transportation of vital first-aid commodities to disaster-affected areas during emergency response where the capacities of the arcs in the road network, the supply amounts and the resource requirements are considered to be random. Mete and Zabinsky (2010) develop a stochastic optimization approach selecting the storage locations and amounts of medical supplies to minimize warehouse operation costs, the response time and unfilled demand rate balancing the preparedness and risk despite the uncertainties of disaster events. Bemley et al. (2013) develop a two-stage stochastic pre-positioning model to maximize expected amount of repaired ports providing short-term port recovery from weather events such as hurricanes.

Scenario based approaches are also utilized in the pre-positioning literature. Balçık and Beamon (2008) propose a scenario-based model for a pre-positioning system balancing the costs against the risks to determine the number and the location of distribution centres in a relief network and the amount of each relief commodity stored at each facility. Duran et al. (2011) develop a mathematical model to obtain the configuration of the supply network that minimizes the average response time over all the demand instances and decide which warehouse to open and how to allocate the inventory among them.

Commercial studies on lateral transhipment are not directly related to disaster response, but still have some common characteristics to humanitarian logistics settings. Some of these characteristics are the uncertainty in demand, existence of possible future states, and uncertainty in the number of facilities to be established. These characteristics are related to the uncertainty in the time, place and the effect of a disaster. Most of the commercial lateral transhipment studies are related to repairable spare parts. In one of the earliest studies on lateral transhipment, Lee (1987) presents a model of pooling groups with identical retailers. Demand of one retailer is satisfied from another retailer in the same pooling group. Different priority rules between available retailers and optimal stocking levels for various service levels are also analysed. Axsater (1990) generalizes the pooling group idea to non-identical retailers. His method shows an improvement on Lee (1987)'s work when the proportion of emergency transhipments is large. Commercial studies differ from humanitarian logistics by their demand rate and item value. Commercial lateral transhipment is often used for low demand and high value items. On the other hand, lateral transhipment in humanitarian logistics is used during a demand surge (i.e. high demand) and for low value items (e.g. bottled water and meals-ready-to-eat).

Lateral and emergency shipments occur in response to stock outs. Wong et al. (2006) study a multi-item, continuous review model of two-location inventory systems for repairable spare parts. The objective of the study is to minimize the total costs for inventory holding, lateral transhipments and emergency shipments subject to a target level for the average waiting time per demanded part at each of the two locations. Kutonoğlu and Mohajan (2009) consider a two-echelon service parts logistics system with one central warehouse and a number of local warehouses that meet all the time-based service level constraints at minimum total cost including inventory holding cost, transportation cost, and penalty cost due to lost demand. Time-based service level constraints are similar to allowable maximum response time or maximum distance constraints in humanitarian logistics.

Ozkapici et al. (2016) study the problem of locating disaster relief facilities in the city of Istanbul utilizing the Bosphorus strait. The authors consider maritime transportation for relief item distribution in the city of Istanbul where two main ports and a container ship located on the Marmara Sea are considered as main supply facilities. Ozkapici et al. (2016) conclude that including maritime transportation into the relief item distribution system provides a more flexible humanitarian logistics system for Istanbul. Inspired from Ozkapici et al. (2016), one of the mathematical models developed in this study uses maritime transportation with lateral transhipment opportunities.

Three works can be cited as the most related to this study in humanitarian logistics. Reyes et al. (2013) show that lateral transhipment in a disaster relief system is more efficient using a simulation model based on system dynamics. Stanger et al. (2013) illustrate the use of lateral transhipment in blood transportation for UK hospitals. They demonstrate the real life benefits of lateral transhipment based on comprehensive case studies and surveys. Mulyono and Ishida (2014) build a logistics and inventory model using probabilistic cellular automata for the enterprise inventory model and self-repair network model, which is applicable to humanitarian relief situations. Mulyono and Ishida (2014) use a real life data set from a volcanic eruption (Sinabung Mountain - September 2013) in Indonesia to validate their model. Although Reyes et al. (2013), Stanger et al. (2013), and Mulyono and Ishida (2014) illustrate the use of lateral transhipment in humanitarian relief situations; they do not utilize a mathematical programming model in their studies. In this study, the main objective is to investigate whether lateral transhipment in humanitarian logistics provides flexibility and decreases average travel distance comparing mathematical models with and without lateral transhipment.

3. Description of the Relief Item Distribution System

In this section, a description of the proposed relief item distribution system, sources of the data used and the assumptions are given, respectively. A distribution system with two echelons is proposed here for a possible earthquake scenario where we have in the upper echelon the relief facilities and in the lower echelon demand locations. Each demand location is assigned to only one relief facility and relief items are transported from relief facilities to demand locations according to this assignment. This type of material shipment is called as direct shipment. Lateral transhipment between relief facilities is also possible. Any relief facility can engage in lateral transhipment with a neighbour relief facility. This type of material shipment is called as lateral transhipment. In lateral shipment any relief facility can satisfy demand of any demand location assigned to it by using excess stock of the neighbour relief facility. The suggested distribution system for relief items is presented in Figure 1.

<<Insert Figure 1 about here>>

For each relief facility, it is allowed to use only one neighbour relief facility for lateral transhipment. One standard “relief item package” is delivered to each family of four people. This package contains bottles of water and food cans. We assume that relief facilities are willing to release true information about their inventory position to other relief facilities and capacity of land vehicles is assumed to be enough for deliveries.

4. Mathematical Models

Mixed integer programming formulations of direct shipment model, lateral transhipment between supply points model and maritime lateral transhipment model are presented in this section, respectively.

4.1 Model with the Direct Shipment only (DT)

Let index sets of *I* and *J* represent the set of possible relief facilities and the set of demand locations, respectively. We define the decision variables of the DT model as:

$$y_i: \begin{cases} 1, & \text{if relief facility } i \text{ is opened,} \\ 0, & otherwise. \end{cases}$$

$$m_{ij}: \begin{cases} 1, & \text{if demand location } j \text{ is assigned to relief facility } i, \\ 0, & otherwise. \end{cases}$$

q_i: Quantity of relief item held at relief facility *i*,

x_{ij}: Quantity of relief item sent to demand point *j* from relief facility *i*,

and its parameters as:

W: A big number,
N: Quantity of relief items required by a beneficiary at any demand point,
P: Maximum number of relief facilities to open,
R: Maximum distance for a relief item to travel,
F: Maximum number of beneficiaries a school class can serve,
v_{ij}: Vulnerability factor between relief facility *i* and demand location *j*,
d_j: Number of people affected at demand location *j*,
c_i: Number of school classes available at relief facility *i*,
r_{ij}: Distance between relief facility *i* and demand location *j*.

Thus, the complete DT model can be written as:

$$Minimize \quad \frac{\sum_{i\in I}\sum_{j\in J}\left[x_{ij}\, r_{ij}\left(1+v_{ij}\right)\right]}{\sum_{j\in J}\left(d_j N\right)} \tag{1}$$

subject to

$$\sum_{i\in I} x_{ij} \geq d_j N \qquad j\in J \tag{2}$$

$$r_{ij}\left(1+v_{ij}\right)m_{ij} \leq R \qquad i\in I, j\in J \tag{3}$$

$$\sum_{j\in J} x_{ij} \leq q_i \qquad i\in I \tag{4}$$

$$\sum_{i\in I} y_i \leq P \tag{5}$$

$$\sum_{i\in I} m_{ij} = 1 \qquad j\in J \tag{6}$$

$$\sum_{j\in J} m_{ij} \leq W y_i \qquad i\in I \tag{7}$$

$$x_{ij} \leq W m_{ij} \qquad i\in I, j\in J \tag{8}$$

$$q_i \leq y_i c_i N F \qquad i\in I \tag{9}$$

$$\sum_{i\in I} q_i \leq \left\{\sum_{j\in J} d_j\right\} N \times 1.01 \tag{10}$$

$$x_{ij}, q_i \geq 0 \qquad i\in I, j\in J \tag{11}$$

$$y_i, m_{ij} \in \{0,1\} \qquad i\in I, j\in J \tag{12}$$

The objective function (1) minimizes the average distance travelled per the relief item. Vulnerabilities of the routes affect the distances by inflating them. Horner and Widener (2011) concluded that disruption levels of a network after a disaster increased the average distance between a neighbourhood and its relief centre. Inspired from Horner and Widener (2011)'s conclusion, original distance of a route is inflated here by the vulnerability of that route ranging from 0 to 1.0 where 1.0 represents the most vulnerable case using [$Inflated\ distance = Original\ distance\ \times (1 + \ Vulnerability)$] equation.

Constraint set (2) ensures that demand for relief items at each demand point is met. With the Constraint (3), relief items do not travel more than *R*, and the relief items sent do not exceed the respective inventory held at the relief facility *i* via Constraint (4). Via Constraint (5), at most *P* relief facilities can be opened. Constraints (6-8) make sure that each demand location *i* is assigned to only one relief facility, a demand location can be assigned to a relief facility that is opened and relief items cannot be sent from a relief facility to a demand location unless that demand location is assigned to that relief facility. Constraint set (9) imposes an upper bound on the quantity of relief items to be held at a relief location considering the number of classrooms in the district and the maximum number of people (*F*) that can be served from a school classroom. The parameter *F* is considered like a service level; lower *F* values corresponds to better service for the beneficiaries. Assuming that the total capacity of the facilities is 101% of total demand, Constraint (10) is added.

4.2 Model with Lateral Transhipment option between Supply Points (LTSP)

With the inclusion of the lateral transhipment option to the model, we need a new index for the relief facilities used as lateral transhipment source. Let us denote it as i' under the set *I*. In addition to the parameters used in the DT model, the new parameters related with the relief facilities acting as lateral transhipment sources in the LTSP model are; $r_{i'j}$, the travel distance between relief facilities i' and demand location $j, r_{i'i}$, the travel distance between relief facilities i' and relief facility *i*,$v_{i'j}$, vulnerability factor between relief facilities i' and demand location *j*, and$v_{i'i}$, vulnerability factor between relief facilities i' and relief facility *i*. If we define the additional decision variables as:

$$t_{ii'j}: \begin{cases} 1, & \text{if relief facilities } i \text{ and } i' \text{ engages in lateral transhipment for demand location } j, \\ 0, & otherwise, \end{cases}$$

$\bar{x}_{ii'j}$: Quantity of relief item sent to demand location *j* from facility *i* through facility *i´*,

$$f_{ii'}: \begin{cases} 1, & \text{if relief facilities } i \text{ and } i' \text{ engages in lateral transhipment}, \\ 0, & otherwise, \end{cases}$$

then the complete LTSP model can be represented as:

$$\text{Minimize } \frac{\sum_{i\in I}\sum_{j\in J}\left[x_{ij}r_{ij}\left(1+v_{ij}\right)\right] + \sum_{i\in I}\sum_{i'\in I}\sum_{j\in J}\left[\bar{x}_{ii'j}\left(r_{i'j}\left(1+v_{i'j}\right)+r_{ii'}\left(1+v_{ii'}\right)\right)\right]}{\sum_{j\in J}\left(d_j N\right)} \quad (13)$$

$$subject\ to\ (3), (5), (6), (7), (8), (9), (10),\ and$$

$$\sum_{i \in I} x_{ij} + \sum_{i \in I} \sum_{i' \in I} \bar{x}_{ii'j} \geq d_j * N \qquad j \in J \qquad (14)$$

$$(r_{ii'} * (1 + v_{ii'}) + r_{i'j} * (1 + v_{i'j}))t_{ii'j} \leq R \qquad i \in I, i' \in I, j \in J, i \neq i' \qquad (15)$$

$$\sum_{j \in J} x_{ij} + \sum_{j \in J} \sum_{i' \in I} \bar{x}_{ii'j} \leq q_i \qquad i \in I, i \neq i' \qquad (16)$$

$$\sum_{i \in I} f_{ii'} \leq 1 \qquad i' \in I, i \neq i' \qquad (17)$$

$$\bar{x}_{ii'j} \leq W t_{ii'j} \qquad i \in I, i' \in I, j \in J, i \neq i' \qquad (18)$$

$$\sum_{j \in J} \sum_{i' \in I} t_{ii'j} \leq W y_i \qquad i \in I, i \neq i' \qquad (19)$$

$$\sum_{j \in J} \sum_{i \in I} t_{ii'j} \leq W y_{i'} \qquad i' \in I, i' \neq i \qquad (20)$$

$$\sum_{i \in I} t_{ii'j} \leq m_{i'j} \qquad i' \in I, j \in J, i \neq i \qquad (21)$$

$$\sum_{j \in J} t_{ii'j} \leq W f_{ii'} \qquad i \in I, i' \in I, i \neq i \qquad (22)$$

$$x_{ij}, \bar{x}_{ii'j}, q_i \geq 0 \qquad i \in I, i' \in I, j \in J, i \neq i' \qquad (23)$$

$$y_i, m_{ij}, t_{ii'j} \in \{0,1\} \qquad i \in I, i' \in I, j \in J, i \neq i' \qquad (24)$$

The objective function (13) again minimizes the average distance travelled per a relief item including the vulnerability effect. Constraint (14) ensures that demand of every demand location is satisfied either directly from relief facilities or through lateral transhipment. Constraints (3) and (15) limit the travel distance of relief items. Constraint (16) ensures that the capacity of a relief facility opened is sufficient to meet total demand assigned to that relief facility. Constraint (17) ensures that any relief facility is allowed to engage in lateral transhipment with at most one neighbour relief facility for a demand location. Constraint (18) ensures that relief item cannot be sent through a relief facility unless lateral transhipment is allowed. Constraints (19-20) allow only the open relief facility pairs to engage in lateral transhipment. Constraint (21) allows that lateral transhipment is engaged with the neighbour relief facility to satisfy the demand of location assigned to that neighbour relief facility. Constraint (22) provides that lateral transhipment can be made for demand location *j* if the related two relief facilities engage in lateral transhipment.

4.3 Model with Maritime Lateral Transhipment option between Supply Points (MLTSP)

For the MLTSP model, this time the index for the ports visited for lateral transhipment is defined as k and k' under the set *K*. We also need to define new parameters namely; v_{ik}, vulnerability factor between relief facility *i* and port *k*, $v_{kk'}$, vulnerability factor between port *k* and port *k'*, r_{ik}, distance between relief facility *i* and port *k*,$r_{kk'}$, distance between port *k* and port *k'*, *cap*, capacity of a ship, n_s, number of ships, s_s, speed of a ship, s_t, speed of a land vehicle (e.g. truck). When we define the additional decision variables as:

$\bar{x}_{ikk'i'j}$: quantity of items sent to location *j* from facility *i* through ports *k* and *k'* and facility *i'*,

$z_{kk'}$: number of ships used between port *k* and port *k'* for the shipment of relief items,

$b_{ikk'i'j}$: $\begin{cases} 1, & \text{if relief facilities } i \text{ and } i' \text{ engages in lateral transhipment through ports } k \text{ and } k', \\ 0, & otherwise. \end{cases}$

the MLTSP model can be written as:

$$Minimize \frac{\sum_{i\in I}\sum_{j\in J}\left[x_{ij}r_{ij}(1+v_{ij})\right] + \sum_{i\in I}\sum_{j\in J}\sum_{i'\in I}\left[\bar{x}_{ii'j}\left(r_{i'j}\left(1+v_{i'j}\right)+r_{ii'}(1+v_{ii'})\right)\right] + \sum_{i\in I}\sum_{k\in K}\sum_{k'\in K}\sum_{i'\in I}\sum_{j\in J}\left[\bar{x}_{ikk'i'j}\left(r_{i'j}\left(1+v_{i'j}\right)+r_{i'k'}(1+v_{i'k'})+r_{kk'}*\left(\frac{s_t}{s_s}\right)*(1+v_{kk'})+r_{ik}(1+v_{ik})\right)\right]}{\sum_{j\in J}(d_j N)} \quad (25)$$

$subject\ to$ (3), (5), (6), (7), (8), (9), (10), (15), (17), (18), (19), (20), (21) and

$$\sum_{i\in I} x_{ij} + \sum_{i\in I}\sum_{i'\in I}\bar{x}_{ii'j} + \sum_{i\in I}\sum_{i'\in I}\sum_{k\in K}\sum_{k'\in K}\bar{x}_{ikk'i'j} \geq d_j * N \qquad j\in J \quad (26)$$

$$(r_{ik}*(1+v_{ik}) + r_{kk'}*\left(\frac{s_t}{s_s}\right)*(1+v_{i'k'}) + r_{k'i'}*(1+v_{i'k'}) + r_{i'j}*\left(1+v_{i'j}\right))*b_{ikk'i'j} \leq R \qquad k,k'\in K; i,i'\in I; j\in J, i\neq i', k\neq k' \quad (27)$$

$$\sum_{j\in J} x_{ij} + \sum_{j\in J}\sum_{i'\in I}\bar{x}_{ii'j} + \sum_{j\in J}\sum_{i'\in I}\sum_{k\in K}\sum_{k'\in K}\bar{x}_{ikk'i'j} \leq q_i \qquad i\in I, i\neq i' \quad (28)$$

$$\bar{x}_{ikk'i'j} \leq W * b_{ikk'i'j} \qquad k,k'\in K; i,i'\in I; j\in J, i\neq i', k\neq k' \quad (29)$$

$$\sum_{j\in J}\sum_{i'\in I}\sum_{k\in K}\sum_{k'\in K} b_{ikk'i'j} \leq W * y_i \qquad i\in I, i\neq i' \quad (30)$$

$$\sum_{j\in J}\sum_{i'\in I}\sum_{k\in K}\sum_{k'\in K} b_{ikk'i'j} \leq W * y_{i'} \qquad i\in I, i\neq i' \quad (31)$$

$$z_{kk'} \leq \sum_{j\in J}\sum_{i\in I}\sum_{i'\in I}\bar{x}_{ikk'i'j} \qquad k\in K, k'\in K, k\neq k' \quad (32)$$

$$\sum_{k\in K}\sum_{k'\in K} z_{kk'} \leq n_s \quad (33)$$

$$\sum_{j\in J}\sum_{i\in I}\sum_{i'\in I}\bar{x}_{ikk'i'j} \leq cap * z_{kk'} \qquad k\in K, k'\in K, k\neq k' \quad (34)$$

$$\sum_{k'\in K}\sum_{i\in I}\sum_{k\in K} b_{ikk'i'j} \leq m_{i'j} \qquad i'\in I, j\in J, i\neq i \quad (35)$$

$$x_{ij}, \bar{x}_{ii'j}, q_i, \bar{x}_{ikk'i'j}, \geq 0 \qquad i\in I, i'\in I, j\in J, i\neq i' \quad (36)$$

$$y_i, m_{ij}, t_{ii'j}, b_{ikk'i'j} \in \{0,1\} \qquad i\in I, i'\in I, j\in J, i\neq i' \quad (37)$$

$$z_{kk'}\ integer \qquad k\in K, k'\in K, k\neq k' \quad (38)$$

The objective function (25) minimizes the average distance travelled per a relief item including the vulnerability affect. Constraint (26) ensures that demand of every demand location is satisfied either directly from relief facilities or through lateral transhipment. Constraints (3), (15) and (27) limit the travel distance of relief item. In Constraint (27) the distance between ports is multiplied by the ratio of speed of land vehicle to speed of ship in order to convert the distances travelled by ship in an hour to the distance travelled by land vehicle in an hour. Constraint (28) ensures that the capacity of a relief facility opened is sufficient to meet total demand assigned to that relief facility. Constraints (18) and (29) ensure that relief item cannot be sent through a relief facility unless lateral transhipment is allowed. Constraints (19-20) and (30-31) allow only the open relief facility pairs to engage in lateral transhipment. Constraints (21) and (35) allow lateral transhipments to neighbour relief facility to satisfy demand of demand location that assigned to that neighbour relief facility. Constraint (32) is used in case there is no relief item shipment between ports, any ship cannot be utilized. Constraint (33) ensures that number of ship is limited. Constraint (34) ensures that shipment amount between ports cannot exceed the total capacity of ships used between that ports. Constraints (36-38) define restrictions on decision variables.

5. Experimental Study Applied for a possible Earthquake at the city of Istanbul

An experimental study is conducted to validate the direct shipment model (DT), lateral transhipment between supply points model (LTSP) and maritime lateral transhipment model (MLTSP). Models are solved by GAMS 24.2 with Cplex 12.6 Solver and the average solution times of the models are provided in Table 1.

<<insert table 1 about here>>

5.1. Data sources

The main data sources utilized in this study are the JICA Report (2002) and Ozkapici et al. (2016). Types of data in the system and the methods to update these data are explained in the following. Data set for the experiments are provided on the online version of this article.

In the JICA report, damage estimations and beneficiary populations are provided based on the districts of Istanbul. As a result, 37 districts of Istanbul are taken as locations of demand. For each district, district centre point is obtained and represented with a single coordinate (N°; E°) calculated as the weighted average of the coordinates of its neighbourhoods. The coordinate of each neighbourhood is taken as the coordinate of the Mukhtar office (i.e. local government office located in each neighbourhood in Turkey) belonging to that neighbourhood. Then, the coordinate of a district is calculated by taking the weighted average of coordinates of its neighbourhoods, where the weights are the populations of the neighbourhoods.

There are 37 potential relief facility locations which are the same as the demand locations. The capacities of potential relief facility locations are estimated from available public school buildings. As a result, the capacity of each potential relief facility is different.

JICA report (2002) states the possible number of heavily, moderately and partly damaged buildings for each district. By using the Equation (39), for each district the average number of people living in one building is calculated.

$$A = \frac{Population\ of\ the\ District}{Number\ of\ Buildings\ in\ the\ District} \qquad (39)$$

The population data of districts in the above formulation are obtained from the Turkish Statistical Institute (2013). The number of people affected from the earthquake in each district is calculated by using the Formula (40) as in the JICA Report (2002) where *B*, *C* and *D* corresponds to number of heavily damaged buildings, moderately damaged buildings and partly damaged buildings, respectively.

$$Number\ of\ affected\ people = A * (100\% * B + 50\% * C + 10\% * D) \quad (40)$$

The number of relief items needed in each district is calculated by the Formula (41). It is assumed that the single relief item is delivered to a family of four people. As a result, formulation includes a multiplication by 0.25 (=*N*).

$$Relief\ items\ required = 0.25 * number\ of\ affected\ people\ in\ that\ district \quad (41)$$

Distances between relief facilities and demand locations and between relief facility pairs are obtained from Google Maps™. The shortest distance between two points is selected from alternatives given by Google Maps™. Travel time of relief item in the system is restricted to ensure that in a determined time interval the relief item reaches to the affected people. Maximum travel time is restricted to one and two hours. In the experimental study, we assume that the relief items are carried by trucks with an average speed of 40 km/h (= s_t).

Vulnerability of the roads between demand locations and relief facilities and between relief facility pairs are determined according to the road blockage probability of 7 - 15 meters wide roads obtained from JICA report. For each colour denoted on Figure 2, vulnerability coefficient is determined and its values are shown in Table 2 for different vulnerability cases.

<<insert Figure 2 about here>>

<<insert Table 2 about here>>

To calculate the vulnerability coefficient of each path between the demand locations and relief facilities and between relief facility pairs, emergency road network proposed by the JICA report (2002) is used. This proposed emergency network is overlapped with the map of the road blockage caused by building collapse on medium width road. The map shown in Figure 2 is divided into equal squares. Shortest path is determined on the emergency road network for each pair of district by using Google Maps™. Then the numbers of red, orange, yellow, green, blue and grey squares are counted on that path. The vulnerability of that path is calculated as the average of the multiplication of the number of coloured squares on the path and the corresponding coefficient of that colour.

The number of classes in public schools in each district is used to determine the capacity of relief facilities. Total number of school classes available in districts is multiplied by 0.9 due to the assumption that 10% of the school classes may be damaged during disaster. The parameter *F* can be interpreted as a service quality level, the equal average number of people to be served from each school class. United Nations High Commissioner for Refugees (UNHCR)

Emergency Handbook (UNHCR, 2015) recommends at least one final distribution point (i.e. a school in our study) for 5,000 people and a maximum 5 km walking distance for beneficiaries.

For the most probable earthquake scenario stated by JICA, number of beneficiaries is calculated as 2,027,467 and the total number of classrooms is calculated to be 61,201 in the 37 districts of Istanbul. If the schools in all 37 districts were used for relief delivery and all of the classrooms were used in Istanbul, the parameter *F* would take a value of 33 (= 2,027,467/61,201). This best case would not manageable due to the coordination complexities and operational costs. Therefore, we vary the parameter *F* between 50 and 100 to reach feasible results. If parameter *F* is taken as 50, beneficiaries walk less than 0.3 km to reach a nearby school classroom for relief distribution and a school serves to at most 750 beneficiaries. If parameter *F* is taken as 100, beneficiaries walk less than 0.5 km to reach a nearby school classroom for relief distribution and a school serves to at most 2,500 beneficiaries on average. These parameters are well below the recommended standards set by the UNHCR.

5.2 Results of DT and LTSP Models

Firstly, solution of DT and LTSP models are presented and compared for varying number of relief facilities (*P*) and maximum number of people (*F*) that can be served from a school classroom. In these models, there is no material shipment between Anatolian side and European side due to the possible damage of the main bridges connecting the two sides of the city of Istanbul. On the other hand, in the model (MLTSP) where maritime transportation is allowed, relief items are transported between Anatolian and European sides and MLTSP model results are compared with the LTSP model results.

DT and LTSP models are solved for varying number of relief facilities (*P*); 15, 20, 25, 30, maximum number of people (*F*) that can be served from a school classroom; 50, 75, 100, vulnerability factor of roads; low, medium, high and maximum allowed distance travelled of relief item (*R*); 40km, 60km, 80km. We observe that the vulnerability factor of the roads and maximum allowed distance travelled of relief item (*R*) do not affect the location of the relief facilities and the lateral transhipment percentages significantly. Therefore, while comparing the models in this section we always assume that the maximum allowed distance travelled of relief item (*R*) is 40 km (its minimum value) and vulnerability factor of roads are high (its maximum value).

As seen on Figure 3, we observe that the average distance travelled per relief item in LTSP model is always equal or better than the average distance travelled value per relief item in DT model as expected since LTSP model is a relaxation of the DT model. Moreover, we also see that to achieve the best service quality level (when only 50 (=*F*) people are served from a classroom) lateral transhipment between the relief facilities is a requirement and at least 25 relief facilities should be opened. For the medium service quality level (*F*=75), the distribution system can be managed both with and without the lateral transhipment but the lateral transhipment flexibility results in around 50% improvement in the average distance travelled per relief item. For the low service quality level (*F*=100), the lateral transhipment option adds no value.

<<insert Figure 3 about here>>

In Figure 4, the percentages of lateral transhipments are presented for LTSP Model. There exists a smooth increase of the percentage of lateral transhipment as the maximum number of people (*F*) that can be served from a school classroom decreases. In other words, as the authorities require a higher quality service to beneficiaries, the lateral transhipment percentage increases. When only 50 people are served from a classroom, at the highest service level, 12-14 % of the relief items are supplied via lateral transhipment. Also as expected, the increase in the number of relief facilities causes the lateral transhipment amount to decrease.

<<insert Figure 4 about here>>

5.3 Inclusion of Maritime Transportation into the LTSP Model

LTSP model allows only land transportation in either side of the city (i.e. Anatolian and European sides). In the case of high vulnerability, sending relief items to demand locations using land vehicles is more difficult due to high risk of road blockages. Hsieh (2014) discussed ports' effect on creating extra transportation capacity and the risk of port failures with respect to vulnerability. Istanbul has many seaports on each side and daily maritime transportation is made between these ports. In case of a disaster, in addition to land transportation these ports can be used to transport relief items.

5.3.1 Distribution System Description and Data Sources of the MLTSP Model

In MLTSP model, transhipment between ports is possible. As a result, two transhipment nodes are added to the existing nodes at this case. Figure 5 illustrates the flow of the relief item in the suggested distribution system.

<<insert Figure 5 about here>>

Istanbul Sea Buses (abbreviated as IDO in Turkish) is the main company on seaway transportation. IDO ports in İstanbul are considered as transhipment points in MLTSP model. Ports are uncapacitated and ships are ready to make shipment of relief item at each port. Ports located at the same side of Istanbul are not allowed to make relief item shipment between each other. In the model MLTSP, one type of ship is used. Capacity is taken as 6,100 relief items and the speed is taken 56 km/h (s_s), averages of available sea bus types. Loading and unloading time is assumed to be small within the overall trip duration. Maximum number of ships that can be utilized for relief item transportation is determined as 25 (n_s), the number of IDO sea buses.

Distances between relief facilities and ports are calculated using Google Maps™. The shortest distance between two points is selected on Google Maps™. Distance between ports are calculated on Google Earth™ as sea miles and then converted to km. The vulnerability between ports is set as 0.001 due to the fact that there is no risk of blockage on the seaway resulting from building collapse.

5.3.2. Comparison of MLTSP Model with LTSP Model

As seen in Figure 6, MLTSP model begins to give better average distance travelled values than LTSP model only when the service level requirement is the highest (F=50). To be able to serve the city of Istanbul at the highest service level (F=50) with 20 relief facilities only, maritime transportation is also a requirement in addition to the lateral transhipment. But when the relief facilities number increases to 25, the distribution system can be managed both with and without the maritime transportation and maritime transportation results in around 7% improvement in the average distance travelled per relief item.

<<insert Figure 6 about here>>

In Figure 7, we observe that the lateral transhipment percentage among the overall distribution amount can increase up to 18% with the inclusion of the maritime transportation option to the distribution system. Interestingly, the percentage of total lateral transhipment in LTSP is greater than the percentage of total lateral transhipment in MLTSP when more than 20 relief facilities are opened at the highest service level (F=50). To understand the reason of having lower percentage of lateral transhipment in the MLTSP model, it should be noted that demand of districts located in European side is larger than the demand of districts located in Anatolian side. In addition to that, the number of classes of districts located in Anatolian side is greater than the number of classes of districts located in European side. These two facts results in relief facilities located in Anatolian side to have more excess inventory to make lateral transhipment between relief facilities.

<<insert Figure 7 about here>>

6. Conclusion

In this study, lateral transhipment opportunities are included into the humanitarian relief chain. Direct shipment model (DT), lateral transhipment model (LTSP) and maritime lateral transhipment model (MLTSP) are developed and these models are compared between each other by using a real life earthquake scenario developed for Istanbul by JICA (Japanese International Cooperation Agency) with varying parameters. Lateral transhipment and maritime transportation with lateral transhipment cases are examined the first time in the literature for the Istanbul case.

Since using highways is more difficult and time consuming in high vulnerability case, all models are studied for the high vulnerability scenario to allow lateral transhipment between both sides of Istanbul via seaway. MLTSP model is compared with LTSP model to examine the effect of lateral transhipment on seaway between Anatolian and European sides of

İstanbul. Since demand of districts located in European side is larger than the demand of districts located in Anatolian side and maximum level of inventory holding capacity of districts (number of school classes of districts) located in Anatolian side is greater than maximum level of inventory holding capacity of districts located in European side, all lateral transhipment on seaway is directed from Anatolian side to European side.

We use the classes in public schools in each district as the relief facilities which directly serve to beneficiaries. Thus, the number of people served from a classroom represents a quality level of the service provided to the beneficiaries in this study. We observe that to achieve the highest service quality (when only 50 people are served from a classroom), minimum number of relief facilities to open is 25 only if lateral transhipment is utilized. This number decreases to 20 if maritime transportation is also allowed and the percentages of lateral transhipments are significant under these settings.

Although maritime transportation brings a small improvement to the system only for the high service level requirements, it could still be a promising alternative with additional ports and ships. With the medium service quality level, the distribution system can be managed both with and without the lateral transhipment but the lateral transhipment flexibility results in around 50% improvement in the average distance travelled per relief item over direct shipment model.

The most probable earthquake scenario stated by the JICA Report is used in this study. All of four scenarios in the JICA report can be studied together by developing stochastic models in the future. Developed models have relaxing assumptions on the capacity and number of land vehicles, loading/unloading time for LTSP and MLTSP model. These assumptions can be abandoned in the future.

References

1. Afshar A and Haghani A (2012). Modeling integrated supply chain logistics in real-time large-scale disaster relief operations. *Socio-Economic Planning Sciences* **46**(**4**): 327-338.
2. Altay N and Green WG (2006). OR/MS research in disaster operations management. *European Journal of Operational Research* **175(1):** 475-493.
3. Axsater S (1990). Modeling emergency lateral transhipments in inventory systems. *Management Science* **36:** 1329–1338.
4. Axsater S (2006). Inventory control (2nd ed.). Springer:New York.

5. Balçık B and Beamon BM (2008). Facility location in humanitarian relief. *International Journal of Logistics: Research and Applications***11(2):**101–121.
6. Barbarosoglu G and Arda Y (2004). A two-stage stochastic programming framework for transportation planning in disaster response. *Journal of the Operational Research Society* **55:** 43-53.
7. Bemley JL, Davis LB and Brock III LGB (2013). Pre-positioning commodities to repair maritime navigational aids. *Journal of Humanitarian Logistics and Supply Chain Management***3:** 65-89.
8. Caunhye AM, Nie X and Pokharel S (2012). Optimization models in emergency logistics: A literature review. *Socio-Economic Planning Sciences* **46:** 4-13.
9. Duran S, Ergun O, Keskinocak P and Swann J (2013). Humanitarian Logistics: Advanced Purchasing and Pre-positioning of Relief Items. Handbook of Global Logistics. In: Springer (Ed.). *International Series in Operations Research & Management Science:* New York, pp 447-462
10. Duran S, Gutierrez MA and Keskinocak P (2011). Pre-positioning of emergency items worldwide for CARE international. *Interfaces* **41:** 223-237.
11. Galindo G and Batta R(2013). Prepositioning of supplies in preparation for a hurricane under potential destruction of prepositioned supplies. *Socio-Economic Planning Sciences***47**(**1**): 20-37.
12. Guha-Sapir D, Hoyois P, Below R(2014). *Annual Disaster Statistical Review 2013: The Numbers and Trends*. Brussels: CRED.
13. Horner MW, Widener MJ (2011).The effects of transportation network failure on people's accessibility tohurricane disaster relief goods: a modeling approach and application to a Florida case study. *Natural Hazards***59**(**3**):1619–1634
14. Hsieh CH (2014). Disaster risk assessment of ports based on the perspective of vulnerability. *Natural Hazards***74**(**2**):851–864.
15. Huang M, Smilowitz K and Balcik B(2012). Models for relief routing: Equity, efficiency and efficacy. *Transportation research part E: logistics and transportation review***48**: 2-18.
16. JICA Report (2002). The study on a disaster prevention/mitigation basic plan in Istanbul including seismic micronization in the Republic of Turkey. Final Report. Japan International Cooperation Agency, December.
17. Khayal, D., Pradhananga, R., Pokharel, S., & Mutlu, F. (2015). A model for planning locations of temporary distribution facilities for emergency response. *Socio-Economic Planning Sciences*, 52, 22-30.
18. Kutanoglu E and Mohajan M (2009). An inventory sharing and allocation method for a multi-location service parts logistics network with time-based service levels. *European Journal of Operational Research* **194:**728-742.
19. Lee HL (1987). A multi-echelon inventory model for repairable items with emergency lateral transhipments. *Management Science* **33:** 1302-1316.

20. Lin, Y. H., Batta, R., Rogerson, P. A., Blatt, A., & Flanigan, M. (2012). Location of temporary depots to facilitate relief operations after an earthquake. *Socio-Economic Planning Sciences*, *46*(2), 112-123.
21. Mete HO and Zabinsky BZ (2010). Stochastic optimization of medical supply location and distribution in disaster management. *International Journal of Production Economics* **126:** 76-84.
22. Mulyono NB and Ishida Y (2013). Humanitarian logistics and inventory model based on probabilistic cellular automata. *International Journal of Innovative Computing, Information and Control* **10:** 357-372.
23. Ozkapıcı BD, Ertem MA and Aygüneş H (2016). Intermodal Humanitarian Logistics Model Basedon Maritime Transportation in Istanbul. *Natural Hazards*, DOI: 10.1007/s11069-016-2318-9.
24. Reyes P, Man J and Jaska P (2013). A disaster relief inventory model based on transhipment. *Independent Journal of Management & Production* **4:** 481-509.
25. Stanger SHW, Wilding R, Hartmann E, Yates N,Cotton S (2013). Lateral transshipments: an institutional theory perspective. *International Journal of Physical Distribution & Logistics Management* **43**(**9**): 747 – 767.
26. Tatham PH and Pettit SJ (2010). Transforming humanitarian logistics: the journey to supply network management. *International Journal of Physical Distribution & Logistics Management* **40:** 609-622.
27. Thomas A and Fritz L (2006). Disaster Relief, Inc. *Harvard Business Review* 1-11.
28. Thomas A and Mizushima M (2005). Fritz institute: Logistics training: necessity or luxury?. *Forced Migration Review* **22:** 60-61.
29. Turkish Statistical Institute, (2013), *"2012 Address Based Population Registration Results"*
30. Ukkusuri SV and Yushimito WF (2008). Location routing approach for the humanitarian pre-positioning problem. *Journal of the Transportation Research Board* **2089:** 18-25.
31. UNHCR (2015). Emergency Handbook:A UNHCR guide to agile, effective and community based humanitarian emergency responses, Available at https://emergency.unhcr.org/ (retrieved on 8th May 2016)
32. Van Wassenhove LN (2006). Humanitarian aid logistics: supply chain management in high gear. *Journal of Operational Research Society* **57:** 475-489.
33. Wong H, Van Houtum GJ, Cattrysse D and Van Oudheusden D (2006). Multi-item spare parts systems with lateral transhipments and waiting time constraints. *European Journal of Operational Research* **171:** 1071-1093.

Table 1: Average Solution Times of the Models

	DT Model	LTSP Model	MLTSP Model
Avg Solution Time (min.)	1	5	30

Table 2: Vulnerability Coefficient of Each Severity Colour for Different Vulnerability Scenarios

	Vulnerability Coefficient		
	Low Vulnerability	*Average Vulnerability*	*High Vulnerability*
Red	0.50	0.75	0.99
Orange	0.30	0.40	0.50
Yellow	0.20	0.25	0.30
Green	0.10	0.15	0.20
Blue	0.05	0.075	0.10
Grey	0	0.025	0.05

Figure Captions

Figure 1: Relief Item Flow in the Distribution System

Figure 2: Road Blockage Caused by Building Collapse Medium Width (7-15m) Road (JICA report, 2002)

Figure 3: Average Distance Travelled for DT and LTSP Models under High Vulnerability when *R*=40 km

Figure 4: Percentages of Lateral Transhipment for LTSP Model for *R*=40 km for High Vulnerability Factor

Figure 5: Relief Item Flow in the Distribution System Defined for MLTSP

Figure 6: Average Distance Travelled in MLTSP and LTSP Models when *R*=40 km, High Vulnerability Factor

Figure 7: Percentages of Lateral Transhipment in MLTSP and LTSP Models when *R*= 40 km, High Vulnerability Factor

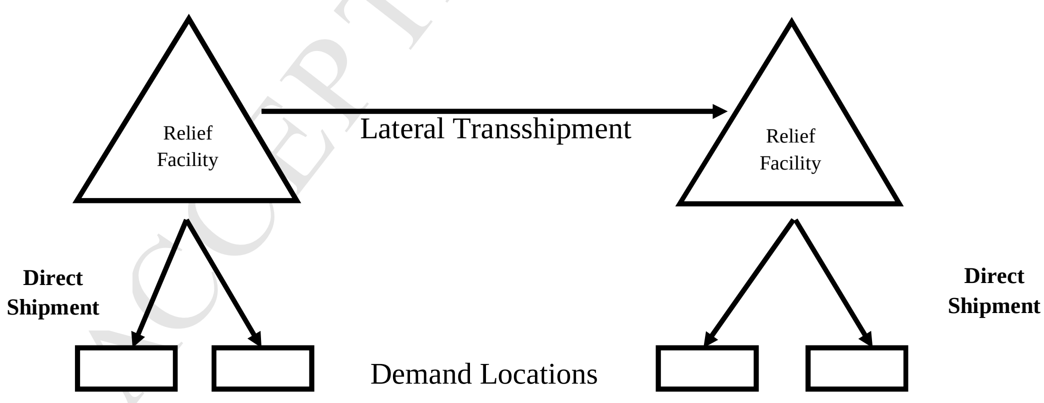

Figure 1: Relief Item Flow in the Distribution System

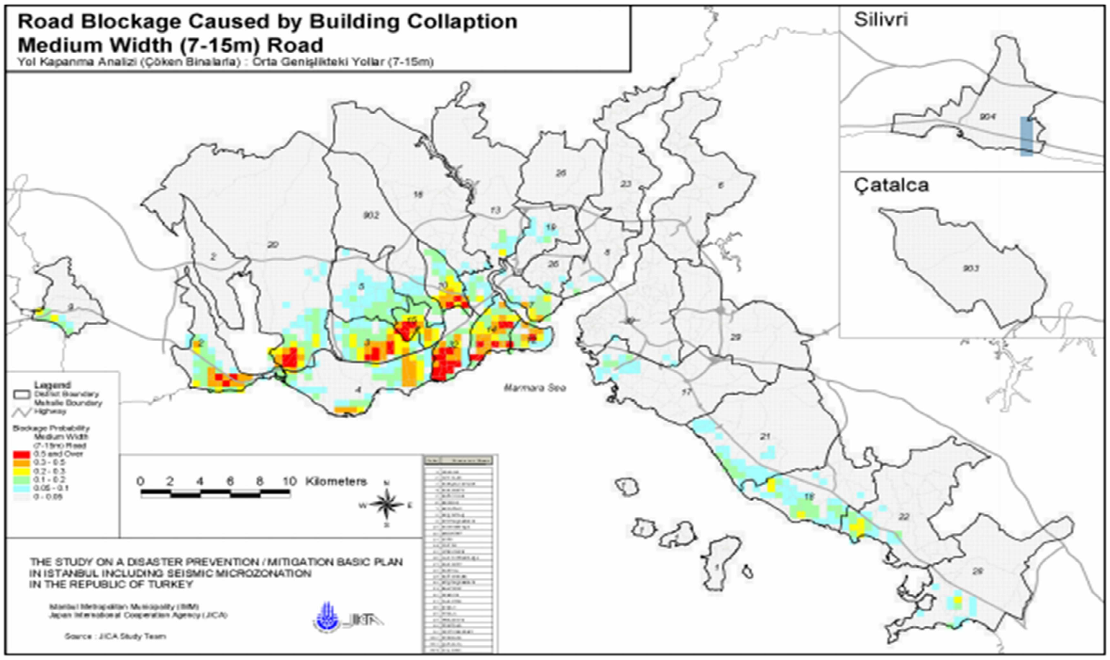

Figure 2: Road Blockage Caused by Building Collapse Medium Width (7-15m) Road (JICA report, 2002)

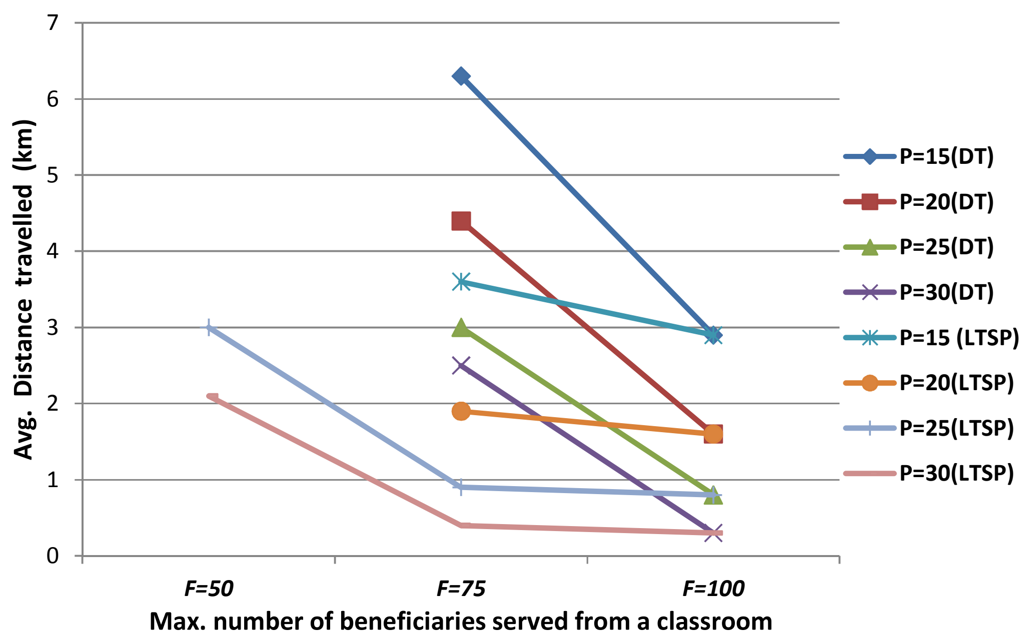

Figure 3: Average Distance Travelled for DT and LTSP Models under High Vulnerability when *R*=40 km

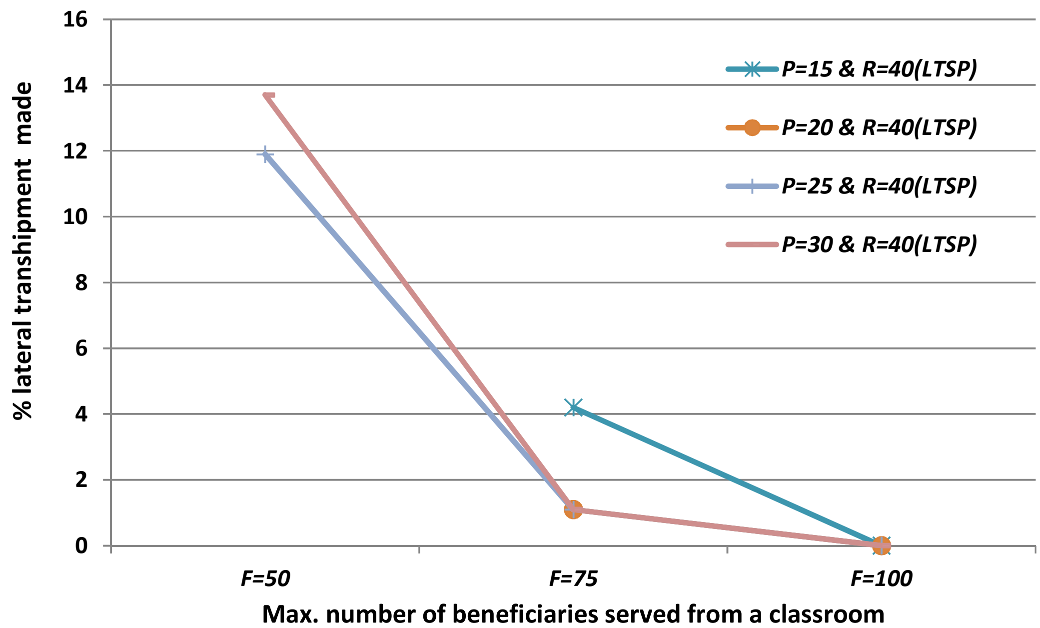

Figure 4: Percentages of Lateral Transhipment for LTSP Model for *R*=40 km for High Vulnerability Factor

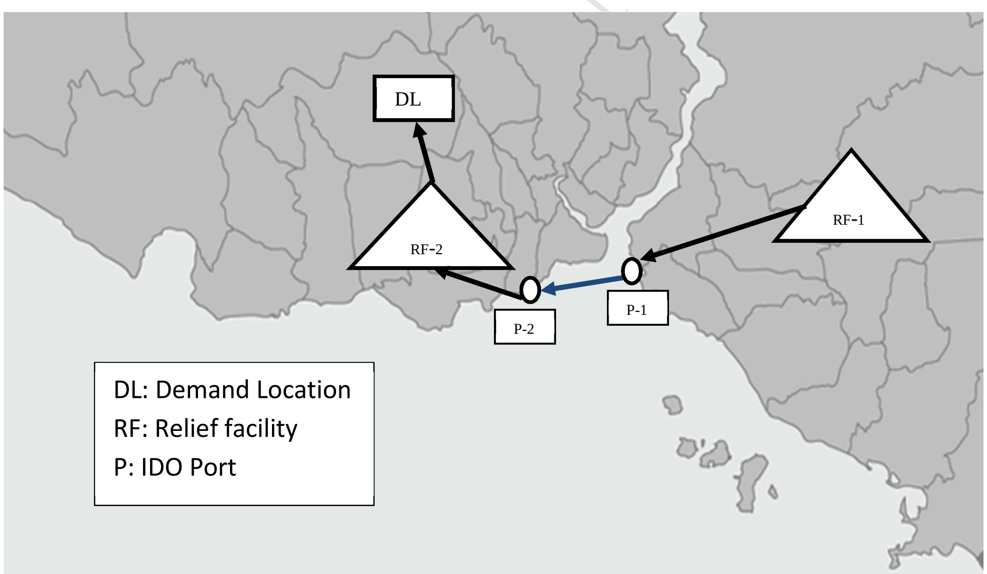

Figure 5: Relief Item Flow in the Distribution System Defined for MLTSP

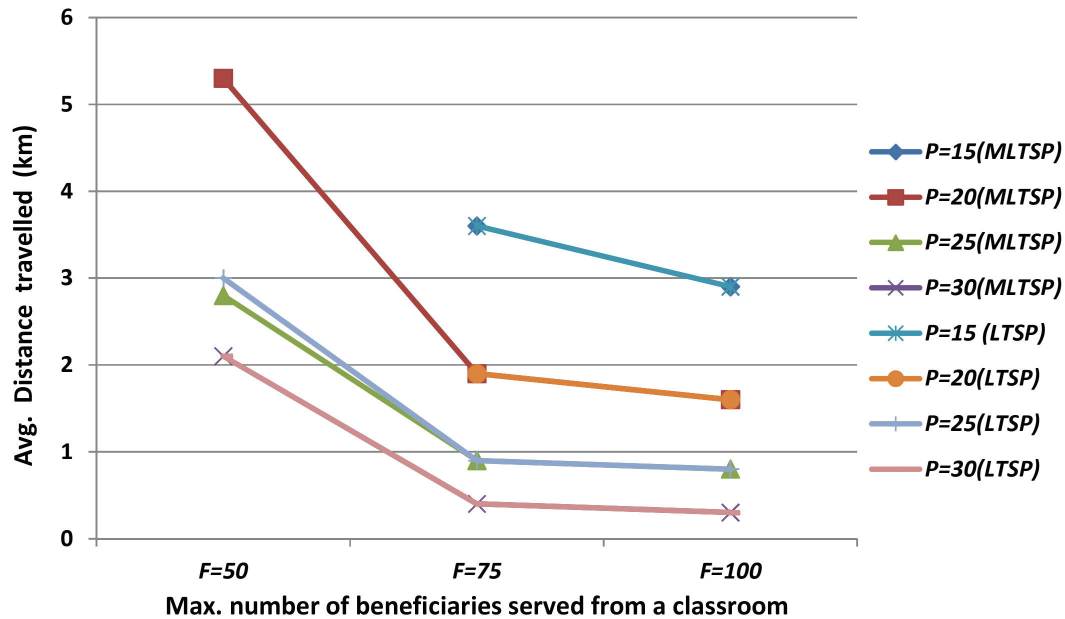

Figure 6: Average Distance Travelled in MLTSP and LTSP Models when *R*=40 km, High Vulnerability Factor

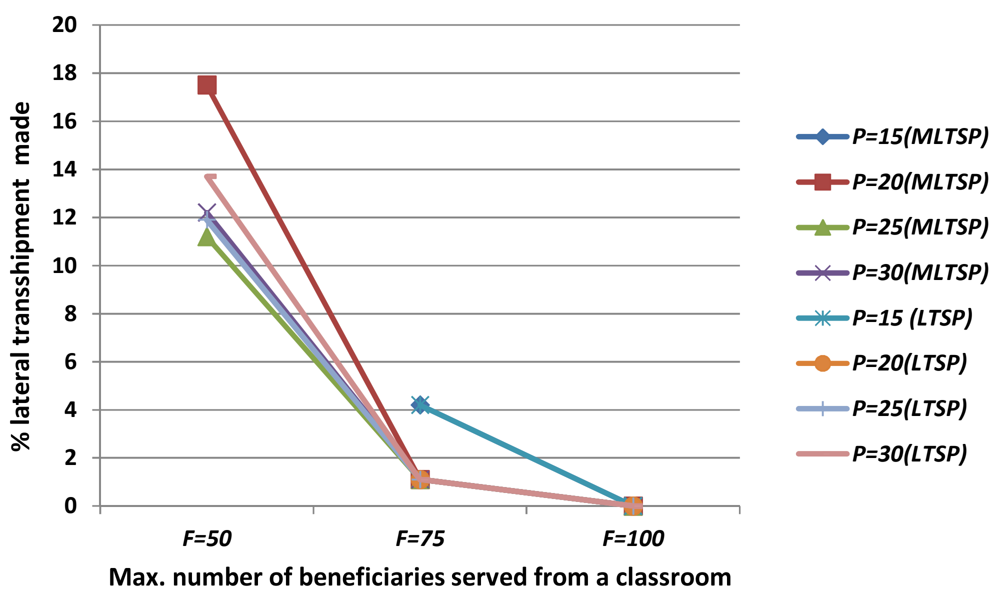

Figure 7: Percentages of Lateral Transhipment in MLTSP and LTSP Models when *R*= 40 km, High Vulnerability Factor

Highlights

- Lateral transhipment is modeled for humanitarian logistics
- Pre-positioning and transportation decisions are addressed
- Heterogeneous capacitated facilities (i.e. schools) are utilized
- Higher service levels require lateral transhipment
- A real life earthquake scenario for Istanbul is used in experiments
- Maritime transportation option is added to lateral transhipment model

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