A Stochastic Optimization Model for Designing Last Mile Relief Networks

Online Supplement

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Appendix A. Deterministic Equivalent Formulation (DEF) The DEF of the proposed two-stage stochastic programming model is presented below.

$$
\begin{aligned}
\text{maximize} \quad & \sum_{j\in J} \bar{\nu}_{0j} y_j + \sum_{s\in S} p^s \sum_{i\in I} \sum_{j\in N_i^s} \nu_{ij}^s x_{ij}^s - \epsilon \sum_{j\in J} \sum_{s\in S} \beta_j^s \\
\text{subject to:} \quad & \sum_{j\in J} y_j \leq \kappa, \\
& R_j \leq K_j y_j, \quad j \in J, \\
& y_j \in \{0,1\}, \quad j \in J, \\
& R_j \geq 0, \quad j \in J, \\
& r_j^s \leq R_j, \quad j \in J,\ s \in S, \\
& \sum_{j\in J} r_j^s = \theta^s, \quad s \in S, \\
& \sum_{j\in N_i^s} x_{ij}^s = 1, \quad i \in I,\ s \in S, \\
& x_{ij}^s \leq y_j \quad i \in I,\ s \in S,\ j \in N_i^s, \\
& x_{jj}^s \geq y_j, \quad j \in J,\ s \in S, \\
& x_{ij}^s \in \{0,1\}, \quad i \in I,\ s \in S,\ j \in N_i^s, \\
& r_j^s \leq \mathrm{PD}_j^s + \beta_j^s \leq \mathrm{TD}_j^s, \quad j \in J,\ s \in S, \\
& \mathrm{TD}_j^s - r_j^s \leq \rho\, \mathrm{TD}_j^s, \quad j \in J,\ s \in S, \\
& r_j^s \geq 0, \quad \beta_j^s \geq 0, \quad j \in J,\ s \in S.
\end{aligned}
$$

Appendix B. Data Set Generation In this section, we present the details of the data generation that are omitted from Section 6.1.

B.1 Damage Levels and Affected Population The Van earthquake (2011) occurred on the North Anatolian Fault (NAF) line in Turkey. Erdik and Eren (1983) present the following attenuation relation to calculate the intensity of an earthquake on the NAF line:

$$I = 0.34 + 1.54M - 1.24 \ln R,$$

where M, R, and I denote the surface wave magnitude (Ms), the shortest distance to fault (km), and the intensity (MSK), respectively. Accordingly, for the Van earthquake with Ms$= 7.2$, we obtain the parameters in Table 1. In our case study, we do not distinguish between the intensity levels of “Strong” and “Very Strong”, and only use the radii $R_1 = 7$ and $R_2 = 16$ to identify the damage intensity levels of areas (as shown in Figure 1). Vincenty’s algorithm (Vincenty, 1975) is used to calculate the distances between cluster centers and the earthquake epicenter.

We estimate the base values of demand based on the damage intensity level of each area. To this end, we first use the publicly available damage assessment reports (Governorship of Van, 2011; Erdik et al., 2012; UCTEA,

M (Ms)	R (km)	I (MSK)	Intensity Definition
7.2	80	6	VI-Strong
7.2	36	7	VII-Very strong
7.2	16	8	VIII-Damaging
7.2	7	9	IX-Destructive

Table 1: The attenuation relation (Erdik and Eren, 1983)

2012) to estimate the proportion of affected households. In particular, we group the demand points according to their damage intensity levels (as defined in Table 1). For each group, we calculate the ratio of residential households that are in the following damage states: "No damage"; "Slight and medium damage"; " Heavy damage and collapse". These ratios, presented in Table 2, are used as the estimated proportion of affected households at each damage state. We note that such a table is provided by Erdik et al. (1996) for some other earthquakes that occurred in Turkey; here, we specifically focus on the Van earthquake.

	Intensity (MSK)		
Damage States	VI or VII (%)	VIII (%)	IX (%)
No damage	27	2	3
Slight and medium damage	51	16	11
Heavy damage and collapse	22	82	86

Table 2: Percentages of affected households

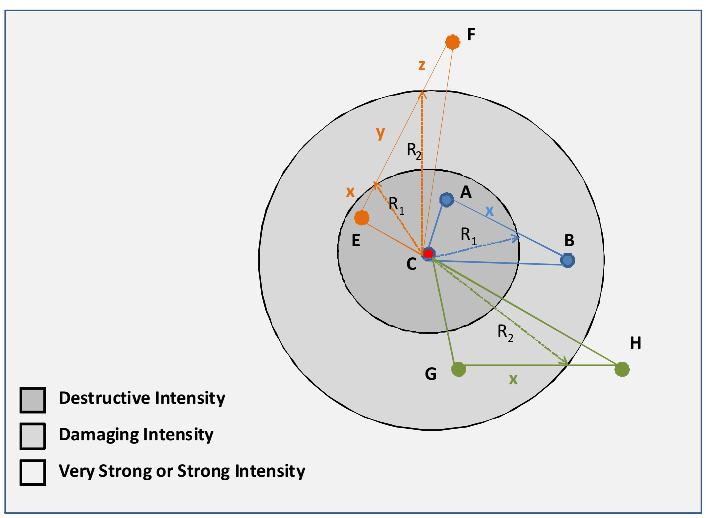


Figure 1: Multiple damage intensity levels (damage areas) for the affected region

B.2 Flood Risk In this section, we explain how we determine the flooding risk scores for each link. These scores decrease as the distance from the lake increases. In our study, we specify two distance thresholds (R_1 and R_2) to consider three risk areas: high-risk, medium-risk, and low-risk (as illustrated in Figure 2). To calculate the shortest distance of each node to the lake, we identify several reference points that define the contours of the Lake of Van. Then comparing these distances with the threshold values R_1 and R_2, we determine the corresponding risk area for each node. The distance between any two points is calculated using Vincenty's algorithm. Then, the risk scores for each link are determined based on the risk areas where its endpoints are located. Depending on the positions of the endpoints, we distinguish six types of links. We associate a different risk score for each type of link as follows.

(i)-(iii) The highest risk score, denoted by H, is assigned to the links whose endpoints are both located in the high-risk area (e.g., the link AB in Figure 2). Similarly, risk scores M and L are assigned to the links with both endpoints in the medium-risk and low-risk areas, respectively.

(iv) For the links with one endpoint in the middle-risk area and the other endpoint in the high-risk area (e.g., the link BC in Figure 2), a value MH in the range $(M,\ H)$ is assigned as a risk score.

(v) For the links with one endpoint in the low-risk area and the other endpoint in the high-risk area (e.g., the link BE in Figure 2), a value LH in the range $(L,\ H)$ is assigned as a risk score.

(vi) For the links with one endpoint in the low-risk area and the other endpoint in the medium-risk area, a value LM in the range $(L,\ M)$ is assigned as a risk score.

In our case study, the threshold values R_1 and R_2 are assumed to be 10 and 20 kilometers, respectively. The risk parameters H, M, and L are chosen as 3, 2, and 1, respectively, while the values of MH, LH, and LM are chosen as the mid-points of the ranges specified above.

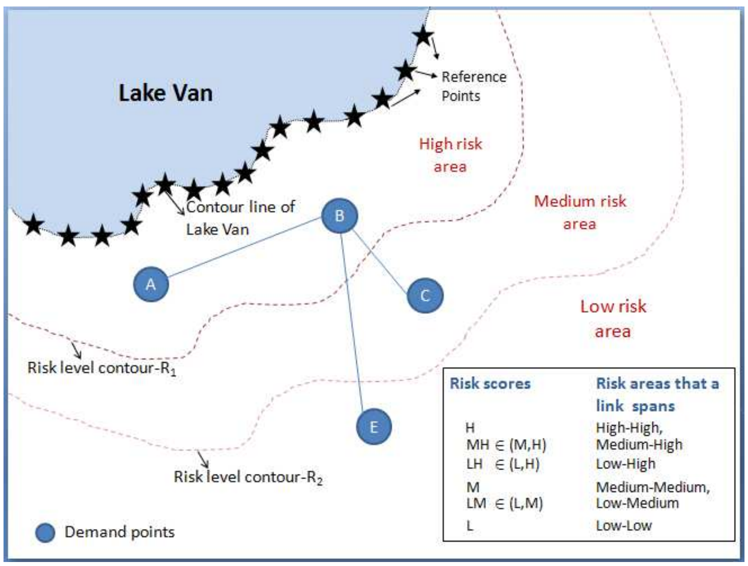


Figure 2: Illustrative figure for flooding risk scores

B.3 Scenario Generation Given the epicenter of the earthquake and the network distances, we specify three damage intensity levels (and so three damage areas) as in Appendix B.1. Then, we generate the realizations of the demands and accessibility scores for each scenario, as explained next.

Generating realizations of demands for a single scenario. The demands randomly deviate from their estimated base values. The realization of the demand at a node is obtained by multiplying its estimated base value by a deviation factor. These factors are sampled from uniform distributions on the intervals $[0.75, 1.30]$, $[0.75, 1.20]$, and $[0.75, 1.10]$ for the nodes in the areas with “destructive”, “damaging”, and “very strong or strong” intensity levels, respectively. We independently sample a separate factor for each node.

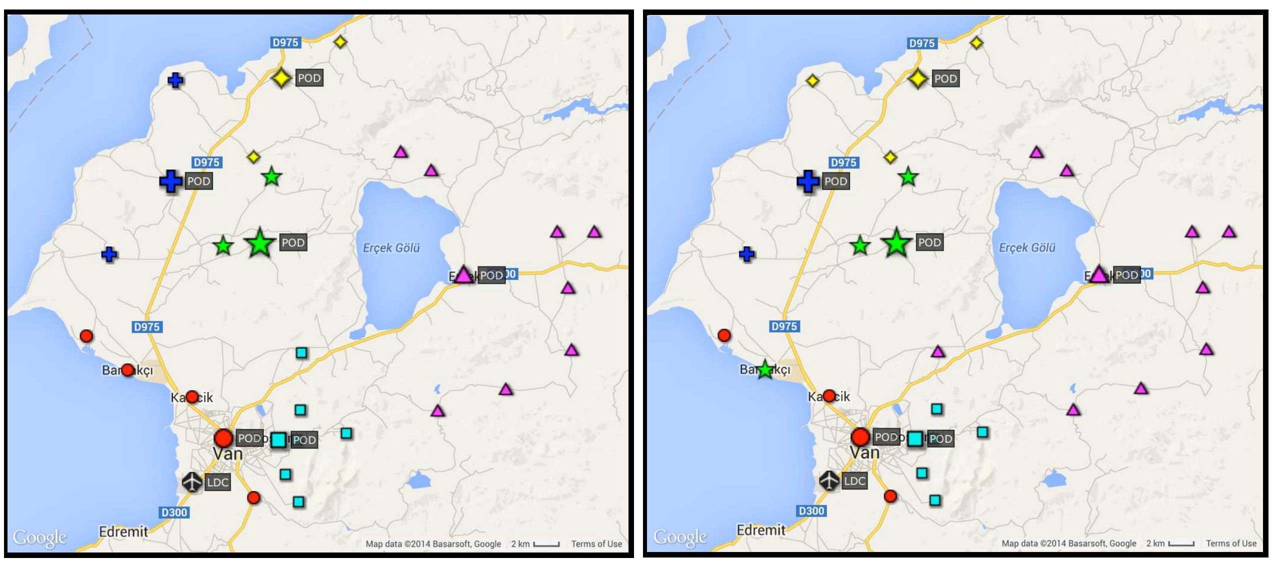
Generating realizations of accessibility metrics for a single scenario. Given the base values for accessibility metrics, we obtain the realizations for a particular link by multiplying its estimated base value by a deviation factor, which is generated randomly considering the damage intensity levels of the areas that the link spans over. We sample a different factor for each link.

For a link that lies entirely in a single damage area (e.g., CA in Figure 1), the deviation factor is sampled from a uniform distribution, whose parameters are speficied as $[l_1, u_1] = [0.4, 0.6]$, $[l_2, u_2] = [0.6, 0, 8]$ and $[l_3, u_3] = [0.8, 1.0]$ for areas with “destructive”, “damaging”, and “very strong or strong” intensity levels, respectively. For a link spanning multiple areas (e.g., AB in Figure 1), we obtain the deviation factor by sampling from a uniform distribution on $[l, u]$, where l and u are the weighted combinations of l_1, l_2, l_3 and u_1, u_2, u_3, respectively. The weights are assigned based on the proportions of the link length in the three areas. In our implementation, where we consider the straight line representation (as shown in Figure 1), the *cosine formula* is used to calculate the weights associated with each link. For instance, the deviation factor associated with link EF in Figure 1 is sampled from a uniform distribution on the interval

$$[l, u] = [\frac{xl_1 + yl_2 + zl_3}{x + y + z}, \frac{xu_1 + yu_2 + zu_3}{x + y + z}].$$

B.4 Online Files The data set related to the case study is available online[1] in the file titled “OnlineAppendix.xls”. The file includes the list of 94 settlements in the main district of Van, the travel times between all settlements, the demographic information used to calculate the mobility scores associated with each demand point, mobility scores, risk scores for all links, and cluster assignments. It also provides the affected populations, the base demands, and the accessibility parameters for each test network.

Appendix C. Example Solution We illustrate an example solution of the hybrid model in Figure 3. As the assignments of the demand points to the PODs are scenario-dependent, the figure presents the assignment decisions for two representative scenarios. In particular, Scenario B assumes higher demand levels than Scenario A. According to the results, the achieved total accessibility is similar for both scenarios, while the MPUD values are 0.9% and 26.8% under Scenario A and Scenario B, respectively.



(a) Scenario A (b) Scenario B

Figure 3: The assignments of demand points to PODs under two scenarios ($\tau = 0.03, c = 2.5$). The LDC (denoted with airport symbol) and the PODs are shown in larger symbols with labels. Each symbol represents an assignment to a particular POD. Maps are created using GPSVisualizer.com, a server that uses Google Maps to produce its outputs.

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