International Journal of Engineering

Journal Homepage: www.ije.ir

Re-configuration of the Relief Network Considering Uncertain Demand and Link Failure in an Earthquake: A Multi-stage Stochastic Programming

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PAPER INFO

Paper history:
Received 17 April 2017
Received in revised form 25 February 2018
Accepted 15 April 2018

Keywords:
Disaster Management
Re-configuring
Re-positioning
Preparedness Facility
Multi-stage Stochastic Programming
Scenario Tree
Link Damage

ABSTRACT

Disasters inevitably trigger far-reaching consequences affecting all living things and the environment. Therefore, top managers and decision-makers in disaster management seek comprehensive approaches to evaluate facilities and network preparedness in dealing with the response phase of predicted disaster scenarios in terms of number of casualties, costs, and unmet demands. In this regard, previous studies on the preparedness phase have often been limited to the location of eligible facilities without considering other important factors such as current assets, entities and configuration. Thus, the present study proposes a reconfiguring and repositioning model in order to simultaneously assess whether existing support bases should remain, be consolidated or phased out as well as whether new support base facilities should be established and subsequently supply and demand requirements considered. In the proposed model, in addition to considering a scenario tree for destruction and demands, network links affected by the intensity of disaster events are also evaluated. Furthermore, in order to increase reliability, the destruction of network links takes into account that link failures give rise to vulnerability in related links. In the proposed model, multi-stage stochastic programming has been implemented on various real destruction and demand scenarios. The results indicate definite advantages in the re-positioning or reconfiguring model compared with current configurations. Moreover, the superior capability of the applied solving approach versus one of the traditional approaches is also appraised.

doi*: 10.5829/ije.2018.31.06c.10*

1. INTRODUCTION

A disaster is a suddenly and dangerous event that strongly influences the infrastructure and function of a society so that human, economic or environmental losses may be some parts of the demolition range.

Any sort of disasters including natural (e.g. earthquakes, floods, hurricanes, tsunamis) and man-made (war, political/tribal disturbance) leads to crucial and far-reaching after effects so that the lack of supportive plans in pre-, during and post-disaster periods will cause the vulnerability or even inability to decline the potential negative outcomes. Disaster management includes four sequential phases that can be classified to mitigation, preparedness, response and recovery. The decisions in mitigation and preparedness are taken to help the further stages and phases such as response and recovery phases.Take for instance of the mitigation phase; 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 especially at the disaster time. In preparedness phase, some strategic decisions including location of shelters, response facilities, disaster management support bases (SBs), and the capacity planning will be made. In this regard, researchers have concentrated on various approaches of facility location problem in disasters notably for uncertainty environment to formulate a model with more adaptation to reality (investigation of Beraldi and Bruni [2] is a case in point). In line with modeling based

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Please cite this article as: H. R. Rezaei, H. Khademi Zare, M. Bashiri, M. B. Fakhrzad, Re-configuration of the Relief Network Considering Uncertain Demand and Link Failure in an Earthquake: A Multi-stage Stochastic Programming, International Journal of Engineering (IJE), IJE TRANSACTIONS C: Aspects Vol. 31, No. 6, (June 2018) 932-942

on the real assumption, it seems that one of the supportive analytical platforms to make an explicit plan for the upcoming disasters is a redesigning or reconfiguring model that can evaluate the gap between current configuration and the optimum reconfiguration from the stand point of costs, fatalities, and other serious criteria that lack of enough attention to them will lead to irreversible consequences. It seems that a reconfiguration model should be able to:

A. Respond to some key questions about the locations such as SBs (as distribution center); which facilities should remain, be established, phased out or consolidated?
B. Determine the distinction between reconfiguring network and the current configuration capabilities during the disaster occurrence in terms of fatalities, costs, shortages, covered demands and any other factor that can be vital in decision-making.

The remainder of the paper is organized as follows. The literature of the preparedness phase for the disaster management is discussed in section 2. In the next section the details about studied problem are given as problem description. The proposed formulation of re-configuring model with consideration of link damage and its extension for a path-in-the-scenario-tree-based formulation are presented in section 4. Section 5 analyzes the results of two numerical examples. Thereafter, the paper ends with some conclusions and future research suggestions.

2. LITERATURE REVIEW

In this section, in order to highlight the contribution of the paper, the researches in the classification of preparedness mathematical models and failure effects on infrastructures have been surveyed.

The distribution of published works reveals that concentration on preparedness and response phase outweighs the mitigation and recovery phases. This means that the researchers have drawn more attention to preventive and responding decisions before and after the disasters (for more realization and better evidences see Figure 1 derived from literature [3]).

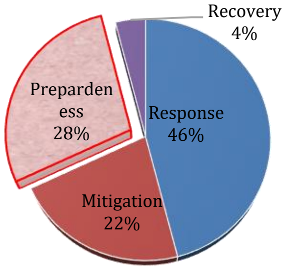


Figure 1. Distribution of researches based on phase of disasters derived from ref. [3]

Generally speaking, Governments, non-governmental organizations (NGOs) and humanitarian organizations can improve the agility and quality of the Humanitarian Relief Logistics (HRL) if they would participate in relevant policy-making or in resources allocation to pre-determined network in which desirable network and facility characteristics and also required goods of Relief Logistic Centers (RLCs) are decided and authorized in advance that a disaster occurs. The above-mentioned problem is known as Location with Relief Distribution and Stock Pre-positioning (LRDSP) problem in the HRL literature. 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 tool 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 [4] have proposed pre-positioning of the emergency supplies for natural disasters in a large-scale problem. The aforementioned papers [4, 5] have emphasized on the unlimited budget but sometimes sufficient and available budget can be financially prohibitive. Hence, in order to quenching the calamity as well as improving the reliability of the logistics network in our proposed model, the weighted shortages have been considered as an objective function while the budget considerations have been assumed in the constraints. Vargas-Florez et al. [6] have aimed to propose a supply chain model to support the relief in case of crisis. The authors have considered the determination of warehouse location as well as 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. 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 the efficiency, efficacy and balance for relief pre-positioning, simultaneously. They have considered some functions including the 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 [7] 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 [4] 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 [12, 13]. Shishebori [14] has developed a facility-location network in a real case study so that the backup facilities and failure costs are a 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 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 RLCs considering some criteria including cost, technical issues, availability risk and coverage.

Since this paper considers link failure, therefore some papers that have considered failure and destruction assumptions in prepositioning models have been surveyed. There are two sorts of implementation of destruction on failure links called endogenous and exogenous approaches. The exogenous approach models the failure effects through defining what damage will be at every link or location, for every disaster scenario, while the endogenous damages are computed via a distance based or impact based functions. Zarrinpoor et al. [16] have designed a health service network including candidate location of hospitals, treatment units and demand nodes. They have considered congestion, exogenous failure (predefined binary parameter based one destruction scenario) on model and a robust approach derived from literature [17] as a solving approach. As mentioned above in the scope of the LRDSP investigations, Rawls and Turnquist [4] have studied a pre-positioning of supply where damage to supplies is exogenously considered as the predetermined scenarios, similar to study of Jia et al. [18].

In contrast to aforementioned researches with exogenous failure considerations, Verma and Gukler [19] have taken endogenous failure into account in a prepositioning model. They have addressed the uncertainty in the magnitude of damages caused by a large-scale disaster via the definition of a distance-damage function. In addition, Salman and Yucel [20] have provided another joint link failure approach based on reliability and proximity ordering of the existing link in the junctions. The authors have measured the distance between two links as the minimum distance between the corresponding four pairs of nodes. Our study differs from Salaman and Yucel's method [20] in terms of more accurately measurement approach for distance of two links thorough determination of the sub-nodes distances on entire link rather than only attention to start and finish nodes on the link. This approach makes more exact proximity set around the closed link after disaster (especially in the earthquake). Moreover, as another main extension, the acceptable links' strength versus actual values is comprised in order to clarification of the link status. To the best of authors' knowledge, the present paper can contribute for proposing the reconfiguration of the relief network. In what follows, the main contributions of this paper (which differentiate our efforts from the other efforts dedicated to the LRDSP category) are briefly expressed:

- Proposing a reconfiguration model for relief logistics and relations between echelons in a three-level relief logistics network.
- Considering four decisions for the support base facilities including maintaining the existing facilities, new establishment, and consolidation the existing ones with other facilities or completely phase out the redundant facilities.
- Considering an endogenous failure approach with more accurate distance function between closed link and other links.
- Considering the distance based coverage radius in order to quick response to demand requests.
- Appling a multi-stage stochastic programming to overcome uncertainty.

3. PROBLEM DESCRIPTION

The basic settings for repositioning model are defined by three echelons: suppliers, SBs (or DCs) and demand points (such as hospitals, shelters and etc.). In this regard, some significant concerns should be responded for the echelons and their relations such as:

A. Will the current configuration that has been established according to a valid model in the past be optimum confronting the new situation?
B. If we are going to plan for the future and according to available budget, which set of preventive

decisions will decline the fatalities, costs and other crucial factors?

C. If we have a predefined scenario tree for destruction and demands in the post disaster horizon, which solving approaches can respond to above concerns and overcome the uncertainty?

3. 1. Reconfiguration It is indisputable that long-term population changes are likely to have impacts on infrastructure and population distribution. The impacts of these changes must be evaluated on existing relief network that has been established beforehand because the previous location and network may not be optimum for current situation. Consider two main suppliers for relief goods, two existing SBs, three new eligible SBs, and three known demand point for DRL. To visualize in desire manor and as a simple illustration, Figure 2 can be a hypothetical result of applying the model and the solution method.

3. 2. Planning Horizons The planning horizons are divided to two main classifications including pre- and post-disaster horizons while each main horizon may consist one or more periods. The pre-disaster horizon is related to strategic decisions whereas post-disaster's variables are associated with details of the relief goods flow and storage throughout first 72h.

3. 3. Dealing with Uncertainty In the present investigation, uncertainty is associated with destruction scenarios that depend on level of magnitude, longitude, latitude and peak ground acceleration (PGA).

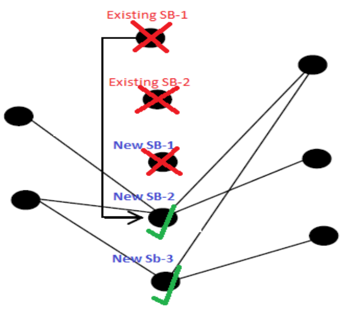


Figure 2. New configuration of network as a sample after model implementation

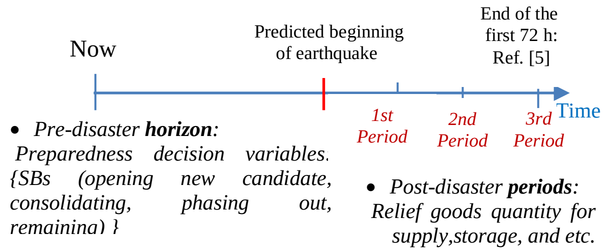


Figure 3. Decisions from now up to the first 72 h

The destruction scenario tree makes the requested demands and indirectly, link destruction.

4. PROPOSED MODEL

In this section, after presentation of the notation in section 4.1, we propose the multi-stage stochastic programming model in a MIP formation in section 4.2, then in the section 4.3, non-anticipatively constraints will be presented and in the section 4.4., in order to adding the failure link assumptions to the model, the preprocessing steps are proposed.

4. 1. Notation In what follows the notations of the sets, parameters and decision variables are defined.

(Nomenclature)	
Sets and Indices:	
I	Set of suppliers, indexed by $i=1,\ldots,\lvert I\rvert$
EJ	Set of existing SBs, $e=1,\ldots,\lvert EJ\rvert$
NJ	Set of new candidate SBs, $n=\lvert EJ\rvert+1,\ldots,\lvert EJ\rvert+\lvert NJ\rvert$
J	Set of all SBs, ($J=EJ\cup NJ$), $j=1,\ldots,\lvert J\rvert$
K	Set of demand nodes, $k=1,\ldots,\lvert K\rvert$
R_{jk}	Set of initial routes between j and k, $r_{jk}=1,\ldots,\lvert R_{jk}\rvert$
C	Set of commodities, $c=1,\ldots,\lvert C\rvert$
S	Set of scenarios (events) in each period, $s=1,\ldots,\lvert S\rvert$
$\bar{S}$	Set of paths, each path consists of some sequential events in the scenario tree, $\bar{s}=1,\ldots,\lvert\bar{S}\rvert$
T	Set of the time periods, $t=0,\ldots,\lvert T\rvert$ (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 $\bar{s}$
$PR_{cijt\bar{s}}$	Cost per unit for Production and transportation of commodity c from supplier i to SB j at time period t on path $\bar{s}$
$TR_{cjkrt\bar{s}}$	Shipment cost per unit of commodity c from SB j to demand node k thorough r-th route of transportation at time period t on path $\bar{s}$
$IC_{cjt\bar{s}}$	Unit handling cost of relief good c at SB j during time period t on path $\bar{s}$
FC_j	Fixed cost of handling and maintenance for active SB j until forecasted time for crisis occurrence
RV_j	Estimated revenue achieved from cultural and social activities in SB j until forecasted time for crisis occurrence
NC_n	Fixed cost of establishing new candidate SB n (excluding fixed cost of handling and maintenance)
CB_e	Income from phase-out of the redundant existing

	SB e (sale of land, building)
CRL_{ej}	Overhead cost caused by consolidating *SB e* to *SB j*
CCP_{cj}	Cost per unit for capacity mobilization of the SB *j* (commodity c)
$CPRL_{ce}$	Throughput capacity of the commodity *c* at SB *e* available for consolidation to the others
$BDG_{\bar{s}}$	The budget available now for satisfying the demands on path $\bar{s}$
P_{cit}^{MAX}	Maximum procurement capacity of commodity *c* prepared by supplier *i* at period *t*
CP_{cj}^{MAX}	Maximum capacity of SB *j* for commodity *c*
CP_{cj}^{0}	Initial capacity of SB *j* for commodity *c*
II_{cj}^{0}	Current or initial inventory level of commodity *c* at existing SB *j* (it can be zero for the new SBs)
IRL_{ce}	Throughput relief goods *c* at SB *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)
$FL_{rjkt\bar{s}}$	Availability of *r-th* route connecting SB *j* to demand node *k* at time period *t* on path $\bar{s}$ (binary value)
μ_c	Capacity coefficient of commodity *c*
CY_{rjkt}	The available capacity of the *r-th* route between *SB j* and demand node *k* at time period *t*
Decision Variables (Continuous Variables):	
$X_{cijt\bar{s}}$	Amount of relief good *c* provided by supplier *i* to SB *j* at time period *t* on path $\bar{s}$
$Y_{cjkrt\bar{s}}$	Amount of relief good type *c* shipped from SB *j* to demand node *k* through *r*-th route at time period *t* on path $\bar{s}$
$W_{ckt\bar{s}}$	Shortage of *c* requested by demand point *k* at period *t* on path $\bar{s}$
$II_{cjt\bar{s}}$	Inventory level of commodity *c* being held at *j* at the end of time period *t* on path $\bar{s}$
CP_{cj}	Internal extended capacity of the commodity *c* to be added to SB *j* (excluding consolidated and equipped capacity from other SBs)
Decision Variables (Binary Variables):	
Z_{ej}	Consolidation decision of SB *e* to SB *j* (for those indices in which $e \neq j$, SB *e* is consolidated with *j*)
Z_{jj}	Decision for remaining open (SB *e*) or establishment decision of the new SB *n* ($Z_{jj} = Z_{ee} \cup Z_{nn}$)

4. 2. Formulation The objective function and the constraints of the proposed model are presented in this section. In this regard, the minimization objective function includes a commodity-based loss function throughout post disaster's periods ($t>0$) that is associated with weighted shortage of demands. The weights simultaneously depend on the necessity of the commodities at each period and the criticality of demand nodes. Moreover, the probability of each path up to each period ($P_{t\bar{s}}$) is calculated based on consecutive multiplying the probabilities of events on considered path up to the period *t*.

$$Min \sum_{t\in T, t>0} \sum_{\bar{s}\in\bar{S}} \sum_{c\in C} \sum_{k\in K} P_{t\bar{s}} . W_{ckt\bar{s}} . CW_{ckt\bar{s}} \tag{1}$$

Relations (2) are composed eight terms that must be less than available budget for each path of scenario tree ($\bar{S}$) not a scenario of particular period.

$$\begin{aligned}
&\Bigg[\Bigg[\overbrace{\sum_{c\in C}\sum_{i\in I}\sum_{j\in J}\sum_{t\in T} PR_{cijt\bar{s}} . X_{cijt\bar{s}}}^{(2-1)} + \\
&\overbrace{\sum_{c\in C}\sum_{j\in J}\sum_{k\in K}\sum_{r\in R_{jk}}\sum_{t\in T\setminus\{0\}} TR_{cjkrt\bar{s}} . Y_{cjkrt\bar{s}}}^{(2-2)} \\
&+ \overbrace{\sum_{c\in C}\sum_{j\in J}\sum_{t\in T} IC_{cjt\bar{s}} . II_{cjt\bar{s}}}^{(2-3)}\Bigg] + \overbrace{\Bigg[\sum_{j\in J}(FC_j - RV_j).Z_{jj}\Bigg]}^{(2-4)} + \\
&\overbrace{\Bigg[\sum_{n\in NJ} NC_n . Z_{nn}\Bigg]}^{(2-5)} - \overbrace{\Bigg[\sum_{e\in EJ} CB_e .(1-Z_{ee})\Bigg]}^{(2-6)} \\
&+ \overbrace{\Bigg[\sum_{e\in EJ}\sum_{\substack{j\in J\\(j\neq e)}} CRL_{ej} . Z_{ej}\Bigg]}^{(2-7)} + \\
&\overbrace{\Bigg[\sum_{c\in C}\sum_{j\in J} CCP_{cj} . \Bigg(CP_{cj} + \Big(\sum_{\substack{e\in EJ\\(e\neq j)}} CPRL_{ce} . Z_{ej}\Big)\Bigg)\Bigg]}^{(2-8)}\Bigg] \leq BDG_{\bar{s}}, \forall \bar{s}\in\bar{S}
\end{aligned} \tag{2}$$

Terms (2.1) and (2.2) emphasize on the expenses of the procurement and shipment from the suppliers to SBs and then to the demand points. Term (2.3) considers the storage costs in the SBs. Also, terms (2.4)-(2.8) deal with strategic decisions so that term (2.4) considers the cost of maintenance the SBs (whether the active existing SBs or the newly established ones) and the predicted revenue that can be attained by temporary using the SBs for cultural and social benefits in the pre-disaster (2.5) determines the establishment cost of the new SBs that should be opened. Moreover, term (2.6) considers the income resulting from the closure of the existing redundant SBs. Term (2.7) considers the cost for consolidating the redundant existing SBs to the other active SBs and (2.8) emphasizes on the expanding cost of needed extra capacity (mobilization for consolidation or internal development). The right-hand side budget is determined based on available budget of considered path not a specific scenario.

Inequalities (3) shows the maximum capacity of supplying the relief in both pre and post disaster horizons (pre disaster *t=0* and post disaster *t>0*).

$$\sum_{j \in J} X_{cijt\bar{s}} \leq P_{cit}^{MAX} \quad ,\forall c \in C, i \in I, t \in T, \bar{s} \in \bar{S} \tag{3}$$

Constraint (4) expresses that initial, consolidated and internal development of capacity for each SB cannot exceed the maximum capacity.

$$\left(CP_{cj} + \left(\sum_{\substack{e \in EJ \\ (e \neq j)}} CPRL_{ce}.Z_{ej} \right) \right) \leq \left(CP_{cj}^{MAX} - CP_{cj}^{0} \right).Z_{jj} \quad ,\forall c \in C, j \in J \tag{4}$$

Equalities (5) and (6) set the inventory level of pre disaster and post disaster horizons, respectively (i.e. inventory equilibrium). The pre disaster storage level is determined in equality (5) for each SB based on its own initial storage, consolidated relief goods provided by redundant SBs and ordered goods as precautionary reserve before disaster occurrence. Besides, relation (6) specifies the inventory level of each post disaster's period so that the inventory (on-hand quantity) and dispatched relief goods at each period are procured by ordering at that period and the remained inventory received from previous period.

$$II_{cjt\bar{s}} = II_{cj}^{0} + \sum_{e \in Ej(e \neq j)} IRL_{ce}.Z_{ej} + \sum_{i \in I} X_{cijt\bar{s}}, t = 0, \forall c \in C, j \in J, \bar{s} \in \bar{S} \tag{5}$$

$$\sum_{r \in R_{jk}} \sum_{k \in K} Y_{cjkrt\bar{s}} + II_{cjt\bar{s}} = II_{cj(t-1)\bar{s}} + X_{cijt\bar{s}} \ ,\forall c \in C, j \in J, t \in T \setminus \{0\}, \bar{s} \in \bar{S} \tag{6}$$

inequalities (7) and (8) represent the capacity of SBs' infrastructures in order to keeping the inventories and received orders.

$$II_{cjt\bar{s}} \leq \left(CP_{cj} + \left(\sum_{\substack{e \in EJ \\ (e \neq j)}} CPRL_{ce}.Z_{ej} \right) \right) + CP_{cj}^{0}.Z_{jj} \quad ,t = 0, \forall c \in C, j \in J, \bar{s} \in \bar{S} \tag{7}$$

$$II_{cj(t-1)\bar{s}} + \sum_{i \in I} X_{cijt\bar{s}} \leq \left(CP_{cj} + \left(\sum_{\substack{e \in EJ \\ (e \neq j)}} CPRL_{ce}.Z_{ej} \right) \right) + CP_{cj}^{0}.Z_{jj} \quad ,\forall c \in C, j \in J, t \in T \setminus \{0\}, \bar{s} \in \bar{S} \tag{8}$$

Constraint (9) indicates the required demands that should be met at each period and each considered path in scenario tree. This relation will lead to shortage recognition that has been mentioned in the objective function (1). Moreover, FL_{rjk} will be clarified in section (4.4) based on the proposed preprocessing procedure for failure links. Also the available capacity of each route is determined in the relation (10).

$$\sum_{r \in R} \sum_{j \in J} FL_{rjkt\bar{s}}.Y_{cjkrt\bar{s}} + W_{ckt\bar{s}} \geq D_{ckt\bar{s}}, \forall t \in T \setminus \{0\}, c \in C, k \in K, \bar{s} \in \bar{S} \tag{9}$$

$$\sum_{c} \mu_c.Y_{cjkrt\bar{s}} \leq FL_{rjkt\bar{s}}.CY_{rjkt}, \forall r \in R, j \in J, k \in K, t \in T, \bar{s} \in \bar{S} \tag{10}$$

Constraint (11) ensures an existing SB cannot be consolidated into another existing one, unless destination SB remains active. In order to reduction of constraints, the cardinality $|EJ|$ is resulted by summation of the constraints $Z_{ej} \leq Z_{jj}$ over set EJ with the equal RHS. Similarly, constraint (12) assures the above condition for the newly established SBs.

$$\sum_{e \in EJ} Z_{ej} \leq |EJ| Z_{jj}, \forall j \in EJ \tag{11}$$

$$\sum_{e \in EJ} Z_{ej} \leq |EJ| Z_{jj}, \forall j \in NJ \tag{12}$$

Also, inequality (13) determines that each SB can be merged with the unique destination SB. Equality (14) has been considered because we have no relief to dispatch in the pre-disaster horizon (*t=0*). As it mentioned in (15), collection of non- anticipatively constraints will be discussed in the next section.

$$\sum_{j \in J(j \neq e)} Z_{ej} \leq 1, \forall e \in EJ \tag{13}$$

$$Y_{cjkrt\bar{s}=0}, t = 0, \forall c \in C, j \in J, k \in K, r \in R, \bar{s} \in \bar{S} \tag{14}$$

{Non-Anticipatively Constraints} Section 4.3 (15)

$$X_{cijt\bar{s}}, Y_{cjkrt\bar{s}}, II_{cjt\bar{s}}, CP_{cj} \geq 0 \tag{16}$$

$$Z_{ej}(e \neq j), Z_{jj} : (Z_{ee}, Z_{nn}) = \{0,1\} \tag{17}$$

Finally, Constraints (16) and (17) restrict decision variables to be positive and binary.

4. 3. Non-Anticipatively Approach In this section, split-variable formulation is proposed. For this purpose, the issue may be understood by looking at the Figures 4 and 5, where vertical dotted lines are drawn correspond to non-anticipatively requirements (two scenarios at each period). 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 $\{s\}_t$, for example and according to Figures 4 and 5, at period *t=0* whatever occurs, the decision variables can be considered equal for all coming paths that cannot be recognizable in advance (i.e. $\{1\}_0 = \{1,...8\}$). It is clear that in the first period of the post disaster (t=1) and for the known scenario (scenario 1) paths 1, 2, 3 and 4 are unpredictable to know from now (i.e. $\{1\}_1 = \{1,...4\}$) hence all variables that are being decided just now, must be equal for the other indistinguishable paths. We have a set of decision variables for each decision node. The decision variables corresponding to a node must be equal to the variables of the other different paths at the same time t if paths are indistinguishable at time t and may occur (non-anticipatively). Therefore, we define non-anticipatively constraints and the set $\bar{s}$ for the decision variables (except for strategic ones) as follows:

$$X_{cijt\bar{s}} = X_{cijt\bar{s}'}\ ,\ \forall \bar{s},\bar{s}' \in \{s\}_t \tag{15-1}$$

$$Y_{cjkr\bar{s}} = Y_{cjkr\bar{s}'}\ ,\ \forall \bar{s},\bar{s}' \in \{s\}_t \tag{15-2}$$

$$II_{cjt\bar{s}} = II_{cjt\bar{s}'}\ ,\ \forall \bar{s},\bar{s}' \in \{s\}_t \tag{15-3}$$

4. 3. Failure Link In order to decision about the binary value of $FL_{rjk\bar{s}}$ (route status) that is affected by the destruction intensity on scenario paths and distance from closed links, the below steps are proposed:

Step 1. Identify all possible routes ($r=1,\ldots,|R_{jk}|$ routes) between j and k and denote the existing nodes of links on r-*th* route by $\{j = n_1^{jkr}, n_2^{jkr},\ldots,n_p^{jkr},n_{p+1}^{jkr},\ldots,n_f^{jkr} = k\}$. Then, set initial survival value for each route equal to 1 ($FL_{rjk\bar{s}} = 1$) with the initial assumption that all links of each route will be active. Notice that only one closed link suffices to close the route.

Step 2. Define λ_{jk}, which specifies the acceptable coverage distance between j and k that may differ due to priority of emergency for each demand node.

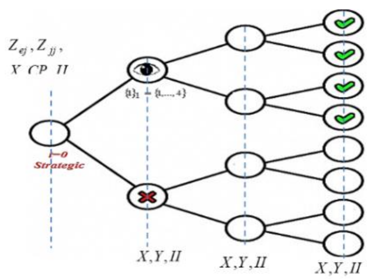


Figure 4. A sample scenario tree with 8 paths

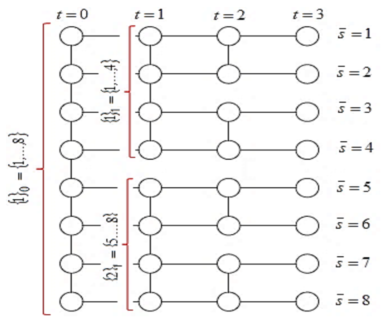


Figure 5. A non-anticipatively structure

Step 3. Denote acceptable survival rate (LTB:the larger the better) for each link according to each period and considered path on scenario tree by $SR^{t,\bar{s}}_{n_p^{jkr},n_{p+1}^{jkr}} \in [0,1]$ and actual survival value by $V^{t,\bar{s}}_{n_p^{jkr},n_{p+1}^{jkr}} \in [0,1]$.

Step 4. Set $FL_{rjk\bar{s}} = 0$ (demolished) if at least one of the below conditions are met for r-*th* route between j , k:

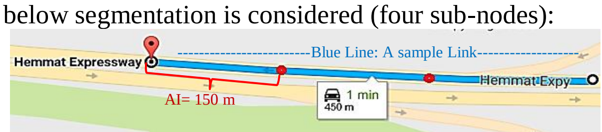
i. $Len_{jkr} > \lambda_{jk}$ **:** Distance Coverage

Where Len_{jkr} is the length of r-th route between j, k.

ii. $SR^{t,\bar{s}}_{n_p^{jkr},n_{p+1}^{jkr}} > V^{t,\bar{s}}_{n_p^{jkr},n_{p+1}^{jkr}}, \forall p = 1,\ldots,f-1$ **:**Link stability

Notice that a route may be ruined at any period by happening a set of events on scenario tree's path, for this reason, relation (ii) considers both scenario tree's path and periods to determin the links status.

Step 5. Define the intervals based on distances for each link by *AI*, then determine the points (sub-nodes including two main nodes and other nodes in between) of each link based on *AI*. For example suppose a sample section of a route's link (Len:450m), if *AI=150*, the below segmentation is considered (four sub-nodes):



Step 6. Calculate the euclidean disatance between two links considering the minimum distance between the corrossponding pair of two links' sub-nodes. Let us notate the distance between the first hypotetical link $(n_p^{jkr},n_{p+1}^{jkr})$ and the second link $(n_{p'}^{j'k'r'},n_{p'+1}^{j'k'r'})$ by $DL((n_p^{jkr},n_{p+1}^{jkr}),(n_{p'}^{j'k'r'},n_{p'+1}^{j'k'r'}))$. It is worth to noting that the proposed distance calculation between pair of sub-nodes leads to form the more accurately vicinity set around a closed link. The following sample for distance calculation between Golestan Street and Khorvardin Boulevard stresses that distance between two links based on start and end nodes of links (single line) [20] can be ameliorated by the proposed steps 5 and 6 (double-line).

Step 8. For each failure link ($SR^{t,\bar{s}}_{n_p^{jkr},n_{p+1}^{jkr}} > V^{t,\bar{s}}_{n_p^{jkr},n_{p+1}^{jkr}}$) that was recognized in step 4, create vicinity set if the link $(n_{p'}^{j'k'r'},n_{p'+1}^{j'k'r'})$ has the conditions of

$DL((n_p^{jkr},n_{p+1}^{jkr}),(n_{p'}^{j'k'r'},n_{p'+1}^{j'k'r'})) < VD^{t,\bar{s}}((n_p^{jkr},n_{p+1}^{jkr}),(n_{p'}^{j'k'r'},n_{p'+1}^{j'k'r'}))$ (where $VD^{t,\bar{s}}$ is venture distance around $(n_p^{jkr},n_{p+1}^{jkr})$ at period t on path $\bar{s}$). If $V^{t,\bar{s}}_{n_p^{jkr},n_{p+1}^{jkr}} > V^{t,\bar{s}}_{n_{p'}^{jkr},n_{p'+1}^{j'k'r'}}$, change the condition of $(n_{p'}^{j'k'r'},n_{p'+1}^{j'k'r'})$ to closed for all t and all paths by zero value: $FL_{r'j'k t\bar{s}} = 0$

5. COMPUTATIONAL RESULTS

In this section, two problems (*P1* and *P2*) are expressed to highlight the merits of the proposed model. In this regrad, a network including suppliers, SBs and demand points have been considered and the problem dimentions have also been summerized in Table 2. The disruption scenarios and its related demands have been derived from literature [21]. For example, the charachtristics of a scenario for a period of P_1 have been tuned based on magnitude (6.531), longitude (51.131), latitude (35.844), PGA at city centre (186.59) and return period (333). Moreover, the selected districts for eight demand nodes are 5, 15, 16, 22, 20, 7, 14 and 1, respectively. Also, all main costs for reconfiguration have been gathered through inquiries done based on locations of the facilities (FC, NC, RV). Also, transportation costs have been calculated based on distances of real reference points using GIS software. To solve the problem, the model and solving approach are implimented in GAMS software (CPLEX solver).

After solving the proposed model, some results including weighted unmet demands (objective function), covered demands and reconfiguration of facilities have been reported in Table 3.

For both P_1 and P_2, we have solved three problems so that problems P_{11}, P_{12} and P_{13} represent the reconfiguration model solved by multi stage stochastic programming (P_{11}), countiniuing the existing configuration when faced with disaster (P_{12}) and finally reconfiguration model solved by subtitution of the expected values instead of scenario tree (P_{13}) for P_1.

TABLE 2. Numerical examples' characteristics

Items	P1	P2
Number of Suppliers	4	5
Number of SBs	7	9
Existing SBs	5	5
Candidate SBs	2	4
Demand Nodes	8	16
Commodity classification	4	4
Max routes	4	4
Periods (after disaster occureance)	3	3
Scenarios (No. of Paths)	8	27

In what follows three solved problems of P_1 are disscussed for better understanding. After solving P_{11}, three existing SBs of five SBs must remain (1, 3 and 5), two new SBs must be established (6 and 7) and finally SB-2 and SB-4 are redundant and only the capacities of SB-4 can be consolidated to the new SB-6. The results of P_{11} indicate that coupling the proposed model and multi stage stochastic programming have redesigned a modified relief network so that if the predicted disaster occures, the unmet demands will not exceed 17%. That means the network reliability for demand coverage is more than 83.1%. Moreover, the results attained by encountering the existing configuration (SBs 1, 2, 3, 4 and 5) with the same predicted demands, budget and other inputs that have been considered in P_{11}, show that the coverage of demands during the forecasted disaster equals to 46.1% while this coverage rate for P_{11} was 83.1%. Likewise, the weighted unmet demands (objective function) significantly decline from 1,118,855 (P_{12}) to 209,039 (P_{11}). Breifly, it can be similarly understood from Table 3 that P_{11} can definitly overcome the uncertainty versus subtitition of mean value (MV) instead of scenarios at each period. As it can be undoubtedly undestood, implimentation of multi-stage stochastic programming on the proposed reconfiguration model compared with implimentation of MV(P_{13}) leads to increase the coverage from 16.2% to 83.1%.

TABLE 3. Results of the numerical examples

	Problem No.	Available budget (E+11)	Objective function	Covereed demands (%)	Active SB(s)-existing	Active SB(s)-new	Consolidated SB(s)	Redundant SB(s)
	P.1.1	6.2	209,039	83.1	1,3,5	6,7	4 to6	2,4
P1	P.1.2	6.2	1,118,855	46.1	1,2, 3,4,5	-	-	-
	P.1.3	6.2	3,341,972	16.2	1,2, 3,5	6,7	4 to 6	4
	P.2.1	8.0	510,895	92.3	1,3,5	6,7,9	-	2,4
P2	P.2.2	8.0	1,254,789	70.9	1,2, 3,4,5	-	-	-
	P.2.3	8.0	2,146,702	40.6	1,2, 3,5	6,7,9	-	4

Figure 6 illustrates the top 10 configuratios in terms of demand coverage percentage and objective function. Moreover Table 4 presents more details of five top configurations. As the last analysis, the impact of *VD* on the vicinity set of each closed link has been appraised in Figure 7. The disaster with low impact leads to the less affected and seismic zones. As the intensity increases, the seismic zones extend and overshadow the more range of link vicinity. For example in P_1, we have simplified the problem by considering a fixed *VD* instead of $VD^{t,\bar{s}}$. Figure 7 illustrates that less than 3 km impact radius around each closed link leads 76.1% coverage while the impact of 4 km make less coverage (64.4%). To evaluate the quality of stochastic solutions for P_1, let us define *EV* and EEV_t . Let Obj_{EV} be the optimal value of the objective function in the average scenario deterministic model, *EV*. *EV* is defined where the expected value of each parameter on the scenario tree for each time period is fixed, as follows:

$$Obj_{EV} = Min\sum_{t\in T} \bar{a}_t x_t + \bar{b}_t y_t$$

$$\bar{A}'_{t-1}.x_{t-1} + \bar{A}_t\ .x_t + \bar{B}'_{t-1}.y_{t-1} + \bar{B}_t\ .y_t = \bar{d}_t,\ \ \forall t\in T$$

$$x_t \in X, y_t \in Y, \forall t\in T$$

EEV_t is the optimal value of problem solved by multi-stage stochastic programming (Equations (1)-(17)), where the decision variables (x) until stage $t\ -1$ are fixed using the optimal value of the average scenario model (*EV*).

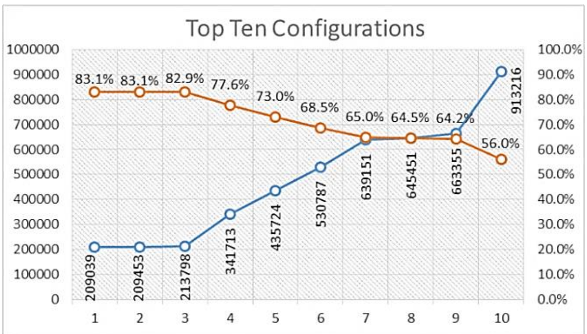


Figure 6. Top ten configuration of P_1 assessed by coverage percentage of demands and O.F.

TABLE 4. Locations for top five configuration of P_1

Rank	Active Existing SBs	New Stablishment	Consolidation
1	1,3,5	6,7	4 to 6
2	1,3,5	6,7	2 to 6
3	1,3,5	6,7	
4	1,2,3	6,7	
5	1,3,	6,7	

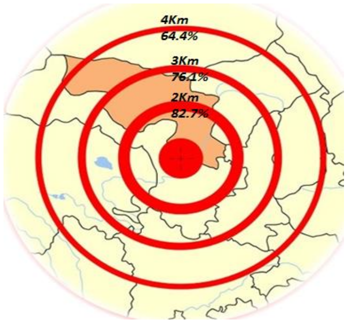


Figure 7. Effect of V.D. on demand coverage percentage

$$EEV_t = \begin{cases} eq.(1)-(17) \\ s.t.\ \ x_1^{\omega} = \bar{x}_1 \qquad \forall \omega\in\Omega \\ \dots \\ \qquad x_{t-1}^{\omega} = \bar{x}_{t-1}\ \ \forall\omega\in\Omega \end{cases}$$

Escudero et al. [22] have defined a *VSS* (value of stochastic solution) relation for a *MSSP*, even for those problems that have no feasible solution as in the case of substitution of the *EV* solutions in the *EEV* model, so that for any minimization model based on *MSSP*, we have the below criterion shown for performance evaluation of stochastic solution resulting from *MSSP*:

$$VSS_t = EEV_t - MSSP \qquad (VSS\text{-}Performance)$$

The positive values for *VSS* in Table 5 demonstrate the appropriate quality of stochastic solutions obtained by *MSSP*. The more periods and stages that are spent, the higher value of solutions are concluded. This trend shows the considerable value of applying the *MSSP* in this problem. For *T=0* (preparedness phase), *EEV* will be equal to objective function of *MSSP* [22].

6. CONCLUSION

In this paper, a novel reconfiguration model for the prepardeness and quick response to disaster (particlarly earthquack) was investigated. The contributions of the present research can be expressed in novel reposition and reconfiguration model for relief network. Moreover, the effect of link failure on the surrounding links has been considered based on a new compatible approach to multi-stage stochastic programming. In this regard, the total unmet demands and the demand coverage obtained by the proposed model and solving approach not only were superior to solutions of the MV, but these results also outweight the results of continiuing the current configuration. Although this research has used destruction scenarios derived from the literature, it is suggested that the model is implimented in a real case study. The future researches are proposed in Table 6.

TABLE 5. Value of stochastic solution at each stage (P_1)

Decision Stage	T=0	T=1	T=2	T=3
VSS	*0*	*96191*	*112650*	*121833*

TABLE 6. Future research road map

Proposed Future Research	References
Integration of link restoration and reconfiguration model for more responsiveness	[25]
Consideration of standard time and disatance coverage simultaneousely.	[10]
Adding the optimality and feaseability cuts to accelerate the solving approach for the large scale problems	[27]

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Re-configuration of the Relief Network Considering Uncertain Demand and Link Failure in an Earthquake: A Multi-stage Stochastic Programming

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P A P E R I N F O

Paper history:
Received 17 April 2017
Received in revised form 25 February 2018
Accepted 15 April 2018

Keywords:
Disaster Management
Re-configuring
Re-positioning
Preparedness Facility
Multi-stage Stochastic Programming
Scenario Tree
Link Damage

چکیده

بحران ها همواره و بی تردید اثرات و پیامدهای انسانی و غیر انسانی جدی را ایجاد می نمایند به نحوی که مدیران و تصمیم سازان کلان این حوزه به دنبال رویکردهایی برای ارزیابی سطح آمادگی کنونی پیکره بندی تسهیلات خود از نظر میزان تلفات، هزینه ها و تقاضاهای برآورده نشده در مواجهه با بحران پیش بینی شده در برنامه ریزی فازهای آمادگی و پاسخ می باشند. در این راستا، تحقیقات کنونی در فاز آمادگی اغلب محدود به مکان یابی تسهیلات جدید بدون توجه و ملاحظه ی دارایی ها، موجودیت ها و پیکره بندی های موجود می باشد. در این مقاله، یک مدل موقعیت یابی یا پیکره بندی مجدد پیشنهاد شده است تا به طور همزمان در خصوص نگهداری یا بستن تسهیلات کنونی نگهداری و توزیع اقلام امداد در مراکز پشتیبانی، احداث تسهیلات جدید، نحوه ی ادغام تسهیلات بلا استفاده با سایر تسهیلات فعال و همچنین نحوه جریان امداد میان سطوح تامین کنندگان، مراکز پشتیبان (مراکز توزیع) و نقاط تقاضا تصمیم سازی گردد. در مدل پیشنهادی، علاوه بر ملاحظه ی یک درخت سناریو برای ویرانی های زلزله و تقاضاها، لینک های شبکه نیز تحت تاثیر شدت رخدادهای بحران در درخت سناریو قرار می گیرند. بنابراین، تخریب لینک ها به نحوی در نظر گرفته شده اند که لینک های خراب و ویران منجر به بسته شده نزدیک ترین لینک ها با مقاومت کمتر خواهند شد. به منظور حل مدل، یک رویکرد برنامه ریزی چند مرحله ای تصادفی بر دو مسئله با سناریوهای تخریب و تقاضاهای واقعی اعمال گردیده است. نتایج، برتری محسوس را در پیکره بندی مجدد پیشنهادی در قیاس با پیکره بندی موجودنشان می دهد. همچنین بهبود بکارگیری روش برنامه ریزی تصادفی چند مرحله ای در مقابل یکی از روش های سنتی نیز مورد بررسی قرار گرفته است.

***doi**: 10.5829/ije.2018.31.06c.10*