A Stochastic Optimization Approach for Locating Humanitarian Disaster Relief Centers

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Abstract
This paper discusses a 4-stage location-allocation disaster relief network. The objective of the proposed network design approach is to minimize the travel time from commercial storage centers to distribution centers, and from distribution centers to demand centers, closest to the affected area. Various scenarios of disasters occurrence, scenario-dependency of storage and distribution centers' capacities, transportation disturbances and lost capacities, and various types of transportation modes have also been considered in the form of constraints. The proposed approach has been applied to a real case study in northern Tehran and the results have been thoroughly analyzed and discussed.

Keywords
Humanitarian supply chain, stochastic disturbance, optimization, capacity loss, transportation modes

1. Introduction
Natural disasters (e.g., earthquakes, floods, tornados, etc.) are hard to predict ahead of time, and they often lead to serious injuries and significant property and infrastructure damages. The value of using a relief model in response planning to prevent and mitigate the impact of these catastrophic events is undeniable. This paper discusses such a model of a humanitarian supply chain based on a real-world example. The purpose of the proposed model is to minimize the relief delivery time while satisfying the demands of the affected area population. To reflects reality, the model is stochastic, with both disturbance and capacity loss of the relief storage and distribution accounted for.

2. Literature Review
High effectiveness and timeliness of post-disaster relief is critical to maximize assistance to the victims and survivors and minimize mortality and financial losses. A significant body of research on various aspects of humanitarian supply chains has been carried out in the past decade. To find the best solution improving chances of survival, various approaches such as, for example, mathematical optimization, simulation, system design and decision making have been explored in the context for most common disasters, such as floods, earthquakes and hurricanes.

2.1. Mathematical Optimization approach
Finding an optimal humanitarian supply chain design by using mathematical models is one of the most common approaches. For instance, (Das and Hanaoka, 2013) have suggested a single-objective, single-period robust location-allocation model in which the cost of distributing relief commodities has been minimized. (Özdamar *et al.*, 2014) have proposed a multi-objective, single period deterministic location-routing model in which the cost of debris cleanup operations have been minimized. (Bai, 2016) has proposed a single-objective, multi-period fuzzy location model in which cost, travel time and unmet demand of relief commodities have been minimized. (Alem *et al.*, 2016) have recommended a single-objective, multi-period stochastic location model in which the cost of distributing relief commodities has been minimized. (Pramanik *et al.*, 2016) have suggested a multi-objective, multi-period fuzzy location model in which both cost and travel time of relief commodities have been minimized. (Rezaei-Malek *et al* 2016) have offered a multi-objective, multi period robust location model in which both costs and response time for relief commodities and establishing storage sites have been minimized. (Haghi *et al.* 2017) have proposed a multi-objective, single-period stochastic location-allocation model in which the cost has been minimized and the coverage of distributing relief commodities and curing injured people have been maximized. (Jha *et al.*, 2017) have suggested a multi-objective, single-period stochastic location-allocation-routing model in which the cost has been minimized and the coverage of distributing relief commodities and transferring victims to shelters have been maximized. (Noham

and Tzur 2017) have proposed a single-objective, multi-period stochastic location-allocation model in which the coverage of storage sites in the preparation phase has been maximized.

2.2. Simulation approach

In order to explore how a relief model will perform in realistic scenarios, some researches have used simulation approach. For example, (Bayram *et al*., 2015) have recommended a multi-objective, single period deterministic location-routing model in which the travel time for transferring victims to shelters has been minimized. (Zheng et al., 2015) have suggested a single objective, single-period deterministic routing model in which the travel time for distributing relief commodities has been minimized. (Verma and Gaukler, 2015) have recommended a single-objective, single-period stochastic location model in which the cost of establishing storage sites in the preparation phase has been minimized.

2.3. System Design approach

Among all the system design tools, GIS is the most common tool which has been implemented in the papers. As an example, (Najafi *et al*., 2013) have proposed a multi-objective, multi-mode, multi-commodity, and multi-period robust model in which unmet demands for relief commodities and unserved injured people has been minimized. (Ahmadi *et al*., 2015) have proposed a multi-objective, multi-period stochastic location model in which the travel time of distributing relief commodities have been minimized. (Hu *et al*., 2015) have recommended a multi-objective multi period deterministic location model where the travel time of distributing relief commodities has been minimized.

2.4. Decision Making approach

AHP method is one of the most important tools of decision making. For instance, (Ye *et al*., 2015) have used this method and suggested a single-objective single-period deterministic location-allocation model in which the number of storage sites in the preparation phase has been minimized.

2.2. Multi-methods approach

A number of other researchers have used a combination of methods to design a humanitarian supply chain model. (Afshar and Haghani, 2012) have presented a single-objective location-routing deterministic model which its goal was to minimize unmet demands for relief commodities through damaged points. (Barzinpour and Esmaeili, 2014) has recommended a multi-objective, single-period deterministic location-allocation model in which the coverage of the supply chain has been maximized and its total cost has been minimized. (Jabbarzadeh *et al*., 2014) have suggested a single-objective, multi period robust location-allocation model in which the total cost of supplying blood for victims has been minimized. (Kilci *et al*., 2015) have proposed a single-objective, single-period deterministic location-allocation model in which the coverage for transferring victims to shelters has been minimized. (Hong *et al*., 2015) have suggested a multi-objective, single-period stochastic location model in which the costs of improving routes' reliability to accelerate relief services have been minimized. (Salman and Yücel, 2015) have advised a single-objective, single-period stochastic location-allocation model in which the coverage has been maximized in order to improve routes' reliability for accelerating relief services. (Marcelin *et al*., 2016) have advised a single-objective single-period deterministic location-allocation model in which the cost of distributing relief commodities has been minimized.

3. Problem Statement

Humanitarian supply chain (HSC) can be considered as the key element of mitigating impacts of disaster because it addresses a range of disasters-related issues, such as, for example, disaster preparedness, supplies and services delivery to victims, debris cleanup and renovation. In this paper, the key decision parameters have been identified in order to optimize the disaster responsiveness. The humanitarian supply chain model of this study consists of the four stages:

1. Commercial storage centers
2. Distribution centers
3. Demand centers
4. Damaged area

In addition, to make the model more realistic, a few additional assumptions have been implemented:

- Given that natural disasters are unpredictable; the proposed model is stochastic by nature. For this assumption, we consider various scenario of disasters occurrence.

- In addition, when a natural disaster strikes, it can lead to capacity loss and disruption for both commercial storage and distribution centers. Therefore, a specific percentage of capacity loss and disruption has been assumed for each of the commercial storage and distribution centers.
- Given the extent of a disaster, some affected areas may need to be supplied from several distribution centers. Therefore, it has been assumed that several demand centers should been established in these areas in order to be fair and make sure that all demands have been timely met.
- Each commercial storage center, distribution center and demand center has its own capacity which should be identified and during the planning phase.
- Each damaged area's demands have been estimated and specified based on prior demographic analysis.
- Moreover, different transportation modes may be required to deploy for relief transfer commodities from commercial storage centers to distribution centers, and then from distribution centers to demand centers. Each of these transportation modes has an its own capacity, pace and planning.
- Figure 1 shows the proposed model, consisting of four stages. There are multi distribution centers which receive relief supplies and services from commercial storage centers and deliver them to demand centers at the time of disaster occurrence or soon afterwards. Demand centers will deliver relief supplies to the damaged area by considering the need of each area.

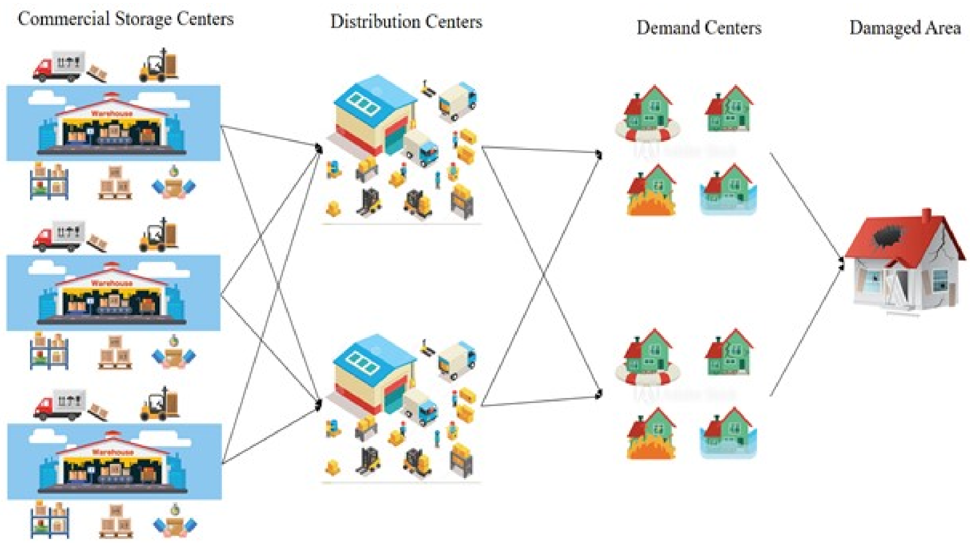

Figure 1. Schematic view of the humanitarian supply chain network

4. Mathematical Model

In this section the stochastic mathematical model is presented. Notations used in the model and their definitions are outlined in Table 1 in the Appendix 1.

4.1.Objective

The objective of the model is to minimize the travel time from commercial storage centers to distribution centers, and from distribution centers to demand centers.

$$min \sum_{s} P^s * (\sum_{i} \sum_{j} \sum_{r} LP_{ij}^{r} NV_{ij}^{rs} + \sum_{j} \sum_{m} \sum_{k} L_{jk}^{m} * Xs_{jk}^{ms}) \quad (1)$$

4.2.Constraints

The problem is subject to a variety of constraints which have been previously mentioned.

$$\sum_{m} \sum_{k} Xs_{jk}^{ms} \leq C_j * Y_j * (1 - a_j^s) \; \forall j, s \quad (2)$$

Equation (2) indicates that for each distribution center and under each scenario, the quantity transferred commodity from distribution center j to demand point k with transportation mode m and under scenario s should be lower than the capacity of distribution center j if it has been opened.

$$\sum_{m}\sum_{j} Xs_{jk}^{ms} = d_k^s \,\forall k, s \tag{3}$$

Equation (3) indicates that for each demand center and under each scenario, the transferred commodity from distribution center j to demand point k with transportation mode m and under scenario s should be equal to the demand of node k under scenario k.

$$\sum_{r}\sum_{j} NV_{ij}^{rs} \leq U_i * Cap_i * (1 - b_i^s) \forall i, s \tag{4}$$

Equation (4) indicates that for each storage center and under each scenario, the transferred commodity from demand center i to distribution center j with transportation mode r and under scenario s should be lower than the capacity of storage center i if it has been opened.

$$\sum_{i} U_i \leq NI \tag{5}$$

Equation (5) indicates that the number of established storage centers should be lower than Maximum number of open storage centers.

$$\sum_J Y_j \leq NJ \tag{6}$$

Equation (6) indicates that the number of established distribution centers should be lower than Maximum number of required distribution centers.

$$\sum_r \sum_i NV_{ij}^{rs} = \sum_m \sum_k Xs_{jk}^{ms} \,\forall j, s \tag{7}$$

Equation (7) indicates that for each distribution center and under each scenario, the total quantity of transferred commodities from distribution center j to demand point k with transportation mode m and under scenario s should be equal to the total amount of transferred commodities from demand center i to distribution center j with transportation mode r and under scenario s.

$$NV_{ij}^{rs} \leq Kap_r \forall i, j, r, s \tag{8}$$

Equation (8) indicates that for each storage center, each distribution center, each transportation mode from storage center to distribution center, and under each scenario, the transferred commodity from storage center i to distribution center j with transportation mode r and under scenario s should be less than the capacity of transportation mode r.

$$Xs_{jk}^{ms} \leq Zar_m \forall k, j, s, m \tag{9}$$

Equation (9) indicates that for each distribution center, each demand center, each transportation mode from distribution center to demand center, and under each scenario, the transferred commodity from distribution center j to demand point k with transportation mode m and under scenario s should be less than the capacity of transportation mode m.

$$U_i, Y_j \epsilon \{0,1\} \forall i, \forall j \tag{10}$$

$$NV_{ij}^{rs}, Xs_{jk}^{ms} \geq 0 \forall i, \forall j, \forall k, \forall r, \forall m, \forall s \quad (11)$$

Finally, equations (10-11) indicate the type of decision variables used in the model.

5. Case Study

With about 14.5 million inhabitants in its metropolitan area, Tehran, Iran, is one of the most populous cities in the world. Due to its location, the city is vulnerable to both earthquakes and floods (Fig. 2). Tehran is also ranked 6th globally as most vulnerable to natural disasters, particularly earthquakes. The earthquake disaster has been chosen as the case study for analysis. Among 22 districts of Tehran, the northernmost 6 districts (Fig. 3) are considered to be most vulnerable to earthquakes. That regions are home to almost 4 million people. These regions (1, 2, 3, 4, 5 and 22) have been chosen as the locations of potential demand centers in the case study.

The supply chain design aims to minimize the travel times from commercial storage centers to distribution centers, and from distribution centers to demand centers. It is assumed that the distribution centers are located in the same districts as well. As a result, overall supply chain's responsiveness is also optimized.

In order to maximize both the responsiveness and coverage, 22 commercial storage centers have been considered in all 22 districts of Tehran. Therefore, some of these centers may be affected by the earthquake and lose some parts of their capacity. The distances from commercial storage centers to distribution centers, and from distribution centers to demand centers have been estimated by using Google Maps online service. Water, food, blankets, and temporary shelters have been considered as essential commodities. Moreover, in order to consider various scenarios, three severity levels for the magnitude of the earthquakes, regardless to the earthquakes' locations has been assumed. These levels are massive, (7 to 10 degrees on a Richter's scale), medium (5 to 7 degrees) and mild (3 to 5 degrees), respectively.

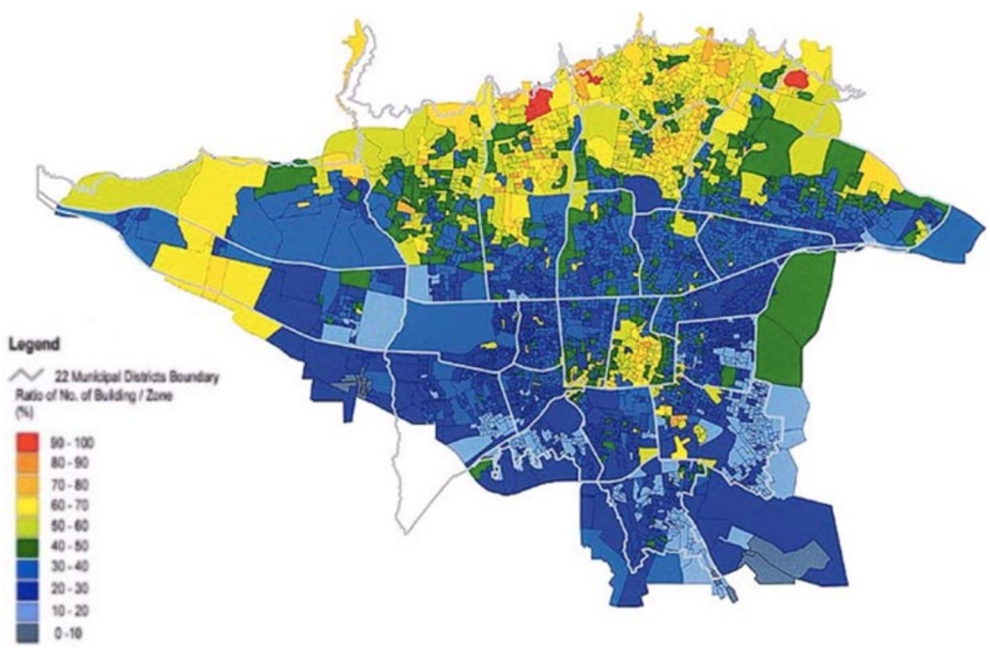

Figure 2. Tehran's vulnerability to earthquakes (Municipality of Tehran, 2010)

The needs of each demand centers after the disaster have been estimated by experts' opinion for each scenario. In the first scenario, the demand of each node will affect 2 percent of its population, in the second scenario will be 1 percent of its population and in the last scenario will be 0.5 percent of its population. Two modes of transportation have been suggested in this paper. Tables 2 and 3 show transportation modes from commercial storage centers to distribution centers, and from distribution centers to demand centers, respectively.

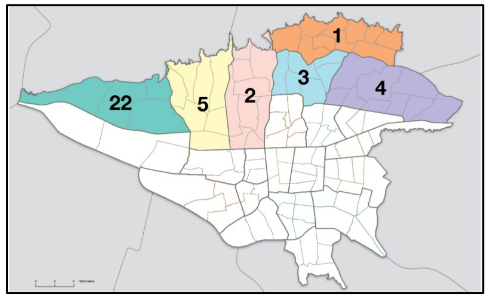

Figure 3. The case study's selected demand centers

Table 2. Transportation modes between commercial storage and distribution centers

Transportation Mode	**Single Capacity (m^2)**	**Number**	**Total Capacity**
Trailer	170	325	55250
Container	45	325	14625

Table 3. Transportation modes between distribution and demand centers

Transportation Mode	**Single Capacity (m^2)**	**Number**	**Total Capacity**
Truck	18	350	6300
Mini-Truck	10	350	3500
Pickup Truck	14	350	4900

Maximum number of open commercial storage centers is set at 18, and maximum number of required distribution centers is set at 8. In addition, since both commercial storage centers and distribution centers have been located in relative proximity, a probability of capacity loss has been considered for both commercial storage and distribution centers under considered scenarios. The highest probability of capacity loss would belong to the first scenario and the lowest of loss capacity would belong to the last scenario.

6. Results and Analysis

The proposed model has been implemented in GAMS win64 24.1.2 using Interl® Core™ i3-3110M CPU 2.4 GHz processor with 4 GB of RAM. Summary of the results have been provided in both Table 4 and Figure 4. The first column of the obtained results shows what would be the minimum value of the model's if we consider both travel time of various transportation modes, and the amount of delivered relief supplies. The next two other columns show the optimal locations of Commercial Storage Centers and Optimal Distribution Centers. In addition, Figure 4 shows where this optimal commercial storage centers and distribution centers will be located on the map.

Table 4. Summary of the results

Objective Value	**Optimally Located Commercial Storage Centers**	**Optimally Located Distribution Centers**
474,390	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 15, 16, 17, 18, 19, 21, 22	1, 2, 3, 5, 6, 8, 9, 10

In order to further analyze the results, sensitivity of the objective function value to changes in probability of loss capacity of both commercial storage centers and distribution centers have been analyzed. The results are shown in Figures 5. As can be seen in Figure 5, by increasing the probability of distribution center's capacity loss, the value of the objective will be increased either. This is because if the capacity loss of a distribution center increased, personnel from the demand centers must travel further to satisfy their need. Therefore, the travel time would increase.

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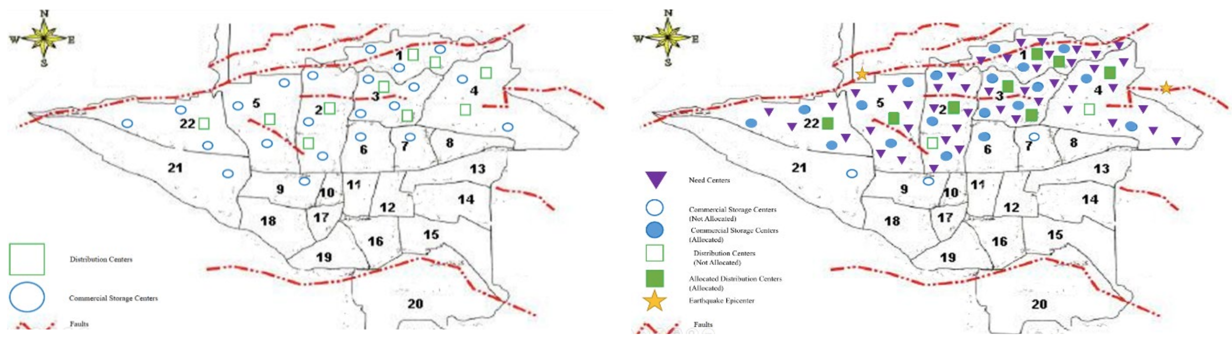

Figure 4. Maps of the affected areas. A. Original setup of the storage and distribution centers; B: Location of the epicenter and demand centers – solid items indicate storage and distribution centers selected through optimization.

Similarly, as Figure 5 shows, by increasing the probability of commercial storage center's capacity loss, the value of the objective will be increased as well. This is because if the capacity loss of a commercial storage increased, distribution centers must travel further to satisfy their need. Therefore, the travel time would increase. In addition, it would impossible to increase the probability of capacity loss of distribution centers more than what have been assumed for solving the model.

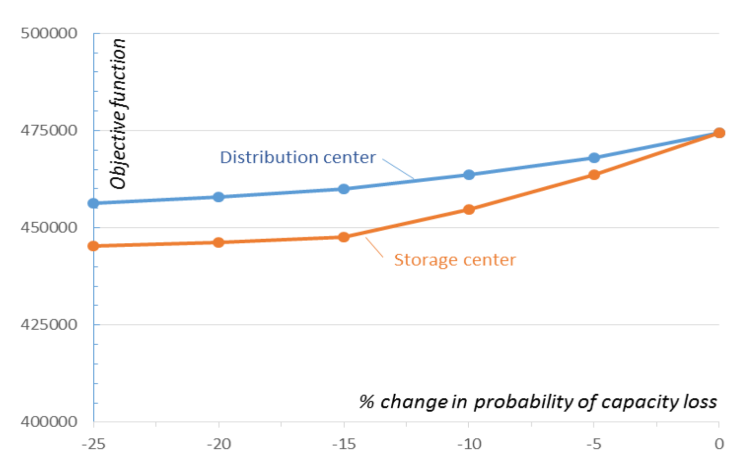

Figure 5. Sensitivity of the objective function to changes in probability of capacity losses of commercial storage and distribution centers

7. Validation

The preliminary validation of the proposed model was carried out by using random numbers. In this method, the value of the objective function was obtained repeatedly in multiple runs by using random numbers instead of real data. (Sargent, 2011) In order to obtain fairly accurate validation, the mean of the value of the random number's objective functions after 50 runs has been compared with the value of the objective value which has been obtained by using real data. Table 5 shows the results. Since the standard deviation which has been represented in Table 5 is really low compare to the objective function value, it can be realized that the proposed model is validated. Besides, the desirability of the real data's objective function value is more than the desirability of the mean of random number's objective functions value, and this can be considered as another sign of model's validation.

Table 5. Validation Results

Real Data's Objective Function Value	The Mean of Random Number's Objective Functions Value	Standard Deviation
474,390	477,722	2,689

8. Conclusions and Future Work

8.1. Conclusion

In this paper, the humanitarian supply chain design has been represented in the form of a stochastic optimization model. The proposed model has been applied to specific data and conditions in the northern regions of Tehran. Decision variables of this model include the location of commercial storage centers and distribution centers, and the amounts of allocated commodities from commercial storage centers to distribution centers, and from distribution centers to demand centers. The effect of various scenarios of occurring disasters, the probability of capacity loss in both commercial storage centers and distribution centers and different transportation modes from commercial storage centers to distribution centers and from distribution centers to demand centers on the travel time have been analyzed in this model.

8.2. Future Recommendations

Considering pre-disaster phase, perishability of relief commodities (such as drugs), uncertainty in the delivery time of commodity, shortage and the ability to add or remove transportation modes can be considered as the potential future research directions.

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Appendix 1 Notation

Table 1. Notations used in the mathematical model

Sets and Indices

I	Set of commercial storage centers $i\epsilon I$	S	Set of scenarios
J	Set of distribution centers $j\epsilon J$	R	Set of transportation modes from storage centers to distribution centers $r\epsilon R$
K	Set of demand points $k\epsilon K$	M	Set of transportation modes from distribution centers to demand centers $m\epsilon M$

Parameters

C_j	Capacity of distribution center *j*	Zar_m	Capacity of transportation mode *m* from distribution centers to demand centers
Cap_i	Capacity of storage site *i*	NI	Maximum number of open storage centers
a_j^s	Probability of lost capacity of distribution center *j* under scenario *s*	NJ	Maximum number of required distribution centers
b_i^s	Probability of lost capacity of storage center *j* under scenario *s*	P^s	Probability of scenario *s* occurring
d_k^s	Demand of node k under scenario *s*	LP_{ij}^r	Travel time for vehicle r between nodes *i* and *j*
Kap_r	Capacity of transportation mode *r* from storage centers to distribution centers	L_{jk}^m	Travel time for vehicle m between nodes *j* and *k*

Variables

U_i	Binary variable. Equals to 1 if storage center *i* is open and zero otherwise.
Y_j	Binary variable. Equals to 1 if distribution center *j* is open and zero otherwise.
Xs_{jk}^{ms}	Quantity of assigned commodity from distribution center *j* to demand center *k* with transportation mode *m* under scenario *s*
NV_{ij}^{rs}	Quantity of assigned commodity from storage center *i* to distribution center *j* with transportation mode *r* under scenario *s*