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Designing Large-Scale Disaster Response Routes Network in Mitigating Earthquake Risk Using a Multi-Objective Stochastic Approach

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ABSTRACT

The disaster response routes play a crucial role in transporting injured people and goods during the 72 golden hours after disaster. These routes connect the major disaster relief centers. Prior identification of the disaster response routes for a city enables the response teams to reach the disaster locations quickly and conduct relief and rescue operations without being obstructed by the outbound flow of evacuees from the city. These routes should not generally be used by the public unlike the evacuation routes. In this paper, a multi-objective stochastic disaster response routes design problem is presented. In this study, with the goal of reducing vulnerability, the disaster response routes network can be protected against disaster scenarios to maintain its connectivity using more independent routes. An exact approach including a bounded objective function method for considering the multi-objective functions, including the network factors (*OD* connectivity, vulnerability, and management) and an exact method (branch-and-cut) for solving the proposed model are suggested. The results for Sioux-Falls and Tehran networks show the effectiveness of the model.

1. Introduction

The lessons learned from past natural catastrophe experiences place much emphasis on preparedness to respond effectively to disaster (Üster and Dalal, 2017). In an emergency logistic network, the disaster relief and the wounded people trips are two major disaster response trips to towards to the hospitals and the refugee camps. Most of these disaster response trips are done on transportation networks (Anaya-Arenas et al., 2014). Given that, in seismic cities, to overcome the post-earthquake transportation problems, the emergency transportation network must be considered, especially in the first 72 hours after the disaster when the traffic conditions are not normal (JICA, 2004; Özdamar et al., 2004; Shariat Mohaymany et al., 2013).

The disaster response routes (DRRs) appear to have been planned seriously when traffic jams after earthquake disasters were observed in cities, including San Francisco (1989), Los Angeles (1994), and Kobe (1995). However, few papers have been found to be related to the DRRs. Some reports indicate that the related studies have been done by municipalities and related organizations on the disaster response routes in different cities, including Tokyo (JICA, 2004), British Columbia (Joint Emergency Liaison Committee, 2005), Tehran (JICA, 2004), Sydney (Royal Roads University, 2014), and Istanbul (Konu, 2014). If the appropriate DRRs are not planned for disaster relief forces, the activities of these groups may be disturbed (Khademi et al., 2015). These routes are part of the transportation network. Their quick opening has priority in emergency situations, such as severe disasters. To operate the DRRs, several groups such as municipality directors and authorities, disaster management teams, police, military and medical personnel are involved. Therefore, it is necessary to develop a simple, operational and efficient decision-making support system for the identification of the DRRs (Nikoo et al., 2018).

The disaster response routes design problem (DRRsDP) as the mitigation phase (pre-disaster) strategy determines the disaster response routes network (DRRsN) for connecting the major disaster relief centers in mitigating earthquake risk. Simultaneous existence of multi-goals from the perspective of different potentially conflicting authorities, the policy makers, and the relief forces result in applying the conflicting objectives in the optimization model. The challenge comes largely from the resources are

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usually limited in quantity and the multiple authorities involved in disaster reduction often have conflicting interests (Hu et al., 2016). In addition, existence of several possible disaster scenarios in cities leads to the use of stochastic approaches in the DRRsDP. Further, limited number of military forces for controlling the DRRs and limited cost for preparation, including design, retrofit, and the maintenance of the DRRs usually paid annually and in different phases leads to taking the budget constraints into consideration.

In this paper, a multi-objective stochastic approach for designing large-scale disaster response routes network in mitigating earthquake risk with regard to the above challenges has been proposed. The proposed mathematical model for the DRRsDP considered three objectives: 1) network *OD* connectivity, 2) network vulnerability, and 3) network length.

The organization of the paper is as follows. To create a background for the practical implications and the contributions of this study, the literature review and the contributions of the paper are provided in Section 2. In Section 3, the DRRsDP is presented. In Section 4, the results of applying the proposed method on the well-known Sioux-Falls and Tehran network are presented, and finally, in Section 5, the conclusion is presented.

2. Literature Review and Contribution

In this section, first, a review of the literature is presented. Then, the research gaps and the main contributions of the paper are summarized.

2.1 Concepts

Identification of the DRRs is the main objective of the DRRsDP. The *DRRs* are the predefined roads, railroads, and maritime routes that provide the best emergency services in response to major disaster (Royal Roads University, 2014). The DRRsN is designated to assist the emergency vehicles and forces. In general, the *DRRs users* and the *relief forces* can be classified into three categories: response, service, and specialist forces. The *response forces* such as ambulances, firefighters, police officers, and key managers are known as the emergency responders. The *services forces*, including emergency plan volunteers, hospital staff, traffic controllers, public service personnel, public health authorities, and service crews (e.g., water, electricity) are service providers during the emergency period, and the *specialist forces* such as the military, structural engineering inspectors, technicians, supply personnel, and maintenance crews as respondents who act in case of call to carry out specific activities. Those users (i.e., vehicle or person) carrying the responder identification will be allowed to access and travel on DRRs. The *military forces* control the accessibility of these routes, and as soon as these routes are activated, residents are asked to use other routes to help empty these routes (Joint Emergency Liaison Committee, 2005; City of Pitt Meadows, 2013; Royal Roads University, 2014; Nikoo et al., 2018). Those users (i.e., proper vehicle or personal identification) carrying responder identification will be allowed to access and travel on DRRs (Fig. 1). The entire DRRs will not be automatically activated in the event of a disaster unless it is necessary. It is possible that only one lane of a multi-lanes route will be needed, and the rest will remain available for the use of the general public. The closure time duration is meant to be flexible if needed and may change during a disaster. Identification of these routes is one of the most important parts of the relief and rescue plans of disaster areas before the disasters happen. The DRRs are designed to provide access to transportation network for emergency responders within 72 hours of a disaster. Thus, the DRRs are the first routes to be cleared. Accordingly, the protection of the DRRs links are desirable.

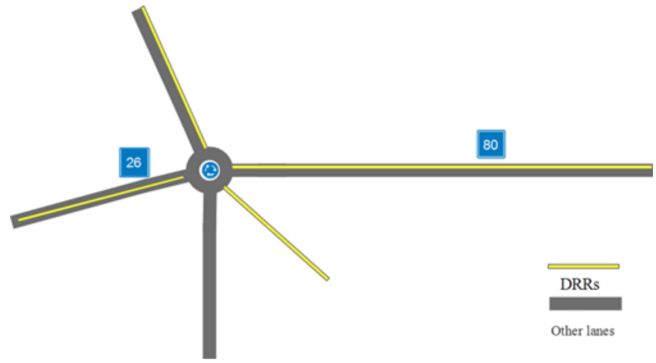


Fig. 1. Disaster Response Routes

2.2 Related Models

The DRRs network is a section of an emergency transportation network. In Nikoo et al. (2018), a relatively comprehensive review of the related concepts of emergency transportation network has been presented. The related research in the area of the application of the emergency network design problems from the transportation perspective fall into two main categories: emergency transportation network and distribution network.

The emergency transportation network problem includes the evacuation route planning problems (ERP) and the disaster response routes problems (DRP). Therefore, the proposed model can be defined as a category of DRP.

The ERP is made for each individual at an operational level (Kongsomsaksakul et al., 2005; Abdelgawad and Abdulhai, 2009; Lim and Rhee, 2010; Ng et al., 2010; Hu et al., 2017). Given the transportation network, the population, and a set of destinations, the goal of the ERP is to produce routes that minimize the evacuation time for the population (Hu et al., 2017). Most of the previous studies have aimed at finding the routes for public use rather than identifying links for emergency network, especially before disasters even though the post-disaster routing problems for emergency vehicles to restore network connectivity have been studied (Çelik et al., 2015; Kasaei and Salman, 2016; Akbari and Salman, 2017).

A number of models are focused on the DRP (Viswanath and Peeta, 2003; Shariat Mohaymany and Pirnazar, 2007; Nikoo et al., 2018). The determination of the DRRs is the main objective of the DRP. The latest work in this field is by Nikoo et al. (2018), presents a three-objective model for designing the emergency transportation network. This model focuses on the system objectives in developing countries. The problem has three objective functions designated to identify the optimal routes for emergency responses considering the length, the travel time and the number of paths as the performance metrics of network vulnerability. In the DRP, identifying critical routes under disaster conditions was emphasized.

The emergency distribution problems (EDP) include the relief distribution, the vehicle routing, the victim evacuation, and the relief delivery problems such as Caunhye et al. (2016), Li et al. (2017), Rivera-Royero et al. (2016), and Tavana et al. (2017). These problems deal with distributing commodities and victims to related centers.

In the DRP, a weighted sum method (Viswanath and Peeta, 2003), a goal programming approach (Shariat Mohaymany and Pirnazar, 2007), and a combined solution approach of a lexicographic and a weighted sum method (Nikoo et al., 2018) for solving the multi-objective model are used. The performance of these methods strongly depends on the choice of the relative weights of objective functions components and the decision-maker's role. In addition, this solution approach does not generate all solution set. In this paper, a solution strategy reducing the decision-maker' roles in solving the proposed model is suggested based on a bounded objective function method for considering the objective functions.

The above mentioned models do not consider the DRRs and the operational objectives for determining the emergency transportation network. In Nikoo et al. (2018), the protection strategies and the disaster scenarios have not been considered. Their model can be used independently if the protection budget is unlimited.

So far, there has been a lack of attention given to the determination of the DRRs and no standard factors are defined to determine the appropriate DRRs. In Faturechi and Miller-Hooks (2014), a review of the literature on the transportation performance metrics in disasters is presented. The desirable characteristics of the DRRsN can be expressed through network significance factors.

The network significance factors are the goal of the DRRs planners (e.g., authorities or government) who have a system view of the network. Based on previous studies the *OD* connectivity between disaster centers, vulnerability, cost, management (length), total travel time and demand for disaster response trips are influential factors in the emergency transportation network.

The significance of considering network vulnerability performance metric is shown in the emergency transportation network (Nikoo et al., 2018). The existence of more independent paths and paths with short travel time in the DRRs decreases the vulnerability by considering the random nature of earthquakes (Khademi et al., 2015). During natural disasters, access to new information about network disruptions is often extremely limited. In Nikoo et al. (2018), the average values of paths (flow/emergency response trips) are minimized by considering the parameter for reducing the emergency response trips in each link. In this average flow function, there may be some links with high flow; thus, there would be a need to control the *path-link* values (i.e., paths traversing a link) using the capacity parameter. In addition, determining this parameter is required for an initial analysis. Considering this point, in this paper, the network link-based vulnerability min-max function is introduced.

The amount of link reinforcement indicates the *protection cost* of the DRRsN, which is considered in the transportation protection problems (TPP) (Peeta et al., 2010; Du and Peeta, 2014). The *design cost* is considered in the network design problem (NDP) such as the EDP. In this paper, both the retofit cost and the design cost (i.e., network cost) are considered in the DRRsDP. As shown in Nikoo et al. (2018), due to the limited number of relief or military forces that can be used for controlling and managing the DRRsN, the length of the DRRs should be limited (i.e., network management).

In addition, as shown in Babaei et al. (2019) and Viswanath and Peeta (2003), the population coverage is another important operational factor. In this paper, the coverage of points is considered via the links; thus, in our paper, the network significance factors as the multiple objectives functions are defined and considered in determining the DRRs.

As already noted, this paper has the following main contributions which distinguish it from the previous studies: 1) presenting the disaster response routes design problem (DRRsDP) and 2) applying the proposed model for large-scale transportation network considering disaster scenarios.

3. Disaster Response Routes Design Problem

The sets, parameters and decision variables used throughout this paper are provided in the notations section.

3.1 Inputs and Nomenclature

Consider the *G (N, A)* in which *N* is a set of *nodes* and *A* is a *link* set (Fig. 2). As shown in Fig. 2, a set of links includes *road, candidate, suggested,* and *connector* links. The *road links* belong to the available network, while the *candidate links* can be candidates of the network protection strategies ($\bar{a} \subset A$). The *suggested links* are a set of candidate links for improving the DRRs ($\underset{-}{a} \subset A$). The *connector* links for connecting nodes have zero travel time. A set of nodes includes *access* and *coverage* points. The *access* points and the *coverage* points are not directly connected to the network, but instead by means of a set of *connector* links. Schools, mosques/churches/etc, and *zones* (i.e., regions with high population density that are virtual) are examples of the *coverage* points where after an earthquake people may temporarily be settled in (k_{14}, k_{15}, and k_{16} in Fig. 2). Coverage of a zone as a special type of a point is associated with the ability of a link to provide access to a zone (i_{17} and i_{18} in Fig. 2). A *disaster response trip* corresponds to a flow that connects a pair of *access* points (*OD* pairs). For example, $OD = (n_{10}, n_{13})$, disaster response

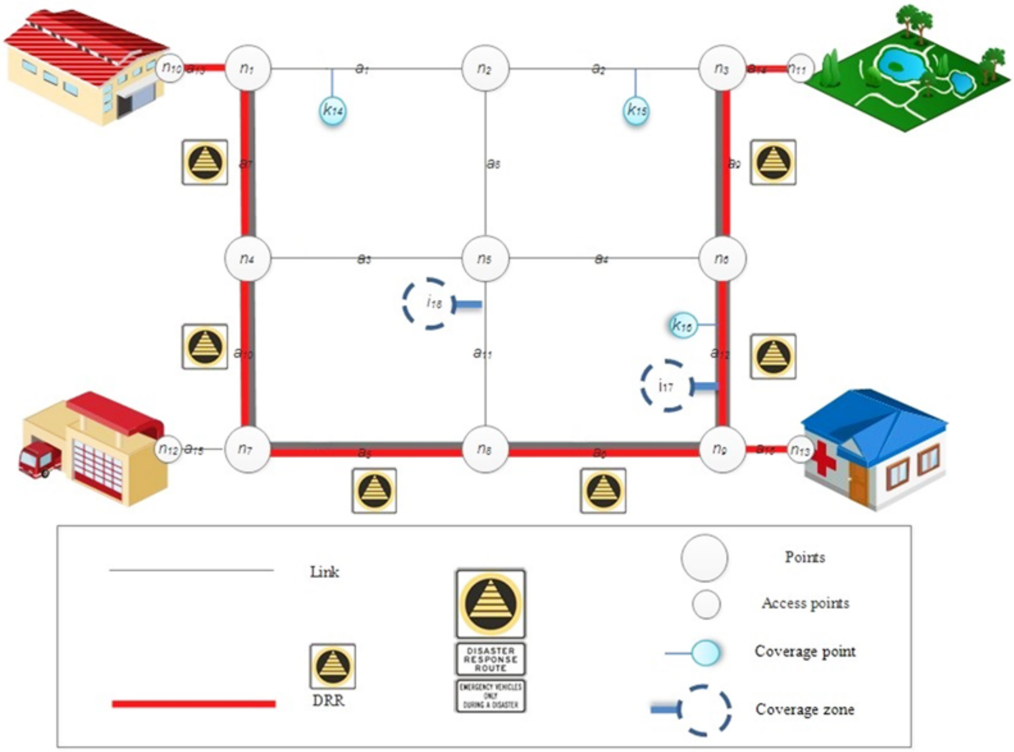


Fig. 2. Model Schematic Network

trip connects the emergency medical service point (n_{10}) to relief center point (n_{13}), including the links $\{a_{13}, a_7, a_{10}, a_5, a_6, a_{16}\}$. In general, based on the demand scenarios (*OD set*), access from *access* points to one or more of the closest *access* points is possible. These points are presented as *d*, providing the *emergency services*. For example, *OD set* appeared in Fig. 2 is $OD = \{(n_{10}, n_{13}), (n_{10}, n_{12}), (n_{12}, n_{11}), (n_{10}, n_{12})\}$. In practice, the budget can be allocated in different phases and time periods. Therefore, the *OD*

Table 1. Main Inputs

Item	Attributes
OD	• Origin • Destination • Emergency service type • Disaster response trips types
Link	• Type • Suggested links • Travel time • Length
Route	• Origin • Emergency service type • Destination • Travel time • Type
Cover point	• Type
Earthquake scenario	• Probability of scenario • Survival probability of each link in each scenario • Survival probability of each link after complete protection

pairs can be categorized according to their importance at several levels. For each trip set, a possible route is considered as a path connecting the *OD* pair. Set of routes is shown by *R*. Each route contains a set of sequential links. As shown in Fig. 2, the selected links are marked with the DRRS signs. Here, we assume that a set of possible future disaster scenarios *S* and their associated probabilities are given. As Table 1 indicates, the basic inputs of the model include attributes of links, *ODs*, routes, cover points, and earthquake scenarios. The disaster scenarios need further explanation. More accurate details are presented in the following.

3.1.1 Earthquake Scenarios

The stochastic programming problems are usually conducted in the form of the two-stage problem along with a finite number of scenarios (Carpentier et al., 2015). Several types of disasters may occur in cities and several different disaster scenarios are caused by the activity of various faults. The survival probability of each link must be determined under each scenario. A *disaster scenario* $s \in S$ is indicated by the survival probability of link (a) in the event of a disaster s (p_a^s). In each scenario, one realization probability of the network upon disaster impact is used. Advanced analysis can lead to the estimations of the failure condition of links. Based on these estimations, the disaster scenarios are created. Link failure occurs due to different reasons, such as the destruction of the nearby buildings or the collapse of bridges (Edrissi et al., 2013). Link failure probability is usually classified into four categories: no damage, minor damage, moderate damage, and major damage (Shiraki et al., 2007). Bridge failure probability to a structure is usually classified into five categories, ranging from no damage to complete collapse. Advanced structural analysis can lead to probabilistic assessment of structural damage for a given disaster in terms of a set of discrete failure probabilities associated with each of the damage categories (Liu, 2009). For example, seismic vulnerability of the bridge is expressed in the form of fragility curves that are an essential issue for risk assessment of transportation networks (Wu and Liu, 2018). These curves represent the probability of exceeding a bridge failure probability under certain intensity of ground motions (Chandrashekaran and Banerjee, 2014). These values can be estimated based on various structural engineering techniques and available data and can be estimated or replaced by another method. Disaster experts such as seismologist and flood experts have predictions of the probabilities of various disaster occurrences. In vulnerable cities such as Tehran (JICA, 2004), studies similar to those noted above have been conducted. The survivability of retrofitted links in future disaster is increased (Liu, 2009). The estimation of the survival probability of the links in our work is based on the assumption of linearity and linear extrapolation as considered in (Du and Peeta, 2014). These studies can be used as an estimation of the survival probability of link as input for the disaster scenarios of the proposed model.

3.2 Model Formulation

To better understand the problem, the equivalent program of the stochastic problem is presented (Eqs. (1) – (19)). F_1, F_2, and F_3 are the three objective functions of the DRRsDP (Eq. (1)). The objective functions, the model constraints, and the suggested solving method are discussed below:

$$Min(F_1, F_2, F_3), \quad (1)$$

$$F_1 = \sum_s \sum_{od} M \;.d_{od}^s, s \in S, (o,d) \in OD, \quad (2)$$

$$F_2 = Max\{\sum_s P^s (1 - \overline{p}_{\overline{a}}^s) t_a w_a^s, \forall a, \overline{a} \in A, s \in S\}, \quad (3)$$

$$F_3 = \sum_a l_a y_a, a \in A, \quad (4)$$

$$\sum_r \delta_r^{od} x_r^s + d_{od}^s = N_{od}^s \quad , \quad \forall (o,d) \in OD, \forall s \in S, r \in R, \quad (5)$$

$$E_a . y_a \geq \sum_r \delta_r^a . x_r^s \quad , \quad \forall a \in A, \forall s \in S, r \in R, \quad (6)$$

$$y_a \leq w_a^s, \forall a \in A, \forall s \in S, \quad (7)$$

$$w_a^s = \sum_r \delta_r^a . x_r^s, \forall a \in A, \forall s \in S, r \in R, \quad (8)$$

$$M \;. z_k^g \geq \sum_a \delta_a^k . y_a \quad , \quad \forall k \in K, a \in A, \quad (9)$$

$$z_k^g \leq \sum_a \delta_a^k . y_a \quad , \quad \forall k \in K, a \in A, \quad (10)$$

$$\frac{\sum_k z_k^g}{N_g} \geq \propto_g \quad , \quad \forall g \in G, k \in K, \quad (11)$$

$$\sum_a C_a c_a + \sum_a \mathrm{C}\, S_a cs_a \leq bB, a \in A, \quad (12)$$

$$\overline{p}_{\overline{a}}^s = c_a q_{\overline{a}}^s + (1 - c_a) p_{\overline{a}}^s, \forall \overline{a} \in A, \forall s \in S, \quad (13)$$

$$\overline{p}_{\overline{a}}^s \geq f_{\overline{a}} . y_{\overline{a}}, \forall \overline{a} \in A, \forall s \in S, \quad (14)$$

$$c_a \leq y_a, \forall a \in A, \quad (15)$$

$$cs_a = y_a, \forall a \in A, \quad (16)$$

$$x_r^s, y_a, z_k^g, cs_{\bar{a}} \in \{0,1\}, \forall r \in R, \forall a \in A, \forall k \in K, \forall \bar{a} \in \bar{A}, \quad (17)$$

$$w_a^s, d_{od}^s \in \mathbb{N}, \forall a \in A, \forall OD \in OD, \forall s \in S, \quad (18)$$

$$c_{\overline{a}} \in (0,1), \forall \overline{a} \in \overline{A} \cdot \quad (19)$$

3.2.1 Objective Functions

The three objectives of the DRRsDP are to minimize network *OD* connectivity, network vulnerability, and network length and are discussed below.

3.2.1.1 Network *OD* Connectivity

The connectivity of access points is necessary. Each *OD* pairs must be connected to each other if possible. The focus of the DRRsDP is ensuring appropriate connectivity for the users of DRRs in the immediate aftermath of disasters. The model looks for a set of routes to connect *OD* pairs in the suitable condition. The emergency response trips set connects different *OD* pairs. The DRRsN is generated based on the possible routes between *o* and *d*. The *OD* connectivity penalty function (F_1) is intended to cover *OD* pair set Eq. (2). There must be at least one route to connect the access points. If no route exists between an *OD* pair in a DRRsN, the associated traversal cost is a fixed penalty (*M*).

3.2.1.2 Network Vulnerability

The nominated DRRs should have the least vulnerability performance metric. In this model, the relative significance of the network is considered by minimizing the link vulnerability index ($Max\{\sum_s t_a w_a^s, \forall a \in A\}$) as the main objective in the DRRsDP Eq. (3). In this paper, the network link-based vulnerability min-max function (i.e., modified Network-based Path-Link performance metric (NPL_m)) is introduced (Eq. (20)). It leads to the nonlinearity of the model; however, it also leads to better distribution of the emergency response trips without the need for pre-processing and the additional parameter. If we compare two DRRsN with the same length and survival probability, a network with a lower path-link variable (w_a^s) on each link would be more desirable. The network link-based vulnerability min-max function (F_2) is considered based on the NPL_m.

$$NPL_m = Min\{Max\{\sum_s t_a w_a^s, \forall a \in A\}\} \quad (20)$$

3.2.1.3 Network Length

The manageability of the DRRs is a key factor in designing a DRRsN. In addition, this network should always be ready considering the limited resources. The network management, including controlling and operation of the DRRs is aimed to increase the manageability of the DRRsN. On the other hand, allocation of relief forces in the disaster situation is very important. Furthermore, the DRRsN should have short length considering the control points (e.g., intersection points) and the military and relief forces; therefore, reducing the length of the network (F_3) can also be the goal of the decision makers Eq. (4).

3.2.2 Constraints

In this study, connecting and accessing the RCs is one of the most important constraints. *OD* is an emergency response trip set and N_{od}^{s} is the number of *OD* access paths in each scenario, which should travel from *o* to destination *d*. Several *OD* sets (i.e., emergency response trips) can be defined in this model in which each emergency response trip has its origin and destination as mentioned above. There are various routes between each origin-destination (*o* and *d*), which allows the model to select a limited number of routes. If N_{od}^{s} is considered as being equal to 1, a route is selected to access *o* to *d*. If N_{od}^{s} is more than one, multiple routes can be selected (constraint (5)). If the link *a* is not in the selected DRRsN, y_a is 0, and otherwise, it is 1. Constraint (6) and constraint (7) relate the link and route selection variables. If route *r* is selected, the corresponding link *a* would be selected through the parameter δ_r^a, representing the link–path incidence relationships. The maximum number of passing routes of link can be separately considered for each link. Constraint (6) ensures that the total number of relief access routes on each link *a* must not exceed its capacity E_a. w_a^s indicates the number of weighted routes of disaster scenario *s*, which pass through the link *a* considering the *OD* pair significance Eq. (8). The route selection variable x_r^s is binary (0 or 1), which is related to the y_a link selection variable.

Only some places and areas should be covered by the DRRsN. Constraint sets (9) to (11) ensure the minimum coverage level $\propto_g$ (i.e., required coverage) in the model. By choosing the links y_a through Eqs. (9) and (10), the points covered by set K (z_k^g) are determined. Constraint (9) and constraint (10) relate the link and point coverage variables. Constraint (11) calculates the ratio of the number of points covered to the total coverage points and controls the required coverage of $\propto_g$. In case of 100% coverage, the related required coverage is set to 1.

If there is an estimate of the survival probability of a link (p_a), this constraint can be used to determine the best allocation according to the available budget (*B*). The constraints on the protection cost ($C_a c_a$) and the design cost ($CS_a cs_a$) are considered (constraint (12)). The p_a^s probability can be increased to q_a^s by investing an amount equal to C_a (constraint (13)).The removal of damaged links in the DRRsN by considering the optimum protection level of a link is modeled as constraint (14). This parameter (f_a) shows the desired amount of protecting each link. In addition, the available budget *B* and budget plan *b* (i.e., the fraction of the full DRRsN protection budget) to increase their survival probabilities in the DRRs are considered. Constraint (15) guaranties the selection of the DRRsN links that are retrofitted and constraint (16) guaranties the selection of the suggested links. The design cost involves engineering costs to build, upgrade, or create temporary links in the DRRsN. The suggested links decision variables either for creation or preparation are considered as cs_a. These links requiring engineering costs to build or create new or temporary links in the DRRsN can be 0 or 1.

Constraints (17) to (19) determine the type of decision variables.

3.2.3 Solving Method

The priority of goals in this model is a part of the DRRsDP concept. In the disaster mitigation phase, the level of service (e.g., travel time or volume/capacity ratio) that the DRRs can provide is less important, and the *OD* connectivity is definitely the first priority (Chu and Chen, 2015). After that, the second highest priority is to reduce the network vulnerability, because the existence of DRRs is the most important factor during the first 72 hours after the disaster. The network management is the third priority; thus, in the DRRsDP, the network *OD* connectivity, vulnerability, and length are more important than the other factors.

In this paper, a bounded objective function method is used to transfer the multi-objective problem into a single-objective integer linear programming (ILP). The suggested bounded objective function method is a type of ε-constraint method. The most common exact approach to solving multi-objective problems is the ε-constraint methods. In a research by Miettinen (2012), it is proven that the solution to a ε-constraint method problem is Pareto optimal; thus, the solution of the suggested approach is Pareto optimal. So, it is possible to find every Pareto optimal solution of any multi-objective problem by the suggested bounded objective function method regardless of the convexity of the problem.

The DRRsDP involves a set of connected goals (F_2, F_3) (21). The bounded objective function method minimizes the single most important objective function F_1. The possibility of reduction of the network length can be considered as the next goal. The objective function F_3 is used to form additional constraints. F_1 as a penalty function is summed to the F_2. In the proposed solution method, the network length can be determined in the first step after the model is solved. The sum of the selected link length should not be greater than *L* (constraint (22)). The branch-and-cut method is used to solve the single objective form of the DRRsDP (21 – 23). The gap tolerance is considered as a termination criterion.

$$Min \quad F_2 + F_1 \tag{21}$$

s.t

$$F_3 \le L \tag{22}$$

$$\text{Other constraints} \tag{23}$$

4. Case Studies

The results for the medium and large size networks are studied in this section. The case studies are tested and coded in Java programming language using CPLEX software on a computer with Quad Core CPU at 2.1 GHz with 8 GB RAM.

4.1 Medium Size Network

The network includes 24 nodes and 76 links, which is known as the Sioux-Falls as appeared in Fig. 3. The basic inputs of the model include link attributes, *OD* set, coverage points, and eventually the characteristics of the disaster scenarios. The links and the coverage points are shown in Fig. 3 ($\propto_g = 0.5$). Usually, *OD* sets are made by the decision makers. In these examples, four generated *OD* set, *OD*-1, *OD*-2, *OD*-3, and *OD*-4 are considered (Table 2). In addition, the budget, the budget plan, and the optimum protection level are the main parameters. The results and the suggested DRRsNs are presented and evaluated. The DRRsN and the protection strategies are the main output of the model.

4.1.1 Main Output: Disaster Response Routes Network

In this section, the model has been implemented for multi-scenarios. The five distributions for survival probability as inputs are considered. The survival probabilities can be different on each link and in each scenario ($p_{\bar{a}}^{s}$). The attributes of generated disaster scenarios including the average, the minimum, the maximum, and the distribution of survival probability of link are indicated in Table 3. Further, the cost for protecting and adding links is considered for each disaster scenario.

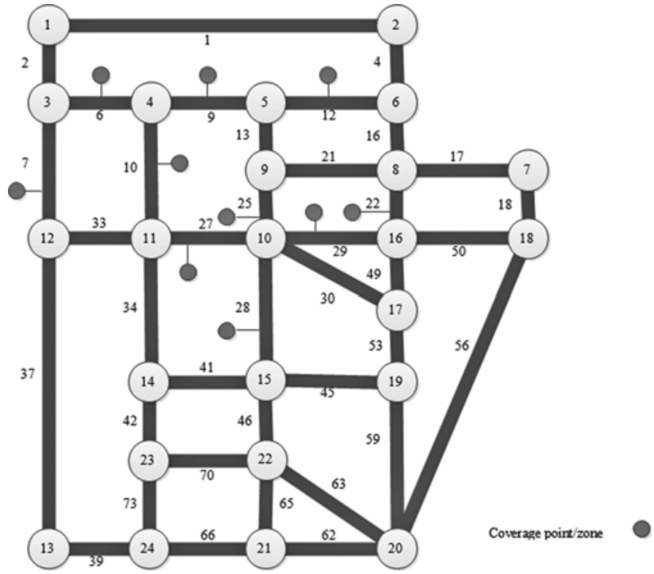


Fig. 3. Input Network

The model is implemented for the *probability of scenarios* (i.e., probability of scenario_1, probability of scenario_2, probability of scenario_3, probability of scenario_4, probability of scenario_5) = (0.4, 0.3, 0.2, 0.05, 0.05). Table 4 shows the length of selected DRRsN with different values for different *optimum protection level of link* and *budget plans* (i.e., the fraction of the full DRRsN protection budget) for the demand sets. In this section, the budget plan is set to {0.025, 0.05, 0.075, 0.1, 0.2, 1}. In addition, the optimum level of link retrofit has values equal to 0.7, 0.8, and 0.9. The DRRsN can be selected

Table 2. *OD* Pair Set

OD set	Number of *OD* pairs	*OD* pair
OD-1	10	(11, 12), (11, 22), (14, 23), (9, 16), (17, 20), (8, 10), (21, 22), (14, 15), (5, 10), (11, 14)
OD-2	20	(9, 16), (11, 23), (1, 10), (10, 23), (9, 15), (14, 22), (10, 21), (15, 23), (7, 17), (11, 22), (8, 17), (20, 21), (21, 22), (4, 11), (7, 8), (10, 19), (19, 22), (13, 22), (4, 10), (11, 15)
OD-3	30	(11, 14), (9, 15), (19, 22), (20, 21), (16, 22), (21, 22), (10, 21), (5, 10), (11, 15), (14, 22), (15, 16), (12, 13), (9, 16), (15, 23), (14, 15), (11, 13), (7, 16), (11, 16), (9, 11), (22, 24), (10, 23), (7, 17), (4, 10), (11, 17), (19, 20), (11, 12), (11, 23), (16, 20), (4, 11), (8, 17)
OD-4	43	(1, 10), (4, 10), (4, 11), (5, 10), (7, 8), (7, 16), (7, 17), (8, 10), (8, 17), (9, 11), (9, 16), (10, 19), (10, 21), (10, 23), (11, 12), (11, 13), (11, 14), (11, 15), (11, 16), (11, 17), (11, 22), (11, 23), (12, 13), (13, 22), (14, 15), (14, 22), (14, 23), (9, 15), (15, 16), (15, 17), (15, 20), (15, 23), (16, 19), (16, 20), (16, 22), (17, 19), (17, 20), (17, 22), (19, 20), (19, 22), (20, 21), (21, 22), (22, 24)

Table 3. Disaster Scenarios

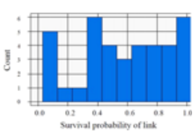
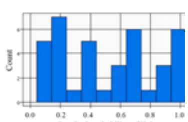
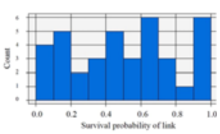
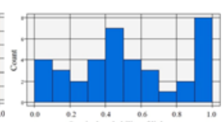
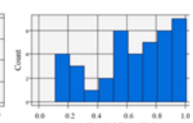
Disaster scenario			Scenario_1	Scenario_2	Scenario_3	Scenario_4	Scenario_5
Survival probability of link	$p_{\bar{a}}^{s}$	Min	0.03	0.04	0.05	0.03	0.11
		Max	0.99	0.96	0.94	0.97	0.97
		Distribution					

Table 4. The Suggested DRRsNs Length: Budget Plans and Optimum Level of Link Protection Trade-Off

OD set	Optimum protection level of link	Budget plans				
		1	**0.2**	**0.1**	**0.075**	**0.05**
				DRRsNs length (Km)		
	0.9	259.8	248.2	184.9	179.9	-
OD-4	**0.8**	266.6	266.6	191.6	174.9	158.2
	0.7	266.6	266.6	216.6	184.9	163.2
	0.9	259.9	248.2	188.3	166.6	-
OD-3	**0.8**	259.9	259.9	**204.9**	184.9	154.9
	0.7	259.9	256.6	209.9	188.3	169.9
	0.9	223.2	223.2	189.9	169.9	-
OD-2	**0.8**	243.2	243.2	208.3	179.9	-
	0.7	233.2	233.2	208.3	184.9	148.3
	0.9	193.3	169.3	166.6	173.3	-
OD-1	**0.8**	188.3	179.9	163.3	156.6	154.9
	0.7	194.9	193.3	188.3	174.93	153.3

based on the available budget; for example, the suggested DRRsN length for *OD*-3, $f_a = 0.8$ and $b = 0.1$ is about 205 Km. In general, the DRRsNs length has decreased due to budget reduction.

A sample DRRsN is indicated in Fig. 4. In this case, it is assumed that the *OD* set is categorized into two levels. First, the model is implemented for the higher level demand pair (first-level). Then, based on the selected links (output of level 1), it is implemented for the second-level *OD* set group (level 2). Three links are added at level 2. In addition, node 7 is selected as the appropriate location between candidate points 7 and 18. One of the outputs of the model is a retrofit percentage or a retrofit strategy for the selected links of the DRRsN as shown in Fig. 4. As an example, some links require retrofit percentage over 0.81 (or retrofit strategy type 1) and 2 links require retrofit percentage below 0.81 (or retrofit strategy type 2). In addition, link 21 is a suggested link, which requires to be prepared completely for the DRRsN.

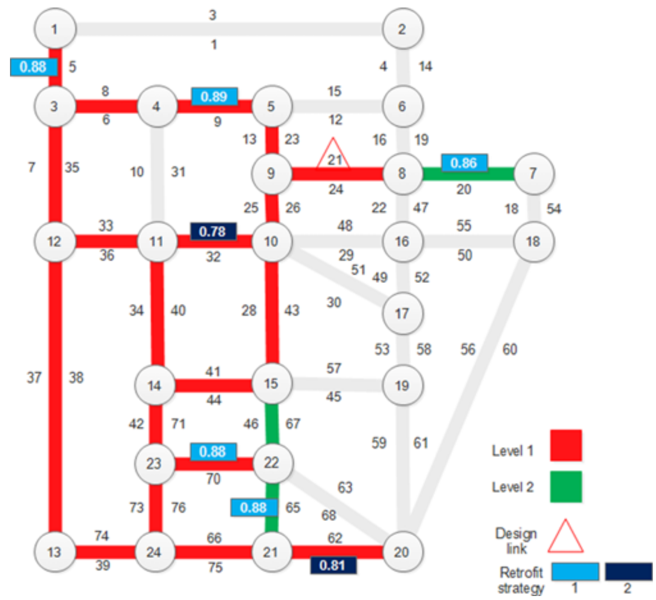
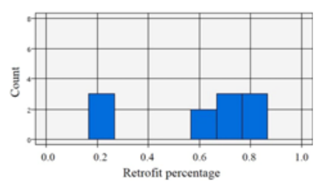
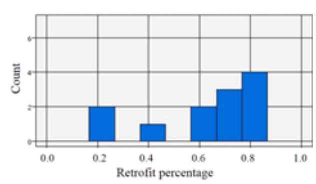
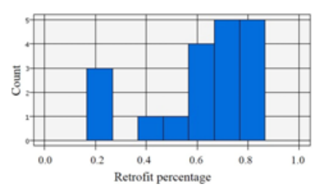


Fig. 4. A Sample DRRsN

Table 5. Outputs: Network Length and Retrofit Strategy

Maximum allowable length (L)	Network length	Number of links	Number of suggested links	Number of protection links	Retrofit percentage (c_a) distribution
200	161.6	23	2	19	
160	126.6	18	4	12	
120	108.2	15	3	11	

For example, the relationship between the maximum allowable length (200, 160, 120) and the selected DRRsN is shown in Table 5. Some links are considered as a suggested link ($OD-1$, $B=100{,}000$, $b=0.1$, $L=300$, $f_a=0.85$). The number of protection (number of selected links for protection) and suggested links is another output of the suggested model. The DRRsN length, the retrofit strategy distribution, the number of links, the number of protection links, and the number of suggested links for different maximum allowable length (L) for the DRRsN are shown in Table 5. For instance, from 18 selected links with $L = 160$, 12 links need to be reinforced, while 4 links are selected to be designed. The retrofit percentage of each link is shown in the retrofit strategy distribution field of Table 5. The retrofit strategy distribution shows all protection decision for each link (c_a). Naturally, the larger networks need a higher cost for retrofitting for which ranking the links can be planned based on this result.

4.1.2 Sensitivity Analysis

In this section (OD-1, OD-2), seven disaster scenarios on the Sioux-Falls network with the same values for the survival probability of each link are considered $S=\{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7\}$. For example, for disaster scenario $s=0.1$, $p_a^{0.1}$ for each link is set to 0.1. The cost for protecting each link is considered 1000 units. In this section, the model has been implemented for each scenario separately (one-scenario). In Fig. 5, the relation between the survival probability and the network vulnerability is evaluated ($f_a=0.85$, $B=38{,}000$, $b=0.75$). The NPL_m has increased with decreasing survival probability of links. As shown in Fig. 5, if more budget is allocated to the DRRsN, the network has a lower vulnerability index.

In Fig. 6, the protection cost is compared considering the optimum protection level of links ($B=38{,}000$, $b=0.5$). As indicated in Fig. 6, the protection cost naturally enhanced by increasing the optimum protection level for each link. With regard to the optimum protection level of link, the suggested DRRsN confers a higher cost with decreasing the survival probability of each link. For these seven disaster scenarios, NPL_m value has been 10. To keep the network vulnerability value at a minimum value (10), more cost needs to be assigned for links with low survival probability.

The relationship between the required coverage, the network length, and NPL_m is shown in Table 6. The required coverage changes for $\propto_g=\{0.1, 0.3, 0.5, 0.7, 0.9\}$ and disaster scenario $s=0.4$ are analyzed in this section for OD sets. As the required coverage increases, NPL_m is increased, reaching 36 in $\propto_g=0.9$. Generally, the network length is increased by increasing the required coverage. The interesting result is that if there is a possibility of reducing vulnerability index, the solution goes to the network with larger length.

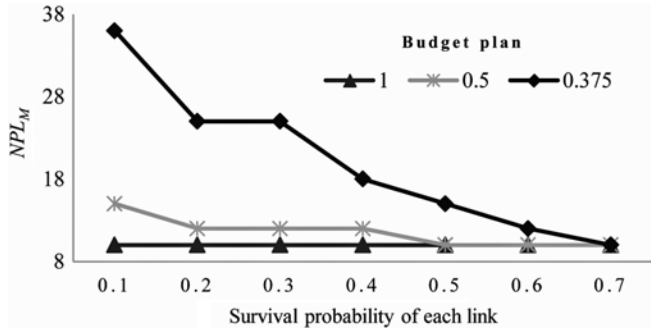


Fig. 5. Disaster Scenarios and Network Vulnerability

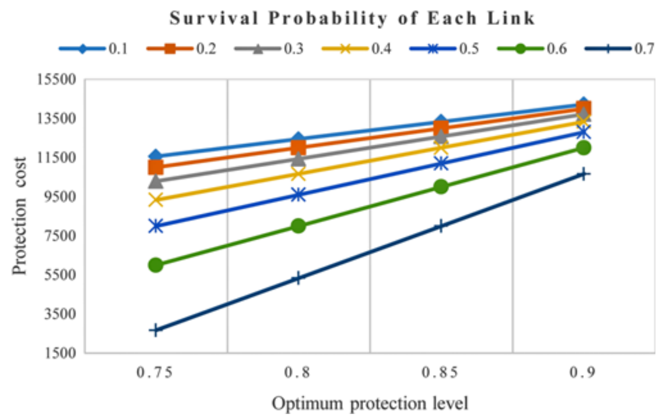


Fig. 6. Optimum Protection Level of Link and Protection Cost

4.1.3 Discussion

As expected, different DRRsNs are suggested for different weights of scenarios (i.e., probability of scenarios). The results of the samples of probability of scenarios are shown in Table 7. Without considering a disaster scenario (one-scenario) in the model, the DRRsN has more length compared to other DRRsNs

Table 6. Required Coverage vs Network Vulnerability and Length

OD set	Required coverage									
	0.1		0.3		0.5		0.7		0.9	
	Network length (Km)	NPL_m	Network length (Km)	NPL_m	Network length (Km)	NPL_m	Network length (Km)	NPL_m	Network length (Km)	NPL_m
OD-1	109.9	10	109.9	10	118.3	10	123.3	10	131.6	10
OD-2	159.9	12	159.9	12	164.9	15	164.9	18	163.3	18
OD-3	176.6	16	176.6	16	176.6	20	166.6	24	166.6	24
OD-4	171.6	20	171.6	20	171.6	30	163.3	36	164.9	36

Table 7. Discussion: DRRsN

Approach	Disaster scenario		Probability of scenarios	DRRsN	
				Network length (Km)	Protection cost
Without considering disaster scenarios	-		(0, 0, 0, 0, 0)	184.9	-
One-scenario	scenario_1		(1, 0, 0, 0, 0)	158.27	3,289.62
	scenario_2		(0, 1, 0, 0, 0)	178.26	7,334.35
	scenario_3		(0, 0, 1, 0, 0)	151.61	7,867.66
	scenario_4		(0, 0, 0, 1, 0)	151.61	6,950.62
	scenario_5		(0, 0, 0, 0, 1)	178.26	4,752.01
Multi-scenarios	(scenario_1 scenario_2, scenario_3, scenario_4, scenario_5)	Samples	(0.4, 0.3, 0.2, 0.05, 0.05)	191.59	5,941.03
			(0.3, 0.4, 0.05, 0.2, 0.05)	181.59	4,114.40
			(0.05, 0.3, 0.4, 0.05, 0.2)	194.92	5,475.85
			(0.05, 0.2, 0.3, 0.4, 0.05)	194.92	5,003.4
			(0.2, 0.05, 0.05, 0.3, 0.4)	188.26	4,848.17

with a disaster scenario (184.9 Km). Given the budget constraints and a scenario, networks with less lengths are suggested. The protection cost for the DRRsN is the lowest cost for scenario_1 (1, 0, 0, 0, 0) (158 Km), while it is the highest one for scenario_3 (0, 0, 1, 0, 0) (151.6 Km). Taking into account several scenarios (i.e., multi-scenarios) simultaneously, in order to maintain the network vulnerability in a minimum value, the network length has been increased. In these samples, in the last step, only some solutions remained, indicating the performance of the suggested solution strategy. The type of demand is more important than the number of demand sets. The maximum solving time using suggested solution approach is about 600 seconds, which is acceptable. Using the proposed model, with a small increase in the length, a DRRsN network is suggested taking into account the simultaneous effect of several disaster scenarios. The results show the effectiveness of the suggested approach.

4.2 Large Size Network

To investigate the solution algorithm performance, a large network of Tehran city is applied in this section. The presented study considered a subset of the Tehran road network with arterial roads and freeways. This network has 3,001 links. Based on the existing seismic data (e.g., historical and instrumental), Tehran has so far been hit by over 1,000 large or small earthquakes within the 200 km surrounding Tehran (Negarestani et al., 2014). Given this data, three main active faults are Mosha-Fesham, North Tehran, and South Rey. In this case study, three disaster scenarios based on three faults are designed and generated. Other parameters were estimated based on the available data. The important disaster response trips (i.e., *OD* set) that are considered are presented in Table 8. The *OD* set is created based on the opinion of experts and the data provided by Tehran Disaster Mitigation and Management Organization (TDMMO). These disaster response trips origin or destination has generally

Table 8. Tehran *OD* Set

DC	HADC	SHADC	Others
DCs to related HADC DCs to the related entrance gate DCs to DCs railway stations and airports to DCs DMC to DCs	Entrance gates to the related HADC HADCs to the nearest HADC HADC to the related SHADCs DMC to HADCs	SHADC to the nearest fire-fighting station Red Crescent stations to the nearest SHADC hospitals to the nearest SHADC EMS to the nearest SHADC fire-fighting stations to the nearest SHADC SHADCs to the nearest EMS SHADCs to the nearest Red Crescent station SHADCs to the nearest refugee camp SHADCs to the nearest hospital	Refugee camps to the related entrance gate

HADC: Humanitarian Aid Distribution Center
SHADC: Support HADCs
DMC: Disaster Management Headquarters
EMS: Emergency Medical Services
DMC: Disaster Management Center
DC: Distribution Centers

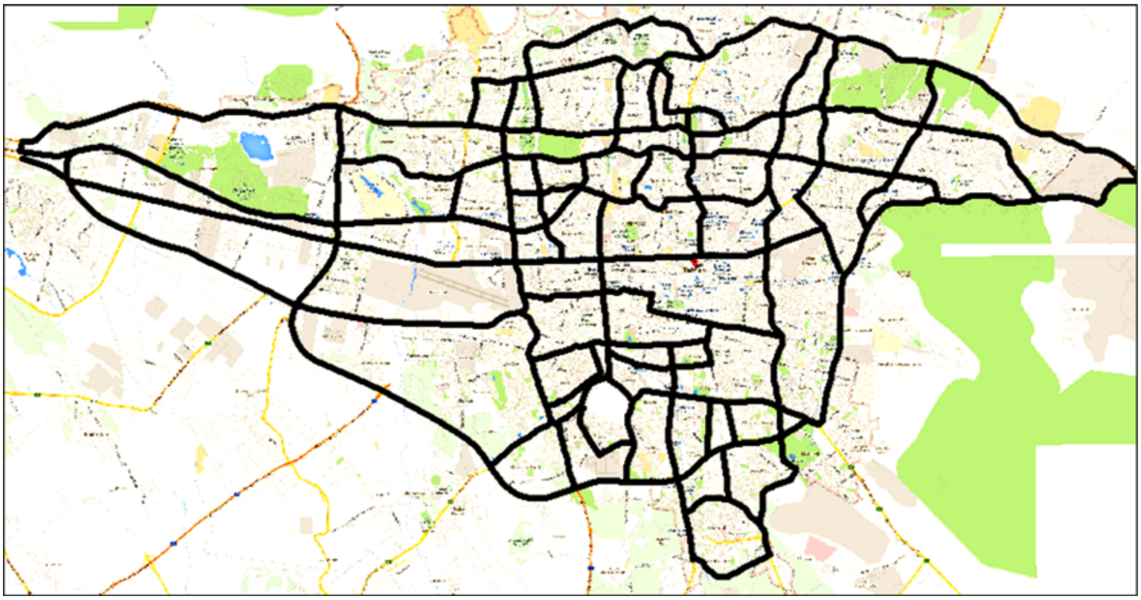


Fig. 7. A Suggested DRRsN

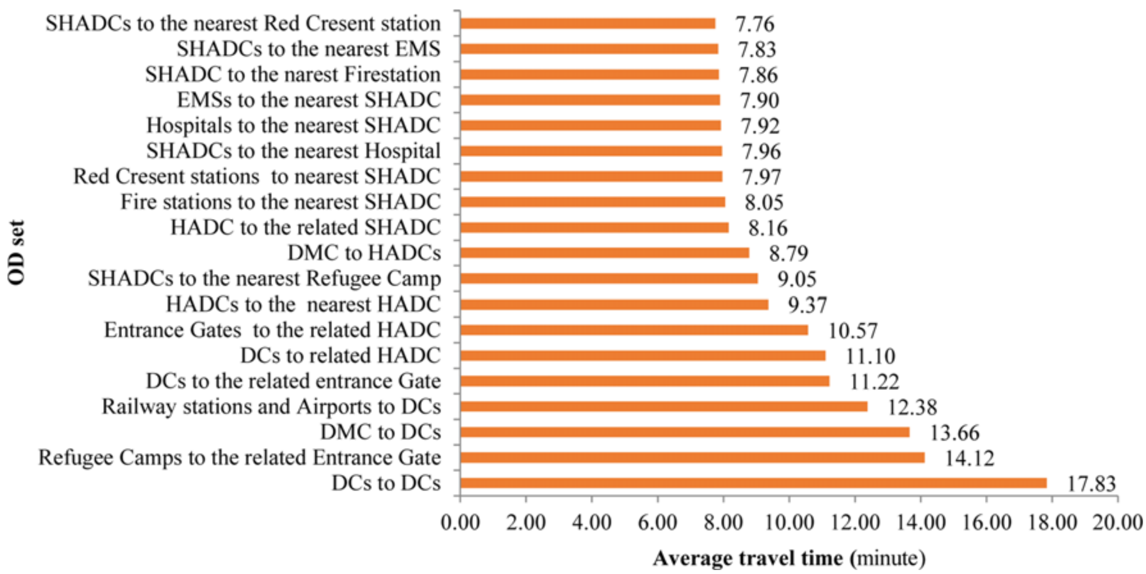


Fig. 8. Average Travel Time of the Disaster Response Routes

included DCs, HADCs, SHADCs, and refugee camps. The CPU time for five different *OD* sets with different sizes (10 to 100) is evaluated, indicating 26.54, 91.41, 92.46, 65.24, and 80 secs, respectively.

A suggested DRRsN for the *OD* set with 400 pairs was 740 Km, which is shown in Fig. 7. The protection cost is estimated at 8,670,000 units. The CPU time was 2352.6 sec. This network has 11 main complete streets. As indicated in Fig. 8, DCs to DCs, refugee camps to the related entrance gate, DMC to DCs, railway stations and airports to DCs, DCs to the related entrance gate, DCs to related HADC, and entrance gates to the related HADC have an average trip time greater than 10 minutes. SHADC to the nearest Red Crescent station trip sets with the average time of 7.76 minutes has the quickest response. The disaster response routes play a crucial role in transporting injured people and goods during the golden time (i.e., the first 72 hours after disaster). These disaster relief vehicles/users' routes connect the disaster centers and should not generally be used by public people and vehicles unlike the post-disaster evacuation routes. These routes can be used for movement of relief forces.

5. Conclusions

Pre-identified routes that can best handle emergency services in response to a catastrophic disaster are defined as the DRRsN. The DRRs are a critical part of the overall emergency transportation system. Identification of these routes is one of the most important parts of relief and rescue programs of disaster areas before the earthquakes happen.

In this paper, an optimization model has been presented to determine the large-scale disaster response routes network to mitigate the risk of earthquake. For this purpose, a multi-objective non-linear stochastic programming model, including network *OD* connectivity, network vulnerability, and network length has been developed to identify the DRRsN by considering the network cost as the main constraint of the DRRsDP. The DRRs are designed to provide access to the transportation network for emergency responders within the first 72 hours after an earthquake. The DRRsN provides services such as moving and collecting victims and injured people, maintaining order and regulations, rescuing people and restoring essential services. These routes can be used for movement of relief forces including firefighting vehicles, police forces, ambulances, military equipment, vehicles with DRRs tags and vehicles driven by people with the DRRs identification cards. Another important output of the model is a retrofit percentage or a retrofit strategy for the selected links.

In this study, the results for medium and large networks are shown. As the number of *OD* pairs increased, the network vulnerability and the total travel time increased as well. In addition, network vulnerability has increased due to decrease survival probability of links. To maintain a minimum network vulnerability, more costs should be allocated to links with a lower probability of survival. Mainly, by increasing the coverage required by the points, the length of the network increases. In general, the DRRsNs length has decreased due to budget cut. The DRRsN can be selected based on the available budget. If more budget is assigned to the DRRsN, the lower vulnerability function is expected. Furthermore, as the level of optimal protection for each link increased, the cost of protection naturally increased. Naturally, larger networks need a higher cost for retrofitting for which ranking the links can be planned based on this result.

The proposed model can be applied for large-scale transportation networks such as Tehran according to earthquake scenarios. Travel time includes more than 10 minutes on average for disaster response trips to distribution centers, refugee camps, entrance gates, disaster management centers, railway stations, airports, and humanitarian aid distribution. Travel time of the disaster response routes can be used for evaluation and relocation of the access points locations. In addition, the proposed model can be used to locate the new disaster relief centers. Also, network performance functions including *OD* connectivity, vulnerability, and length introduced in this study can be used to evaluate or compare existing or suggested DRRsNs.

An exact approach including a bounded objective function method and an exact solution methodology has been applied. The suggested solving approach has reduced the role of decision makers in determination solutions. In order to reduce the solving time, other solution methodology can be evaluated and suggested. Although this paper deals with urban routes, the proposed model can be used for the interurban routes by considering some assumptions. In this paper, the proposed model has considered the DRRs for earthquake scenarios. The other disasters such as floods have their own characteristics. Regardless of the type of disaster, the DRRs should connect the major disaster relief centers to reduce vulnerability. Therefore, the proposed model along with some assumptions can be used to design the DRRsN associated with adopting the survival of the link probability and the retrofit strategy parameters for other disasters. Therefore, in the design of DRRsN, other features of disaster can be considered jointly or separately in future research work. In addition, the impact of DRRs topology on disaster response services has not yet been evaluated.

Acknowledgments

Not Applicable

Nomenclature

A = Set of all links of transportation network, a
$\overline{A}$ = Set of road links that are candidates of the network protection strategies, $\overline{a} \subset A$
$\underline{A}$ = Set of suggested links, $\underline{a} \subset A$
B = Budget for the DRRsN protection
b = Budget plan, the fraction of the full network protection budget (B)
$C_{\bar{a}}$ = Protection cost, cost for protecting link $\bar{a}$
$c_{\bar{a}}$ = Retrofit percentage for candidate link $\bar{a}$
$C_{\underline{a}}$ = Design cost, cost for adding suggested link $\underline{a}$
$cs_{\underline{a}}$ = 1 if suggested link $\underline{a}$ is used, and 0 otherwise
d^s_{od} = Number of unconnected disaster response trips (o, d) under scenario s
E_a = Maximum permitted number of paths traversing link a
$f_{\bar{a}}$ = Optimum protection level of link $\bar{a}$
K = Set of coverage points, $k_g \in K$ (g denotes the type of k)
L = Maximum allowable length for the DRRsN
l_a = Length of link a
M = A large enough positive number
N = Set of all nodes, n
N_g = Number of cover points with type g
N^s_{od} = Number of access routes that should provide multiple connections between each OD pair under scenario s
OD = Set of origin-destination, (o, d)
P^s = Probability of scenario s
$p^s_{\bar{a}}$ = Survival probability of link $\bar{a}$ under scenario s
$\bar{p}^s_{\bar{a}}$ = Survival probability of link $\bar{a}$ under scenario s after allocating the protection cost
$q^s_{\bar{a}}$ = Survival probability of link $\bar{a}$ under scenario s after complete protection
R = Set of all routes, r
S = Set of all disaster scenarios, s

T_r = Travel time of route r

t_a = Travel time of link a

w_a^s = Number of paths traversing link a (path-link) under scenario s

x_r^s = 1 if route r under scenario s is used, and 0 otherwise

y_a = 1 if link a is used, and 0 otherwise

z_k^g = 1 if cover point k with type g is used, and 0 otherwise

δ_r^a = Parameters for link–path incidence relationships. If link a is on route r, $\delta_r^a = 1$; otherwise, $\delta_r^a = 0$.

δ_r^{od} = Parameters for OD point-path incidence relationships. If route r connects point o to d, $\delta_r^{od} = 1$; otherwise, $\delta_r^{od} = 0$

δ_a^k = Parameters for cover point-link incidence relationships. If link a covers point, k $\delta_a^k = 1$; otherwise, $\delta_a^k = 0$

$\propto_g$ = Required coverage of points with type g

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