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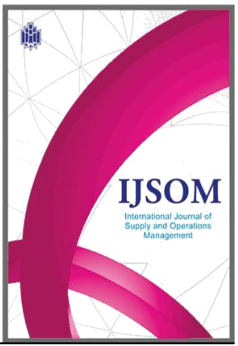

# Developing a Fuzzy Goal Programming Model for Optimizing Humanitarian Supply Chain Operations

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## Abstract

Reviewing natural disasters that occurred in recent decades indicates that the occurrence of such disasters has imposed heavy costs and casualties on governments and societies and led to growing concerns in this field. In this regard, adopting proper decisions and taking appropriate and real-time measures in each phase of the crisis management cycle can reduce possible damages during disasters and decrease the vulnerability of society. Hence, the present study aims to propose a fuzzy goal programming (FGP) model in two stages of the primary disaster and the secondary disaster. The initial disaster aims at providing relief services and commodities to disaster-affected areas while the purpose of the secondary disaster, which happens after the occurrence of the primary disaster, is to provide aid to disaster centers and transfer injured individuals to relief centers. The proposed mathematical model was first endorsed by using the FGP approach and then, validated by using the NSGAII metaheuristic algorithm and adjusting the parameters of the Taguchi method. The results revealed that the proposed model could improve the programming and flexibility of relief measures in disaster-affected areas in both primary and secondary stages. It was also found that the use of a metaheuristic algorithm facilitated the evaluation and decision-making procedures in big disasters and verified the efficiency of the algorithm in large dimensions.

**Keywords:** Critical logistics, Primary & secondary Disaster, Fuzzy goal programming, NSGAII, Taguchi methods.

## 1. Introduction

Natural disasters occur across the globe in different seasons of the year, leaving numerous casualties and imposing heavy costs on governments (Cao et al., 2018). Natural disasters are floods, earthquakes, tsunami, hurricanes, storms, and meteorites, each of which may have numerous harmful consequences, depending on their intensity and location. Thus, planning, predicting, and taking preventive measures are required to be prepared for such disasters (Samani et al., 2018). As mentioned, disasters impose large costs and casualties on societies and therefore, it is necessary to provide logistic programs to encounter natural threats and implement crisis management. Despite the advancements in science and technology, such disasters have an unexpected and unpredictable nature, highlighting the accessibility of preventive plans and emergency responses after the occurrence of a disaster. For example, the available limited resources should be optimally allocated to the affected individuals to meet their requirements at a satisfactory level (Song et al., 2018).

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Iran has experienced natural disasters such as floods and earthquakes with different intensities, causing great costs and casualties. As a result, providing emergency responses to post-disaster crises is necessary for improving the efficiency and effectiveness of the relief operation. The presence of schemes and plans to deal with the consequences of disasters, as well as the improvement of public awareness, leads to the reduction of casualties and costs, which is a major objective of responses and relief reactions. It should be noted that the nature of incidents such as floods entails real-time reactions with high speed in the shortest possible time. In other words, in such emergency and complicated situations, the decision-maker should perform the relief and rescue operations both quickly and effectively, and help injured individuals. To achieve this goal and take real-time measures, it is necessary to have access to a well-defined, efficient system, in which all the necessary activities, sequences, and communications are identified (Jha et al., 2017). Hence, providing logistic programming for transporting commodities to affected areas is regarded as one of the essential activities. To meet the objectives of crisis management in disasters, presenting relief services, distributing commodities to the damaged areas, and transferring injured individuals are strategic and sensitive tasks, since improving the efficiency of commodity and injuries transportation extensively influences the rescue rate after the disaster (Goli and Bakhshi, 2017). Thus, most disaster relief problems mostly focus on optimizing routing decisions and locating road vehicles with several approaches for the modeling process.

Considering the use of helicopters in vast areas, we used this device for programming under medical emergencies and disaster relief. Given the importance of disaster relief, the present study considered the distribution of medical auxiliary materials, vaccines, and other commodities, including tents, blankets, and medicine from the located warehouses to the areas damaged after the disaster. Furthermore, transferring injured individuals from the damaged areas to hospitals was also addressed for the evacuation process. The objective is to determine a set of routes with the minimum flying time from a hospital to another one, in addition to minimizing the fuel consumption of the helicopters. In general, an efficient humanitarian supply chain management should respond to the faced situations in the shortest possible time. The present study focused on locating warehouses and the last stage of the relief supply chain, i.e., last-mile delivery problems that are increased in disaster relief. Hence, a mathematical model was developed based on the last mile delivery concepts. The purposes intended in this research are dealing with natural disasters and developing a new quick-reaction model for the quick relief of areas, as well as expanding these concepts based on the quick disaster response phase and real-life constraints.

## 2 Literature Review

So far, a large body of research has been conducted on the humanitarian supply chain. Fathalikhani et al. (2019) considered a setting consisting of relief donors and non-governmental organizations (NGOs) that might adopt competitive or cooperative inter-organizational interaction for disaster management. They assumed that the government could intervene in the relief operation by adopting at least one of two policies of maximizing social welfare and minimizing budget consumption. By using the game theory, they investigated four scenarios and thus, four mathematical programming models to evaluate the effects of interaction between NGOs and governmental policies on the performance of aid donors, NGOs, and government. Erbeyoglu and Bilge (2020) suggested that having a suitable number of located strategic warehouses and distribution centers is an important key for critical resources that provides effectiveness, efficiency, and fairness when responding to a disaster. Their model was selected to be a suitable combination of relief commodities at the right time. Moreover, the linear mixed-integer model was aimed at finding a robust network design that met demands for the entire given disaster scenarios and helped achieve a better response in the reaction phase when delivering relief commodities. Gul Qureshi and Taniguchi (2020) proposed a humanitarian procurement model and investigated limited available resources, distribution justice, and the remaining capacity of the road network in a multi-round optimization setting. A case study was conducted in Osaka, Japan, aiming to determine efficient locations for the warehouses of important infrastructures and supply strategy by using scenario analysis.

Rodriguez et al. (2018) highlighted the establishment of resource procurement to help disaster casualties, develop proper programs for such activities, and reduce suffering. Crisis management increases organizations' collaboration and shares resources to cope with emergencies. As a result, a successful operation substantially relies on the cooperation of organizations. Chapman and Mitchell (2018) stated the necessity of organizing efficient relief operations and ensuring the supply of requirements of the entire affected population after a large disaster. However, uncertainty often influences the entire aspects of relief attempts after a disaster. Relief distribution centers and the public awareness of such centers are essential for the quickness and efficiency of relief attempts. Yu et al. (2018) used deprivation cost as a key economic indicator of human suffering concerning emergency procurement. Later, an improved method was proposed for effectively and fairly allocating essential resources in emergency procurement that considered human suffering by using this economic representation. A dynamic programming model was introduced for a multi-round resource re-allocation problem extracted to represent the disaster response phase with specific attention to the human suffering caused by delayed delivery. Vahdani et al. (2018) proposed a two-stage multi-objective integer programming model to address the placement of distribution centers and warehouses with different capacities, decisions related to the commodities stored in warehouses and distribution centers established in the first phase. In the second phase, by considering hard real-time constraints, operational programming was performed for routing and delivering commodities in the damaged areas to increase the total cost, travel time, and route reliability. Then, the multi-objective particle swarm optimization (MOPSO) and non-dominated sorting genetic algorithm II (NSGAII) were employed to solve the problem and evaluate the accuracy of the mathematical model and the efficiency of the proposed algorithms by numerical samples. The results of the algorithms were provided for thirty-five problems.

In another study, Mohammadi et al. (2016) developed a bi-level model for locating the transfer points and distribution centers of relief commodities under earthquakes. Relief facilities and transfer points were located at the first level while routing was performed at the second level for transferring casualties to the predefined places. Further, three scenarios were considered for the faults of Tehran, Iran, including Mosha, Ray, and North Tehran faults, with the probabilities of 0.35, 0.30, and 0.35, respectively. Finally, considering the multi-objective nature of the model, it was solved by using the epsilon-constraint method and GAMS software. According to the results, ten points were selected for establishing transfer points next to highways. Zahiri et al. (2017) developed a multi-level model under uncertainties to program the distribution centers of relief commodities. The uncertainties included the demands and capacities of the facilities, which were considered by using triangular fuzzy numbers. The variables included the inventory level of the warehouses, the flow of commodities from the suppliers to the warehouses, and the flows of commodities from the warehouses to the damaged places. It was observed that the capacities of the suppliers and warehouses were inversely related to the total cost and an increase in the capacities of the suppliers and warehouses decreased the costs in the model. Furthermore, the penalty cost for the unsupplied demand had a significant impact on the system performance such that an increase in the penalties might lead to the coverage of the entire demand points. By considering the demands for blood derivatives such as plasma and platelets as a probabilistic variable, Salehi et al. (2017) introduced a multi-round probabilistic model for designing a blood distribution network after an earthquake. The blood supply chain had three levels of donors, blood collection centers, and blood transfusion centers. The model was proposed at two levels for the pre-earthquake and post-earthquake periods in Tehran. The number of temporary blood collection facilities was determined at the first level while post-earthquake scenarios, including the delivery of blood products, were formed at the second level. Finally, the model was validated by using the Monte Carlo method.

Mahootchi et al. (2017) suggested a bi-level probabilistic model for pre-earthquake and post-earthquake crisis management. Relief centers were located at the first level and then, allocated to the affected areas at the second level. The decision variables included commodity storage and the shortage level of each center. The multi-product multi-round model was validated for probable earthquakes in Tehran. On the other hand, Zokaee et al. (2016) evaluated a tri-level supply chain consisting of suppliers, relief distribution centers, and damaged places, aiming to improve the satisfaction of the affected individuals and reduce costs. To this end, penalties were imposed on the shortage of commodities. The model involved uncertainties in parameters such as demand and cost and was solved by using the robust optimization method. The case study of this research was made in Alborz Province, Iran, as a prone site to natural disasters such as earthquakes. Douglas et al. (2016) introduced a bi-level model for inventory distribution in a disaster relief supply chain, in which the consideration of the location uncertainties was regarded as an innovation of their study.

In their research, the vehicles were considered heterogeneously with different capacities and the case study was carried out in Brazil to demonstrate the efficiency of the model. The case study was solved by a heuristic algorithm. Cavdur et al. (2016) developed a bi-level model for allocating relief commodities to damaged areas under earthquake conditions, to reduce the traveled distance and minimize unsupplied demand. For this purpose, scenarios were defined on the disaster time and environmental conditions such as traffic. The inclusion of a trade-off between demand and supply and the consideration of production operation efficiency were among the innovations of their research. Ultimately, the case study was a possible earthquake in Turkey to implement the model. Xu et al. (2016) located shelters for injured individuals after an earthquake by using mathematical modeling and an electronic system to acquire geographical information. The model was a p-median model whose objectives were maximizing the coverage level and minimizing shelter distance. The proposed algorithm included three steps of 1) selecting candidate shelters, 2) analyzing the coverage of each shelter, and 3) choosing the deterministic locations of the shelters. The implementation of the model on Yangzhou, China, indicated the validity and accuracy of the model. Table 2 summarizes the non-Iranian critical logistic studies. Regarding the above local and foreign studies, the present study seeks to evaluate using relief logistics in natural disaster-induced crises. The necessity of adopting quick decisions and executing operations with limited resources has created knowledge of crisis management. In this respect, it is necessary to model consecutive events, considering the investigations of recent crises across the world. As mentioned, such disasters that occur as consecutive events are introduced as primary and secondary disasters in the crisis management literature, i.e., the occurrence of a disaster in an area causes a secondary disaster in the places affected by the first crisis. For example, the primary disaster of an earthquake, which damages infrastructures such as water distribution facilities, makes possible a secondary disaster such as floods. Thus, it is required to take measures needed for locating, routing, and allocating relief commodity distribution centers, relief centers, shelters, and optimal paths to reach the damaged places. Given the nature of relief in most consecutive disasters and the importance of relief quickness in the relief management procedure, the proposed model attempts to minimize the relief time in both phases of primary and secondary disasters. In the primary disaster, this goal can be achieved through optimally locating facilities to send relief commodities to the damaged places and routing to transfer injured individuals to the medical centers, assuming that a secondary disaster happens following the primary disaster and no relocation exist for establishing the equipment to respond to the secondary disaster. For the secondary disaster, to minimize the relief time and accelerate the transfer of the individuals (whose homes were destroyed) to shelters, the optimal routing is performed to transfer homeless people and maximize the relief coverage for a fairer operation.

## 3. Mathematical model

After natural disasters, speed and presence with relief commodities in the damaged areas are the most important factors to improve the effectiveness of relief measures. Relief speed can also be reflected in factors such as the speed of transferring injured individuals to the medical centers and the homeless to the shelters. The fair coverage of relief in damaged areas is another factor that improves the satisfaction of the affected individuals, especially when disasters such as floods occur and affect a large geographical area. In such cases, it is crucial to provide a balance in the relief commodities in the entire affected areas.

Fig. 1 illustrates a four-level supply chain structure employed to send relief commodities to affected areas. The first level involves the main warehouses of relief commodities, which are either permanent or temporary facilities in predefined numbers and locations. The second level includes temporary facilities in the form of relief commodity distribution centers, shelters, and temporary medical centers. The numbers and potential locations of the temporary facilities are defined before the disaster, among which the best candidates are selected to be activated to minimize the time of transporting relief commodities and transferring injured individuals to the medical centers. The third level consists of the disaster-affected areas. The accurate and definite statistics of the casualties cannot be found immediately after the disaster. Thus, the demands for relief commodities and consequently, for voluntary aid are considered as uncertain parameters. Voluntary aids are sent to the distribution centers. The warehouses have initial inventories of different relief commodities and the governmental aid is also sent to the warehouses at the beginning of the relief period.

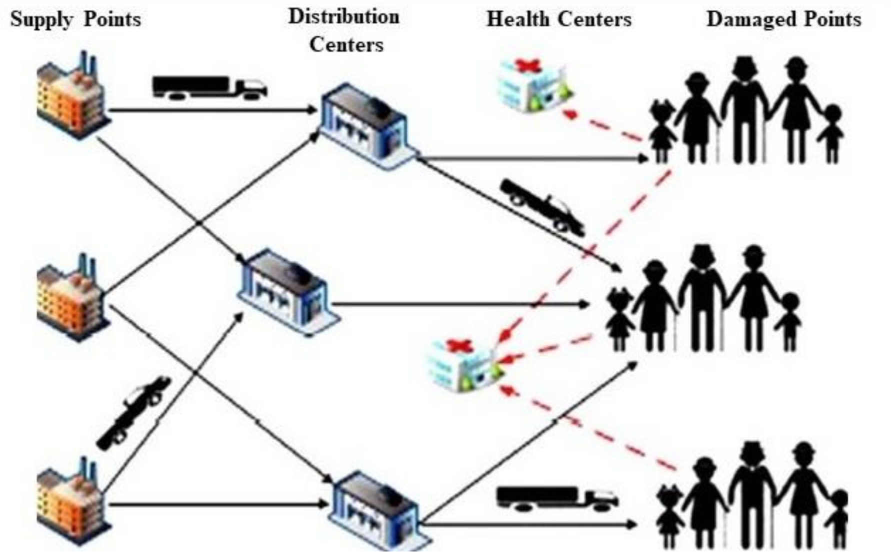

**Figure 1.** Relief Network examined in the study

### 3.1. Modeling assumptions

The assumptions of the model are as follows:

- The numbers and locations of the main warehouses are known and definitive;
- The candidate numbers and locations of temporary distribution centers (i.e., intermediary points), medical centers, and shelters are known and definitive;
- The numbers and locations of the damaged areas are known;
- The supply points (or warehouses) have specific capacities for receiving and sending commodities;
- The intermediary points (or temporary distribution centers), shelters, and temporary medical centers have specific capacities for receiving and sending commodities and injured individuals;
- The network arcs are the routes that connect the supply points to the distribution centers, the distribution centers to the damaged places, the damaged places to the shelters and medical centers, and the supply points to the damaged places;
- A variety of relief commodities is considered;
- The volumes and weights of the commodities are known;
- Each vehicle has a specific transportation capacity;
- Each transportation mode uses its specific paths;
- The roads may become blocked after the disaster;
- The demands of the damaged places are considered as an uncertainty parameter,
- Since primary and secondary disasters may happen, separate schedules are used to respond to the primary and secondary disasters;
- The secondary disaster has a specific probability and may even not occur after the primary disaster in the same place;
- A two-stage disaster happens, and the second stage occurs after the first stage; and
- Injured individuals are divided into two groups, including those who need treatment and those who need shelters.

### 3.2. Defining the mathematical model symbols

**<u>Indexes</u>**

I: the warehouse node,

J: the temporary procurement center node,

K: the node of the damaged place in the primary and secondary disasters,

M: the set of candidate nodes of the temporary medical center,

N: the shelter node,

L: the type of vehicles (i.e., trucks and helicopters),

C: the relief commodity,

D: the type of injury (i.e., injuries classification based on treatment or their transfer to shelters),

S: the scenario in the primary and secondary disasters – two scenarios are considered in the mathematical model, which are the first scenario (an earthquake as the primary disaster and flood as the secondary disaster), and the second scenario (an earthquake as the primary disaster and fire as the secondary disaster).

### Parameters

$P_s$ : the probability of scenario s in the primary and secondary disasters,

$T\delta_{lij}$ : the transfer-shipment time of vehicle L between nodes i and j,

$\delta'_{ljj'}$ : the transfer-shipment time of vehicle L between nodes j and j',

$Tc_{ljk}$ : the transfer-shipment time of vehicle L between nodes j and k,

$Tcc_{lkk'}$ : the transfer-shipment time of vehicle L between nodes k and k',

$U_{knd}$ : the transfer time of injured individuals of type d from demand node k to shelter n in the secondary disaster,

$z_{kmd}$ : the transfer time of injured individuals of type d from demand node k to medical center m in the primary disaster,

$B_0$ : the relief time in the primary disaster,

$B_1$ : the relief time in the secondary disaster,

$dem_{kcs}$ : the demand for commodity c in node k under scenario s,

$capp_{ic}$ : the amount of commodity c that can be supplied by node i,

$o_{kd}$ : the number of injured individuals of type d in node k in the primary and secondary disasters,

$ca_{nd}$ : the capacity of shelter n for receiving injured individuals of type d in the secondary disaster,

$se_{md}$ : the capacity of medical center m for receiving injured individuals of type d in the primary disaster,

$ccap_j$ : the volumetric capacity of temporary procurement center j,

$\beta_{kd}$ : the percentage of injured individuals type d in disaster center k,

$MM$ : is a large number,

### Decision parameters

$Q_{lijcs}$ : the amount of commodity c supplied from I and stored in node i by vehicle l under scenario s,

$Q^1{}_{lijj'cs}$ : the amount of commodity c sent by temporary procurement center j to procurement center j' through vehicle L under scenario s,

$Y_{ljkcs}$ : the amount of commodity c transported by vehicle L from node j to node k under scenario s,

$Y^1{}_{ljk'kcs}$ : the amount of commodity c transported by vehicle L from center k' to center k under scenario s,

$T_{LKs}$ : the arrival time of vehicle L in disaster center k under scenario s,

$X_{kcs}$ : the stored amount of commodity c in node k under scenario s,

$AA_{lkmds}$ : the number of injured individuals type d transferred by vehicle L from node k to medical center m under scenario s,

$A_{lknds}$ : the number of injured individuals type d transferred by vehicle L from node k to shelter n under scenario s,

$b_{kcs}$ : the shortage of commodity c in node k under scenario s,

$e_{kds}$ : the number of the unhandled injuries type d in node k under scenario s

$ZZ_{js}$ : is 1 if a temporary procurement center is established in node j under scenario s, otherwise, it is zero.

$H_{ms}$ : is 1 if a medical center is established in node m under scenario s; otherwise, it is zero.

$D_i^+$ : is the positive deviation from the goal considered by the objective function i

$D_i^-$ : is the negative deviation from the goal considered by the objective function i.

$Hs_{ns}$ : is 1 if shelter n is established under scenario s, otherwise, it is zero.

$X_{lijs}^1$ : is 1 if vehicle L moves from supplier i to temporary procurement center j under scenario s, otherwise it is zero

$X_{lijj's}^2$ : is 1 if vehicle L moves from temporary procurement center j to temporary procurement center j' under scenario s, otherwise it is zero

$X_{ljks}^3$ : is 1 if vehicle L moves from temporary procurement center j to disaster center k under scenario s, otherwise it is zero

$X_{ljkk's}^4$ : is 1 if vehicle L moves from disaster center k to disaster center k' under scenario s; otherwise it is zero.

$X_{lkms}^5$ : is 1 if vehicle L moves from disaster center k to medical center m under scenario s, otherwise it is zero.

$X_{lkns}^6$ : is 1 if vehicle L moves from disaster center k to shelter n under scenario s, otherwise it is zero.

### 3.3. Objective Function

$$MIN\ Z1C = p_s\left(\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n T\delta_{lij} * X_{lijs}^1 + \delta'_{ljj'} * X_{lijjs'}^2 + Tc_{ljk} * X_{ljks}^3 + Tcc_{lkk'} * X_{ljkk's}^4 + U_{knd} * X_{lkns}^6 + z_{kmd} * X_{lkms}^5\right) + D_1^- + D_1^+ \tag{1}$$

$$MIN\ Z2C = p_s(\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n U_{knd} * X_{lkns}^6) + D_2^- + D_2^+$$

The first objective function is the minimization of the scheduling of vehicles routing for the primary disaster response phase and the location of temporary procurement centers in the primary disaster. The second objective function is the least time of transferring injured individuals to the shelters in the secondary disaster.

$$MIN\ C = p_s\left(\sum_{L}\sum_{K} T_{LKs}\right) + D_3^- + D_3^+ \tag{2}$$

This objective function is the minimization of the golden time of relieving and transferring injured individuals to the temporary medical centers in the secondary disaster.

$$MAX\ C = p_s\left(\sum_{i}\sum_{j}\sum_{k}\sum_{l}\sum_{m}\sum_{n} X_{lijs}^{1} + X_{lijj's}^{2} + X_{ljks}^{3} + X_{ljkk's}^{4} + X_{lkns}^{6} + X_{lkms}^{5}\right) + D_4^- + D_4^+ \tag{3}$$

The third objective function is to maximize the coverage of the disaster-affected areas based on vehicle routing, relief commodity transportation, and injured transfer in the secondary disaster.

**Table 1.** Objective functions

| | **Objective function** | **Method** |
|---|---|---|
| Primary disaster | Minimizing the time of transporting relief commodities and transferring injured individuals to the medical centers | Locating temporary procurement centers<br>Locating shelters<br>Locating temporary procurement centers<br>Locating shelters<br>Locating medical centers<br>Optimal routing between warehouses and temporary procurement centers<br>Routing between temporary procurement centers (transfer shipment) |
| Secondary disaster | Minimizing the schedule of transferring injured individuals to the shelters<br>Maximizing the coverage of the disaster-affected areas | Routing the transfer of injured individuals to shelters<br>Allocating temporary warehouses and shelters to disaster centers |

## Constraints

$$\sum_{l}\sum_{j} Q_{lijcs} + \sum_{l}\sum_{j'\neq j}\sum_{J} {Q^1}_{lijj'cs} \leq capp_{ic} \qquad \forall i,c,s \tag{4}$$

Constraint (4) states that the amount of commodities moved between a warehouse and a procurement center should be lower than the capacity of the vehicles.

$$\sum_{l}\sum_{i}\sum_{c} Q_{lijcs} + \sum_{l}\sum_{j'\neq j}\sum_{c}\sum_{i} {Q^1}_{lij'jcs} \leq ccap_j \qquad \forall j,s \tag{5}$$

Constraint (5) determines that the amount of commodities sent to a procurement center should be lower than the available capacity of the procurement center.

$$\sum_{l}\sum_{i} Q_{lijcs} + \sum_{l}\sum_{j'\neq j}\sum_{i} {Q^1}_{lij'jcs} = \sum_{l}\sum_{k} Y_{ljkcs} + \sum_{l}\sum_{k'\neq k}\sum_{K} {Y^1}_{lJkk'cs} \qquad \forall j,c,s \tag{6}$$

Constraint (6) implies that the commodities sent by a warehouse of other procurement centers to a procurement center can be resent to the disaster center, with the surplus commodities being sent to the other procurement centers.

(7)

$$\sum_{l}\sum_{j} Y_{ljkcs} + \sum_{l}\sum_{k1\neq k}\sum_{J} {Y^{1}}_{lJk\prime kcs} = dem_{kcs} + X_{kcs} - b_{kcs} \quad \forall\, k,c,s$$

Constraint (7) states that the demand for the disaster center is either directly supplied by the supply centers (senders) or by the commodities sent to another disaster center. Furthermore, the disaster centers can have the storage or shortage of commodities.

$$\sum_{l}\sum_{m} AA_{lkmds} + e_{kd} = o_{kd} \qquad \forall k,d,s \tag{8}$$

Constraint (8) regulates the transfer of injured individuals in the primary disaster-affected area to medical centers.

$$\sum_{l}\sum_{n} A_{lknds} + e_{kd} = o_{kd} \qquad \forall k,d,s \tag{9}$$

Constraint (9) states that injured individuals in a secondary disaster-affected area or commodity-transporting vehicles can move to shelters.

$$\beta_{kd}\sum_{l}\sum_{m} AA_{lkmds} + (1-\beta_{kd}) * \sum_{l}\sum_{n} A_{lknds} \leq o_{kd} \quad \forall k,d,s \tag{10}$$

Constraint (10) determines the number of injured people.

$$\sum_{l}\sum_{k} AA_{lkmds} \leq se_{md} \qquad \forall\, m,d,s \tag{11}$$

Constraint (11) specifies that the number of injured individuals moved to a medical center should be smaller than the capacity of the medical center.

$$\sum_{l}\sum_{k} A_{lknds} \leq ca_{nd} \qquad \forall n,d,s \tag{12}$$

Constraint (12) controls the number of injured individuals that lost their homes due to the secondary disaster and moved to a shelter center with a capacity smaller than that of the shelter.

$$\sum_{i}\sum_{j}\sum_{k}\sum_{l}\sum_{m}\sum_{n} T\delta_{lij} * X^{1}_{lijs} + {\delta'}_{ljj\prime} * X^{2}_{lijj's} + Tc_{ljk} * X^{3}_{ljks} + Tcc_{lkk'} * X^{4}_{ljkk's} + z_{kmd} * X^{5}_{lkms} \leq B_0 \qquad \forall\, s \tag{13}$$

Constraint (13) states that scheduling before a secondary disaster, in which relief commodities are transferred transversely, should be less than that of the approved time.

$$\sum_{i}\sum_{j}\sum_{k}\sum_{l}\sum_{m}\sum_{n} T\delta_{lij} * X^{1}_{lijs} + {\delta'}_{ljj\prime} * X^{2}_{lijj's} + Tc_{ljk} * X^{3}_{ljks} + Tcc_{lkk'} * X^{4}_{ljkk's} + U_{knd} * X^{6}_{lkns} \leq B_1 \tag{14}$$

Constraint (14) is the schedule constraint in the secondary disaster and states that the transfer-shipment times should be shorter than the scheduled.

$$\sum_{c} Q_{lijcs} \le MM * X^{1}_{lijs} \quad \forall l,i,j,s \tag{15}$$

$$\sum_{c} Q_{lijj'cs} \le MM * X^{2}_{lijj's} \quad \forall l,i,j,j' \neq j,s \tag{16}$$

Constraints (15) and (16) control the relationship between routing and the amount of commodities transported by the suppliers to the temporary procurement centers.

$$\sum_{c} Y_{ljkcs} \le MM * X^{3}_{ljks} \quad \forall l,j,k,s \tag{17}$$

$$\sum_{c} Y^{1}{}_{ljkk'cs} \le MM * X^{4}_{ljkk's} \quad \forall l,j,k,k' \neq k,s \tag{18}$$

Constraints (17) and (18) regulate the relationship between routing and the amount of commodities sent by the procurement centers to the disaster-affected areas.

$$\sum_{j} X^{1}_{lijs} \le 1 \qquad \forall l,i,s \tag{19}$$

Constraint (19) deals with the number of times that a vehicle leaves a supply center and determines that the vehicle can leave the supply center and move to the temporary procurement center only once.

$$\sum_{L} X^{1}_{lijs} + \sum_{j'\neq j}\sum_{L} X^{2}_{lj'js} \le 1 \quad \forall i,j,s \tag{20}$$

$$\sum_{j'\neq j}\sum_{L} X^{2}_{lijj's} \le 1 \quad \forall i,j,s$$

Constraint (17) limits the times of entering a procurement center.

$$\sum_{i}\sum_{l} X^{1}_{lijs} + \sum_{i}\sum_{j'\neq j}\sum_{l} X^{2}_{lij'js} = \sum_{k}\sum_{l} X^{3}_{ljks} + \sum_{i}\sum_{j'\neq j}\sum_{l} X^{2}_{lijj's} \quad \forall j,s \tag{21}$$

Constraint (21) explains that the times of entering a procurement center should be the same as the times of leaving the procurement center since the temporary procurement centers do not keep vehicles.

$$\sum_{k} X^{3}_{ljks} \le 1 \quad \forall l,j,s \tag{22}$$

Constraint (22) limits the times a vehicle enters the disaster center

$$\sum_{i}\sum_{l} X_{lijs}^{1} + \sum_{i}\sum_{j' \neq j}\sum_{l} X_{lij'js}^{2} = ZZ_j \qquad \forall j, s \tag{23}$$

Constraint (23) controls the establishment of temporary procurement centers.

$$\sum_{l}\sum_{k}\sum_{d} AA_{lkmds} \leq MM * H_{ms} \qquad \forall m, s \tag{24}$$

Constraint (24) controls the establishment of temporary medical centers.

$$\sum_{i} X_{lijs}^{1} \geq \sum_{i}\sum_{j' \neq j} X_{lijj's}^{2} \qquad \forall j, l, s \tag{25}$$

Constraint (25) necessitates routing at the beginning between suppliers and temporary procurement centers.

$$\sum_{j} X_{ljks}^{3} \geq \sum_{j}\sum_{k' \neq k} X_{ljkk's}^{4} \quad \forall l, K, s \tag{26}$$

Constraint (23) necessitates routing at the beginning between temporary distribution centers and the damaged areas.

$$\textstyle\sum_{d} AA_{lkmds} \leq MM * X_{lkms}^{5} \qquad \forall l, k, m, s \tag{27}$$

Constraint (27) deals with routing between the disaster center and medical centers.

$$\sum_{d} A_{lknds} \leq MM * X_{lkns}^{6} \qquad \forall l, k, n, s \tag{28}$$

$$\sum_{l}\sum_{k}\sum_{d} A_{lknds} \leq MM * Hs_{ns} \qquad \forall n, s$$

Constraint (28) controls routing between the disaster center and shelters and the establishment of shelter centers.

$$\begin{gathered} T_{LK} \leq \sum_{I}\sum_{J}\sum_{C} T\delta_{lijc} * X_{lijs}^{1} + \sum_{J}\sum_{C} Tc_{ljkc} * X_{ljks}^{3} + \sum_{K' \neq K}\sum_{J}\sum_{C} Tcc_{lk'Kc} * X_{ljk'ks}^{4} \\ T_{LK} \leq 48 \end{gathered} \tag{29}$$

Constraint (29) schedules the transportation of commodities to the disaster center and determines that the golden hour should be shorter than 24 hours.

According to Inuiguchi and Ramık (2000), the above model can be rewritten as

$$
\begin{array}{ll}
\mathrm{Min}\ \mathrm{Z} = \mathrm{f.y} + \left(\dfrac{\mathrm{c}_{(1)} + \mathrm{c}_{(2)} + \mathrm{c}_{(3)} + \mathrm{c}_{(4)}}{4}\right).\mathrm{x} & \\
\mathrm{A.x} \geq (1 - \alpha_{\mathrm{m}}).\mathrm{d}_{(1)} + \alpha_{\mathrm{m}}.\mathrm{d}_{(2)} & \forall \mathrm{m} \\
\mathrm{B.x} = 0 & \\
\mathrm{s.x} \leq \mathrm{N.y} & \\
0.5 \leq \alpha_{\mathrm{m}} \leq 1 & \\
\mathrm{x} \geq 0 & \forall \mathrm{m} \\
\mathrm{y} \in \{0,1\} &
\end{array}
\tag{30}
$$

Considering the proposed method, the mathematical model was considered as fuzzy in the demand section. Thus, the demand constraint is modified as follows:

$$
\sum_{l}\sum_{j} Y_{ljkcs} + \sum_{l}\sum_{k1\neq k}\sum_{J} Y^{1}{}_{lJk\prime kcs} \geq (1-\alpha)\ dem_{kcs(1)} + \alpha.dem_{kcs(2)} + X_{kcs} - \ b_{kcs}\ \forall\ k,c,s
\tag{31}
$$

$$
\sum_{l}\sum_{j} Y_{ljkcs} + \sum_{l}\sum_{k1\neq k}\sum_{J} Y^{1}{}_{lJk\prime kcs} \leq (1-\alpha)\ dem_{kcs(4)} + \alpha.dem_{kcs(3)} + X_{kcs} - \ b_{kcs}\ \forall\ k,c,s
$$

## 4 Findings

Relief logistics and crisis management are important in the sense that the disaster response phase in crisis management should be performed in the shortest amount of time. According to previous evaluations, the occurrence of primary disasters intensifies secondary disasters such that the higher the delay of responses to the primary disaster, the greater the destructive effects of secondary disasters on the disaster-affected areas. By considering primary and secondary disasters, humanitarian logistics are essentially discussed at four levels: 1) the warehouses of relief commodities, 2) temporary procurement centers for supporting the logistic procedure of sending relief commodities to the disaster-affected areas in both primary and secondary disasters and those that require effective and timely relief, 3) medical centers that are responsible for treating injured individuals in the primary disaster, and 4) shelter centers that are responsible for handling injured individuals in the secondary disaster. Regarding the two-phase occurrence process of disasters in the evaluation (i.e., primary and secondary phases), land and air transportation were employed depending on the volume and number of transportable relief commodities and the cost and schedule of transportation. Two possible scenarios were incorporated:an earthquake was predicted in the first scenario and the second scenario was either flood or fire as the secondary disaster. Then, the essential constraints of the transportation capacity and golden hour were applied to the transportation equipment. Also, a multi-criteria mathematical model was developed in which the first objective function was to schedule routing vehicles for the disaster response phase. This evaluation seeks to minimize the shipment time of relief commodities and relief service to injured people and their transfer to the temporary treatment centers. The second objective function is to minimize the golden hour, with the upper bound of 48 hours. The third objective function is to minimize routing in the secondary disaster and to transfer injuries to pre-determined shelters. Generally, natural disasters are so complicated that humans have failed to predict such events, despite deploying numerous preventive methods in the form of globally structured networks and continuously analyzing data by powerful computers. This section analyzes the results.

**Inputs**

To validate the proposed model, an example with random data was evaluated. The main parameters included

i) The transfer-shipment time of vehicle *L* between warehouse *i* to node *j* (in min)

**Table 2.** The transfer-shipment time between a warehouse and an intermediary node

| | **J1** | **J2** | **J3** | **J4** |
|---|---|---|---|---|
| **L1.S1** | 12 | 15 | 15 | 14 |
| **L1.S2** | 13 | 14 | 15 | 12 |
| **L1.S3** | 12 | 13 | 13 | 15 |
| **L2.S1** | 14 | 12 | 13 | 14 |
| **L2.S2** | 14 | 12 | 13 | 14 |
| **L2.S3** | 15 | 13 | 14 | 12 |
| **l3.S1** | 14 | 12 | 15 | 14 |
| **l3.S2** | 14 | 13 | 13 | 12 |
| **l3.S3** | 13 | 13 | 13 | 14 |
| **l4.S1** | 12 | 15 | 13 | 13 |
| **l4.S2** | 14 | 13 | 13 | 12 |
| **l4.S3** | 12 | 14 | 14 | 13 |

This parameter represents the transfer-shipment time from a supplier to a procurement center, which occurs in the primary disaster scenario and transports relief commodities to procurement centers according to the demand volume.

ii) The transfer-shipment time of vehicle *L* between nodes *j* and *j'* (in min)

**Table 3.** The transfer-shipment time between nodes *j* and *j'*

| | **J1** | **J2** | **J3** | **J4** |
|---|---|---|---|---|
| **L1.J1** | | 8 | 10 | 10 |
| **L1.J2** | 8 | | 11 | 8 |
| **L1.J3** | 11 | 9 | | 10 |
| **L1.J4** | 13 | 11 | 11 | |
| **L2.J1** | | 10 | 12 | 12 |
| **L2.J2** | 13 | | 9 | 13 |
| **L2.J3** | 9 | 11 | | 10 |
| **L2.J4** | 11 | 9 | 11 | |
| **l3.J1** | | 9 | 11 | 13 |
| **l3.J2** | 9 | | 13 | 9 |
| **l3.J3** | 9 | 10 | | 13 |
| **l3.J4** | 10 | 12 | 9 | |
| **l4.J1** | | 9 | 11 | 8 |
| **l4.J2** | 12 | | 11 | 10 |
| **l4.J3** | 11 | 10 | | 10 |
| **l4.J4** | 11 | 11 | 10 | |

Table 3 shows the transfer-shipmen time for procurement management in the primary disaster. This procedure continued after the secondary disaster. Indeed, the inventory of a procurement center is higher than that of the disaster-affected areas in the primary disaster. Therefore, in the secondary disaster, the inventories of the temporary procurement centers are moved between the procurement centers to reduce the handling time of the disaster phase. As a result, relief commodities are delivered to the disaster-affected areas in the secondary disaster phase in a shorter amount of time.

iii) The transfer-shipment time of vehicle *L* between nodes *j* and *k* (in min)

**Table 4.** The transfer-shipment time of vehicle *L* between node *j* and node *k*

| | **K1** | **K2** | **K3** |
|---|---|---|---|
| **L1.J1** | 7 | 9 | 9 |
| **L1.J2** | 5 | 10 | 7 |
| **L1.J3** | 8 | 11 | 11 |
| **L1.J4** | 6 | 5 | 11 |
| **L2.J1** | 12 | 9 | 6 |
| **L2.J2** | 11 | 10 | 6 |
| **L2.J3** | 9 | 11 | 5 |
| **L2.J4** | 9 | 12 | 9 |
| **l3.J1** | 7 | 9 | 10 |
| **l3.J2** | 8 | 12 | 11 |
| **l3.J3** | 7 | 6 | 6 |
| **l3.J4** | 7 | 8 | 10 |
| **l4.J1** | 6 | 8 | 11 |
| **l4.J2** | 9 | 9 | 5 |
| **l4.J3** | 11 | 8 | 9 |
| **l4.J4** | 10 | 6 | 11 |

This parameter is adjusted in the primary and secondary disaster conditions, both of which have the same transfer-shipment time because of the same transportation distance. Road (trucks) and air (helicopters and quadcopters) vehicles were incorporated. Table 5 describes the transfer-shipment times.

iv) The transfer-shipment time of vehicle *L* between nodes *k* and *k'* (in min)

**Table 5.** The transfer-shipment time between nodes *k* and *k'*

| | **K1** | **K2** | **K3** |
|---|---|---|---|
| **L1.K1** | 6 | 4 | 4 |
| **L1.K2** | 6 | 7 | 5 |
| **L1.K3** | 6 | 4 | 7 |
| **L2.K1** | 7 | 4 | 5 |
| **L2.K2** | 5 | 6 | 5 |
| **L2.K3** | 6 | 6 | 5 |
| **l3.K1** | 5 | 4 | 4 |
| **l3.K2** | 6 | 5 | 6 |
| **l3.K3** | 7 | 4 | 5 |
| **l4.K1** | 5 | 5 | 5 |
| **l4.K2** | 6 | 6 | 6 |
| **l4.K3** | 6 | 6 | 6 |

Based on the definition of transfer-shipment between disaster-affected nodes, commodities are shared in the primary and secondary disasters. Table 6 describes this parameter.

v) The transfer-shipment time of injured individuals type d from demand node k to shelter n in the secondary disaster (in min)

**Table 6.** The transfer-shipment time of an injured individual type d from demand node k to shelter n in the secondary disaster

| | D1 | D2 |
|---|---|---|
| **K1.N1** | 15 | 13 |
| **K1.N2** | 13 | 15 |
| **K2.N1** | 12 | 14 |
| **K2.N2** | 14 | 15 |
| **K3.N1** | 14 | 14 |
| **K3.N2** | 13 | 15 |

In the primary disaster, it was assumed that the injured people needed medical care. Additionally, the time of transferring the injured people to temporary medical centers is introduced in this parameter

vi) The transfer-shipment time of injured individuals of type d from demand node k to medical center m in the primary disaster

**Table 7.** The transfer-shipment time of injured individuals of type d from demand node k to medical center m in the primary disaster

| | D1 | D2 |
|---|---|---|
| **K1.M1** | 14 | 13 |
| **K1.M2** | 14 | 15 |
| **K2.M1** | 13 | 12 |
| **K2.M2** | 14 | 12 |
| **K3.M1** | 15 | 13 |
| **K3.M2** | 15 | 15 |

In the primary disaster, two types of injury are assumed: 1) injury m1 in the primary disaster when injured individuals require medical care and 2) injury m2 in the secondary disaster when individuals need shelters.

vii) The demand for commodity *c* in node *k* under scenario *s*

**Table 8.** Demand for commodity *c* in node *k* under scenario *s* (ϴ-1)

| | SS1 | SS2 |
|---|---|---|
| **K1.C1** | 32 | 63 |
| **K1.C2** | 74 | 42 |
| **K1.C3** | 44 | 67 |
| **K2.C1** | 54 | 79 |
| **K2.C2** | 39 | 36 |
| **K2.C3** | 50 | 66 |
| **K3.C1** | 68 | 54 |
| **K3.C2** | 76 | 57 |
| **K3.C3** | 66 | 48 |

viii) Table 9 introduces the demands of disaster-affected areas in two primary disaster conditions.

**Table 9**. The demand for commodity c in node k under scenario s (ϴ-2)

| | SS1 | SS2 |
|---|---|---|
| **K1.C1** | 89 | 81 |
| **K1.C2** | 89 | 97 |
| **K1.C3** | 83 | 90 |
| **K2.C1** | 99 | 86 |
| **K2.C2** | 92 | 99 |
| **K2.C3** | 88 | 91 |
| **K3.C1** | 99 | 91 |
| **K3.C2** | 87 | 92 |
| **K3.C3** | 98 | 93 |

ix) Table 10 describes the demands of disaster-affected areas in two primary disaster conditions.

**Table 10**. The demands of disaster-affected areas in two primary disaster conditions (Ɵ-3)

| | **SS1** | **SS2** |
|---|---|---|
| **K1.C1** | 117 | 117 |
| **K1.C2** | 126 | 136 |
| **K1.C3** | 109 | 137 |
| **K2.C1** | 101 | 128 |
| **K2.C2** | 123 | 120 |
| **K2.C3** | 121 | 102 |
| **K3.C1** | 132 | 101 |
| **K3.C2** | 113 | 129 |
| **K3.C3** | 102 | 125 |

**Table 11.** The demands of disaster-affected areas in two primary disaster conditions (Ɵ-4)

| | **SS1** | **SS2** |
|---|---|---|
| **K1.C1** | 148 | 160 |
| **K1.C2** | 168 | 168 |
| **K1.C3** | 173 | 162 |
| **K2.C1** | 179 | 161 |
| **K2.C2** | 167 | 159 |
| **K2.C3** | 176 | 171 |
| **K3.C1** | 176 | 143 |
| **K3.C2** | 170 | 156 |
| **K3.C3** | 144 | 157 |

Table 11 presents the demands of disaster-affected areas in two secondary disaster conditions. The collected data were classified into two groups of primary and secondary disasters, including disasters such as floods, earthquakes, fire, and storms. Reviewing twenty recent disasters in previous studies indicated that 70% of the total disasters were primary, 30% of which have led to secondary disasters, and accordingly, the probabilities of the scenarios were adjusted. Considering the goals in the validation of the mathematical model, the results of the objective functions and goal deviation were obtained as

**Table 12.** The results of the fuzzy goal programming model

| **Deviation from the second objective function** | **Deviation from the first objective function** | **The ideal objective function** | **The goal of the objective function in the secondary crisis** | **The goal of the objective function in the initial crisis** |
|---|---|---|---|---|
| ٠ | 8/104 | 8/104 | 700 min | **1200 min** |

According to Table 12, relief was provided to the entire areas in 1200 min in the primary disaster, showing a goal deviation of 8104 min. Also, a relief schedule of 7000 min was adjusted for the secondary disaster, on which relief was provided to the entire areas affected by the secondary disaster.

## Evaluating the mathematical model by the NSGAII algorithm

The efficiency of metaheuristic algorithms is directly related to the adjustment of parameters and their operators so that an incorrect selection of parameters for a metaheuristic algorithm leads to an inefficient response. There are various methods for adjusting the parameters of an algorithm, including Taguchi methods, most of which are empirical. This study sets parameters such that the optimal Pareto solution could be obtained based on the performance evaluation criteria. To this end, different values of parameters were examined for different parameters, and then, the results were compared to obtain a good empirical adjustment of the algorithm parameters for different problems. Table 13 shows the adjustment of the algorithm parameters.

**Table 13.** The adjustment of the parameters

| **Problem size** | **Cr(1)** | **Cr(2)** | **Elitism** | **Mr** | **Population size** | **Number of generation** |
|---|---|---|---|---|---|---|
| **S** | 0.425 | 0.425 | 0.1 | 0.05 | 50 | **30** |
| **M** | 0.42 | 0.42 | 0.1 | 0.06 | 150 | **100** |
| **L** | 0.415 | 0.415 | 0.1 | 0.07 | 200 | **150** |

To investigate sample problems at different scales, the mean evaluation indexes are calculated for each numerical example by implementing the NSGAII algorithm for five times. Consequently, the results were compared to those of ideal goal programming by using the same criteria. It should be noted that this comparison is significant for small- and sometimes medium-scale problems since goal programming are inefficient for large-scale problems and fail to accurately solve the problem.

Table 14 reports the performance criteria for NSGAII and goal programming for the set of examples.

**Table 14.** The evaluation results of performance indexes for the two proposed algorithms

| **Test number** | **Size problem** | | | **GP** | | | | **NSGAll** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **k** | **j** | **Size** | **Cpu time** | **Nons** | **Domain** | **Quqlity** | **Cpu time** | **Nons** | **Domain** | **Quality** |
| **1** | 4 | 2 | S | 960’’ | 2 | 3 | 0.5 | 2’’ | 2 | 3 | 0.5 |
| **2** | 4 | 3 | S | 80 | 2 | 17 | 0.5 | 5 | 2 | 17 | 0.5 |
| **3** | 5 | 2 | S | 420 | 3 | 4 | 0.5 | 10 | 3 | 4 | 0.5 |
| **4** | 5 | 3 | S | 780 | 2 | 16 | 0.5 | 5 | 2 | 16 | 0.5 |
| **5** | 6 | 2 | S | 960 | 3 | 5 | 0.5 | 20 | 3 | 5 | 0.5 |
| **6** | 6 | 3 | S | 900 | 2 | 3 | 0.5 | 4 | 2 | 3 | 0.5 |
| **7** | 7 | 2 | S | 720 | 3 | 7 | 0.5 | 10 | 3 | 7 | 0.5 |
| **8** | 7 | 3 | S | 1740 | 2 | 8 | 0.83 | 25 | 3 | 12 | 0.17 |
| **9** | 8 | 2 | M | 2520 | 1 | 0 | 1 | 20 | 3 | 9 | 0 |
| **10** | 8 | 3 | M | 5400 | 4 | 18 | 0.58 | 50 | 3 | 11 | 0.42 |
| **11** | 10 | 2 | M | 3060 | 1 | 0 | 1 | 135 | 6 | 16 | 0 |
| **12** | 10 | 3 | M | Inf | 0 | 0 | 0 | 80 | 3 | 10 | 1 |
| **13** | 15 | 3 | M | Inf | 0 | 0 | 0 | 13 | 3 | 10 | 1 |
| **14** | 20 | 3 | M | Inf | 0 | 0 | 0 | 12 | 4 | 14 | 1 |
| **15** | 30 | 3 | M | Inf | 0 | 0 | 0 | 244 | 4 | 14 | 1 |
| **16** | 50 | 5 | L | Inf | 0 | 0 | 0 | 860 | 4 | 9 | 1 |
| **17** | 70 | 5 | L | Inf | 0 | 0 | 0 | 1356 | 5 | 20 | 1 |
| **18** | 100 | 5 | L | Inf | 0 | 0 | 0 | 1930 | 6 | 10 | 1 |

The quality variation results of the proposed methods indicate that

1) The NSGAII and goal programming algorithms yielded the same results for the small-scale problems – the quality evaluation index was obtained 0.5 for both algorithms.
2) The performance of the NSGAII algorithm was somewhat lower than that of the epsilon-constraint method for the medium-scale problems. Since the NSGAII algorithm is approximate, it is rational that its results are less accurate than those of accurate counting methods such as goal programming, and
3) Since goal programming fails to yield results in a rational time for large-scale problems, the results of the NSGAII algorithm are acceptable for decision-makers.

## 6 Conclusion and future work suggestions

Natural disasters such as earthquakes, floods, storms, and drought occur every year across the world. These natural disasters impose casualties and costs. Since such disasters are often large, relief demand is highly uncertain, and relief centers that supply requirements in normal conditions cannot supply demands on time in disaster conditions. Thus, the present study proposed a fuzzy goal programming model to evaluate relief in primary and secondary disasters. Finally, the proposed model was validated by using the goal programming approach and NSGAII metaheuristic algorithm. The results indicated that the two algorithms had a satisfactory performance for crisis management and improved the relief procedure.

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