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A Multi-Objective Location-Routing Problem Model for Multi-Device Relief Logistics under Uncertainty Using Meta-Heuristic Algorithm

Adel Pourghader Chobar[1,*], Majid Sabk Ara[2], Samaneh Moradi Pirbalouti[3], Mehdi Khadem[4], Saeed Bahrami[5]

[1] Department of Industrial Engineering, Faculty of Industrial and Mechanical Engineering, Qazvin Branch, Islamic Azad University, Qazvin, Iran; apourghader@qiau.ac.ir.

[2] Faculty Member in Guilan ACECR, Educational Member in Guilan UAST, Guilan, Iran; Majid.sabkara@gmail.com.

[3] Department of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran; Samaneh_moradi@ut.ac.ir.

[4] Department of Industrial Management, Faculty of Management and Economics, Science and Research Branch, Islamic Azad University, Tehran, Iran; info.khadem@gmail.com.

[5] Department of Computer Science, Farhangian University, Tehran, Iran; Sae_bahrami@yahoo.com.

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Abstract

During natural and abnormal accidents, many people are injured, and a large number of wastes and rubbish are produced, so it is necessary to collect the injured and take them to treatment centers, which must be done in the reaction phase. Also, in the recovery and reconstruction phase, since a large amount of hazardous and non-hazardous waste is produced during accidents, effective measures should be taken to collect and recycle them if necessary. Both of these cases can be considered as a reverse logistics problem. This paper investigates reverse logistics planning in the response, improvement, and reconstruction phases in earthquake conditions. Due to the nature of the problem, it is expected that we will face a multi-objective problem, and the problem condition causes the issue of uncertainty. By increasing the dimensions of the problem, the NSGA-II meta-heuristic algorithm has been used to solve the two-objective model of the problem and the result indicates that the proposed solution algorithm works well and the quality of the answer and its solution time are appropriate. The results indicate that as capacity increases, the number of distribution centers built to meet demand decreases and the distribution center constructed may be far from some shelters, leading to increased transportation costs. According to the mentioned issues, this research uses reverse logistics in the response and recovery phases. Also, information about Tehran city will be used as data for the case study.

Keywords: Routing, Location, Crisis relief, Reverse logistics, Response phase.

1 | Introduction

One of the issues in crisis management, especially in the field of emergencies, is the optimal location to accommodate citizens in the face of or after an accident. One of the most important issues that are considered by the responsible organizations in the field of crisis management after the occurrence of unexpected events is the selection of a suitable and safe place for the establishment of disaster-affected populations [1]. Since a large number of people are injured during natural and abnormal accidents, and a large number of wastes are produced, it is necessary to plan to collect the injured and take them to treatment centers, which must be done in the reaction phase [2], [3]. Also, in the recovery and reconstruction phase, because a large amount of hazardous and non-hazardous waste is produced during accidents, efficient measures should be taken to collect and recycle them. The cases can be considered a reverse logistics problem [4]. Crisis management can be defined as a rule

Corresponding Author: apourghader@qiau.ac.ir

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of thumb to prevent or address the potential risks of any natural or unnatural crisis [5]. According to global statistics published during the last 7-8 years, the Islamic Republic of Iran is ranked seventh among the top 10 accident-prone countries in the world, which is a high-risk country. According to published reports, in the last two decades, nearly 10% of the total population of Iran has been killed, damaged, or injured as a result of natural disasters [6], [7]. One of the effective ways to reduce financial costs and casualties caused by crises is to determine suitable locations for constructing temporary medical centers and temporary accommodation centers in the crisis. Also, effective plans for allocating different aid networks should be considered [8], [9], [10].

Therefore, the efficient location and allocation of temporary medical and accommodation centers can reduce health and financial risks [11]. Any failure in these actions will significantly increase the losses. This paper will investigate the problem of reverse logistics planning in response, improvement, and reconstruction phases in earthquake conditions. Due to the nature of the problem, it is expected that we will face a multi-objective problem, and the problem situation raises the issue of uncertainty. Because of the mentioned issues, the article's subject is to use reverse logistics in the response and recovery phases. Also, information about Tehran city will be used as data for the case study. This article is presented in 7 sections. In the Sections 1 and 2, the introduction and literature review are mentioned. The problem statement and mathematical modeling are described in the Sections 3 and 4. We present a numerical example and a case study in the Sections 5 and 6. Finally, in the Section 7, the conclusion is presented.

2 | Literature Review

Ghasemi and Khalili-Damghani [12] have proposed a sustainable mathematical model for locating distribution centers, controlling the stock of relief goods, and allocating centers to hospitals in earthquake conditions. Estimating the demand for relief goods through computer simulation and interactive design of basic urban infrastructure is one of their innovations. The simulation-optimization model is solved using sustainable optimization. The case study was considered in Tehran. The results indicate the proper performance of the proposed model. Goli et al. [13] have investigated a robust multi-stage production planning problem based on different scenarios under uncertain seasonal demand. The main objectives are to minimize total costs, including domestic production, outsourcing, labor, maintenance, shortages and employment/unemployment costs, and to maximize customer satisfaction. To deal with demand uncertainty, a robust optimization method has been used for the proposed mixed integer linear programming model. Then a goal programming method is implemented to counter the multi-purpose goal and validate the proposed robust model. The results obtained from different comparison criteria show the high quality of the proposed solution methods in terms of speed and accuracy in finding the optimal solution. Alizadeh et al. [14], presented a multi-period model for locating relief facilities in natural crises. The main purpose of their research is to maximize the coverage of hospitals and distribution centers. The Lagrange approach has been used to solve the proposed model. The results of the case

Study indicate that increasing demand reduces the level of coverage in the regions. Alinaghian et al. [15] located and allocated crisis relief centers in the pre-and post-earthquake conditions. Consideration of temporary relief centers to prevent crowding of the injured is one of the innovations of this research. To solve the proposed model, the harmonic algorithm, the Tabu search, and the neighborhood search have been used. Numerous numerical examples solved with sustainable optimization show the proper performance of the proposed model. Manopiniwes and Irohara [16] have proposed a mathematical model for locating temporary relief centers in flood conditions. The primary purpose of the research is to minimize supply chain costs such as location and transportation. Therefore, the proposed model is considered as a multi-period to be considered in different periods of demand. The consideration of several modes of transportation is one of the innovations. The results of solving the case study problem indicate the proper performance of the proposed model. Goli et al. [17] hackers designed a fuzzy Mixed Linear Programming (MILP) model for the Cell Formation Problem (CFP), which involves scheduling parts within cells in a Cell Production System (CMS) that includes several Automated Guidance Vehicles (AVG) are responsible for it. This paper attempts to investigate the role of AGVs and human factors as essential components of automation systems in cell formation and component scheduling under fuzzy processing time. The proposed objective function involves minimizing the length of time and intercellular movements of the components. Experimental results show that our proposed algorithms have high performance in terms of efficiency and computational accuracy compared to CPLEX and two other well-known algorithms, namely Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO).

Dunn and Gonzalez-Otalora [18] developed an adaptive algorithm to increase resilience, location, and allocation of relief stations in flood conditions. Considering probabilistic uncertainty and reliability for the centers are among their innovations. ArcGIS software has also been used to locate the centers. The primary purpose of the research is to minimize the costs of the whole system, including location costs. The proposed system has been solved for various examples, and the performance of results has been satisfactory. Cavdur et al. [19] proposed new strategies for distributing relief goods and human resources in terms of crisis. Therefore, a probabilistic two-level model for locating and allocating temporary relief centers is presented. The first level is the pre-crisis phase, and the second level is the post-crisis phase. Minimizing the total costs is done in the first phase, and allocating resources to centers is conducted in the second phase. The sensitivity analysis results of the case study indicate that with increasing demand, allocation costs increase sharply. Ejlali et al. [20] have studied the response phase of the disaster management cycle. To do this, they have proposed an integrated multi-purpose model for the provision of a three-tier relief cycle under uncertainty and periodically. In this model, inventory transfer, vehicle routing, distribution and delivery of relief goods are modeled periodically. In addition, in order to solve the proposed mathematical model, a super-innovative particle swarm algorithm in combination with a variable neighborhood search based on the Pareto Archive is proposed. The results show that compared to the genetic algorithm, the particle swarm algorithm is able to generate integrated, qualified and more dispersed responses. In addition, the results show that the solving time of the genetic algorithm was less than the proposed algorithm.

Zhan et al. [21] proposed a mathematical model for locating and allocating relief stations in terms of supply and demand uncertainty. One of the main goals of the research is to minimize the shortage and unsatisfied demand. The case study is considered for Zhengyang Province in southern China. The PSO approach has been employed to solve the proposed model. The results show that with an increase in the number of suppliers, the amount of unsatisfied demand decreases. Noyan and Kahvecioğlu [22] presented a probabilistic mathematical model for locating and allocating distribution centers to post-crisis relief resources. Consideration of justice in crisis relief, budget constraints, and availability of resources in a multi-level supply chain are among the innovations of this research. The Branch-and-cut algorithm is applied to solve the proposed problem. Also, validating the proposed model for the 2011 earthquake in Turkey is tested. Habibi-Kouchaksaraei et al. [23] presented a robust multi-objective model for locating blood centers and hospitals in the case of a crisis. The main purpose of this study is to determine the optimal number of facilities and their allocation strategy under different scenarios. The proposed model has been solved by ideal planning. Also, Ghaemshahr city has been selected as a case study to show the accuracy of the model performance. Maharjan and Hanaoka [24] presented a multi-objective mathematical model for locating temporary hubs in earthquake conditions. The purpose of this study is to minimize costs and unsatisfied demand for injured people. A fuzzy weighting strategy has been employed, and the case study of the 2015 Nepal Earthquake is considered.

The problem of location and routing is also one of the issues that have been recently proposed in the field of accidents [25]. They designed a heuristic method to solve the problem while presenting a metaheuristic method based on a genetic algorithm [26]. Cao et al. [27] have developed a decision-making problem for relief agencies to prepare emergency flood logistics in a multi-device situation. In this research, the flood logistics problem is modeled as stochastic programming. So four types of supporting activities are considered, and all network nodes are divided into five groups. Rath and Gutjahr [28] analyzes the transportation of large volumes of goods efficiently to minimize death with several means of transport (multimodal mode) for relief operations. They examined and located central warehouses to minimize shipping costs. Finally, the path to crisis relief is examined through routing approaches. Fetter and Rakes [29] conducted a study on post-accident waste recycling, concluding that large volumes of waste are produced after an accident. They developed a model for the optimization of recycling and waste disposal sites. Özdamar and Demir [30] presented a model in which relief supplies are sent to the damaged areas, and the injured people are released and transferred to the hospital. Brown et al. [31] discussed waste management, addressing various aspects such as temporary storage sites, recycling, disposal, and social health and economic issues.

By studying the relevant research, we can understand:

– *Because of our problem's nature and the uncertainty in the real-world data, a limited number of papers have considered uncertainty in their problems. So, we can consider uncertainty in the research, especially the fuzzy method.*
– *Using case studies and actual data: Since the application of real problems can be a good measure for its efficiency, applying the proposed model can contribute to the research process.*
– *Another important contribution is the solution method, which due to the problem models, employing heuristic and meta-heuristic methods seems necessary.*

3 | Problem Statement

This research presents an integrated model in two phases of preparation and response for location, allocation, and routing in crisis relief logistics. The occurrence of crisis is also one reason that makes the uncertainty of the model more necessary. The uncertainty considered in this paper is scenario-based and will be done based on various optimization scenarios. These scenarios can vary depending on the time of the earthquake or the severity and weakness of the earthquake. In this paper, the problem of reverse logistics planning in response, improvement, and reconstruction phases in earthquake conditions will be investigated. Due to the nature of the problem, it is expected that we will face a multi-objective problem. Also, the prevailing conditions of the problem raise the importance of uncertainty, in which case the problem is debatable both under data certainty and uncertainty. According to the mentioned issues, the paper's subject is to use reverse logistics in the response and recovery phase.

In order to prepare for disasters, in the pre-crisis preparation phase, vulnerable areas are identified, and a number of shelters for the emergency departure of victims and several distribution centers are built to transport relief goods in terms of crisis. Determining the optimal location and capacity of these facilities requires information on the crisis. Since the crisis has not yet occurred, the required information should be estimated by predicting the situation after the accident, using experts' opinions, and reviewing events.

That have occurred in the past. The proposed network includes damaged areas, shelters, distribution centers, hospitals, and waste collection centers. The proposed model includes two phases of pre-crisis preparation and crisis response. Since before the crisis, information on the demand while the accident is not available, in the first place, the location and capacity of shelters and distribution centers are defined. In the second place, the allocation of hospitals to the damaged areas, damaged areas to the shelters, damaged areas to the waste collection centers, disaster areas to the hospitals are determined. Then, the distribution of relief goods from the distribution centers to the shelters and the selection of the optimal routes to evacuate the earthquake victims are conducted.

Since there are many uncertainties at the time of crisis, the model is considered under uncertainty to be more in line with real-world conditions. The definition of different scenarios illustrates this uncertainty. One of the uncertain parameters is supply (including the capacity of hospitals to receive the injured and relief personnel to be sent from each hospital). The other uncertain parameter is demand (including the number of relief personnel needed in each accident area, the number of injured in need of hospital services in each damaged area, healthy earthquake-damaged population, and outpatients injured need to be evacuated in each damaged area, and the number of corpses needed to be evacuated in the damaged area).

Also, the probability of routes' availability to evacuate earthquake victims is considered uncertain. Because it is possible to destroy parts of the hospitals' capacity and infrastructures such as roads due to the crisis. Uncertainty in demand can also be affected by the severity of the accident. The model is multi-objective, multi-commodity, multi-period, multi-device, and multi-capacity. Research contributions are as follows:

I. This research aims to include different sections of the relief logistics network involved in crisis relief operations. So, the proposed model includes accident areas, distribution centers, shelters, burial centers, and hospitals. Considering more levels in the relief chain makes the model more integrated, closer to the real world, and more practical.
II. In the real world, problem parameters are time-dependent and dynamic; however, many studies consider their planning horizon to be single-period rather than multi-period. In this research, the model is considered in several periods.
III. Many research formulated their problem on the assumption of a single commodity. However, in a crisis, we are faced with several essential goods that need to be distributed, such as drinking water, food, medicine, clothing, relief tents, etc. In some cases, these goods must be distributed simultaneously; therefore, the model should be formulated as several goods. In this research, various relief goods have been considered.
IV. Many studies consider one type of vehicle and one mode of transportation. But in this research, several modes of transportation (multi-vehicle) with different types of vehicles have been considered.
V. In this research, a model is proposed with the various sources of uncertainty in an integrated method, including supply, demand, which is very important because the interaction between these sources of uncertainty makes the decision difficult.
VI. In this research, several capacity options are considered for distribution centers. Also, the capacity of shelters is part of the model output and is determined by the model.
VII. In most researches, the proposed models are single-objective to minimize the total cost or total time. In fact, in most articles, the objective is to minimize costs or humanitarian goals. The proposed model is multi-objective, including the objectives of cost minimization and humanitarian objectives simultaneously.
VIII. In this model, the objective functions are considered in the form of mini-max, including justice in the distribution of services. To simplify, these objectives have changed to service and satisfaction levels constraints.
IX. The distribution of perishable products should also be considered in the study; because goods such as drinking water, food, and medicine, which are essential items for distribution, are perishable.
X. Finally, we applied the model to a real-world case study.

4 | Mathematical Modeling

The characteristics and assumptions of the model are as follows:

- *The number and location of hospitals, waste collection centers, and accident areas are fixed.*
- *The weight and volume capacity of each vehicle to transport goods or people is defined.*
- *Several capacity options are considered for the construction of distribution centers.*
- *Potential locations for shelters and distribution centers are identified.*
- *Each vehicle is allowed to transfer a specific load.*
- *Justice considerations in services' distribution such as goods, evacuation of the injured, and dispatch of relief personnel are considered in the model, and limitations are expressed for the level of satisfaction. This leads to covering the demand of different regions to a certain extent.*

Symbols used in mathematical models

In this section, the indices, parameters, and decision variables used in the model are stated

Indices

t, t': periods along the planning horizon, t,t′=1,2,…,T.

f: potential nodes for construction of shelters, f=1, 2,…,F.

g: nodes of waste collection centers, g=1, 2,…, G.

r: a special type of medical and relief personnel, r=1,2,…, R.

j: a special capacity option for centers, j=1,2,…, J.

y: a special route, y=1,2,…, Y.

d: nodes of earthquake-affected areas, d=1,2,…, D.

l: potential nodes for the construction of distribution centers, l=1,2,…, L.

q: hospital nodes, q=1,2,…, Q.

o, p: potential nodes for the construction of distribution centers and hospitals, o,p=1,2,…, N.

c: a special product related to distribution centers, c=1,2,…, C.

v: a special vehicle, v=1,2,…, V.

h: a special type of wounded, h=1,2,…, H.

s: a special scenario, s=1,2,…, S.

Parameters

Costs

pl_f : fixed cost of building a shelter on site f.

vl : variable cost of shelter per unit of capacity per person.

f'_{lj} : cost of constructing a distribution center in location l with capacity option j.

FK_v : fixed cost of starting the vehicle v.

vrc_v : variable cost of moving a v-type vehicle per unit distance.

Demands

d'_{rds} : number of required relief personnel of type r in the affected area d at the beginning of the earthquake and in scenario s.

d''_{hds} : number of type h injured in need of service in the affected area d at the beginning of the earthquake and in scenario s.

pp_{ds} : healthy earthquake population and outpatients injured in need of evacuation in the affected area d in scenario s.

cr_{ds} : the number of corpses in need of evacuation in the affected area d in scenario.

Capacities

cw^{v} : weight capacity of type v vehicle to transport goods.

cv^{v} : volume capacity of type v vehicle to transport goods.

cm^{v} : number capacity of type v vehicle to transport relief personnel.

cph^{v} : number capacity of type v vehicle to transport the injured.

ss^{rqs} : the number of medical and relief personnel of type r provided in hospital q in scenario s.

bd_{hqs} : the capacity of hospital q to accept type h injured in scenario s.

cpp^{v} : number capacity for v-type vehicle to carry earthquake victims and outpatients.

cpc^{v} : number capacity of type v vehicle to carry corpses.

cy_{j} : capacity option j for distribution centers.

Distances

q_{qd} : distance between hospital q and accident area d.

q'_{op} : distance between nodes o and p.

q''_{qd} : distance between the affected area d and the hospital q.

q'''_{dg} : distance between the affected area d and the waste collection center g.

ing^{y}_{df} : the length of route y from the affected area d to the shelter f.

M_{Big} : a large positive number.

wt_{c} : weight of one unit of product type c.

vlm_{c} : the volume of one unit of product type c.

po_{s} : probability of scenario s.

co_{c} : a proportion of the capacity of the distribution center for storing product c.

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pb_{dfs}^{y} : the probability of a successful passage on route y from the affected area d to shelter f in scenario s.

vrh_{ct} : consumption amount of product c at period time t per injured person.

Decision variables

Location

$$lo_f = \begin{cases} 1, & if\ the\ shelter\ is\ constructed\ in\ site\ f, \\ 0, & other\ wise. \end{cases}$$

$$lo'_{lj} = \begin{cases} 1, & if\ thistribution\ center\ is\ constructed\ whit\ capacity\ j\ in\ site\ l, \\ 0, & other\ wise. \end{cases}$$

Routing

$$ru_{dfs}^{y} = \begin{cases} 1, & if\ route\ y\ is\ selected\ from\ d\ to\ f\ in\ scenario\ s, \\ 0, & other\ wise. \end{cases}$$

$$alw_{dg} = \begin{cases} 1, & if\ affected\ area\ d\ is\ allowed\ to\ carry\ goods\ to\ the\ sorting\ center\ g, \\ 0, & other\ wise. \end{cases}$$

The flow between facilities:

Ib_{cops}^{t} : the amount of c-type goods that is transported from node o to node p in scenario s at time t.

gc_{rqds} : the number of r-type relief personnel transported from hospital q to the affected area d in scenario s.

kn_{hdqs} : the number of type h injured people who are transported from the affected area d to hospital q in scenario s.

Bc_{dfs} : the number of earthquake victims or outpatients injured who are transported from area d to shelter f in scenario s.

pd_{dgs} : the number of corpses which are transported from the accident site d to the waste collection center g in scenario s.

The number of vehicles:

vn_{dfs}^{v} : the number of v-type vehicles which are driven from the accident area d to shelter f in scenario s.

vn'^{v}_{dgs} : the number of vehicles type-v which are driven from the accident area d to the waste collection center g in scenario s.

vn''^{v}_{dqs} : the number of v-type vehicles driven from the accident area d to hospital q in scenario s.

vn'''^{v}_{qds} : the number of v-type vehicles driven from hospital q to accident area d in scenario s.

vc_{ops}^{vt}: the number of v-type vehicles driven from node o to node p at period time t in scenario s.

Shortages

Bs_{cfts}: the amount of unsatisfied demand for product c in shelter f at time t in scenario s.

Bm_{rds}: unsatisfied demand of medical personnel r in affected area d during the earthquake in scenario s.

Bw_{hds}: the number of unserved injured people j in the affected area d during earthquake in scenario s.

Surpluses

sf_{cfts}: the amount of surplus goods c in shelter f at time t in scenario s.

sd_{rds}: the number of surplus personnel r in the affected area d in scenario s.

Other variables

k'_{cfts}: the amount of required products c in shelter f at time t and in scenario s.

ch_f: shelter capacity on site f.

In this section, the presented mathematical model is described in detail. The model includes location, allocation and routing in crisis situations and is in the form of multi-product, multi-period and multi-device.

Objective functions

In this model, two objective functions are considered. These functions include:

$$\mathrm{Min}\, f_1 = \sum_{s=1}^{s} Po_s \sum_{h=1}^{H} \max_d \{Bw_{hds}\}. \tag{1}$$

$$\begin{aligned} \mathrm{Min}\, f_2 = {} & \sum_{f=1}^{F} Pl_f, lo_f + \sum_{f=1}^{F} vl, ch_f + \sum_{l=1}^{L}\sum_{j=1}^{J} f'_{ij}, lo'_{ij} + \sum_{s=1}^{S}\sum_{v=1}^{V} vrc_{v'}, \\ & po_s[\sum_{d=1}^{D}\sum_{q=1}^{Q} q''_{dq}, vn''^{v}_{dqs} + \sum_{d=1}^{D}\sum_{f=1}^{F}\sum_{y=1}^{Y} \ln g^{y}_{df'} vn^{v}_{dfs} + \sum_{d=1}^{D}\sum_{g=1}^{G} q'''_{dg}, vn'^{v}_{dgs} \\ & + \sum_{q=1}^{Q}\sum_{d=1}^{D} q_{qd}, vn'''^{v}_{qds} + \sum_{o=1}^{O}\sum_{p=1}^{P}\sum_{t=1}^{T} q'_{op}, vc^{vt}_{ops}] + \sum_{s=1}^{S}\sum_{v=1}^{V} fk_v, \\ & po_s[\sum_{d=1}^{D}\sum_{q=1}^{Q} vn''^{v}_{dqs} + \sum_{d=1}^{D}\sum_{f=1}^{F} vn^{v}_{dfs} + \sum_{d=1}^{D}\sum_{g=1}^{G} vn'^{v}_{dgs} + \sum_{q=1}^{Q}\sum_{d=1}^{D} vn'''^{v}_{qds} + \sum_{o=1}^{O}\sum_{p=1}^{P}\sum_{t=1}^{T} vc^{vt}_{ops}]. \end{aligned} \tag{2}$$

Model constraints

In this section, the constraints of the proposed model are described in detail.

$$\sum_{d=1}^{D} gc_{rqds} \le ss_{rqs}, \forall r, q, s \tag{3}$$

$$\sum_{j=1}^{J} lo'_{lj} \le 1, \quad \forall l \tag{4}$$

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$$\sum_{d=1}^{D}\sum_{v=1}^{V} Bc_{dfs} \le ch_f, \quad \forall f,s \tag{5}$$

$$\sum_{p=1}^{P} Ib^{t}_{clps} \le \sum_{j=1}^{J} cy_j.lo'_{lj}.co_c, \quad \forall c,I,t,s \tag{6}$$

$$\sum_{y=1}^{Y} ru^{y}_{dfs} \le 1, \quad \forall d,f,s \tag{7}$$

$$Bc_{dfs} \le M_{Big}.\sum_{y=1}^{Y} ru^{y}_{dfs}.pb^{y}_{dfs}, \quad \forall d,f,s \tag{8}$$

$$\sum_{y=1}^{Y} ru^{y}_{dfs} \le Io_f, \quad \forall d,f,s \tag{9}$$

$$\sum_{d=1}^{D} Bc_{dfs}.vrh_{ct} = k'_{cfts}, \quad \forall f,t,c,s \tag{10}$$

$$\sum_{t=1}^{T}\sum_{o=1}^{O} Ib^{t'}_{cofs} - \sum_{t=1}^{T}\sum_{p=1}^{P} Ib^{t'}_{cfps} - \sum_{t=1}^{T} k'_{cf'ts} = sf_{cfts} - Bs_{cfts}, \quad \forall f,c,t,s \tag{11}$$

$$\sum_{q=1}^{Q} gc_{rqds} - d'_{rds} = sd_{rds} - Bm_{rds}, \quad \forall d,r,s \tag{12}$$

$$\sum_{q=1}^{Q} Kn_{hdqs} + Bw_{hds} = d''_{hds}, \quad \forall d,h,s \tag{13}$$

$$ch_f \le M_{Big}, Io_f, \quad \forall f \tag{14}$$

$$\sum_{f=1}^{F} Bc_{dfs} = pp_{ds}, \quad \forall d,s \tag{15}$$

$$\sum_{g=1}^{G} pd_{dgs} = cr_{ds}, \quad \forall d,s \tag{16}$$

$$\sum_{c=1}^{C} Ib^{t}_{cops}.wt_c \le \sum_{v=1}^{V} vc^{vt}_{ops}.cw^{v}, \quad \forall o,p,t,s \tag{17}$$

$$\sum_{r=1}^{R} gc_{rqds} \le \sum_{v=1}^{V} vn'''^{v}_{qds}.cm^{v}, \quad \forall q,d,s \tag{18}$$

$$\sum_{h=1}^{H} kn_{hdqs} \le \sum_{v=1}^{V} vn''^{v}_{dqs}.cph^{v}, \quad \forall d,q,s \tag{19}$$

$$Bc_{dfs} \le \sum_{v=1}^{V} vn^{v}_{dfs}.cpp^{v}, \quad \forall d,f,s \tag{20}$$

$$\sum_{c=1}^{C} Ib^{t}_{cops}.vlm_c \le \sum_{v=1}^{V} vc^{vt}_{ops}.cv^{v}, \quad \forall o,p,t,s \tag{21}$$

$$pd_{dgs} \le \sum_{v=1}^{V} vn'^{v}_{dqs}.cpc^{v}, \quad \forall d,g,s \tag{22}$$

$$\sum_{d=1}^{D} kn_{hdqs} \le bd_{hqs}, \quad \forall h,q,s \tag{23}$$

$$pd_{dgs} \le M_{Big} alw_{dg}, \quad \forall d,g,s \tag{24}$$

$$k'_{cfts}, Bs_{cfts}, Bm_{rds}, Bw_{hds}, Sf_{cfts}, Sd_{rds}, vn^{v}_{dfs}, vn'^{v}_{dgs}, vn''^{v}_{dgs}, vn'''^{v}_{dgs}, vc^{vt}_{ops}, lb^{t}_{cops'} \tag{25}$$
$$gc_{rqds}, kn_{hdqs}, Bc_{dfs}, pd_{dgs}, ch_f \ge 0 \,\&\, \text{Integer}, lo_f, lo'c_{lj}, ru^{y}_{dfs}, alw_{dg} \in \{0,1\}.$$

The *Objective Function (1)* is related to the level of satisfaction and minimizes the maximum number of unserved injured people in the accident areas (considering justice). The *Objective Function (2)* minimizes total costs. *Constraint (3)* shows that the number of r-type relief personnel sent from hospital q should not exceed the number of staff available at that hospital. *Constraint (4)* ensures that a maximum of one distribution center with a specific capacity option is established at each location. *Constraint (5)* shows that the number of people affected by the earthquake who are transferred to shelter f from different affected areas should not exceed its maximum allowable capacity. *Eq. (6)* ensures that the number of products c shipped from distributor l does not exceed the supply quantity. *Constraint (7)* indicates that a maximum of one route is selected from each affected area to each shelter. *Constraint (8)* states that the earthquake victims are transferred from the affected area d to shelter f if a route is selected between them and that route is available. *Constraint (9)* ensures that a route is selected from the affected area d to shelter f if a shelter has been constructed at location f. *Eq. (10)* determines the demand for goods in each shelter. *Constraint (11)* expresses unsatisfied demand or surplus goods in each shelter.

Constraint (12) defines unsatisfied demand and surplus relief personnel for each affected area. *Eq. (13)* shows unserved wounded people for any type of injury in an accident area. *Constraint (14)* states that a capacity will be allocated to a shelter in area f if a shelter has been constructed. *Constraint (15)* indicates that all healthy earthquake victims and outpatients must be evacuated from the affected areas. *Eq. (16)* ensures that all corpses are evacuated from the affected areas. *Constraint (17)* expresses the limitation on the weight capacity of vehicles to transport goods. *Constraint (18)* indicates the limitation of the capacity of vehicles to transport relief personnel. *Eq. (19)* expresses the limitation of the capacity of vehicles to transport the injured people. *Constraint (20)* shows the limitation of the capacity of vehicles to move earthquake victims. *Constraint (21)* expresses the limitation on the volumetric capacity of vehicles to transport goods. *Constraint (22)* indicates the limitation of the capacity of vehicles to transport corpses. *Eq. (3)* to *(23)* ensures that the number of casualties h served in each hospital does not exceed the capacity of that hospital to receive casualties h. *Constraint (24)* states that if the corpses of the affected area d are transported to the waste collection center g, the transfer of the corpses from this area to the waste collection center g is permitted. *Constraint (25)* states that the variables are integers, zero, and one.

5| Numerical Example in Small and Medium Dimensions

In this study, to prove the accuracy and performance of the genetic algorithm, the proposed model is solved in small and medium dimensions. If the solution approach is accurate, the proposed model is solved in large dimensions (case study). Some parameters of the numerical example are as follows.

Table 1. Capacity of distribution options and consumption of goods.

t_1	nd_{ct}	j_2	j_1	
2	c_1	200	100	cy_j

Table 2. Required relief personnel and injured people in need of service in each area.

d'_{rds}	d_1, s_1	d_2, s_1	d''_{hds}	d_1, s_1	d_2, s_1
r_1	3	4	h_1	2	3

Table 3. The number of earthquake victims and corpses in need of evacuation in each area.

pp_{ds}	s_1	pd_{ds}	s_1
d_1	10	d_1	5
d_2	14	d_2	3

The results of solving the model are indicated in *Table 4*.

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Table 4. Shortage and surplus of goods and relief personnel in shelters and affected areas.

Bs_{cfts}		sf_{cfts}		Bm_{rds}		sd_{rds}		Bw_{hds}	
c_1,f_1,t_1,s_1	2	c_1,f_1,t_1,s_1	0	r_1,d_1,s_1	0	r_1,d_1,s_1	0	h_1,d_1,s_1	0
c_2,f_2,t_1,s_1	0	c_1,f_2,t_1,s_1	0	r_1,d_2,s_1	0	r_1,d_2,s_1	0	h_1,d_2,s_1	0

Table 5. Location and capacity of distribution centers and goods transferred from distribution centers to shelters.

lo'_{lj}		Ib^t_{cops}	
l_1,j_1	1	l_1,f_1,c_1,t_1,s_1	46

Table 6. Flow of relief personnel, injured, earthquake victims and corpses.

gc_{rqds}		kn_{hdqs}		Bc_{dfs}		pd_{dgs}	
q_1,d_1,r_1,s_1	3	q_1,d_1,h_1,s_1	2	d_1,f_1,s_1	10	d_1,g_1,s_1	5
q_2,d_2,r_1,s_1	4	q_2,d_2,h_1,s_1	3	d_2,f_1,s_1	14	d_2,g_2,s_1	3

The cost objective function is also equal to 10685. As can be seen, the results indicate the efficiency of the proposed model. Accordingly, the shelter was built only in the first place, which had a lower fixed cost and considered the balance between construction and transportation costs. The first place is designed for distribution centers and the first capacity. Because in addition to meeting the demand, it has a lower construction cost and distance from the shelter. The allocation of accident areas to hospitals (hospitals to accident areas) is also such that each accident area (hospital) is allocated to the nearest hospital (accident area) according to their capacity. The number of vehicles used is also minimum to meet the current demand.

6 | Case Study

Due to the necessity of studying the earthquakes in Tehran, this is considered in the current research. Therefore, we use the proposed model in this study for the case study of Tehran. In order to prepare for disasters, shelters should be built in different areas to accommodate earthquake victims in times of crisis. For this purpose, Ayatollah Taleghani, Azadegan, Behesht Madaran, and Bayhaqi parks have been considered, which are located at a suitable distance from the affected areas. So that in addition to faster evacuation of earthquake victims, it has the required security in case of aftershocks. Also, warehouses and distribution centers should be built to meet the demands of people in these shelters. For this purpose, three candidate places of Andisheh, Saei, and Shafaq Ghanbari parks were considered. Earthquake victims should be transported to appropriate hospitals and medical centers. The four hospitals of Imam Hussein, 15 Khordad, Dr. Shariati, and Imam Khomeini have been considered due to their closeness to the accident areas and the provision of appropriate general and specialized services. The only recycling center in this study was center 1, where the corpses were to be transported. Demand areas, shelters, distribution centers, hospitals, and recycling centers are listed in *Table 7*.

Table 7. Demand areas, shelters and distribution centers, hospitals and recycling centers in the case study.

Recycling Centers	Hospitals	Distribution Centers	Shelters	Demand Centers
Center 1	Dr. Shariati	Saei	Bayhaqi park	Area 1 (in district 3)
	15 Khordad	Andisheh	Azadegan park	Area 2 (in district 6)
	Imam Hussein	Shafaq Ghanbari	Behesht Madaran park	Area 3 (in district 7)
	Imam Khomeini		Taleghani park	

In this study, three types of relief personnel, including physicians, nurses, and paramedics, are considered who are sent from hospitals of the area. In this study, it is assumed that each medical team includes one physician, two nurses, and four paramedics. Each hospital has a limited capacity to deploy a staff of any type. The number of required relief workers in each area is calculated as a percentage of the area's population and the accident's severity that must be sent to the area from hospitals and Red Crescent centers. The number of required relief personnel of any type in each accident area and the dispatch capacity of each hospital for each type of relief personnel are given in *Tables 8* and *9*.

Table 8. Capacity of dispatching relief personnel in each hospital.

Hospital	Capacity to Dispatch Relief Personnel					
	Scenario 1			Scenario 2		
	Doctor	Nurse	Relief	Doctor	Nurse	Relief
Dr. Shariati	48	96	192	40	80	160
Imam Hussein	55	110	220	50	100	200
Imam Khomeini	55	110	220	50	100	200
15 Khordad	20	40	80	10	20	40

Table 9. The number of required relief personnel in each accident area.

Accident Area	The Number of Required Relief Personnel					
	Scenario 1			Scenario 2		
	Doctor	Nurse	Relief	Doctor	Nurse	Relief
1	25	50	100	25	50	100
2	44	88	176	46	92	184
3	74	148	296	75	150	300

The golden time considered in this study includes the first 72 hours of the accident, which is referred to as the golden time in rescue operations. Some critical operations such as triage operations, evacuation of earthquake victims, and evacuation of the injured should be done during this period.

6.1 | NSGA-II Algorithm Design to Solve the Problem

In general, the main loop of the NSGA-II algorithm is used to generate random answers according to the population size [32], [33]. The values of the objective functions are calculated for each of the answers [34]. In the next step, the answers are ranked. From the ranked answers, based on the mechanism, a number of parents are selected for the intersection and mutation operations, and after checking the constraints, the values of the objective functions are calculated for each of the generated answers. Now the new answers are placed next to the initial answers, and the answers are ranked again [35].

The determined chromosome structure is multi-section, in which the variables related to the routing of products and survivors are considered as a section. The variables related to the demand for survivors' transfer and the demand for products in emergency relief centers are defined in one section. Each section of a chromosome is determined as a matrix whose dimensions vary according to the number of its indices. For example, the chromosome corresponding to the variable k'_{cfts} is as follows:

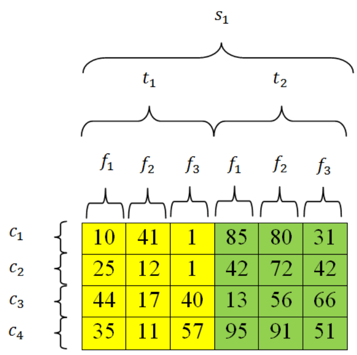

Fig. 1. Chromosome description.

Fig. 2 shows the intersection operator—double-point crossover, as shown in the figure.

Parent 1

23	65	54	55	100	42
42	85	19	129	102	87
54	64	13	410	164	120
421	413	88	200	321	18

Parent 2

11	36	37	28	13	59
73	64	18	100	95	36
48	46	77	205	87	93
214	74	39	45	67	45

Child 1

23	65	37	28	100	42
42	85	18	100	102	87
54	64	77	205	164	120
421	413	39	45	321	18

Child 2

11	36	54	55	13	59
73	64	19	129	95	36
48	46	13	410	87	93
214	74	88	200	67	45

Fig. 2. Two-point intersection operator.

Fig. 3 shows the mutation operator. For this purpose, a row is selected as desired and the selected row is reversed.

Parent

80	50	40	60	70	40
60	60	20	90	400	100
40	40	50	400	460	70
100	320	30	60	120	90

Child

80	50	40	60	70	47
100	400	90	20	60	60
40	40	50	400	460	70
100	320	30	60	120	90

Fig. 3. Reverse mutation operator.

Table 10 lists the important parameters in the NSGA II algorithm.

Table 10. NSGA-II algorithm parameter limitation.

Levels	Operators
0.3-0.5	Mutation
0.1-0.3	Crossover
60-100	nPop
100-200	MaxG

In order to properly adjust the parameters of this algorithm, we execute several problems in different dimensions in Matlab software and convert the results into the Relative Percentage Deviation (RPD) index using the following equation.

$$\text{RPD} = \frac{\left|\text{Algorithm}_{\text{sol}} - \text{Best}_{\text{sol}}\right|}{\text{Best}_{\text{sol}}} \times 100.$$

Table 11 shows the average result of 36 experiments designed for this problem that. In each experiment, the parameters of the algorithm change, and the results change accordingly. In the calculations, two criteria of algorithm execution time and the average distance from the ideal answer are used.

Table 11. Results of solving experiments to determine the parameters.

No.	PC	PM	NPOP	MAX G	RPD for CPU T	RPD for MID
1	0.4	0.2	70	200	0.000936	0.089086
2	0.4	0.2	70	150	0.080889	0.106221
3	0.3	0.2	70	100	0.183879	0.072533
4	0.4	0.2	90	200	0.121030	0.081835
5	0.4	0.2	90	150	0.317544	0.089802
6	0.4	0.2	90	100	0.394311	0.10254
7	0.4	0.2	80	200	0.228580	0.094019
8	0.4	0.2	80	150	0.400998	0.0998
9	0.3	0.2	80	100	0.582745	0.133119
10	0.4	0.3	70	200	0.062442	0.051187
11	0.4	0.3	70	150	0.221910	0.107935
12	0.4	0.3	70	100	0.343994	0.11795
13	0.4	0.3	90	200	0.254190	0.106096
14	0.4	0.3	90	150	0.426385	0.06255
15	0.4	0.3	90	100	0.605615	0.078903
16	0.4	0.3	80	200	0.425143	0.097154
17	0.4	0.3	80	150	0.641270	0.074359
18	0.4	0.3	80	100	0.870551	0.065807
19	0.5	0.2	70	200	0.06645	0.116505
20	0.5	0.2	70	150	0.186367	0.127235
21	0.5	0.2	70	100	0.3215	0.078085
22	0.5	0.2	90	200	0.232018	0.083345
23	0.5	0.2	90	150	0.398559	0.055441
24	0.5	0.2	90	100	0.906233	0.099595
25	0.5	0.2	80	200	0.711694	0.087434
26	0.5	0.2	80	150	0.957835	0.075641
27	0.5	0.2	80	100	1.219782	0.096428
28	0.5	0.3	70	200	0.429919	0.095937
29	0.5	0.3	70	150	0.61582	0.095966
30	0.5	0.3	70	100	0.797894	0.088565
31	0. 5	0.3	90	200	0.672717	0.076064
32	0.5	0.3	90	150	0.924724	0.08278
33	0.5	0.3	90	100	1.18305	0.08229
34	0.5	0.3	80	200	0.93631	0.090635
35	0.5	0.3	80	150	1.25088	0.069776
36	0.5	0.3	80	100	1.454915	0.069679

We enter the values in the minitab18 software, and the results can be seen in *Fig. 4*.

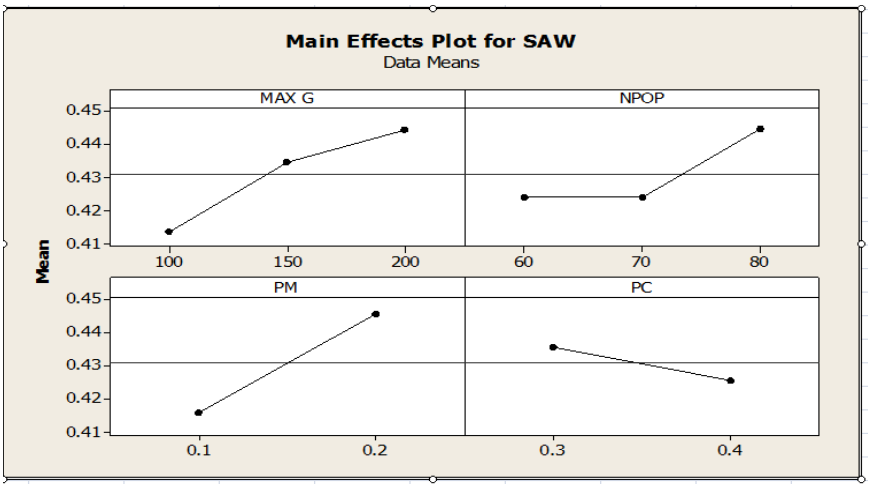

Fig. 4. Minitab software output to determine the parameter of the NSGA-II algorithm.

Convergence of the problem answer to a certain number after several executions is necessary to examine the solution algorithm's performance. According to this criterion, the algorithm used to solve the model in this study works well, and the results are acceptable. *Figs. 5* and *6* show how the solution algorithm reaches a steady-state for the problem after several limited iterations.

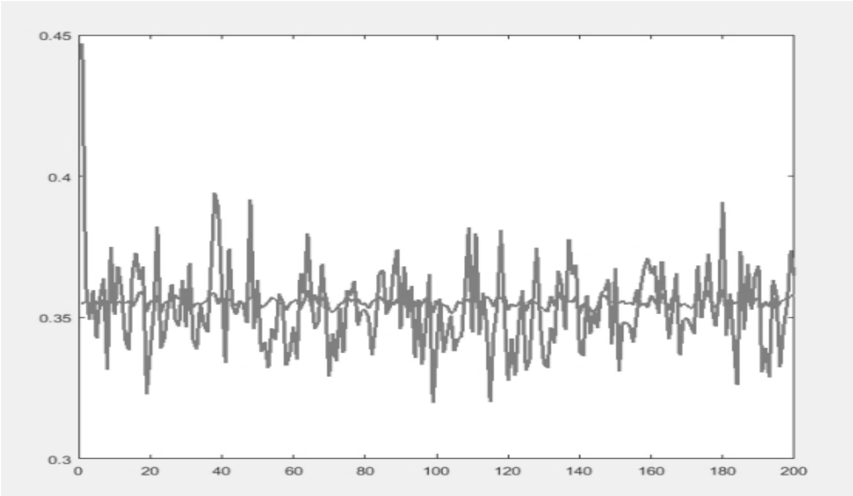

Fig. 5. Convergence of the solutions obtained from the algorithm for the second objective function (cost).

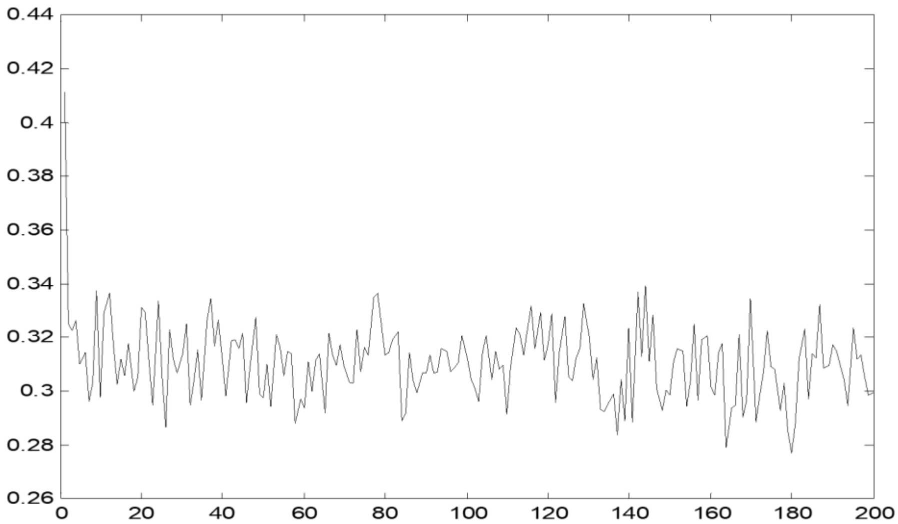

Fig. 6. Convergence of the answers obtained from the algorithm for the first objective function (satisfaction).

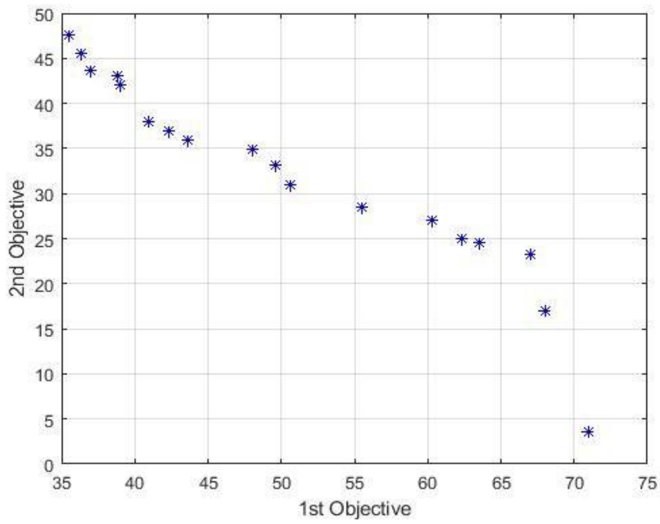

Fig. 7. Two-dimensional representation of Pareto points from a case study.

Fig. 7 shows the Parthian points extracted from the case study. As you know, due to the multi-objective nature of the proposed model, the answers can be drawn as a Pareto front.

Analysis of the impact of distribution center capacity on cost (second objective function). *Table 12* shows the effect of different capacities of distribution centers on the objective function of cost.

Table 12. Analysis of the effect of distribution centers' capacities on the objective function of cost.

Distribution Centers' Capacities	Second Objective Function (Cost)
60000-110000-160000	1368000000
30000-40000-50000	1311000000
60000-550000-60000	1450000000

The trend of these changes is shown in *Fig. 8*.

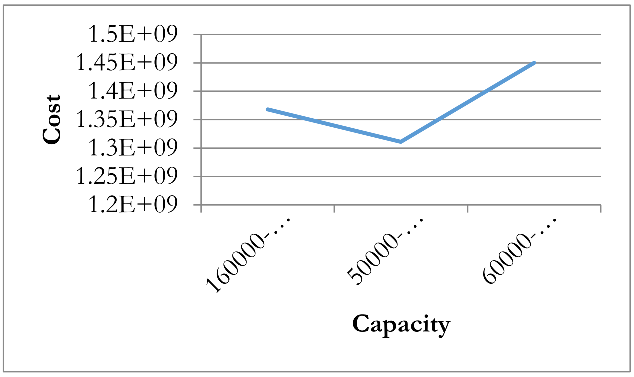

Fig. 8. Analysis of the impact of distribution centers' capacity on cost.

The graph trend is decreasing to a certain point and then increasing; by increasing capacity, the number of distribution centers built to meet demand has decreased, and the distribution center built may be far from some shelters, leading to increased transportation costs. As expected, with the increase of candidate capacities, the cost is reduced because with the increase of capacity, there is no need to build new distribution centers, and the fixed construction cost of these centers is eliminated. This indicates the accuracy of the model behavior and that it is necessary to consider the choice of capacity in the problem and

Analysis of the effect of discharge route length on cost

Table 13 shows the analysis of the effect of discharge route length on cost.

Table 13. Analysis of the effect of discharge route length on co.

Route Length	The Second Objective Function (Cost)
4-7	1328500000
8-11	1362300000
12-15	1376100000

The trend of these changes is shown in *Fig. 9*.

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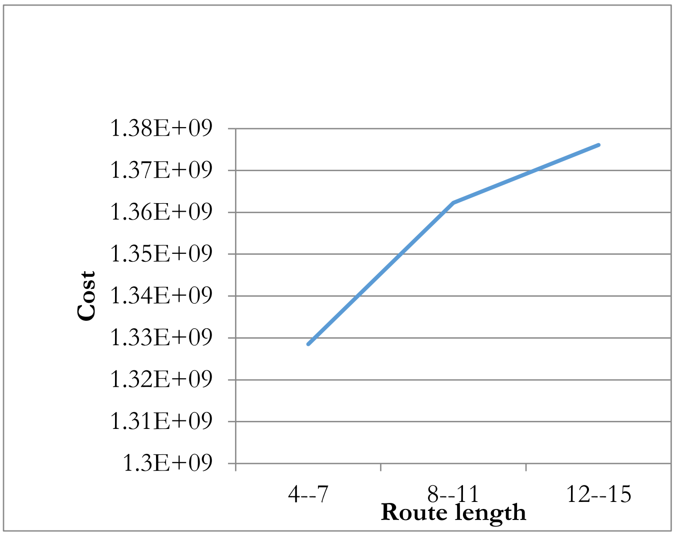

Fig. 9. Analysis of the effect of discharge route length on cost.

As expected, with increasing route length, the cost increases. This indicates the accuracy of the model and that considering the route selection in the problem, balancing the probability of route availability and the route length is necessary.

7 | Conclusion

The proposed mathematical model in this study deals with decisions on post-crisis issues. Also, this considers the location of relief facilities, resource allocation, distribution of relief goods, and transfer of survivors to medical centers according to the objectives of the problem (reducing costs and increasing satisfaction) in several periods. Due to the stochastic nature of the problem, determining the parameters of the problem is critical. For this purpose, statistical distributions were determined according to the available information, a case study, and interviews with experts for the key parameters of the problem. To further explain the model and the results, using the available data about the areas of Tehran, the outputs of solving the model and general analysis of the problem are presented. Finally, due to increasing the dimensions of the problem, the exponential increase of the exact solution time, the operational nature of the problem decisions, and the importance of time in making appropriate decisions, the NSGA-II metaheuristic algorithm has been used to solve the two-objective model. It indicates that the proposed solution algorithm works well, and the quality of the solutions and the solution time are acceptable. The results indicate that as capacity increases, the number of distribution centers built to meet demand decreases. Also, the distribution center constructed may be far from some shelters, leading to increased transportation costs. As expected, with the increase of candidate capacities, the cost is reduced. Because with the increase of capacity, there is no need to build new distribution centers, and the fixed construction cost of these centers is eliminated. This indicates the model's accuracy and that it is critical to consider the choice of capacity in the problem. The following are suggested for future studies:

I. In this research, it is assumed that the information related to demand and supply is certain at the beginning of the planning period. However, in real conditions, this information is changing dynamically, so providing a logistic model in a dynamic way can increase the problem's efficiency.

II. To model the problem's uncertainties using the robust method can be compared with the simulation approach.

III. To apply other exact solution methods of multi-objective problems to solve the problem, such as the exact Banders method

IV. To consider the traffic of transportation routes in modeling the problem.

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