A Multi-stage Stochastic Programming for Redesigning the Relief Logistics Network: A Real Case Study

Hamidreza Rezaei*
Department of Industrial Engineering, Yazd University, Yazd, Iran
+982166803083
Hamidreza.rezaei21@gmail.com

Hasan Khademi Zare
Department of Industrial Engineering, Yazd University, Yazd, Iran
+983531232423
hkhademiz@yazd.ac.ir

Mahdi Bashiri
Department of Industrial Engineering, Shahed University, Tehran, Iran
+98 3319118651
bashiri.m@gmail.com

M. B. Fakhrzad
Department of Industrial Engineering, Yazd University, Yazd, Iran
+989131548146
mfakhrzad@yazd.ac.ir

ABSTRACT
Disasters inevitably cause sweeping problems affecting all surroundings. Therefore, it seems that right decision making for agile and efficient management in disaster management is not negligible. Due to designed network in the past, current entities, facilities and network may not be optimal and to a great extent usable. In this paper a comprehensive model and solving approach have been proposed to redesign the relief network in dealing with the preparedness and response phases. In this regard, previous investigations on the preparedness phase have often been limited to the location of eligible facilities without considering other important factors such as current and working assets, entities and configuration. Thus, the present study proposes a reconfiguring and repositioning model in order to simultaneously assess whether existing distribution centers should remain, be consolidated or phased out as well as whether new facilities should be established and subsequently supply and demand requirements consideration. Moreover, in the proposed model, multi-stage stochastic programming has been implemented on a real data gathered by ArcGIS Software and demand scenarios derived from relevant references. The results based on a real case study in Tehran indicate definite advantages in the re-positioning or reconfiguring model compared with current configurations.

CCS Concepts
• Information systems~Enterprise applications

Keywords
Disaster Management; Relocation; Redesign; Preparedness Facility; Multi-stage Stochastic Programming; GIS Data.

1. INTRODUCTION
Disasters have widespread effects on a diverse range of our surrounding. In terms of terminology, disasters are classified in two group including natural (e.g. earthquakes, floods, hurricanes, tsunamis) and man-made (war, political/tribal disturbance, famine). Moreover, the measures for soothing the disasters' outcomes are also considered in some phases: pre-disaster such as mitigation, preparedness and after disaster such as response and recovery phases. The main objects in disaster management are the reduction of injuries and fatalities rate for humanity purposes and protection of vital infrastructures (i.e. links, bridges, facilities and etc.) against destruction and damage. The decisions in mitigation and preparedness are taken as preventive measures to support the further stages and phases such as response and recovery. Peeta et al. [1] have investigated the best choice for investment in a long-term on strengthening the network's links with the intention of more accessibility and connectivity. On the other hand, the decisions taken in preparedness phase (locations, relations between echelons, capacities and etc.) facilitate the relief in the response phase (for more realization see the investigation of Beraldi and Bruni [2] as a case in point). In the previous papers in the preparedness phase, the main attentions have been focused on the design a new network based on predicted parameters but in this investigation, it has been supposed the relief network that has been designed should be redesigned in order that the post disaster cause less fatalities and damages. In this regard, It seems that the proposed reconfiguration model should be able to consider some vital issues about the location of distribution centers (DCs) including "which facilities should remain, established, phased out or consolidated?". Moreover, it should determine the relations between echelons as well as quantity of relief goods shipped from the suppliers to DCs and then to demand nodes. Finally the proposed model and its solving approach should be able to compare the performance of the reconfigured network and the current configuration during the disaster occurrence in terms of fatalities, costs, shortages, covered demands and any factor that can be vital in decision-making.

The rest of the paper is organized as follows. The literature of the relief network design in the preparedness phase is discussed in section 2. In the next section the problem description is argued, and then the proposed formulation of re-designing model with consideration of scenarios for a path-in-the-scenario-tree-based formulation are presented in section 4. In section 5, a real case study for a specific district of Tehran is implemented and it will indicate that to what extent the proposed approach works applicable. Thereafter, the paper ends with some conclusions and relevant future research ideas in section 6.

2. LITERATURE REVIEW
The distribution of published papers in preparedness phase reveals that this phase has taken considerable attention in the recent

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publications by more than 28% of all papers done in this area [3]. In this section, some studies related to preparedness and response phases are addressed.

In this regard, Rawls and Turnquist [4] have proposed a heuristic algorithm, using Langrangian L-shaped in order to solve a two-stage stochastic scenario-based MIP. Their paper is associated with development of a pre-positioning planning for hurricane in an uncertain environment. In their model, the objective function is to minimize the expected costs over all scenarios and contains the selection of facility locations and their capacities, commodity stocking decisions, unused material holding costs and unmet demand penalties, considering uncertainty in demand for stocked supplies and transportation network availability. Rawls and Turnquist [5] have proposed pre-positioning of emergency supplies for natural disasters in a large-scale problem. The aforementioned papers ([4] and [5]) have emphasized on the unlimited budget and cost function but sometimes sufficient and available budget can be financially prohibitive. Hence, in order to quenching the calamity as well as improving the reliability of logistics network of our proposed model, the weighted shortages have been considered as an objective function while the budget considerations have been assumed as a constraint.

Vargas-Florez et al. [6] have aimed to propose supply chain to support the relief in case of crisis. The authors have considered the determination of warehouse location, the number and the capacity of them. The classification of their model is a pre-positioning not a repositioning model which is discussed in the current work. To put it another way, they have developed a supply chain for disaster regardless the current assets, stocks and existing facilities that are working now. Some researchers have addressed the holistic visions for initial design of LRDSP. Rezaei-Malek et al. [7] have proposed a comprehensive multi objective approach to consider simultaneously the efficiency, efficacy and balance for relief pre-positioning. They have considered total cost, expected time, priority, and demand-weighted utility levels of the delivered relief commodities. However it seems that some re-positioning model needs to be proposed for conformity of existing facilities and eligible facilities. Before Rezaei-Malek et al.'s research paper, some investigations had emphasized the need for efficient and balanced disaster relief logistics (DRL). In this regard, Gutjahr and Nolz [8] have addressed some different combination for HRL's efficacy evaluation including response time, travel distance, coverage, reliability and security. Rodriguez-Espindola and Gaytan [9] contributed to the LRDSP literature through a concurrent determination of the location of emergency shelters and distribution centers (DCs) along with an allocation of required relief centers (RCs) to DCs. They presented a bi-objective mathematical model so that the first objective was minimization of acquisition costs, shipping costs and facility preparation costs (as a measure of efficiency), and the second one minimizes the total priority-weighted distance traveled by goods and people (as an efficacy measure). Ahmadi et al. [10] have proposed a two-stage stochastic, multi-depot, location-routing model considering random travel time, multiple usage of vehicles and standard relief time in order to decide and determine the locations of local depots and routing for last mile distribution after an earthquake. Noyan [11] have proposed a novel extension of Rawls and Turnquist [5] model by considering conditional value at risk (CVaR) as the risk measure on the total cost in addition to its expectation. There also exist chance-constrained variants (Rawls and Turnquist [12]; Hong et al. [13]). Shishebori [14] has developed a facility-location network in a real case study so that the backup facilities and failure costs are partial of his contribution in order to enhancing the reliability. Moreover, Bozorgi-Amiri and Asvadi [15] also have addressed a multi-objective robust optimization approach for a pre-positioning model of disaster so that they have deliberated an exogenously approach to failure in a case study on planning for earthquake scenarios in 22 regions for RLCs in Iran. They have ranked alternative RLCs considering some criteria including cost, technical issues, availability risk and coverage. Two decision-making methods have been applied in their proposed decision making steps including lexicographic goal programming (LGP) and two-step logarithmic goal programming (TLGP).

To the best of authors' knowledge, the present paper can contribute for proposing the reconfiguration of the relief network and relationships as well as improvement of the current configuration while other investigations have drawn attention to design new network regardless interactions among existing facilities and new ones.

3. PROBLEM DESCRIPTION

Suppose a specific district of Tehran (figure 1) that are equipped by 5 existing DCs (located in the past), 2 eligible facilities for new establishment and 40 identified demand points. Demand points are usually the centers that evacuees will be there headlong for being supported such as hospitals, schools and etc. Moreover, there are 4 suppliers to provide desirable relief goods before and after the disaster (suppliers are out of the below map). The redesigned network suggested by the proposed model (section 4) should be able to respond the following issues:

- The new configuration and relations.
- Reconfiguration vs. prior network in terms of shortages and fatalities.

Also some decisions about the distribution centers are considered like: which facility should remain, be phased out, be established or be consolidated to the others.

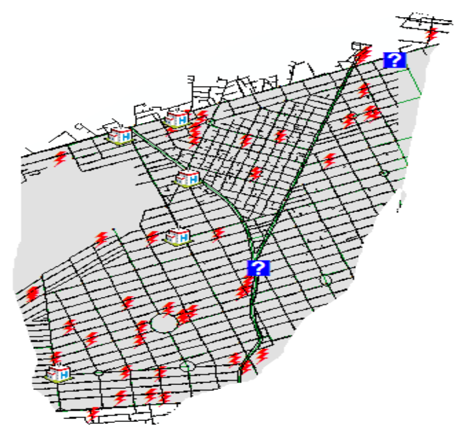

Figure 1. Location of current network (DCs and Demand points)

4. MATHEMATICAL MODEL

In this section, the sets, indices, parameters and decision variables are expressed (in the section 4.1). Then, we propose the multi-stage stochastic programming model in a MIP formation in section 4-2.

4.1. Notation

In what follows the notations of the sets, parameters and decision variables used in the proposed model are presented.

Notation:	
Sets and Indices:	
U	Set of suppliers, indexed by u
DCE	Set of existing DCs indexed by e
DCN	Set of new candidate DCs indexed by n
DC	Set of all DCs, ($DC = DCE \bigcup DCN$), indexed by v
K	Set of demand points, indexed by k
C	Set of relief good type, indexed by c
S	Set of scenarios (events) at each period
$\bar{S}$	Set of paths, each path including sequential and relevant events
T	Set of the time periods, $t = 0,\ldots,\|T\|$ (t=0: pre-disaster)
Parameters:	
$P_{t\bar{s}}$	Probability of occurrence for path $\bar{s}$ up to period t
$CW_{ckt\bar{s}}$	Shortage weight of c requested by demand point k at period t on path $\bar{s}$
$UC_{cuvt\bar{s}}$	Cost per unit for Production and transportation of commodity c from supplier u to DC v at time period t on path $\bar{s}$
$DCC_{cvkt\bar{s}}$	Shipment cost per unit of commodity c from DC v to demand node k at time period t on path $\bar{s}$
$IC_{cut\bar{s}}$	Handling cost per unit for relief good c at DC v during the time period t on path $\bar{s}$
FC_v	Fixed cost of handling and maintenance for active DC v until forecasted time for disaster occurrence
RV_v	Estimated revenue achieved from cultural and social activities in DC v until forecasted time for disaster occurrence
NC_n	Fixed cost of establishing new eligible DC n (excluding fixed cost of handling and maintenance)
CB_e	Revenue gained from phase-out of the redundant existing DC e (sale of land, building)
CRL_{ev}	Overhead cost caused by consolidating DC e to DC v
CCP_{cv}	Cost per unit for capacity mobilization of the DC v (commodity c)
$CPRL_{ce}$	Throughput capacity of the commodity c at DC e available for consolidation to the others
$BDG_{\bar{s}}$	The budget available now for satisfying the demands on path $\bar{s}$
P^{MAX}_{cut}	Maximum procurement capacity of commodity c prepared by supplier u at period t
CP^{MAX}_{cv}	Maximum capacity of DC v for commodity c
CP^{0}_{cv}	Initial capacity of DC v for commodity c
I^{0}_{cv}	Current or initial inventory level of commodity c at existing DC v (it can be zero for the new DCs)
IRL_{ce}	Throughput relief goods c at DC e available for consolidation
$D_{ckt\bar{s}}$	Demand of node k for relief good c in period t on path $\bar{s}$ (for $t=0$, D equals 0)
Decision Variables (Continuous Variables):	
$UV_{cuvt\bar{s}}$	Amount of relief good c provided by supplier u to DC v at time period t on path $\bar{s}$
$VK_{cvkrt\bar{s}}$	Amount of relief good type c shipped from DC v to demand node k at time period t on path $\bar{s}$
$SH_{ckt\bar{s}}$	Shortage of c requested by demand point k at period t on path $\bar{s}$
$I_{cvt\bar{s}}$	Inventory level of commodity c being held at v at the end of time period t on path $\bar{s}$
CP_{cv}	Internal extended capacity of the commodity c to be added to DC v (excluding consolidated and equipped capacity from other DCs)
Decision Variables (Binary Variables):	
Z_{ev}	Consolidation decision of DC e to DC v (for those indices in which $e \neq v$, DC e is consolidated with v)
Z_{vv}	Decision for remaining open (DC e) or establishment decision of the new DC n ($Z_{vv} = Z_{ee} \bigcup Z_{nn}$)

4.2. Mathematical Model

In this section, a formulation in accordance with multi stage stochastic programming is presented. As initiation, the general form of objective function of multi stage stochastic programming is given as follows:

$$Min\ z = C_1 X_1 + E\left(C_2 X_2^{\omega 2} + \ldots + E\left(C_{T-1} X_{T-1}^{\omega T-1,\ldots,\omega 2} + E\left(C_T X_T^{\omega T,\ldots,\omega 2} \right) \right) .. \right)$$

Where X_1 is the first stage Decision and is known based on C_1 in advance but other decisions are completely dependent to prior decisions in scenario tree. For this purpose $P_{t\bar{s}}$ is calculated by multiplying probability of all affected events on a specific path ($\bar{S}$) up to time period t. In what follows the objective function and constraints for a reconfiguration model are given.

The objective function is minimization of penalty for shortages based on each kind of commodities. Relation (2) considers cost conformity to budget. In this regard, budget constraint includes three (main) terms. The first term (2-1) emphasizes on the expense of the procurement and shipment from the suppliers to DCs and then to the demand points as well as inventory expenditures. The second term (2-2) considers first stage and strategic decisions including cost of maintenance the DCs, the establishment cost of the new DCs and available income earned by closure of the existing redundant and secondary usage of the DCs for cultural and social events and plans in the pre-disaster. Moreover some other costs such as consolidating the redundant existing DCs to the other active DCs are mentioned in this term. The last term emphasizes on the expanding cost of needed extra capacity (mobilization for consolidation or internal development). The right-hand side of budget constraint limits the total cost in each scenario path.

Inequalities (3) determines the maximum capacity for supplying the relief goods at pre and post disaster horizons (post disaster $t>0$). Also, relation (4) expresses that initial, consolidated and internal development of capacity for each DC.

$$Min \sum_{t\in T|0} \sum_{\bar{s}\in\bar{S}} \sum_{c\in C} \sum_{k\in K} P_{t\bar{s}}.SH_{ckt\bar{s}}.CW_{ckt\bar{s}} \quad (1)$$

S. t.

$$(2)$$

$$2-1:\left[\left[\sum_{c\in C}\sum_{u\in U}\sum_{v\in DC}\sum_{t\in T} PR_{cuvt\bar{s}}.UV_{cijt\bar{s}} + \right.\right.$$

$$\left.\sum_{c\in C}\sum_{v\in DC}\sum_{k\in K}\sum_{t\in T\backslash\{0\}} TR_{cvkt\bar{s}}.VK_{cvkt\bar{s}} + \sum_{c\in C}\sum_{v\in DC}\sum_{t\in T} IC_{cjt\bar{s}}.I_{cjt\bar{s}}\right]$$

$$2-2:+\left[\sum_{v\in DC}(FC_v).Z_{vv} - \sum_{v\in DC}(RV_v).Z_{vv}\right]+\left[\sum_{n\in NJ} NC_n.Z_{nn}\right]$$

$$-\left[\sum_{e\in EJ} CB_e.(1-Z_{ee})\right]+\left[\sum_{e\in EJ}\sum_{\substack{j\in J\\(j\neq e)}} CRL_{ej}.Z_{ej}\right]+$$

$$2-3:\left[\sum_{c\in C}\sum_{v\in DC} CCP_{cv}.CP_{cv} + \sum_{c\in C}\sum_{v\in DC}\sum_{\substack{e\in DCE\\(e\neq v)}} CPRL_{ce}.Z_{ev}\right]\right] \le BDG_{\bar{s}}, \forall \bar{s}\in\bar{S}$$

$$\sum_{v\in DC} UV_{cuvt\bar{s}} \le P_{cut}^{MAX} \quad ,\forall c\in C, u\in U, t\in T, \bar{s}\in\bar{S} \quad (3)$$

$$\left(CP_{cv} + \left(\sum_{\substack{e\in DCE\\(e\neq v)}} CPRL_{ce}.Z_{ev}\right)\right) \le \left(CP_{cv}^{MAX} - CP_{cv}^{0}\right).Z_{vv} \quad (4)$$

$$,\forall c\in C, v\in DC$$

$$I_{cvt\bar{s}} - I_{cv}^{0} = \sum_{\substack{e\in DCE\\(e\neq v)}} IRL_{ce}.Z_{ev} + \sum_{i\in I} UV_{cuvt\bar{s}}, t=0, \forall c\in C, \quad (5)$$

$$v\in DC, \bar{s}\in\bar{S}$$

$$I_{cvt\bar{s}} - I_{cv(t-1)\bar{s}} = UV_{cuvt\bar{s}} + \sum_{k\in K} VK_{cvkt\bar{s}}, \forall c\in C, \quad (6)$$

$$v\in DC, t\in T\backslash\{0\}, \bar{s}\in\bar{S}$$

$$I_{cvt\bar{s}} \le \left(CP_{cv} + \left(\sum_{\substack{e\in DCE\\(e\neq v)}} CPRL_{ce}.Z_{ev}\right)\right) + CP_{cv}^{0}.Z_{vv} \quad (7)$$

$$,t=0, \forall c\in C, v\in DC, \bar{s}\in\bar{S}$$

$$I_{cv(t-1)\bar{s}} + \sum_{i\in I} UV_{cuvt\bar{s}} \le \left(CP_{cv} + \left(\sum_{\substack{e\in DCE\\(e\neq v)}} CPRL_{ce}.Z_{ev}\right)\right) + \quad (8)$$

$$CP_{cv}^{0}.Z_{vv} \quad ,\forall c\in C, v\in DC, t\in T\backslash\{0\}, \bar{s}\in\bar{S}$$

$$\sum_{v\in DC} VK_{cvkt\bar{s}} \ge D_{ckt\bar{s}} - SH_{ckt\bar{s}}, \forall t\in T\backslash\{0\}, c\in C, \quad (9)$$

$$k\in K, \bar{s}\in\bar{S}$$

$$Z_{ev} \le Z_{vv}, \forall e\in DCE, v\in DCE \quad (10)$$

$$Z_{ev} \le Z_{vv}, \forall v\in DCN, \forall e\in DCE \quad (11)$$

$$\sum_{\substack{v\in DC\\(v\neq e)}} Z_{ej} \le 1, \forall e\in DCE \quad (12)$$

$$UV_{cuvt\bar{s}} = UV_{cuvt\bar{s}'}, \quad \forall \bar{s},\bar{s}'\in\{s\}_t \quad (13)$$

$$VK_{cvkt\bar{s}} = VK_{cvkt\bar{s}'}, \quad \forall \bar{s},\bar{s}'\in\{s\}_t \quad (14)$$

$$I_{cvt\bar{s}} = I_{cvt\bar{s}'}, \quad \forall \bar{s},\bar{s}'\in\{s\}_t \quad (15)$$

$$UV_{cuvt\bar{s}}, VK_{cvkt\bar{s}}, I_{cvt\bar{s}}, CP_{cv} \ge 0 \quad (16)$$

$$Z_{ev(e\neq v)}, Z_{vv} : (Z_{ee}, Z_{nn}) = \{0,1\} \quad (17)$$

Equalities (5) and (6) are the inventory equilibrium for all horizons. Inequality (7) and (8) state the capacity of DCs in terms of the infrastructures and ability for keeping the inventories and received orders. Constraint (9) indicates the shortage and unmet demands based on required demands on path of scenario tree. Moreover, Constraint (10) guarantees that an existing DC cannot be consolidated into another existing one, unless destination DC remains active. Similarly, constraint (11) ensures the above condition for the new active DCs. In this regard, relation (12) ensures unique DC for consolidating with each destination (DC). Equalities (13-16) are non-anticipatively constraints. We have a set of decision variables at each decision node that their values are equal for all paths that go through that node because the decided variables at that node must be equal to the variables of the other different paths at the same time *t* if paths are indistinguishable at time *t* (non-anticipatively). Let us denote the set of paths which are not distinguishable from s (scenario s not path $\bar{s}$) up to time period t by $\{s\}_t$, Therefore, we define non-anticipatively constraints and the set $\bar{s}$ for the decision variables (except for strategic ones) as relations (13-15).

5. CASE STUDY

As it described in section 3, GIS data of a district of Tehran city has been applied in this paper to illustrate the applicability of the proposed model and solving approach. In this regard, figure 2. Shows the reconfigured network after solving the problem. In this regard, two new facilities should be established so that after mobilization of these new DCs (new *DC1* and new *DC2*), existing *DC1* will be eliminated, existing *DC2* will be consolidated to new *DC1* and existing *DC4* will be consolidated to new *DC2*. Moreover, existing *DCs* (#3 and 5) should remain active. This new configuration has been designed by dedicating 1E+11 IRR (Iran's Currency) budget with 99% demand coverage. It is possible to analyze more and less budget by the proposed model so that for less and more budget, figure 3 indicates the demand coverage of current network and reconfigured one facing with predefined disaster and different budgets. The results shows the considerable improvement for redesigned network. It is worth to noting that all the weights for commodities, costs have been gathered from expert judgment. Also, the scenario definition for demand nodes have been indirectly derived from reference [16]. Moreover, all distances and location have been calculated by ArcGIS software.

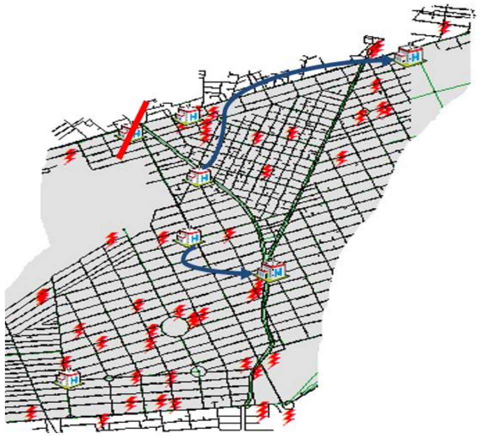

Figure 2. Redesigned relief network

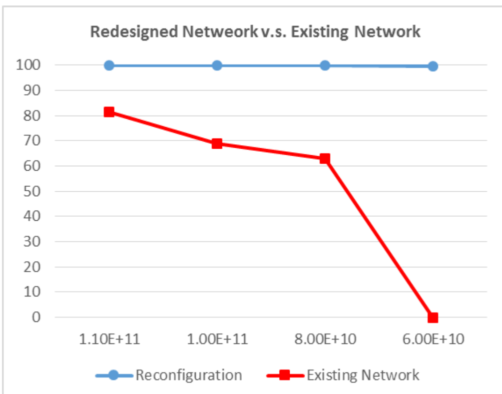

Figure 3. The effect of reconfiguration on demand satisfaction based on available budget

6. CONCLUSION

In this paper, an attempt has been made to propose a mathematical model of relief network reconfiguration based on GIS data. In this regard, the proposed model suggests the optimal locations for the existing and eligible facilities considering reasonable relation among the echelons. Also, based on scenario tree structure of demands, a split-variable formulation has been designed for applying a multi-stage stochastic programming. A real case study has been investigated in order to applicability evaluation and the effect of redesigned network on the demand coverage in comparison with continuing the current facilities in facing with the disaster. In this regard, the results of redesigned network emphatically dominated the existing infrastructure for confronting the disaster. Although this model indicates the distinct superiority versus existing situation but some consideration are suggested to study as future research such as consideration of congestion in roads and modelling the link failure in case of earthquake.

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