*Journal of Quality Engineering and Production Optimization*

*Vol. 6, No. 2, Summer & Autumn 2021*

*http://jqepo.shahed.ac.ir*

*Research Paper*

DOI: 10.22070/JQEPO.2021.15033.1208

# Robust planning for debris clearance and relief distribution with split delivery and fairness

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***Abstract*** *–This research focuses on the response phase of disaster management to plan debris clearance and relief distribution operations. For this purpose, a mathematical model is proposed under fairness concern and split delivery, in which various decisions such as facility location, vehicle routing, and scheduling are considered. Due to the uncertainty in different parameters such as demand for relief items, the amount of debris, costs, and service times, a robust optimization approach is employed to handle the uncertainties of the parameters. Finally, in order to illustrate the applicability and validity of the proposed model, a real case study is investigated.*

***Keywords***– *Debris removal, Relief distribution, Location-routing; Scheduling; Robust optimization.*

## I. INTRODUCTION

Natural disasters and man-made disasters can result in massive amounts of debris, which can have various consequences, including casualties, infrastructure disruption, instability, and relocation (Berktaş et al. 2016; Hu et al. 2017; Mohammadi et al. 2020). Pre-disaster, response and post-disaster stages are the primary phases in the disaster management cycle to mitigate these impacts (Sabbaghtorkan et al., 2020). Victim evacuation, debris removal (DR), and relief item distribution (RID) are the three critical methods in the response phase (Ahmed, 2019). DR and RID, in particular, have a proven effect in reducing injuries and casualties while also increasing survivors' endurance (Wang et al., 2016; Li and Teo, 2019). In this context, two types of methods, including primary debris clearance (DC) and long-term debris removal, have been considered for the DR phase (Crowley, 2017; García-Alviz et al., 2021). The first one, considered in the current study, should be completed within 72 hours to deal with road backlogs to carry with RID operations (Nabavi et al., 2021).

According to the Federal Emergency Management Agency (FEMA), developing a complete strategy to manage DR and RID activities is required, which includes establishing temporary facilities such as debris disposal and distribution centers and scheduling and routing vehicles (Vahdani et al. 2021). Needless to say, these activities are costly and time-consuming; therefore, creating a custom plan to achieve this goal might help speed up the restoration process (Ward et al., 2000). Another stumbling block is the equitable distribution of relief supplies. Clearly, providing a fair and equitable plan for distributing relief materials to survivors stored in warehouses or distribution centers is a critical measure and indisputable truth. There are a few policies in the literature for this goal, such as maximizing the minimal

*Manuscript Received:30- August -2021 & Revised: 27- Nov -2021 & Accepted: 14- December -2021*
*ISSN: 2423-3781*

rate of demand satisfaction, minimizing demand inequality, reducing the latest arrival time, and incorporating a service level gap as a restriction (Noham & Tzur, 2018). Moreover, the reflection of uncertain conditions in the arranging and handling many issues (Vahdani et al., 2011; Vahdani et al., 2012a,b; Vahdani et al., 2013a,b; Mohammadi et al., 2014; Vahdani and Naderi-Beni, 2014; Niakan et al., 2015; Vahdani, 2015; Vahdani et al., 2017; Vahdani and Ahmadzadeh, 2019, 2021; Ahmadzadeh and Vahdani, 2017), particularly in the emergency assistance supply chain, is startling. As a result, programming in the face of uncertainty is gaining traction in the design, planning, and management of operations in this field. Indeed, uncertain parameters can significantly impact the effectiveness of humanitarian logistics planning, and ignoring this concern will result in ineffective solutions. A wide range of characteristics, including demand, facility capacity, cost, travel time, have been examined in the humanitarian logistics literature in an uncertain environment (Mohammadi et al. 2020). In this regard, robust optimization is one of the essential ways for addressing the uncertainty problem, as it may reduce the obstacles of stochastic programmings, such as intractability, large sample size, and precise probability distribution (Vahdani et al., 2012, Vahdani, 2014; Tajik et al., 2014; Mousavi and Vahdani, 2017; Saedinia et al., 2019).

To the best of our knowledge, several studies have been conducted to determine RID's location, scheduling, and routing decisions (Vahdani et al., 2018a,b; Dufour et al., 2018). In addition, a limited number of studies have been offered to determine the scheduling and routing options in the context of DR. Feng and Wang (2003) introduced a multi-objective optimization approach for synchronizing homogenous crew routing and scheduling procedures. The first goal was to extend the entire time of road repairs, the second was to increase the total number of lives saved, and the third was to reduce the risk of restoration work. Yan and Shih (2007) addressed an emergency repair problem involving routing and scheduling considerations to minimize the emergency restoration time as the objective function. Yan and Shih (2009) expanded on this research by taking RD decisions and operation time constraints into account. Yan and Shih (2012) offered an ant colony algorithm to solve their model in (2007). Tang et al. (2009) presented a similar study to combine crew routing and scheduling decisions by minimizing overall operation periods when travel and restoration times are unclear.

To overcome the issues of uncertainty, they used a two-stage stochastic programming approach. Yan et al. (2014) suggested a dynamic optimization model for integrating scheduling, routing, and rescheduling decisions in an emergency restoration problem. By Özdamar et al. (2014), a removal scheduling problem was presented as a bi-objective mathematical model, where the first objective function was to increase transportation network accessibility throughout removal operations, and the second was to reduce overall completion time. Xu and Song (2015) suggested an optimization approach to minimize the total operation times of DR in order to rebuild damaged roads and RID operations scheduling. Akbari and Salman (2017a) investigated an arc routing problem in order to restore connectivity to a broken network. The goal of the objective function was to reduce the time it took to restore many homogeneous automobiles. Akbari and Salman (2017b) investigated a comparable problem with a different target function, minimizing vehicle total arrival time. Morshedlou et al. (2018) examined a homogeneous multi-crew routing and scheduling problem in order to restore connectivity to a damaged network by maximizing the infrastructure network's resilient measure. Moreno et al. (2020) developed a heterogeneous multi-crew routing and scheduling problem to restore a damaged network in which a group of damaged nodes must be recovered to connect them to demand nodes. The goal function was to reduce overall accessibility time to achieve this goal. It should be noted that there has been no research into synchronizing DR and RID in terms of location, scheduling, routing, and fairness distribution decisions. Hence, this paper offers a novel mathematical model for planning DC and RID under fairness concern and split delivery, in which various decisions such as facility location, vehicle routing, and scheduling are considered. Due to the uncertainty in different parameters such as demand for relief items, the amount of debris, costs, and service times, a robust optimization approach is employed to handle the uncertainties of the parameters.

The remainder of the paper is structured as follows: Section 2 describes the problem definition and formulation. Section 3 offers the robust counterpart model. A case study and numerical experiments are provided in Section 4. Finally, conclusions and future research are presented in Section 5.

## II. PROBLEM DEFINITION AND FORMULATION

Due to the increase in unexpected events and natural disasters such as earthquakes in recent years, planning to respond to these events seems necessary. Distribution of relief items and debris removal operations are among the essential measures that should be taken after an earthquake. Earthquakes in urban and rural areas destroy buildings and leave large amounts of debris and debris, which delays relief operations and disrupts the movement of goods to critical areas. Also, if the critical areas are not cleared of debris, these places will gradually become garbage dumps by people living in the area and have potential risks to the environment and the health of the people in the area. Therefore, coordinating debris disposal operations and distributing relief items among the affected areas to maintain people's health is one of the crucial challenges in natural disaster management addressed in this study. For this purpose, a multi-echelon relief chain network including distribution centers, critical areas, debris transport depots, and debris disposal centers has been considered. Decisions in this regard include locating distribution centers and debris disposal centers, allocating critical areas, designing routes, split delivering in different operations, as well as scheduling and coordinating between different vehicles for debris disposal operations and distribution of goods.

One of the critical issues in relief logistics is unequal demand volume and unequal service access. Relief Logistics strives to meet the most significant possible demand in the fastest possible time, so if certain restrictions are not considered, the demand for the nearest critical areas allocated to distribution centers will be met, and the remaining goods will be sent to further critical points. The allocation of relief aid in this way is not desirable and is unfair. Therefore, restrictions related to the fair distribution of relief items between critical points have been considered in this model. In this case, directing the transportation of goods from distribution centers to critical areas is done in such a way that first a subset of distribution centers will be opened, and critical areas and means of transporting goods will be allocated to distribution centers. Also, split deliveries are considered if the amount of required relief items in each critical area is greater than the vehicle's capacity. So that each critical area can receive relief items more than once by different means of transportation according to the service level gap, it should be noted that the transport fleet is heterogeneous with different speeds and capacities. There is a significant amount of debris from the debris removal operation in each critical area, which must be transported by debris trucks to the established disposal centers before the rescue equipment reaches the area so that the distribution and relief operations can be easily done. In fact, in each critical area, the route cleaning and debris removal operations are carried out, and then the means of transporting the goods can enter the area to distribute the goods. The amount of debris in the area is calculated based on the truck's load (full truckload). The volume of debris in a critical area may be more than one truckload, in which case the requests are divided into several requests, and the entire volume of debris in the area must be transferred to disposal centers. The operation process is such that each truck starts its movement from the depot, loads a complete load of debris from a critical area in each mission, and discharges it at the debris disposal site. This process continues according to the maximum distance set for trucks. The trucks will also return to the depot after completing the mission. It should be noted that any critical area and any debris disposal site can be visited frequently by different trucks. Therefore, the assumption of split delivery has been considered in debris disposal operations.

### *A. Sets and indices*

$C$: Set of critical areas

$D$: Set of distribution centers

$O$: Set of debris transport depots

$E$: Set of debris disposal centers

$K$: Set of debris trucks

$V$: Set of relief vehicles

$(i, j, i', j')$: Indices for nodes

### *B. Parameters*

$de_i$: Amount of demand for relief items in critical area $i$ at period $t$ $(i \in C)$

$\delta$: Service level gap

$ow_i$: Amount of collected debris (number of full truckloads) in critical area $i$ at period $t$ $(i \in C)$

$s_i$ : Service time at node $i$ in debris operations

$s'_i$: Service time at node $i$ in relief operations

$f_i$: Fixed opening cost of distribution center $i$ $(i \in D)$

$h_j$: Fixed opening cost of debris disposal center $j$ $(j \in E)$

$L_i$ : Supply capacity of distribution center $i$ $(i \in D)$

$cap_v$ : Capacity of vehicle $v$ in aid distribution process

$dis_{ij}$: Distance between node $i$ and node $j$

$\mu_k$ : Cost per kilometer traveled by the fleet of vehicles

$\gamma_v$ : Speed of relief vehicle

$\gamma'_k$ : Speed of debris vehicle

$MT$: Maximum distance that can be traveled by debris vehicle

$M$: An enough big number

### *C. Decision variables*

$w_j$ : 1 if distribution center $j$ is opened; 0 otherwise

$u_j$: 1 if debris disposal center $j$ is opened; 0 otherwise

$x_{ijv}$: 1 if node $i$ is on the route of vehicle $v$ before node $j$; 0 otherwise

$z_{iv}$: 1 if node $i$ is on the route of vehicle $v$; 0 otherwise

$p_{ji}$: 1 if critical area $i$ is assigned to distribution center $j$; 0 otherwise

$y_{ijk}$ : 1 if node $i$ is on the route of truck $k$ before node $j$; 0 otherwise

$g_{ji}$ : Number of relief items transported from distribution center $j$ to critical area $i$

$Rd_i$: Number of relief items allocated to critical area $i$

$T_{jv}$ : Arrival time of relief vehicle $v$ at node $j$

$T_{jk}$ : Arrival time of truck $k$ at node $j$

$uu_{jv}$ : Subtour elimination variable

### *D. Mathematical model*

$$\min z = \sum_{j\epsilon D} f_j w_j + \sum_{j\epsilon E} h_j u_j + \sum_{i\epsilon D\cup C} \sum_{j\epsilon D\cup C} \sum_{v\epsilon V} \mu_v \,.\, dis_{ij}\, x_{ijv} + \sum_{i\epsilon O\cup C\cup E} \sum_{j\epsilon O\cup C\cup E} \sum_{k\epsilon k} \mu_k \,.\, dis_{ij}\, y_{ijk} \tag{1}$$

*S.t.*:

$$\sum_{i\epsilon O} \sum_{j\epsilon C} y_{ijk} \le 1 \qquad \forall\ k\epsilon K \tag{2}$$

$$\sum_{i\epsilon O} \sum_{j\epsilon C} y_{ijk} = \sum_{j\epsilon O} \sum_{i\epsilon E} y_{ijk} \qquad \forall\ k\epsilon K \tag{3}$$

$$\sum_{i\epsilon O\cup E} y_{ijk} = \sum_{i\epsilon E} y_{jik} \qquad \forall\ k\epsilon K\ , j\epsilon C \tag{4}$$

$$\sum_{i\epsilon C} y_{ijk} = \sum_{i\epsilon C\cup O} y_{jik} \qquad \forall\ k\epsilon K\ \ , j\epsilon E \tag{5}$$

$$y_{ijk} \le u_j \qquad \forall\ \ i\epsilon C\ \ , j\epsilon E\ , k\epsilon K \tag{6}$$

$$\sum_{i\epsilon O\cup E}\sum_{k\epsilon K} y_{ijk} = ow_j \qquad \forall\ j\epsilon C \tag{7}$$

$$\sum_{i\epsilon C}\sum_{k\epsilon K} y_{ijk} \geq 1 \qquad \forall\ j\epsilon E \tag{8}$$

$$\sum_{i\epsilon O\cup C\cup E}\ \sum_{j\epsilon O\cup C\cup E} dis_{ij}\, y_{ijk} \leq MT \qquad \forall\ k\epsilon K \tag{9}$$

$$s_i + \frac{dis_{ij}}{\gamma'_k} \leq T_{jk} + M.\left(1 - y_{ijk}\right) \qquad \forall\ i\epsilon O\ , j\epsilon C\ , k\epsilon K \tag{10}$$

$$T_{ik} + s_i + \frac{dis_{ij}}{\gamma'_k} \leq T_{jk} + M.\left(1 - y_{ijk}\right) \qquad \forall\ i\epsilon C \cup E\ , j\epsilon C \cup E \cup O\ , k\epsilon K \tag{11}$$

$$T_{jk} \leq M. \sum_{i\epsilon O\cup C\cup E} y_{ijk} \qquad \forall\ j\epsilon C \cup E \cup O\ , k\epsilon K \tag{12}$$

$$x_{jiv} \leq p_{ji} \qquad \forall\ j\epsilon D\ , i\epsilon C\ , v\epsilon V \tag{13}$$

$$p_{ji} \leq w_j \qquad \forall\ j\epsilon D\ , i\epsilon C \tag{14}$$

$$w_j \geq z_{jv} \qquad \forall\ j\epsilon D\ , v\epsilon V \tag{15}$$

$$z_{jv} \geq x_{jiv} \qquad \forall\ j\epsilon D \cup C\ , i\epsilon C\ , v\epsilon V \tag{16}$$

$$g_{ji} \leq L_j\ p_{ji} \qquad \forall\ j\epsilon D\ , i\epsilon C \tag{17}$$

$$\sum_{i\epsilon C} g_{ji} \leq L_j\, w_j \qquad \forall\ j\epsilon D \tag{18}$$

$$Rd_i = \sum_{j\epsilon D} g_{ji} \qquad \forall \ i\epsilon C \tag{19}$$

$$Rd_i \leq de_i \qquad \forall \ i\epsilon C \tag{20}$$

$$\frac{Rd_i}{de_i} \leq \frac{Rd_{i'}}{de_{i'}} .\delta \qquad \forall \ i, i'\epsilon C \ ; i \neq i' \tag{21}$$

$$\frac{Rd_i}{de_i} \leq \frac{Rd_{i'}}{de_{i'}} + \left(2 - p_{ji} - p_{ji'}\right) \qquad \forall \ i, i'\epsilon C \ ; i \neq i' \ , j\epsilon D \tag{22}$$

$$\sum_{j\epsilon D} p_{ji} \geq 1 \qquad \forall \ i\epsilon C \tag{23}$$

$$\sum_{j\epsilon D} z_{jv} \leq 1 \qquad \forall \ v\epsilon V \tag{24}$$

$$\sum_{j\epsilon D\cup C} \sum_{v\epsilon V} x_{jiv} \geq 1 \qquad \forall \ i\epsilon C \tag{25}$$

$$\sum_{j\epsilon D} \sum_{i\epsilon C} x_{jiv} \leq 1 \qquad \forall \ v\epsilon V \tag{26}$$

$$\sum_{j\epsilon D\cup C} x_{ijv} + \sum_{j\epsilon D\cup C} x_{j'jv} - p_{j'i} \leq 1 \qquad \forall \ j'\epsilon D \ , i\epsilon C \ , v\epsilon V \tag{27}$$

$$\sum_{v\epsilon V} x_{jiv} \leq 1 \qquad \forall \ i, j\epsilon D \cup C \ ; \ i \neq j \tag{28}$$

$$\sum_{i\epsilon D\cup C} x_{jiv} = \sum_{i\epsilon D\cup C} x_{ijv} \qquad \forall \ j\epsilon D \cup C \ , \ v\epsilon V \tag{29}$$

$$\sum_{j\epsilon D\cup C} \sum_{i\epsilon C} de_i \, x_{jiv} \leq cap_v \qquad \forall \ v\epsilon V \tag{30}$$

$$uu_{jv} - uu_{iv} + |\beta| * x_{jiv} \leq |\beta| - 1 \qquad \forall\ i, j\epsilon C \quad , v\epsilon V \tag{31}$$

$$s'_i + \frac{dis_{ij}}{\gamma_v} \leq T_{jv} + M.\left(1 - x_{ijv}\right) \qquad \forall\ j\epsilon C\ , i\epsilon D \quad , v\epsilon V \tag{32}$$

$$T_{iv} + s'_i + \frac{dis_{ij}}{\gamma_v} \leq T_{jv} + M.\left(1 - x_{ijv}\right) \qquad \forall\ \ i\epsilon C\ \ , j\epsilon C \cup D \quad , v\epsilon V \tag{33}$$

$$T_{jv} \leq M. \sum_{i\epsilon D \cup C} x_{ijv} \qquad \forall\ j\epsilon C \cup D \quad , v\epsilon v \tag{34}$$

$$\sum_{i\epsilon O \cup E} \sum_{k\epsilon K} \max\ \left\{\left(T_{jk} + s_j\right) y_{ijk}\right\} \leq \sum_{i\epsilon D \cup C} \sum_{v\epsilon V} T_{jv}\ x_{ijv} \qquad \forall \quad j\epsilon C \tag{35}$$

$$x_{ijv}\ , z_{iv}\ , p_{ji}, y_{ijk}\ , w_j\ , u_i \in (0\ ,1) \tag{36}$$

$$g_{ji}\ , Rd_i\ , T_{jv}, uu_{jv} \geq 0 \tag{37}$$

The objective function (1) minimizes the total costs of the humanitarian logistics network. The first and second terms calculate the opening costs of distribution and debris disposal centers, respectively. The third and fourth terms compute the traveling costs of relief and debris vehicles, respectively. Constraint (2) ensures that each debris truck leaves the debris transport depot at most once. Constraint (3) ensures that the beginning and the end of the movement of each truck is debris transport depot. Constraints (4) and (5) signify connectivity constraints of debris operations. Constraint (6) guarantees that established debris disposal centers can provide services. Constraint (7) guarantees that debris trucks can meet each critical area more than once. Constraint (8) guarantees each debris disposal center is visited at least once. Constraint (9) restricts the total distance that can be traveled by a debris truck. Constraints (10) and (11) determine the debris trucks' arrival times at nodes. Constraint (12) ensures the linkage between debris trucks' arrival times and their routes. Constraints (13-15) guarantee that established distribution centers can provide services. Constraint (16) ensures that each relief vehicle can travel through link $(i, j)$ if $j$ is on the route of vehicle $v$. Constraints (17) and (18) ensure that the number of relief items supplied by each distribution center cannot exceed its capacity. Also, constraint (18) ensures that an established distribution center can provide service. Constraint (19) signifies the number of relief items received by each critical area from all distribution centers. Constraint (20) restricts the number of assigned relief items to each critical area. Constraint (21) considers the service gap as the maximum ratio among the proportions of satisfied demand at entire critical areas. Constraint (22) signifies that entire critical areas that are received service by the same distribution center will receive equal proportions of their demand. Constraint (23) signifies that each critical area can be served by more than one distribution center. Constraint (24) indicates that each relief vehicle can be assigned to utmost one distribution center. Constraint (25) ensures that each critical area receives more than one service. Constraint (26) ensures that each relief vehicle can be dispatched from only one distribution center.

Constraint (27) ensures that each critical area is assigned to a distribution center that are both on the same route. Constraint (28) ensures that one relief vehicle is selected for each route. Constraint (29) signifies connectivity constraints of relief operations. Constraint (30) represents the capacity of each vehicle. Constraint (31) guarantees sub tour elimination. Constraints (32) and (33) determine the relief vehicles' arrival times at nodes. Constraint (34) ensures the linkage between relief vehicles' arrival times and their routes. Constraint (35) indicates that the arrival time of relief vehicles to each critical area should be greater than the maximum service time by the trucks carrying debris in that area. Constraints (36) and (37) specify the kind of decision variables.

### *E. Linearization*

As constraint (35) is nonlinear, the linearized form of this constraint can be written as Eq. (38), and constraints (39)-(45) are added to the proposed model.

$$\sum_{i\epsilon O\cup E}\sum_{k\epsilon K}\varphi_{ijk} \leq \sum_{i\epsilon D\cup C}\sum_{k\epsilon K} Tx_{ijv} \tag{38}$$

$$\varphi_{ijk} \geq Ty_{ijk} + s_j\, y_{ijk} \qquad \forall\, j\epsilon C\,, i\epsilon O \cup E\,, k\epsilon K \tag{39}$$

$$Ty_{ijk} \geq T_{jk} - \left(1 - y_{ijk}\right).M \qquad \forall\, j\epsilon C\,, i\epsilon O \cup E\,, k\epsilon K \tag{40}$$

$$Ty_{ijk} \leq y_{ijk}.M \qquad \forall\, j\epsilon C\,, i\epsilon O \cup E\,, k\epsilon K \tag{41}$$

$$Ty_{ijk} \leq T_{jk} \qquad \forall\, j\epsilon C\,, i\epsilon O \cup E\,, k\epsilon K \tag{42}$$

$$Tx_{ijv} \geq T_{jv} - \left(1 - x_{ijv}\right).M \qquad \forall\, j\epsilon C\,, i\epsilon D \cup C\,, k\epsilon K \tag{43}$$

$$Tx_{ijv} \leq x_{ijv}.M \qquad \forall\, j\epsilon C\,, i\epsilon D \cup C\,, k\epsilon K \tag{44}$$

$$Tx_{ijv} \leq T_{jv} \qquad \forall\, j\epsilon C\,, i\epsilon D \cup C\,, k\epsilon K \tag{45}$$

## III. ROBUST OPTIMIZATION

In the proposed model, many parameters, including the amount of demand for relief items in critical areas, the amount of collected debris in critical areas, service times, and costs, are considered uncertain parameters to present the robust counterpart mathematical model. In order to handle these uncertainties, a box uncertainty set is considered, which can offer conservative solutions (Ben-Tal et al., 2013). The box uncertainty set can be presented as follows:

$$U_{box} = \left\{\xi \in \mathbb{R}^n; \left|\xi_t - \bar{\xi}_t\right| \le \rho G_t, \quad t = 1,2,\dots,n\right\} \tag{46}$$

Where $\bar{\xi}_t$ signifies the normal value of $t$th parameter of vector $\xi$, $\rho$ is the uncertainty level, and $G_t$ determines the uncertainty scale (Ben-Tal et al., 2013; Saedinia et al., 2019). Regarding the proposed model and above explanation, the robust counterpart is provided. Also, to simplify formulating the robust model, the notations $\mathcal{A}_{ijv}$ and $\mathcal{B}_{ijk}$ are used instead of $(\mu_v . dis_{ij})$ and $(\mu_k . dis_{ij})$. Here, the changed terms of the proposed model regarding implementing the robust optimization approach are rendered.

$$\min\ z_1 \tag{47}$$

*S.t. :*

$$\sum_{j\epsilon D}\left(\bar{f}_j w_j + \eta_j^f\right) + \sum_{j\epsilon E}\left(\bar{h}_j u_j + \eta_j^h\right) + \sum_{i\epsilon D\cup C}\sum_{j\epsilon D\cup C}\sum_{v\epsilon V}\left(\overline{\mathcal{A}_{ijv}}\, x_{ijv} + \eta_{ijv}^{\mathcal{A}}\right) + \sum_{i\epsilon O\cup C\cup E}\sum_{j\epsilon O\cup C\cup E}\sum_{k\epsilon k}\left(\overline{\mathcal{B}_{ijk}} y_{ijk} + \eta_{ijk}^{\mathcal{B}}\right) \le z_1 \tag{48}$$

$$\rho_f \mathcal{G}_j^f \le \eta_j^f \qquad \forall j \tag{49}$$

$$\rho_f \mathcal{G}_j^f \ge -\eta_j^f \qquad \forall j \tag{50}$$

$$\rho_h \mathcal{G}_j^h \le \eta_j^h \qquad \forall j \tag{51}$$

$$\rho_h \mathcal{G}_j^h \ge -\eta_j^h \qquad \forall j \tag{52}$$

$$\rho_{\mathcal{A}} \mathcal{G}_{ijv}^{\mathcal{A}} \le \eta_{ijv}^{\mathcal{A}} \qquad \forall i,j,v \tag{53}$$

$$\rho_{\mathcal{A}} \mathcal{G}_{ijv}^{\mathcal{A}} \ge -\eta_{ijv}^{\mathcal{A}} \qquad \forall i,j,v \tag{54}$$

$$\rho_{\mathcal{B}} \mathcal{G}_{ik}^{\mathcal{B}} \le \eta_{ijk}^{\mathcal{B}} \qquad \forall i,j,k \tag{55}$$

$$\rho_{\mathcal{B}} \mathcal{G}_{ijk}^{\mathcal{B}} \ge -\eta_{ijk}^{\mathcal{B}} \qquad \forall i,j,k \tag{56}$$

$$\sum_{i\epsilon O\cup E}\sum_{k\epsilon K} y_{ijk} \leq \overline{ow_j} - \rho_{ow}\mathcal{G}_j^{ow} \qquad \forall\ j\epsilon C \tag{57}$$

$$\sum_{i\epsilon O\cup E}\sum_{k\epsilon K} y_{ijk} \geq \overline{ow_j} + \rho_{ow}\mathcal{G}_j^{ow} \qquad \forall\ j\epsilon C \tag{58}$$

$$(\bar{s}_i + \rho_s\mathcal{G}_i^s) + \frac{dis_{ij}}{\gamma'_k} \leq T_{jk} + M.\left(1 - y_{ijk}\right) \qquad \forall\ i\epsilon O\ , j\epsilon C\ , k\epsilon K \tag{59}$$

$$T_{ik} + (\bar{s}_i + \rho_s\mathcal{G}_i^s) + \frac{dis_{ij}}{\gamma'_k} \leq T_{jk} + M.\left(1 - y_{ijk}\right) \qquad \forall\ i\epsilon C\cup E\ , j\epsilon C\cup E\cup O\ , k\epsilon K \tag{60}$$

$$Rd_i \leq \overline{de}_i - \rho_{de}\mathcal{G}_i^{de} \qquad \forall\ i\epsilon C \tag{61}$$

$$\frac{Rd_i}{\overline{de}_i} - \frac{Rd_{i'}}{\overline{de}_{i'}} .\delta + (\rho_{de}\mathcal{G}_i^{de} + \rho_{de}\mathcal{G}_{i'}^{de}) \leq 0 \qquad \forall\ i\,, i'\epsilon C\ ; i \neq i' \tag{62}$$

$$\frac{Rd_i}{\overline{de}_i} - \frac{Rd_{i'}}{\overline{de}_{i'}} + (\rho_{de}\mathcal{G}_i^{de} + \rho_{de}\mathcal{G}_{i'}^{de}) \leq \left(2 - p_{ji} - p_{ji'}\right) \qquad \forall\ i, i'\epsilon C\ ; i \neq i'\ , j\epsilon D \tag{63}$$

$$\sum_{j\epsilon D\cup C}\sum_{i\epsilon C}\left(\overline{de}_i + \rho_{de}\mathcal{G}_i^{de}\right) x_{jiv} \leq cap_v \qquad \forall\ v\epsilon V \tag{64}$$

$$(\overline{s'}_i + \rho_s\mathcal{G}_i^s) + \frac{dis_{ij}}{\gamma_v} \leq T_{jv} + M.\left(1 - x_{ijv}\right) \qquad \forall\ j\epsilon C\ , i\epsilon D\ , v\epsilon V \tag{65}$$

$$T_{iv} + (\overline{s'}_i + \rho_s\mathcal{G}_i^s) + \frac{dis_{ij}}{\gamma_v} \leq T_{jv} + M.\left(1 - x_{ijv}\right) \qquad \forall\ i\epsilon C\ , j\epsilon C\cup D\ , v\epsilon V \tag{66}$$

$$\sum_{i\epsilon O\cup E}\sum_{k\epsilon K} \max\left\{\left(T_{jk} + (\bar{s}_i + \rho_s\mathcal{G}_i^s)\right)\ y_{ijk}\right\} \leq \sum_{i\epsilon D\cup C}\sum_{v\epsilon V} T_{jv}\, x_{ijv} \qquad \forall\ j\epsilon C \tag{67}$$

$$\eta_j^f, \eta_j^h . \eta_{ijv}^{\mathcal{A}}, \eta_{ijk}^{\mathcal{B}} \geq 0 \tag{68}$$

## IV. CASE STUDY

In 2017, an earthquake with a magnitude of 7.3 on the Richter scale struck Kermanshah province in western Iran, killing approximately 1000 people and leaving countless others injured and homeless (Ahmadi & Bazargan-Hejazi, 2018; Hosseini et al., 2018). In addition, several structures and masons were destroyed, and basic living facilities such as water and shelter were unavailable. As a result, the necessary relief products and daily consumption commodities for these catastrophe locations must be delivered on a constant and consistent basis to ensure the victims' optimum survival. We identify six villages as catastrophe units in Sarpol-e Zahab city in Kermanshah province, including Tange Hamam, Maleh Kabowd, Baba Skander, Gol-e-Khatu, Zardeh, and Kuyaki-ye Hassan, where the harms were severe. In times of crisis, the Red Crescent facilities in the crisis area and the adjacent provinces help the victims and provide the necessary items. In this study, the Sarpol-e-Zahab Grand Mosque and Red Crescent have been selected as candidates for distribution centers for opening. So that after the opening and allocation of relief vehicles to these centers, relief items will be distributed to critical areas. The demand for each of the critical areas is shown in **Table I**. Also, in each of the critical areas, there are significant amounts of debris from debris removal operations in critical areas, which causes blockage of traffic systems and makes it impossible for rescue equipment to enter the area and distribute goods. Therefore, to clear the area and facilitate the movement of relief equipment, all this debris should be transferred to disposal sites. For this purpose, two places on the outskirts of Sarpol-e-Zahab-Qasr Shirin road have been considered. The volume of debris in each area is calculated based on the full truckload, which can be seen in **Table I**. The associated parameters of distribution centers are provided in **Table II**. It should be noted that the unloading operation takes 15 minutes at the disposal site on average. The service time of the truck at each loading node is approximately 30 minutes on average, and the service time of the means of transport in the relief items distribution operation is on average 45 minutes. The distance between villages and distribution centers is approximately 40 km on average. Moreover, the uncertainty level in the robust model is 0.3. So as to transport the debris, trucks with fixed capacity must be used, where three trucks are sent from the depot to critical areas and unload their cargo in the opened disposal centers after loading. This process is done according to the maximum travel distance, and the trucks return to the depot after completing their mission. All the computational studies are implemented in GAMS software and using BARON solver on a laptop with Core i5 CPUs at 1.6 GHz and 8 GB RAM.

**Table I. Associated parameters of critical areas**

| ***Disaster units*** ($C$) | ($de_i$ , $ow_i$) |
|---|---|
| Tange Hamam (C1) | **(105, 1)** |
| Gol-e-Khatu (C2) | **(137, 1)** |
| Zardeh (C3) | **(105, 1)** |
| Baba Skander (C4) | **(139, 2)** |
| Maleh Kabowd (C5) | **(148, 2)** |
| Kuyaki-ye Hassan (C6) | **(110, 1)** |

**Table II. Associated parameters of distribution centers**

| ***Distribution centers*** | ***Opening cost ($)*** | ***Capacity*** |
|---|---|---|
| Grand Mosque (p2) | 8000 | **800** |
| Red Crescent (p3) | 10000 | **1000** |

**Figs**. **1** to **3** show the obtained solution of the proposed model under a certain condition. The total cost of the humanitarian logistics network is 64677$, and CPU time is 823 seconds. **Fig. 1** shows the path of trucks carrying debris under a certain state. It can be seen that both disposal centers are opened, and truck 1 starts moving from the depot and goes to Baba Skander (C4) and, after loading, moves to the disposal site 1 (D1). After unloading its cargo, this truck goes to Kuyaki-ye Hassan (C6), and after loading, it goes to disposal center 1 (D1) to unload its cargo. Then, to load the debris, it moves to Tange Hamam (C1), unloads its cargo at disposal site 1 (D1), ends its mission, and returns to the depot. It can be seen that each critical area is visited by different trucks regarding the number of full truckloads, and the sequence of visits of the nodes by the trucks is observed correctly. In this way, each empty truck starts moving from the depot and, after visiting a critical area and loading, moves to the disposal center and, after completing several missions, finally returns to the depot. According to this figure, the routes of movement of all trucks are as follows:

$K1 = (O, C4, D1, C6, D1, C1, D1, O)$, $K2 = (O, C4, D2, C2, D1, C5, D2, O)$,
$K3 = (O, C3, D1, C5, D2, O)$

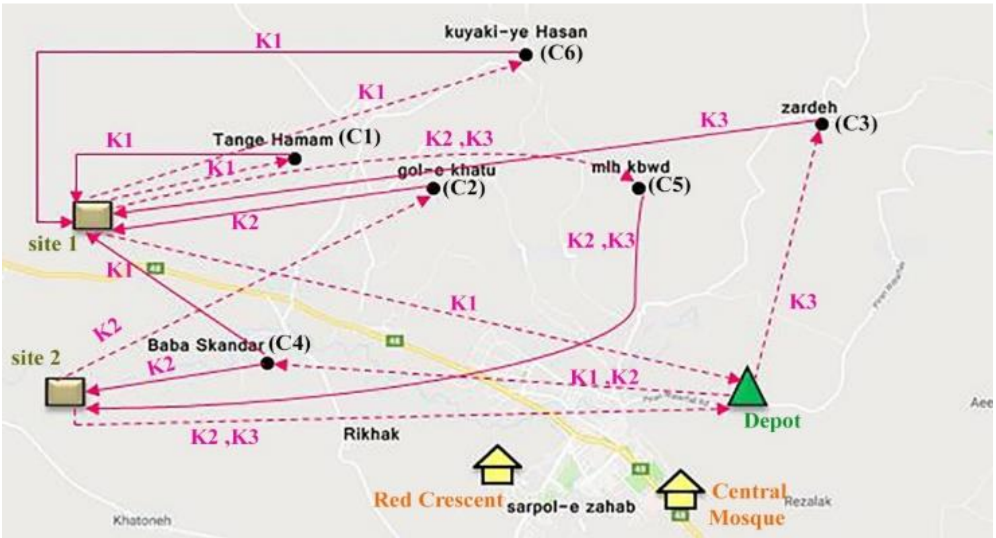


**Fig 1. The route of trucks to unload debris under the certain condition**

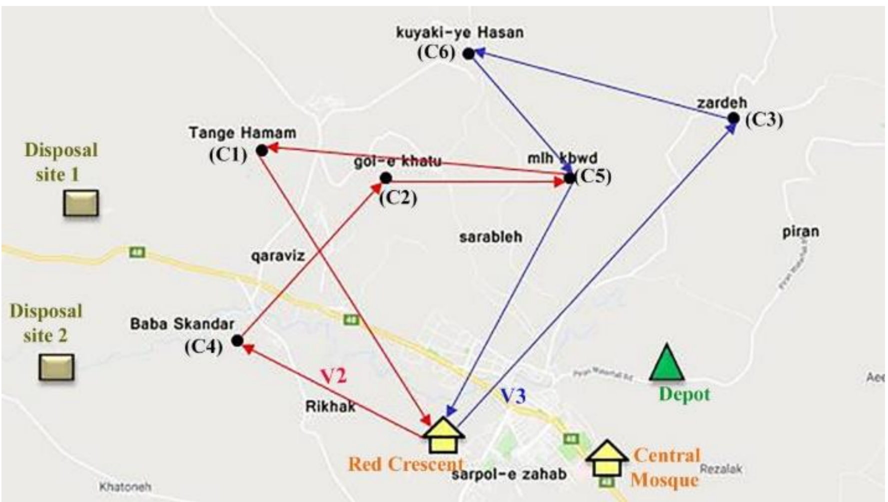


**Fig 2. Distribution of relief items between critical areas under the certain condition**

**Fig. 2** shows the distribution of relief items between critical areas under a certain state. As can be seen, only the Red Crescent distribution center has been established, and vehicles 2 and 3 have been assigned to it. Vehicle 2 distributes relief items to Baba Skander, Gol-e-Khatu, Melah Kabowd, and Tange Hamam, and Vehicle 3 distributes relief items to Zardeh, Kuyaki-ye Hassan, and Maleh Kabowd. As can be seen, due to the high demand for relief items in Maleh Kabowd (c5), this village is met twice by vehicles 2 and 3. So that first part of its demand is met by vehicle 2, then by vehicle 3 the remaining part of its demand is met.

**Fig. 3** shows the schedule of different operations under a certain state. As can be seen, before the vehicle (V2) arrives in Baba Skander, the debris trucks (K1,2) load the debris in this area, which is two full truckloads, and they move towards the disposal centers. The next destination of the vehicle (V2) is Gol-e-Khatu, and there is one full truckload in this area. As can be seen, before the truck (V2) arrives in this area, the debris truck (K2) loads the debris and leaves the area (C2). Also, there are two full truckloads of debris in the area (C5), and before the trucks arrive in this area, the debris trucks (K1,2) load the debris and leave the area.

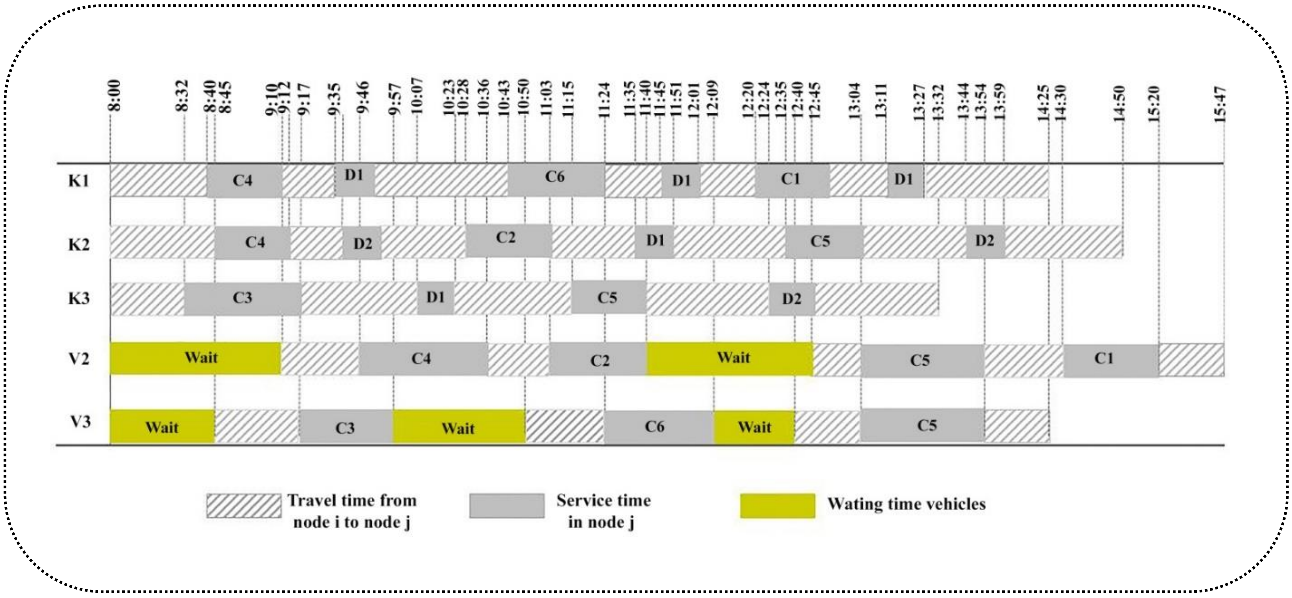


**Fig 3. The schedule of the operations under the certain condition**

**Figs. 4** to **6** show the obtained solution of the proposed model under an uncertain condition. The total cost of the humanitarian logistics network is 83950$, and CPU time is 1000 seconds. **Fig. 4** shows the path of trucks carrying debris under an uncertain state. As can be seen that both disposal centers are opened. According to this figure, the routes of movement of all trucks are as follows:

$K_1 = (O\,, C2\,, D1\,, C5\,, D2\,, C3, D2\,, O)$, $K_2 = (O, C5\,, D1\,, C4\,, D2\,, C1\,, D1\,, O)$,
$K_3 = (O\,, C4\,, D1\,, C5\,, D2\,, C6\,, D1\,, O)$

**Fig. 5** shows the route of relief vehicles in an uncertain state. As can be seen, both distribution centers have been established, and vehicles 1 and 3 have been allocated to Grand Mosque and vehicle 2 to Red Crescent. Vehicle 2 meets Baba Skander and then, due to the high demand of Gol-e-Khatu, responds to part of its demand and finally ends its mission by visiting Tange Hamam and returns to the Red Crescent distribution center. Vehicle 3 responds to part of the demand of Gol-e-Khatu and then responds to the demand of Maleh Kabowd and Zardeh and returns to the distribution center of the Grand Mosque. Vehicle 1 meets Maleh Kabowd and Kuyaki-ye Hassan, respectively, and then returns to the center of the Grand Mosque. **Fig. 6** displays the schedule and sequence of various operations in an uncertain state. It can be seen that before the vehicles arrived in each area, the debris trucks left the area.

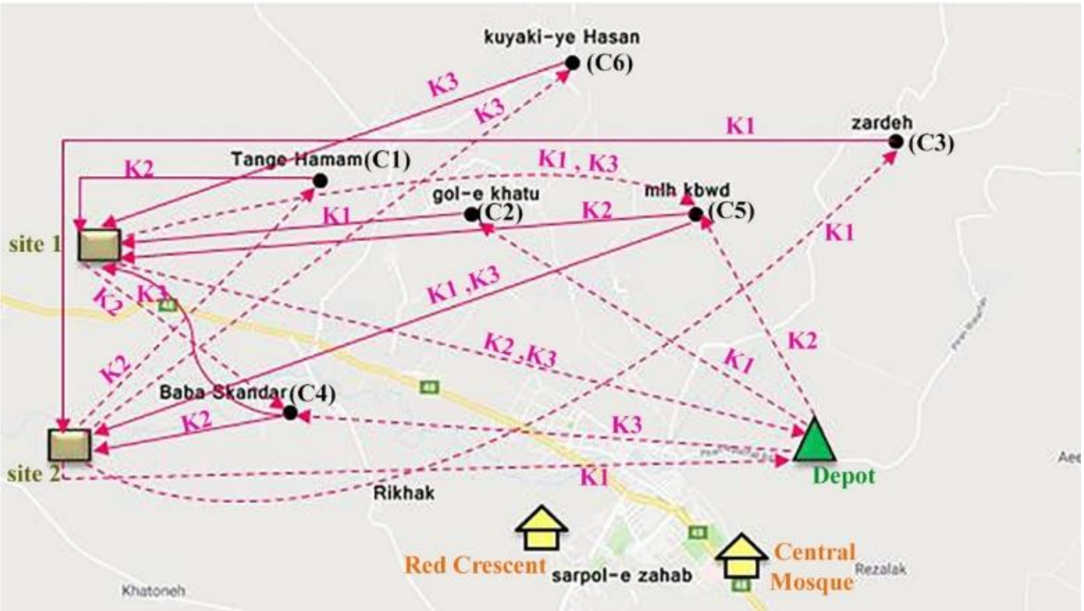


**Fig 4. The route of trucks to unload debris under the uncertain condition**

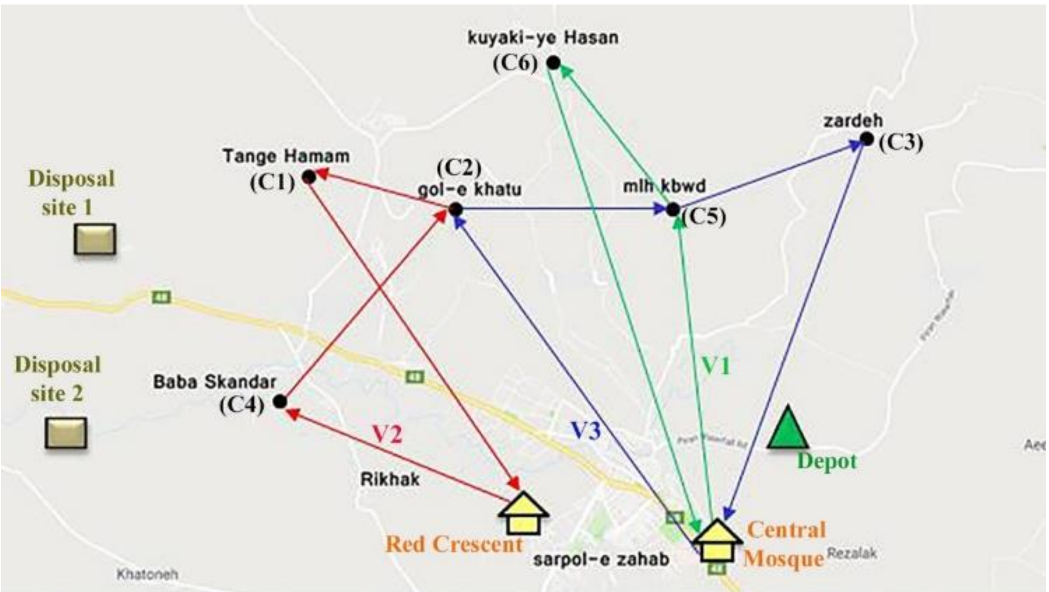


**Fig 5. Distribution of relief items between critical areas under the uncertain condition**

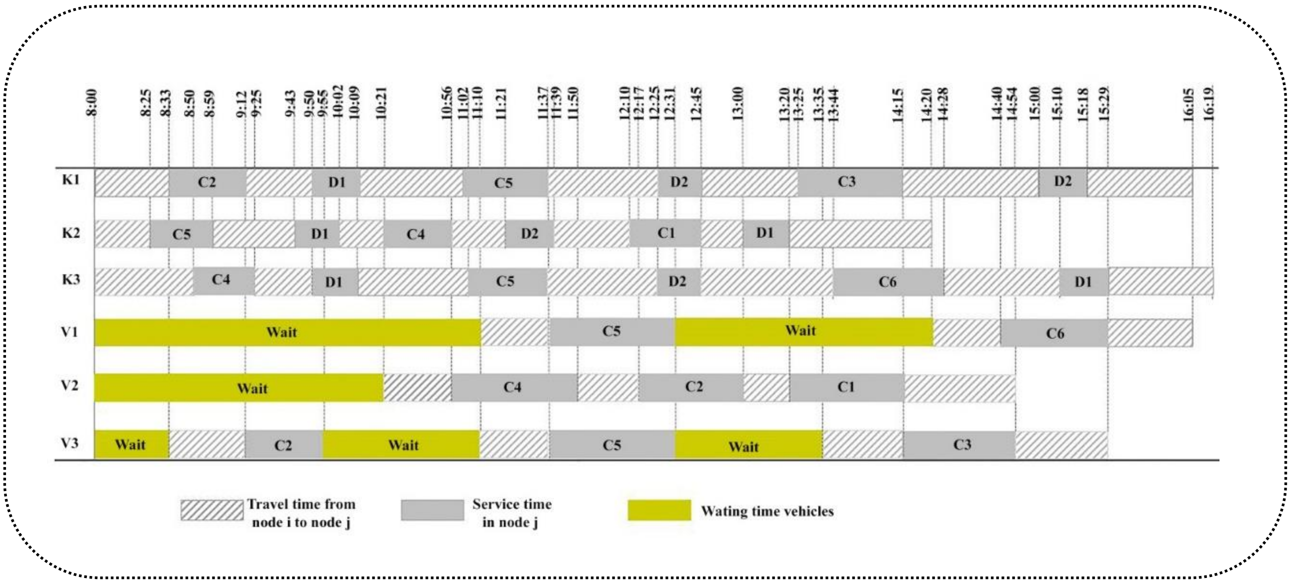


**Fig 6. The schedule of the operations under the uncertain condition**

**Table III** shows the summary of computational results under realizations and different uncertainty levels, in which the robust model provided high-quality solutions in terms of standard deviation with that of the deterministic model. Therefore, although the obtained values of the objective function in the deterministic model are greater than the robust one, the variations of the robust model are smaller than the deterministic model, which is suitable for planning operations under disaster situations.

## V. CONCLUSIONS

In this paper, a novel optimization model was proposed to coordinate debris clearance and relief distribution operations. In the distribution phase, two main characteristics of relief distribution, including split delivery of relief items and fairness, were reflected. A broad range of decisions, including facility locations, vehicle routing, and scheduling, were considered. Moreover, a robust optimization approach was employed to handle the uncertainties of demand, costs, amount of debris, and service times. Finally, a real case study was investigated to demonstrate the validity and applicability of the proposed model. There are some opportunities to expand the current research as the future directions, including (1) offering meta-heuristic algorithms or exact solution approaches to solve the model on a large scale; (2) considering redistricting model to increase the quality of service to disaster units.

**Table III. Summary of computational results under realizations**

| *Test problem* | *Uncertainty level* | *Objective function under values under realizations* | | | |
|---|---|---|---|---|---|
| | | *Mean of objective function under realizations* | | *Standard deviation of objective function under realizations* | |
| | | *Deterministic* | *Robust* | *Deterministic* | *Robust* |
| 1 | 0.3 | 65127 | 84198 | 3478 | 1105 |
| | 0.5 | 71258 | 76487 | 5419 | 879 |
| | 0.7 | 80251 | 87648 | 4725 | 1687 |

**Continue Table III. Summary of computational results under realizations**

| *Test problem* | *Uncertainty level* | *Objective function under values under realizations* | | | |
|---|---|---|---|---|---|
| | | *Mean of objective function under realizations* | | *Standard deviation of objective function under realizations* | |
| | | *Deterministic* | *Robust* | *Deterministic* | *Robust* |
| 2 | 0.3 | 75226 | 80674 | 4521 | 3088 |
| | 0.5 | 85024 | 91652 | 6972 | 2480 |
| | 0.7 | 89375 | 100901 | 8927 | 5331 |
| 3 | 0.3 | 88362 | 96006 | 7648 | 5871 |
| | 0.5 | 100218 | 108215 | 9251 | 6698 |
| | 0.7 | 121574 | 133881 | 8993 | 7215 |

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