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Multi-Objective Optimization Model for Designing a Humanitarian Logistics Network under Service Sharing and Accident Risk Concerns under Uncertainty

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***Abstract** – A multi-objective mathematical model is proposed to design a humanitarian logistics network under uncertain conditions. Three objective functions are considered to formulate this problem. The first one minimizes the total costs of logistics activities, the second minimizes the maximum overload of local distribution centers, and the third minimizes the maximum accident loss throughout the distribution of relief items. What is more, different simultaneous decisions are determined, including facility location-allocation, service sharing, relief distribution, truck routing, transferring service, and the evacuation of victims. Owing to the fact that the planning of humanitarian logistics problems is encountered with miscellaneous uncertain factors, such as demand, supply, costs, and capacities of facilities, a robust optimization approach is employed to tackle these challenges. Furthermore, a number of numerical instances are provided to illustrate the validity of the proposed mathematical model.*

***Keywords**– Humanitarian network design; Vehicle routing; Accident risk; Resource sharing; Uncertainty.*

I. INTRODUCTION

In the course of time, the different types of calamities such as man-made and natural catastrophes typically scarify or endanger numerous people and create plenty of repercussions in the matter of economic conditions. Van Wassenhove (2006) categorized calamities into slow and sudden onsets, such that flooding and hurricanes belong to the first one and tsunamis and earthquakes fit in the second one. In this regard, in an attempt to alleviate the repercussions of these calamities, widespread cooperation should be conducted immediately after any disasters. For this purpose, establishing the distribution centers and emergency stations as the temporal facilities, the evacuation of injuries, and the distribution of relief goods amongst survivors are crucial measures. However, there are plenty of obstacles, which can affect the efficiency of these measures, including the dispersion of disaster districts, the limitation of sources and supplies, varied accidents, growing time of planning, and uncertain nature of these circumstances (Balcik et al., 2010; Coppola, 2006; Nolte et al., 2012; Abounacer et al., 2014).

Additionally, the deficiency of capacity in service provider facilities, such as distribution centers or emergency stations, is one of the main challenges during the arrangement of relief logistics networks (Vahdani et al., 2011). In this regard, adopting a broad range of substitute manners to supply required capacity is a vital measure, now that it might be impossible for service provider facilities to enhance their capacities during the planning horizon. Among various

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manners to overcome this challenge, the disparity model, which was proposed by (Ko et al., 2015), is an efficient approach since it can provide a higher quality of service for associated customers and cluster the districts of customers, including service provider and demand units (Saedinia et al., 2019).

What is more, some kind of relief products such as pharmaceutical products, which are categorized in hazardous materials, might be damaged, lost the health benefits due to the occurrence of an accident, so it is desirable to minimize the maximum accident loss to avoid the possible catastrophic accidents that may lead to uncompensated effects that are particularly vital for these products (Timajchi et al., 2019). Furthermore, the efficiency of the performance of a relief logistics network typically is closely related to estimating the uncertain nature of parameters, so neglecting this issue can provide awkward solutions (Gitinavard et al., 2017; Mousavi et al., 2017). From this perspective, various influential parameters such as demand, cost, and facility capacity have been considered in the literature under uncertain conditions (Birjandi and Mousavi, 2019; Foroozesh et al., 2018; Gitinavard et al., 2017; Mohagheghi et al., 2015; Mousavi et al., 2013, 2014, 2015, 2019; Mousavi and Vahdani 2016, 2017, Niakan et al., 2015; Vahdani et al., 2016, 2017a,b; Mousavi and Tavakkoli-Moghaddam,2013). Subsequently, two efficient solution methodologies, which are termed robust optimization (R.O.) and stochastic programming (S.P.), have been developed to tackle these issues (Mohammadi et al., 2014). It should be noted that the S.P. and R.O. approaches are typically suitable for slow and sudden onsets calamities, respectively. In fact, in slow onsets calamities, a number of meteorological and historical information can be gathered. But in sudden onsets calamities, decision-makers typically are encountered with a deficiency of information.

Ahmadi et al. (2015) investigated a location routing problem (LRP) in order to design a humanitarian logistics network under an uncertain environment, where the objective function minimized the total costs, distribution time, and unfulfilled demand. Also, to tackle the challenges of uncertainty, and S.P. approach was utilized. Additionally, in order to solve the proposed model, a variable neighborhood search algorithm was presented. Ransikarbum and Mason (2016) investigated the recovery activities of a relief logistics network in the post-disaster phase. For this purpose, they proposed a multi-objective mathematical model, where the first objective function maximized the fairness in the relief items distribution, the second one minimized the unfulfilled demand, and the third one minimized the total costs. What is more, a real case study was examined to show the validity of the proposed model. Maharjan and Hanaoka (2017) proposed a mathematical model to determine the location of warehouses in a humanitarian relief network, where the objective function maximized the coverage of demand points. Vahdani et al. (2018a) proposed two multi-stage multi-objective mathematical models to formulate a humanitarian relief network under an uncertain environment, where the first and second objective functions minimized the maximum traveling time and totals costs, respectively, and the third objective function maximized the minimum reliability of routes. Also, they utilized an R.O. approach to tackle the challenges of uncertainty. Moreover, they employed two multi-objective meta-heuristic algorithms to solve the proposed model. Vahdani et al. (2018b) proposed a multi-period multi-objective optimization model to design a humanitarian relief network under road repair concerns, where the first objective function minimized the maximum traveling time of vehicles, the second one minimized the total costs, and the third one maximized the minimum reliability of routes. Moreover, they employed two multi-objective meta-heuristic algorithms to solve the proposed model.

Veysmoradi et al. (2018) presented a multi-objective optimization model to formulate a humanitarian relief problem by considering split delivery and multi-mode transportation assumptions under an uncertain environment. Also, they employed an R.O. approach to overcome the challenges of uncertainty. What is more, a real case study was examined to show the validity of the proposed model. Noyan et al. (2017) proposed two multi-stage optimization models to design a humanitarian relief network under an uncertain environment, in which the conditional value-at-risk approach was utilized to overcome the challenges of uncertainty. Moreover, they proposed an exact unified decomposition methodology to solve the proposed models. Dufour et al. (2018) proposed an optimization framework to design a humanitarian relief network, in which an optimization model, simulation tools, and statistical analysis were employed, where the objective function of the optimization model minimized the total costs. Additionally, a real case study was investigated to compare the results of the proposed framework with that of the current circumstance. Shavarani (2019) proposed a location-allocation model to design a humanitarian relief network, in which the optimum locations of provisional facilities such as relief centers and refuel stations were determined. Moreover, with the intention of solving the proposed model, a variable neighborhood search algorithm was proposed. More importantly, a real case study was examined to show the validity of the proposed model.

Based on conducted studies in the related literature, there is not any research that has investigated the districting disaster regions, service sharing, distribution of relief items, routing of vehicles, evacuating victims, and intra-district service transfer, simultaneously. As a result, this research proposes a multi-objective mathematical model to design a humanitarian logistics network, in which three objective functions are considered to minimize the total costs, the maximum overload of distribution centers, and the maximum accident loss during distribution activities. Due to the fact that the planning of humanitarian logistics problems is encountered with miscellaneous uncertain factors, such as demand, supply, costs, and capacities of facilities, a robust optimization approach is employed to tackle these challenges. Furthermore, a number of numerical instances are provided to illustrate the validity of the proposed mathematical model. The rest of this paper is organized as follows: The proposed model is described in Section 2. The solution approach is introduced in Section 3. The computational results are provided in Section 4. Finally, the conclusions are provided in Section 5.

II. PROBLEM DEFINITION

A multi-level humanitarian logistics network, including suppliers, main distribution centers, and disaster districts, is considered, such that these districts contained disaster units, local distribution centers, and emergency centers. More importantly, with the intention of enhancing the performances of local distribution centers and the accessibility of the survivors to emergency centers, the disparity model is employed to district the disaster regions. Moreover, in order to improve the level of services to recipients, truck routing among disaster units and local distribution centers is considered, such that trucks should return to local distribution centers when they complete their missions.

In this structure, suppliers can provide and deliver the required relief items to main distribution centers; in what follows, the main distribution centers transferred these items to local distribution centers at disaster districts. Next, with respect to the demand level of disaster units, these items will be distributed among them by trucks. What is more, in an attempt to create a healthy balance between the capacities of service provider facilities and demand units, an efficient service transfer mechanism, namely intra-district, is employed. Such that a local distribution center with surplus service capacity can transfer its surplus capacity to high demand local one. Additionally, so as to consider the accidental loss, for each tour, two essential parameters are estimated based on historical data; the occurrence probability and severity index of an accident.

A. Sets and indices

(i, j): Indices for nodes

α: Set of potential suppliers $s \in \alpha$

β: Set of potential main distribution centers $c \in \beta$

K: Set of disaster districts $k \in K$

E: Set of whole spatial regions

A: Set of disaster units $A \subseteq E$

M: Set of local distribution centers $M \subseteq E$

H: Set of emergency centers $H \subseteq E$

V: Set of vehicles $v \in V$

B. Parameters

$\tilde{f}_s$: Constant setting up cost of supplier s

$\tilde{o}_c$: Constant opening cost of main distribution center c

$\widetilde{cz}_{ik}$: Constant opening cost of local distribution center i at district k; $(i \in M)$

$\widetilde{ch}_{ik}$: Constant opening cost of emergency center i at district k; $(i \in H)$

$\widetilde{cx}_{sc}$: Transportation cost per unit of relief items from supplier s to main distribution center c

$\widetilde{cu}_{ck}$: Transportation cost per unit of relief items from main distribution center c to district k

$\widetilde{co}_{ijk}$: Transportation and sharing cost per unit of relief items between local distribution centers i, j within disaster district k; $(i, j \in M)$

$\widetilde{ct}_{ij}$: Transportation cost per unit injured person from disaster unit i to emergency center j $(i \in A, j \in H)$

$\widetilde{ce}_v$: Transportation cost per kilometer for vehicle v

e_{ij}: Distance between nodes $(i, j \in E)$

$\tilde{d}_i$: Demand of disaster unit i; $(i \in A)$

$\widetilde{wf}_i$: The number of injuries at disaster unit i; $(i \in A)$

vq_v: Capacity of vehicle v

$\widetilde{cap}_s$: Capacity of supplier s

$\widetilde{cap}_c$: Capacity of main distribution center c

$\widetilde{cap}_{jk}$: Capacity of emergency center j at district $k; (i \in H)$

$\widetilde{L2}$: Entire capacity of local distribution centers

$\tilde{R}_i^{max}$: Maximum service capacity of local distribution center i; $(i \in M)$

γ : Service loss rate in a local distribution center

μ: Acceptable surplus rate for a district unit

ϑ_{ij}: the severity of the accident in arc (i, j) between 0 and 100%

cp: the unit cost of the product

fv_v: The value of vehicle k

pr_{ij}: Accident occurrence probability of arc (i, j) between 0 and 100%

$\mathbb{M}$: A sufficient big number

C. Decision variables

w_s: 1 if supplier s is selected for setting up; 0 otherwise

y_c: 1 if the main distribution center is opened at location c; 0 otherwise

ZA_{ik}: 1 if disaster unit i is assigned to disaster district k; 0 otherwise $(i \in A)$

Z_{ik}: 1 if local distribution center i is opened at disaster district k; 0 otherwise $(i \in M)$

ZH_{ik}: 1 if emergency center i is opened at disaster district k; 0 otherwise $(i \in H)$

T_{ijk}: 1 if local distribution center i is a server for disaster unit j within disaster district k; 0 otherwise $(i \in M, j \in A)$

zk_{ikv}: 1 if node i is on the route of vehicle v within disaster district k; 0 otherwise

yr_{ijkv}: 1 if node i is on the route of vehicle v before node j at disaster district k; 0 otherwise

vb_{ik}: The sign of net service balance; 1 if and only if mb_{ik} is positive; 0 otherwise

AW_{ijk}: 1 if the injuries of disaster unit i transferred to emergency center j within disaster district k; 0 otherwise $(i \in A, j \in H)$

x_{sc}: Number of relief items transported from supplier s to main distribution center c

u_{ck}: Number of relief items transported from main distribution center c to disaster district k

R_{jk}: Amount of supply provided by local distribution center j at disaster district k; $(j \in M)$

mb_{ik}: Net service balance of local distribution center i within disaster district k before relief items transfer $(i \in M)$

mb_{ik}^{+} : Positive quota of net service balance; $max\{mb_{ik}, 0\}$

mb_{ik}^{-} : Negative quota of net service balance; $min\{mb_{ik}, 0\}$

zs_{ik}: Net surplus in local distribution center i within disaster district k after relief items transfer $(i \in M)$

sv_{ijk}: Transferring relief items from local distribution center i to local distribution center j within disaster district k; defined as negative and positive for incoming and outgoing service, respectively. $(i, j \in M)$

sv_{ijk}^{+}: Positive quota of relief items transfer sv_{ijk}; $max\{sv_{ijk}, 0\}$

sv_{ijk}^{-}: Positive quota of relief items transfer sv_{ijk}; $min\{sv_{ijk}, 0\}$

un_{ikv}: Subtour elimination variable

fx_{ijk}: Number of injuries dispatched from disaster unit i at district k to emergency center j $(i \in A, j \in H)$

qw_{ijkv}: Number of relief items transported between arc (i, j) by vehicle v $(i, j \in A \cup M)$

D. Mathematical model

$$\begin{aligned}\min z_1 = &\sum_{s \epsilon \alpha} \tilde{f}_s w_s + \sum_{c \epsilon \beta} \tilde{O}_c y_c + \sum_{i \epsilon M} \sum_{k \epsilon K} \widetilde{cz}_{ik} z_{ik} + \sum_{i \epsilon H} \sum_{k \epsilon K} \widetilde{ch}_{ik} zh_{ik} + \sum_{s \epsilon \alpha} \sum_{c \epsilon \beta} \widetilde{cx}_{sc} x_{sc} \\ &+ \sum_{c \epsilon \beta} \sum_{k \epsilon K} \widetilde{cu}_{ck} u_{ck} + + \sum_{i \epsilon A \cup M} \sum_{j \epsilon A \cup M} \sum_{k \epsilon K} \sum_{v \epsilon V} \widetilde{ce}_v e_{ij} yr_{ijkv} + \sum_{i \epsilon M} \sum_{j \epsilon M} \sum_{k \epsilon K} \widetilde{co}_{ijk} sv_{ijk} \\ &+ \sum_{i \epsilon A} \sum_{j \epsilon H} \sum_{k \epsilon K} \widetilde{ct}_{ij} \, fx_{ijk}\end{aligned} \tag{1}$$

$$\min z_2 = max \; zs_{ik} \qquad \forall \; i \epsilon M \; , k \epsilon K \tag{2}$$

$$\min z_3 = \max \sum_{i \epsilon A \cup M} \sum_{j \epsilon A \cup M} \sum_{k \epsilon K} \sum_{v \epsilon V} \vartheta_{ij} \big(cp.\, qw_{ijkv} + f v_v\big) \, pr_{ij} \; yr_{ijkv} \tag{3}$$

The first objective function (1) minimizes the total humanitarian logistics costs. The first and second terms calculate the setting up and opening costs of suppliers and main distribution centers, respectively. The third and fourth terms compute the opening costs of facilities within the disaster district, which are local distribution and emergency centers. The fifth to seventh terms calculate the transportation costs. The eighth term computes the sharing costs of relief items among local distribution centers. The ninth term calculates the evacuating transportation costs of injured people. The second objective function (2) minimizes the maximum overload among entire local distribution centers, and the third objective function (3) is to minimize the maximum accident loss during distribution activities.

$\boldsymbol{s.t}$

$$\sum_{c\epsilon\beta} x_{sc} \leq w_s \widetilde{cap}_s \qquad \forall s\epsilon\alpha \tag{4}$$

$$\sum_{s\epsilon\alpha} x_{sc} \leq y_c \widetilde{cap}_c \qquad \forall\, c\epsilon\beta \tag{5}$$

$$\sum_{k\epsilon K} u_{ck} \leq y_c \widetilde{cap}_c \qquad \forall\, c\epsilon\beta \tag{6}$$

$$\sum_{s\epsilon\alpha} x_{sc} = \sum_{k\epsilon K} u_{ck} \qquad \forall\, c\epsilon\beta \tag{7}$$

$$\sum_{c\epsilon\beta} u_{ck} = \sum_{i\epsilon M} R_{ik} \qquad \forall\, k\epsilon K \tag{8}$$

Constraint (4) signifies the restriction capacities of suppliers, and constraints (5) and (6) indicate the restriction capacities of main distribution centers. Also, these constraints ensure that they have been launched or opened by the time they could provide related service. Constraints (7) and (8) ensure the flow balance among suppliers, main distribution centers, and disaster districts.

$$\sum_{k\epsilon K} ZA_{ik} = 1 \qquad \forall\, i\epsilon A \tag{9}$$

$$\sum_{i\epsilon A} ZA_{ik} \geq 1 \qquad \forall\, k\epsilon K \tag{10}$$

$$\sum_{i\epsilon M} Z_{ik} \geq 1 \qquad \forall\, k\epsilon K \tag{11}$$

$$\sum_{k\epsilon K} Z_{ik} = 1 \qquad \forall\, i\epsilon M \tag{12}$$

Constraints (9) and (10) guarantee that each disaster unit could be assigned to only one disaster district, and each disaster district has at least one disaster unit. Constraints (11) and (12) guarantee that each disaster district has at least one local distribution center, and each local distribution center could be assigned to only one disaster district.

$$\sum_{j \epsilon M} T_{ijk} = ZA_{ik} \qquad \forall\ i \epsilon A\ , k \epsilon K \tag{13}$$

$$T_{ijk} \leq Z_{jk} \qquad \forall i \epsilon A\ , j \epsilon M, k \epsilon K \tag{14}$$

$$T_{ijk} \geq yr_{jikv} \qquad \forall\ i \epsilon A\ , j \epsilon M\ , k \epsilon K, v \epsilon V \tag{15}$$

$$Z_{ik} \geq zk_{ikv} \qquad \forall\ i \epsilon M\ , k \epsilon K\ , v \epsilon V \tag{16}$$

$$zk_{jkv} \geq yr_{jikv} \qquad \forall\ j \epsilon A \cup M\ , i \epsilon A \cup M\ ; i \neq j\ , k \epsilon K\ , v \epsilon V \tag{17}$$

Constraint (13) ensures that each disaster unit within each disaster district could be supplied by only one local distribution center. Constraint (14) ensures that a local distribution center has been opened within a disaster district by the time it could provide service for disaster units within one. Constraints (15) to (17) guarantee the logical interrelations between assigning and routing issues.

$$\sum_{i \epsilon M} \sum_{k \epsilon K} R_{ik} \leq \widetilde{L2} \tag{18}$$

$$R_{ik} \leq \tilde{R}_i^{max} z_{ik} \qquad \forall\ i \epsilon M\ , k \epsilon K \tag{19}$$

Constraint (18) guarantees that the total supply of all local distribution centers should not exceed their entire capacity. Also, constraint (19) restricts the amount of supply, which provided by a local distribution center, and ensures it has been opened by the time providing associated service.

$$qw_{jikv} \leq \mathbb{M}.\, yr_{jikv} \qquad \forall (i,j) \epsilon A \cup M \quad , k \epsilon K\ , v \epsilon V \tag{20}$$

$$\sum_{i \epsilon A} \sum_{v \epsilon V} qw_{jikv} yr_{jikv} \leq R_{jk} \qquad \forall\ j \epsilon M\ , k \epsilon K \tag{21}$$

$$\sum_{j\epsilon A\cup M} qw_{jikv} - \tilde{d}_i . zk_{ikv} = \sum_{j\epsilon A\cup M} qw_{ijkv} \qquad \forall\ i\epsilon A\ , k\epsilon K\ , v\epsilon V \tag{22}$$

$$\sum_{i\epsilon A} \tilde{d}_i zA_{ik} \leq (1+\mu) \sum_{j\epsilon M} R_{jk} \qquad \forall\ k\epsilon K \tag{23}$$

Constraint (20) ensures that the relief items can be transported only from established routes. Constraint (21) restricts the transported relief items among arcs with respect to the supply amount provided by local distribution centers. Constraint (22) signifies the number of relief items transported between each arc. Constraint (23) specifies the service supply of each local distribution center within its restrictions.

$$\sum_{i\epsilon M} \sum_{k\epsilon K} zk_{ikv} = 1 \qquad \forall\ v\epsilon V \tag{24}$$

$$\sum_{k\epsilon K} \sum_{v\epsilon V} zk_{ikv} \geq 1 \qquad \forall\ i\epsilon M \tag{25}$$

$$\sum_{i\epsilon A} \sum_{k\epsilon K} T_{ijk} \geq 1 \qquad \forall\ j\epsilon M \tag{26}$$

$$\sum_{k\epsilon K} \sum_{v\epsilon V} zk_{ikv} = 1 \qquad \forall\ i\epsilon A \tag{27}$$

Constraint (24) ensures that each vehicle could be assigned to only one local distribution center of the disaster district. Constraint (25) guarantees that at least one vehicle should be assigned to each local distribution center. Constraint (26) guarantees that at least one disaster unit should be assigned to each local distribution center. Constraint (27) guarantees that each disaster unit could be on the route of one vehicle.

$$\sum_{i\epsilon A\cup M} \sum_{k\epsilon K} yr_{ijkv} \leq 1 \qquad \forall\ j\epsilon A\ , v\epsilon V\ ;\ i \neq j \tag{28}$$

$$\sum_{i\epsilon A\cup M} \sum_{k\epsilon K} \sum_{v\epsilon V} yr_{ijkv} = 1 \qquad \forall\ j\epsilon A\ ;\ i \neq j \tag{29}$$

$$\sum_{j\epsilon A\cup M} \sum_{k\epsilon K} \sum_{v\epsilon V} yr_{ijkv} = 1 \qquad \forall\ i\epsilon A\ ;\ i \neq j \tag{30}$$

$$\sum_{j\epsilon A} \sum_{k\epsilon K} \sum_{v\epsilon V} yr_{ijkv} \geq 1 \qquad \forall\ i\epsilon M \tag{31}$$

$$\sum_{i\epsilon M}\sum_{j\epsilon A}\sum_{k\epsilon K} yr_{ijkv} \leq 1 \qquad \forall\ v\epsilon V \tag{32}$$

$$\sum_{k\epsilon K}\sum_{v\epsilon V} yr_{ijkv} \leq 1 \qquad \forall\ i\epsilon A \cup M\ , j\epsilon A \cup M\ ;\ \ i \neq j \tag{33}$$

$$ZA_{jk} \geq yr_{ijkv} \qquad \forall\ j\epsilon A\ , i\epsilon A \cup M\ , k\epsilon K\ , v\epsilon V \tag{34}$$

$$un_{ikv} - un_{jkv} + n * yr_{ijkv} \leq n - 1 \qquad \forall\ i, j\epsilon A\ , k\epsilon K\ , v\epsilon V\ ; i \neq j \tag{35}$$

$$\sum_{j\epsilon A\cup M} yr_{ijkv} - \sum_{j\epsilon A\cup M} yr_{jikv} = 0 \qquad \forall\ i\epsilon A \cup M\ , k\epsilon K\ , v\epsilon V\ ; i \neq j \tag{36}$$

$$\sum_{i\epsilon A\cup M}\sum_{j\epsilon A} \tilde{d}_j\ yr_{ijkv} \leq vq_v \qquad \forall\ k\epsilon K\ , v\epsilon V \tag{37}$$

Constraint (28) ensures that each vehicle could provide service for each disaster unit at most once. Constraint (29) ensures that each disaster unit is met only once; in other words, only one vehicle could enter and serve each disaster unit. Constraint (30) ensures that only one vehicle can leave each disaster unit. Constraint (31) ensures that at least one vehicle is dispatched from each local distribution center. Constraint (32) guarantees that each vehicle could dispatch at most one local distribution center. Constraint (33) guarantees that at most one vehicle could be selected for each route, and constraint (34) guarantees the logical interrelation between assigning and routing issues. Also, sub-tour elimination, connectivity, and vehicle capacity constraints are guaranteed by constraints (35) to (37).

$$sv_{ijk} + sv_{jik} = 0 \qquad \forall\ i, j\epsilon M\ , k\epsilon K\ ;\ \ i \neq j \tag{38}$$

$$sv_{ijk} = 0 \qquad \forall\ i, j\epsilon M\ , k\epsilon K\ \ ;\ i = j \tag{39}$$

$$sv^{+}_{ijk} \geq sv_{ijk} \qquad \forall\ i, j\epsilon M\ \ , k\epsilon K\ ;\ \ i \neq j \tag{40}$$

$$sv^{-}_{ijk} \leq sv_{ijk} \qquad \forall\ i, j\epsilon M\ \ , k\epsilon K\ ;\ \ i \neq j \tag{41}$$

$$mb_{ik} = R_{ik} - \sum_{j \epsilon A} \tilde{d}_j \, T_{jik} \qquad \forall \, i \epsilon M \, , k \epsilon K \tag{42}$$

$$zs_{ik} = -mb_{ik} - (1-\gamma) \sum_{j \epsilon M} sv_{jik} \qquad \forall \, i \epsilon M \, , k \epsilon K \tag{43}$$

Constraints (38) and (39) guarantee that the transferring services between two local distribution centers have the right signs; also, they ensure that the prevention of service transfer from a local distribution center to itself. Constraints (40) and (41) signify outbound and inbound transferring services, respectively. Constraint (42) denotes the net balance of supplying service in each local distribution center before transferring service, and constraint (43) denotes the overload in a local distribution center.

$$mb_{ik}^{+} \geq mb_{ik} \qquad \forall \;\, i \epsilon M \, , k \epsilon K \tag{44}$$

$$mb_{ik}^{-} \leq mb_{ik} \qquad \forall \;\, i \epsilon M \, , k \epsilon K \tag{45}$$

$$mb_{ik}^{+} \leq \widetilde{L2} \, . \, vb_{ik} \qquad \forall \;\, i \epsilon M \, , k \epsilon K \tag{46}$$

$$mb_{ik}^{-} \geq \widetilde{L2} . \, (vb_{ik} - 1) \qquad \forall \;\, i \epsilon M \, , k \epsilon K \tag{47}$$

$$mb_{ik}^{+} = mb_{ik} - mb_{ik}^{-} \qquad \forall \;\, i \epsilon M \, , k \epsilon K \tag{48}$$

$$\sum_{j \epsilon M} sv_{ijk}^{+} \leq mb_{ik}^{+} \qquad \forall \;\, i \epsilon M \, , k \epsilon K \;\; ; \; i \neq j \tag{49}$$

Constraints (44) and (45) guarantee that mb_{ik}^{+} and mb_{ik}^{-} have right signs, and constraints (46) and (47) impose that only one of them becomes non-zero. Constraint (48) calculates the value of mb_{ik}^{+}, which is utilized in constraint (49) to restrict transferring service.

$$mb_{ik}^{+} \geq sv_{ijk}^{+} \qquad \forall \, i, j \epsilon M \, , k \epsilon K \, ; \quad i \neq j \tag{50}$$

$$mb_{ik}^{-} \leq sv_{ijk}^{-} \qquad \forall\, i,j\epsilon M\,, k\epsilon K\,;\;\; i \neq j \tag{51}$$

$$sv_{ijk}^{+} \leq ZA_{ik}\, \tilde{R}_{i}^{max} \qquad \forall\, i,j\epsilon M\,, k\epsilon K\,;\;\; i \neq j \tag{52}$$

Constraint (50) ensures that a local distribution center, which has extra supply, could render outgoing service transfer. Constraint (51) ensures that the local distribution center, which has extra supply, could not receive incoming service transfers. Constraint (52) ensures that local distribution centers in each disaster district should serve only the disaster units within the disaster district.

$$\sum_{k\epsilon K} ZH_{ik} = 1 \qquad \forall\, i\epsilon H \tag{53}$$

$$\sum_{i\epsilon H} ZH_{ik} \geq 1 \qquad \forall k\epsilon K \tag{54}$$

$$\sum_{j\epsilon H} AW_{ijk} = ZA_{ik} \qquad \forall\, i\epsilon A\;\;, k\epsilon K \tag{55}$$

Constraints (53) and (54) guarantee that each emergency center could be assigned to only one disaster district, and each disaster district has at least one emergency center. Constraint (55) ensures that each disaster unit within each disaster district could be served by only one emergency center.

$$AW_{ijk} \leq ZH_{jk} \qquad \forall\, i\epsilon A\,, j\epsilon H\,, k\epsilon K \tag{56}$$

$$\sum_{i\epsilon A} \sum_{k\epsilon K} AW_{ijk} \geq 1 \qquad \forall\, j\epsilon H \tag{57}$$

Constraint (56) ensures that an emergency center has been opened within a disaster district by the time it could provide service for disaster units within one. Constraint (57) ensures that at least one disaster unit should be assigned to each emergency center.

$$fx_{ijk} = \widetilde{wf}_{i}\, AW_{ijk} \qquad \forall\, i\epsilon A\;\;, j\epsilon H\,, k\epsilon K \tag{58}$$

$$\sum_{i\epsilon A} fx_{ijk} \leq \widetilde{cap}_{jk}\, ZH_{jk} \qquad \forall\, j\epsilon H\,, k\epsilon K \tag{59}$$

$$mb_{ik}, sv_{ijk}, zs_{ik} \epsilon R \tag{60}$$

$$mb_{ik}^{-}, sv_{ijk}^{-} \leq 0 \tag{61}$$

$$mb_{ik}^{+}, sv_{ijk}^{+}, x_{\alpha\beta}, u_{\beta k}, R_{ik}, fx_{ijk}, qw_{ijkv} \geq 0 \tag{62}$$

$$vb_{ik}, w_{\alpha}, y_{\beta}, z_{ik}, zh_{ik}, T_{ijk}, zk_{ikv}, yr_{ijkv}, AW_{ijk} \in (0,1) \tag{63}$$

Constraint (58) signifies the number of dispatched injuries. Constraint (59) signifies the restriction of emergency center capacity; also, this constraint ensures that it has been opened by the time they could provide related service. Constraints (60) to (63) denote the types of decision variables.

E. Robust counterpart model

In the proposed model, a number of influential factors, including opening and setting up costs, the capacities of facilities, transportation costs, the demand of disaster units, and the number of injuries, are considered as uncertain parameters to offer the robust counterpart model, such that each of them is considered as a box uncertainty set. In fact, this type of uncertainty set can provide the most conservative solution, while these uncertain parameters can be considered in the worst possible circumstances simultaneously (Ben-Tal, & Nemirovski, 2000; Vahdani, 2014). The box uncertainty set can be represented as follows:

$$u_{Box} = \left\{ \xi \in \Re^{n} : \left| \xi_t - \overline{\xi_t} \right| \leq \rho G_t, \qquad t = 1,2, \dots, n \right\} \tag{64}$$

where ρ denotes the level of uncertainty, G_t signifies the scale of uncertainty, and $\overline{\xi_t}$ is ξ_t The normal value of the t^{th} parameter of vector ξ (Ben-Tal, & Nemirovski, 2000). With respect to the above description, the changed objective functions and constraints are reformulated as follows:

$$\min \ w_1 \tag{65}$$

$$\min w_2 = max\ zs_{ik} \qquad \forall\ i \epsilon M\ , k \epsilon K \tag{66}$$

$$\min \ w_3 \tag{67}$$

S.t.

$$\sum_{s\epsilon\alpha}\left(\bar{f}_s w_s + \eta_s^f\right) + \sum_{c\epsilon\beta}(\bar{O}_c y_c + \eta_c^O) + \sum_{s\epsilon\alpha}\sum_{c\epsilon\beta}(\overline{cx}_{sc}x_{sc} + \eta_{sc}^{cx}) + \sum_{c\epsilon\beta}\sum_{k\epsilon K}(\overline{cu}_{ck}u_{ck} + \eta_{ck}^{cu}) + \sum_{i\epsilon M}\sum_{k\epsilon K}(\overline{cz}_{ik} + \eta_{ik}^{cz}) + \sum_{i\epsilon A\cup M}\ \sum_{j\epsilon A\cup M}\sum_{k\epsilon K}\sum_{v\epsilon V}\left(\overline{ce}_v e_{ij} yr_{ijkv} + \eta_v^{ce}\right) + \sum_{i\epsilon H}\sum_{k\epsilon K}\left(\overline{ch}_{ik} zh_{ik} + \eta_{ik}^{ch}\right) + \sum_{i\epsilon M}\sum_{j\epsilon M}\sum_{k\epsilon K}\left(\overline{co}_{ijk} sv_{ijk} + \eta_{ijk}^{co}\right) + \sum_{i\epsilon A}\sum_{j\epsilon H}\sum_{k\epsilon K}\left(\overline{c}t_{ij}\, fx_{ijk} + \eta_{ij}^{ct}\right) \le w_1 \tag{68}$$

$$\sum_{i\epsilon A\cup M}\ \sum_{j\epsilon A\cup M}\sum_{k\epsilon K}\sum_{v\epsilon V}\left(cp.\,qw_{ijkv} + fv_v\right) pr_{ij}\left(\vartheta_{ij}\ yr_{ijkv} + \eta_{ij}^{\vartheta}\right) \le w_3 \tag{69}$$

$$\rho_f \mathcal{G}_s^f w_s \le \eta_s^f \qquad \forall s \tag{70}$$

$$\rho_f \mathcal{G}_s^f w_s \ge -\eta_s^f \qquad \forall s \tag{71}$$

$$\rho_O \mathcal{G}_c^O y_c \le \eta_c^O \qquad \forall c \tag{72}$$

$$\rho_O \mathcal{G}_c^O y_c \ge -\eta_c^O \qquad \forall c \tag{73}$$

$$\rho_{cx} \mathcal{G}_{sc}^{cx} x_{sc} \le \eta_{sc}^{cx} \qquad \forall s, c \tag{74}$$

$$\rho_{cx} \mathcal{G}_{sc}^{cx} x_{sc} \ge -\eta_{sc}^{cx} \qquad \forall s, c \tag{75}$$

$$\rho_{cu} \mathcal{G}_{ck}^{cu} u_{ck} \le \eta_{ck}^{cu} \qquad \forall c, \tag{76}$$

$$\rho_{cu} \mathcal{G}_{ck}^{cu} u_{ck} \ge -\eta_{ck}^{cu} \qquad \forall c, k \tag{77}$$

$$\rho_{cz} \mathcal{G}_{ik}^{cz} z_{ik} \le \eta_{ik}^{cz} \qquad \forall i, k \tag{78}$$

$$\rho_{cz}\mathcal{G}_{ik}^{cz}z_{ik} \geq -\eta_{ik}^{cz} \qquad \forall i,k \tag{79}$$

$$\rho_{ce}\mathcal{G}_{v}^{ce}yr_{ijkv} \leq \eta_{v}^{ce} \qquad \forall i,j,k,v \tag{80}$$

$$\rho_{ce}\mathcal{G}_{v}^{ce}yr_{ijkv} \geq -\eta_{v}^{ce} \qquad \forall i,j,k,v \tag{81}$$

$$\rho_{ch}\mathcal{G}_{ik}^{ch}zh_{ik} \leq \eta_{ik}^{ch} \qquad \forall i,k \tag{82}$$

$$\rho_{ch}\mathcal{G}_{ik}^{ch}zh_{ik} \geq -\eta_{ik}^{ch} \qquad \forall i,k \tag{83}$$

$$\rho_{co}\mathcal{G}_{ijk}^{co}sv_{ijk} \leq \eta_{ijk}^{co} \qquad \forall i,k \tag{84}$$

$$\rho_{co}\mathcal{G}_{ijk}^{co}sv_{ijk} \geq -\eta_{ijk}^{co} \qquad \forall i,k \tag{85}$$

$$\rho_{ct}\mathcal{G}_{ij}^{ct}fx_{ijk} \leq \eta_{ij}^{ct} \qquad \forall i,k \tag{86}$$

$$\rho_{ct}\mathcal{G}_{ij}^{ct}fx_{ijk} \geq -\eta_{ij}^{ct} \qquad \forall i,k \tag{87}$$

$$\rho_{\vartheta}\mathcal{G}_{ij}^{\vartheta}yr_{ijkv} \leq \eta_{ij}^{\vartheta} \qquad \forall i,k \tag{88}$$

$$\rho_{\vartheta}\mathcal{G}_{ij}^{\vartheta}yr_{ijkv} \geq -\eta_{ij}^{\vartheta} \qquad \forall i,k \tag{89}$$

$$\sum_{c\epsilon\beta} x_{sc} \leq w_s\left(\overline{cap}_s - \rho_{cap}\,\mathcal{G}_s^{cap}\right) \qquad \forall s\epsilon\alpha \tag{90}$$

$$\sum_{s\epsilon\alpha} x_{sc} \leq y_c\left(\overline{cap}_c - \rho_{cap}\,\mathcal{G}_c^{cap}\right) \qquad \forall\ c\epsilon\beta \tag{91}$$

$$\sum_{k\epsilon K} u_{ck} \leq y_c\left(\overline{cap}_c - \rho_{cap}\, \mathcal{G}_c^{cap}\right) \qquad \forall\ c\epsilon\beta \tag{92}$$

$$\sum_{i\epsilon M}\sum_{k\epsilon K} R_{ik} \leq \overline{L2} - \rho_{L2}\mathcal{G}^{L2} \tag{93}$$

$$R_{ik} \leq \left(\bar{R}_i^{max} - \rho_{R^{max}}\, \mathcal{G}_i^{R^{max}}\right) z_{ik} \qquad \forall\ i\epsilon M\,, k\epsilon K \tag{94}$$

$$\sum_{j\epsilon A\cup M} qw_{jikv} - \sum_{j\epsilon A\cup M} qw_{ijkv} \geq \left(\bar{d}_i - \rho_{d_i}\, \mathcal{G}_i^{d}\right) zk_{ikv} \qquad \forall\ i\epsilon A\,, k\epsilon K\,, v\epsilon V \tag{95}$$

$$\sum_{j\epsilon A\cup M} qw_{jikv} - \sum_{j\epsilon A\cup M} qw_{ijkv} \leq \left(\bar{d}_i + \rho_{d_i}\, \mathcal{G}_i^{d}\right) zk_{ikv} \qquad \forall\ i\epsilon A\,, k\epsilon K\,, v\epsilon V \tag{96}$$

$$\sum_{i\epsilon A} \bar{d}_i\left(1+\rho_{d_i}\right) zA_{ik} \leq (1+\mu)\sum_{j\epsilon M} R_{jk} \qquad \forall\ k\epsilon K \tag{97}$$

$$\sum_{i\epsilon A\cup M}\sum_{j\epsilon A} \bar{d}_j\ (1+\rho_d) yr_{ijkv} \leq vq_v \qquad \forall\ k\epsilon K\,, v\epsilon V \tag{98}$$

$$mb_{ik} \geq R_{ik} - \sum_{j\epsilon A} \bar{d}_j\ (1-\rho_d) T_{jik} \qquad \forall\ i\epsilon M\,, k\epsilon K \tag{99}$$

$$mb_{ik} \leq R_{ik} - \sum_{j\epsilon A} \bar{d}_j (1+\rho_d)\ T_{jik} \qquad \forall\ i\epsilon M\,, k\epsilon K \tag{100}$$

$$mb_{ik}^{+} \leq (\overline{L2} - \rho_{L2}\mathcal{G}^{L2})\,.\, vb_{ik} \qquad \forall\ \ i\epsilon M\,, k\epsilon K \tag{101}$$

$$mb_{ik}^{-} \geq (\overline{L2} + \rho_{L2}\mathcal{G}^{L2})(vb_{ik} - 1) \qquad \forall\ \ i\epsilon M\,, k\epsilon K \tag{102}$$

$$sv_{ijk}^{+} \leq ZA_{ik}\left(\bar{R}_i^{max} - \rho_{R^{max}}\, \mathcal{G}_i^{R^{max}}\right) \qquad \forall\ i,j\epsilon M\,, k\epsilon K\,; \quad i\neq j \tag{103}$$

$$fx_{ijk} \geq \left(\overline{wf}_i - \rho_{wf}\, \mathcal{G}_i^{wf}\right) AW_{ijk} \qquad \forall\, i\epsilon A\ , j\epsilon H\ , k\epsilon K \tag{104}$$

$$fx_{ijk} \leq \left(\overline{wf}_i + \rho_{wf}\, \mathcal{G}_i^{wf}\right) AW_{ijk} \qquad \forall\, i\epsilon A\ , j\epsilon H\ , k\epsilon K \tag{105}$$

$$\sum_{i\epsilon A} fx_{ijk} \leq \left(\overline{cap}_{jk} - \rho_{cap}\, \mathcal{G}_{jk}^{cap}\right) ZH_{jk} \qquad \forall\, j\epsilon H\ , k\epsilon K \tag{106}$$

$$\eta_s^f, \eta_c^O, \eta_{sc}^{cx}, \eta_{ck}^{cu}, \eta_{ik}^{cz}, \eta_v^{ce}, \eta_{ik}^{ch}, \eta_{ijk}^{co}, \eta_{ij}^{ct}, \eta_{ij}^{\vartheta} \geq 0 \tag{107}$$

III. SOLUTION METHOD

With regard to the robust counterpart model, which is represented in the previous section, a fuzzy solution approach is employed to solve this model, which was termed the T.H. method, and it was proposed by Torabi and Hassini (2008). The steps of this method are provided as follows:

Step 1: Determining the positive and negative ideal solutions for each objective function. For this purpose, the proposed model is distinctly solved for each of them, and the positive ideal solutions (PISs) is obtained, $(\mathcal{W}_1^{PIS}, x_1^{PIS}), (\mathcal{W}_2^{PIS}, x_2^{PIS})$ and $(\mathcal{W}_3^{PIS}, x_3^{PIS})$. In what follows, the negative ideal solutions (NISs) are calculated as follows:

$$\mathcal{W}_1^{NIS} = \min\{\mathcal{W}_1(x_2^{PIS}), \mathcal{W}_1(x_3^{PIS})\}, \mathcal{W}_2^{NIS} = \min\{\mathcal{W}_1(x_1^{PIS}), \mathcal{W}_1(x_3^{PIS})\}, \mathcal{W}_3^{NIS} = \min\{\mathcal{W}_1(x_1^{PIS}), \mathcal{W}_1(x_2^{PIS})\},$$

Step 2: Computing the membership function for each objective as follows:

$$\mu_h(x) = \begin{cases} 1 & if \quad \mathcal{W}_h < \mathcal{W}_h^{PIS} \\ \dfrac{\mathcal{W}_h^{NIS} - \mathcal{W}_h}{\mathcal{W}_h^{NIS} - \mathcal{W}_h^{PIS}} & if \quad \mathcal{W}_h^{PIS} \leq \mathcal{W}_h \leq \mathcal{W}_h^{NIS} \\ 0 & if \quad \mathcal{W}_h > \mathcal{W}_h^{NIS} \end{cases} \tag{108}$$

where the satisfaction degree is denoted by $\mu_h(x)$ for the h^{th} objective function.

Step 3: Converting the multi-objective model to a single objective one as follows:

$$max \ \ \lambda(x) = \psi\lambda_0 + (1-\psi)\sum_h \theta_h\, \mu_h(x) \tag{109}$$

S.t.:

$$\lambda_0 \leq \mu_h(x), \quad h = 1,2,3 \tag{110}$$

$$x \in F(x), \quad \lambda_0 and \ \lambda \in [0,1] \tag{111}$$

where $\lambda_0 = min\{\mu_h(x)\}$ signifies the minimum degree of satisfaction degree of objective functions, and ψ and θ_h specify the coefficient of restitution and relative importance of h^{th} objective function.

IV. NUMERICAL EXAMPLE

With the intention of illustrating the validation and practicability of the proposed model, a number of numerical instances are provided in this section. For this aim, a number of influential parameters are represented in Table I. In order to solve the proposed model, both certain and robust counterpart models have been coded in GAMS 24.8.2 software. Moreover, five different test problems have been considered, and their results are provided in Table II under various uncertainty levels.

Table I. Parameters related to main distribution centers

Parameters	***Values***	***Parameters***	***Values***
$\tilde{f}_s$	Uniform (1000,15000)	$\tilde{d}_i$	Uniform (300,900)
$\tilde{o}_c$	Uniform (4000,7000)	$\widetilde{wf}_i$	Uniform (20,40)
$\widetilde{cz}_{ik}$	Uniform (6000,8000)	$\widetilde{cap}_s$	Uniform (8600,9000)
$\widetilde{ch}_{ik}$	Uniform (5000,8000)	$\widetilde{cap}_c$	Uniform (2000,5000)
$\widetilde{cx}_{sc}, \widetilde{cu}_{ck}, \widetilde{co}_{ijk}, \widetilde{ct}_{ij}, \widetilde{ce}_v$	Uniform (50,150)	$\widetilde{cap}_{jk}$	Uniform (3000,6000)
$\widetilde{L2}$	Uniform (1000,2000)	$\tilde{R}_i^{max}$	Uniform (8000,15000)

As shown in Table II, the robust counterpart model has offered the worse solutions in all investigated problems with that of the deterministic model; in the robust model, the worst situation is considered to minimize the risk of planning. Furthermore, an investigation is conducted on the importance of degrees of the objective function, which is provided in Table III. The obtained results reveal that the T.H. method can render efficient and effective solutions for multi-objective problems.

More importantly, the behaviors of the first two objective functions with regard to the increasing number of disaster districts have been investigated, and the obtained results are provided in Figs 1 and 2. As demonstrated, by increasing the number of disaster districts, both mentioned-objective functions are also increased, although the second one is more susceptible to these alterations.

Table II. Sensitivity analysis of the level of uncertainty (ρ) given that ψ =0.4

Test problem	***Deterministic***			***Robust***			
	(z_1, μ_1)	(z_2, μ_2)	(z_3, μ_3)	ρ	(z_1, μ_1)	(z_2, μ_2)	(z_3, μ_3)
1	(547176.6,0.66)	(875 , 0.69)	(6514 , 0.71)	0.3	(574321.8,0.59)	(954,0.79)	(8121,0.76)
				0.5	(651390.6,0.71)	(1108,0.67)	(9057,0.65)
				0.7	(678150.7,0.75)	(1546,0.75)	(10131,0.67)

Continue Table II. Sensitivity analysis of the level of uncertainty (ρ) given that ψ =0.4

Test problem	*Deterministic*			*Robust*			
	(z_1, μ_1)	(z_2, μ_2)	(z_3, μ_3)	ρ	(z_1, μ_1)	(z_2, μ_2)	(z_3, μ_3)
2	(454614.7,0.61)	(1312,0.62)	(5417, 0.77)	0.3	(488791,0.55)	(1456, 0.86)	(6513, 0.75)
				0.5	(568703.4,0.60)	(1791,0.67)	(7643, 0.65)
				0.7	(571215.87,0.59)	(1981, 0.71)	(8331, 0.77)
3	(760915.2, 0.59)	(2876,0.60)	(8033,0.68)	0.3	(889712.8, 0.57)	(3125, 0.70)	(9631, 0.76)
				0.5	(921454.6,0.64)	(3651, 0.66)	(10312, 0.67)
				0.7	(950912.9, 0.67)	(4315, 0.79)	(13139, 0.55)
4	(910981.7,0.60)	(1431,0.63)	(2514,0.79)	0.3	(935463.8,0.65)	(2010, 0.60)	(2878,0.71)
				0.5	(974516.7, 0.66)	(2141, 0.64)	(3056, 0.67)
				0.7	(993265.8,0.69)	(2765, 0.57)	(3221, 0.73)
5	(1061358.3,0.71)	(3145,0.70)	(4656,0.81)	0.3	(1123618.9,0.66)	(4218, 0.76)	(5433, 0.80)
				0.5	(1276170.6,0.68)	(4468,0.69)	(5671, 0.74)
				0.7	(1386761.8,0.64)	(5312,0.58)	(6149,0.67)

Table III. The results of the sensitivity analysis on θ -value for problems

Test problem	$(\theta_1, \theta_2, \theta_3)$	*Deterministic*		
		(z_1, μ_1)	(z_2, μ_2)	(z_3, μ_3)
1	(0.3,0.3,0.4)	(547176.6,0.66)	(875, 0.69)	(6514, 0.71)
	(0.3,0.4,0.3)	(568810.9, 0.61)	(620,0.78)	(6715,0.68)
	(0.4,0.3,0.3)	(510316.8,0.74)	(923,0.64)	(6907,0.62)
	(0.2,0.4,0.4)	(632410.5,0.57)	(590,0.80)	(6491,0.72)
2	(0.3,0.3,0.4)	(454614.7,0.61)	(1312,0.62)	(5417,0.77)
	(0.3,0.4,0.3)	(441670.9,0.63)	(1151,0.80)	(5573,0.73)
	(0.4,0.3,0.3)	(419063.9,0.71)	(1244,0.71)	(4851,0.76)
	(0.2,0.4,0.4)	(512166.9,0.59)	(1063,0.85)	(4402,0.79)

V. CONCLUSION

In this research, a multi-objective mathematical model was proposed to design a humanitarian logistics network, in which three objective functions were considered to minimize the total costs, the maximum overload of distribution centers, and the maximum accident loss during distribution activities. Due to the fact that the planning of humanitarian logistics problem is encountered with miscellaneous uncertain factors, such as demand, supply, costs, and capacities of facilities, a robust optimization approach was employed to tackle these challenges. Furthermore, a number of test problems were provided to illustrate the validity of the proposed mathematical model. The attained results manifest that the proposed model is applicable to design a relief logistics network under an uncertain environment.

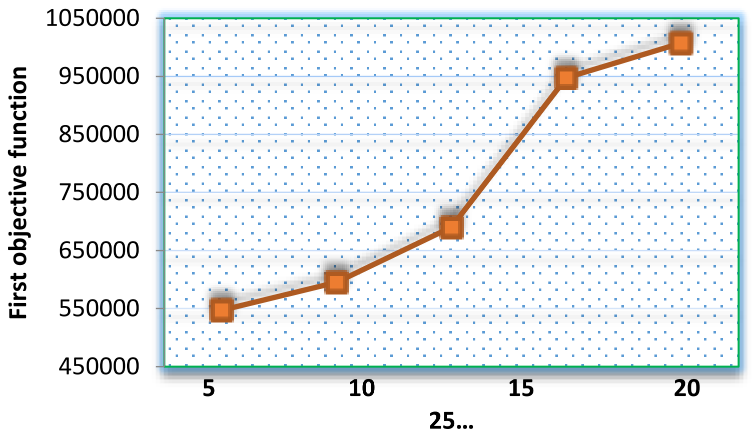

Fig 1. First objective function and number of districts

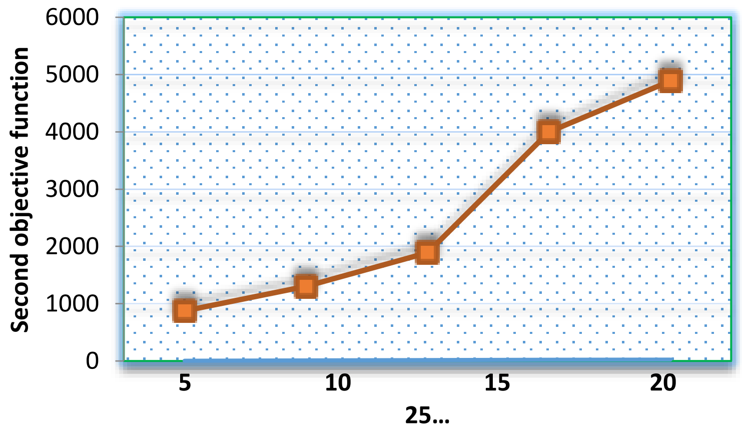

Fig 2. Second objective function and number of districts

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