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A cooperative game theory approach for location-routing-inventory decisions in humanitarian relief chain incorporating stochastic planning

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ABSTRACT

This paper describes a new simulation based mathematical model for locating distribution centres, vehicle routing, and inventory problems under earthquake conditions. In this paper, the proposed network includes affected areas, suppliers, distribution centres, and hospitals. Additionally, the basic infrastructures of the city, which are very fragile at the time of the earthquake, are identified. Then, the demand of each relief commodity is calculated depending on the different earthquake scenarios using simulation. The estimated demand is incorporated into the mathematical model as an uncertain parameter. The proposed methodology is designed as a two-stage model so that in the first stage the location and inventory of distribution centres are addressed. Thereafter, in the second stage the routing decisions are taken for the distribution of relief commodities from the distribution centres and suppliers to the affected areas. Due to the NP-hardness of the second stage model, this model is solved using multi-objective stochastic fractal search. This algorithm is one of the population-based and stochastic optimization techniques and inspired by the natural phenomenon of fractal growth. It should be noted that in the second stage, a cooperative game theory of coalition type is considered, which resulted in synergies that minimize the relief golden time. The kind of cooperation is the use of potential of co-operators' vehicle. In this stage, the possibility for the players to cooperate by sharing people and commodities transportation requests is considered. Also, to validate the model, a real case study is provided for a possible earthquake in Tehran. Finally, the comparison between the simulation results and the values obtained from the real system evaluates the performance of the implemented model. Considering normality and a 95% confidence interval, it can be concluded that the proposed model provides a precise representation of the real system's performance.

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1. Introduction

Over the next 50 years, both natural disasters and man-made disasters are likely to follow a growing trend [1]. Regarding the fact that the occurrence of a disaster (whether natural or man-made) has always had irreparable consequences around the world, disaster relief logistics management has been introduced as a significant issue worldwide [2]. The management of disaster relief logistics helps to reduce the consequences of a disaster [3]. The location of facilities and the amount of relief commodities stored are among the decisions that are being addressed in the pre -disaster preparation phase. There is a direct relationship between the timeliness of pre -disaster services and the effectivity of the relief logistics network during the response phase [4]. Routing decisions for affected areas, hospitals, distribution centres, and the manner of distribution and delivery of relief commodities can have a significant impact on response phase performance. One of the important decisions that affect vehicle routing, and the distribution of relief commodities is how the organizations cooperate with each other during relief operations. Cooperative transportation planning can reduce transportation time and increase coverage level [5]. Given the complexity and uncertainty of disaster situations, the design of an effective and efficient relief logistics network for humanitarian organizations will be very difficult, which may lead to ineffective and inefficient decisions by the involved organizations [6]. Hence, the attention of many researchers has been drawn to the development of various techniques and methods that can help to their model of the relief logistics network under existing constraints and assuming the real conditions of the disaster [7]. Moreover, the proposed decision-making procedure combining exact methods and meta-heuristic algorithms will help engineers and managers to design a disaster relief supply chain network according to existing assumptions and limitations.

In addition, the lack of attention to the effect of different disaster management phases, can be a huge obstacle to an effective response to a disaster [8]. In fact, optimizing the activities of each of these phases cannot guarantee the optimization of the whole relief operation and may lead to inapplicable decisions in disaster situations [9]. In general, a four-echelon disaster relief supply chain includes suppliers, distribution centres, affected areas, and hospitals. Suppliers are responsible for providing relief commodities such as medicine, blankets, food, etc. Relief commodities provided by suppliers are sent to distributors [10]. Distributors send relief commodities to affected areas. Eventually, the injured will be transported from the affected areas to hospitals. In order to estimate the demand for relief commodities in earthquake conditions, it is necessary to identify the basic urban infrastructure [11]. These infrastructures include water, gas, electricity, hospitals, buildings, transportation infrastructure, communication system, etc. [12]. For example, in the event of an earthquake, the destruction of the electrical system can cause damage to hospitals and disrupt the way in which the injured are served [13].

Therefore, a two-stage model for disaster relief logistics management is presented in this paper. At the first stage of the model, pre -disaster decisions including the location of distribution centres and suppliers, inventory management, and the allocation of relief centres to affected areas are made. The main purpose of this stage is to minimize shortage costs, centre establishment costs, and holding costs. To solve the first stage mathematical model, GAMS software is used. At the second stage, post- disaster decisions including cooperative routing for the distribution of relief commodities are made. The main purpose of this stage is to minimize the relief time in all coalitions and maximize the reliability of routes between all nodes. To solve the second stage mathematical model, a multi-objective Stochastic Fractal Search (SFS) and Epsilon-Constraint approach are utilized. To deal with the inherent uncertainty of the problem, the effects of urban fragile infrastructure during the occurrence of the disaster was simulated. This approach identifies the relationship between the number of demands for relief commodities with different scenarios and shows how a change in different scenarios will affect the amount of demand. The scenarios considered in this research includes occurrence time, earthquake intensity, and the desired fault. For example, a seven-magnitude earthquake can disrupt the road and disrupt the power system, etc. Therefore, according to the interaction of basic urban infrastructure, the demand for drinking water, non-drinking water, medicine, food, tents, and blankets is calculated. Commodities are also divided into critical and non-critical types. Critical commodities include drinking and non-drinking water, food, and medicine. Critical commodities are sent from distribution centres to the affected areas and non-critical commodities are transported directly from suppliers to affected areas. The estimated demand enters the mathematical model as a parameter. This approach is called simulation-optimization. Based on the nature of the demand, the demand parameter is subject to uncertainty in the proposed models. Also, the two proposed models are solved separately. The way it works is that in the first model, the location of distribution centres and suppliers, the allocation of distribution centres to suppliers, and the allocation of suppliers and distribution centres to demand points are specified. Therefore, in the second model, the locations of distribution centres, suppliers, and allocation decisions are predetermined. This means that the decisions made in the first phase will affect the decisions made in the second phase.

This paper is organized as follows: a literature review related to the humanitarian relief chain, simulation-optimization model, stochastic planning, and cooperative game theory are stated in Section 2. In Section 3, problem description and research methodology are presented. Moreover, the interaction of basic urban infrastructure at the time of the earthquake is explained in Section 4. In Section 5, mathematical modelling including the pre -disaster model and cooperative post-disaster model along with the process of converting the stochastic model into a deterministic model is examined. Therefore, solution methodology to solve the model and case study to validate the model are provided in Sections 6 and 7, respectively. Finally, the conclusions followed by future work opportunities are provided in Section 8.

2. Literature review

The literature review is divided into 4 subsections which include stochastic planning, humanitarian relief chain, Cooperative game theory and Methodology.

2.1. Stochastic planning

Boonmee et al. [14] suggested a mathematical model for location in humanitarian logistics. The location of distribution centres, warehouses, shelters, debris removal sites, and medical centres has been done in the pre -disaster and post-disaster phases. Four different problems were modelled and solved using deterministic facility location problems, dynamic facility location problems, stochastic facility location problems, and robust facility location problems. The available differences between our research and Boonmee et al. [14] are the consideration of routing and inventory control simultaneously and collaborative routing using game theory in the post-disaster phase that investigates in this paper. The priority of demand according to the type of commodities and demand point and attention to various goals such as minimizing pre -disaster costs, maximizing the reliability of routes, and minimizing relief time.

Torabi et al. [15] presented a two-stage mixed fuzzy-stochastic programming for the planning of pre-positioning and procurement phases. The considered supply chain included suppliers, central and local warehouses, and affected areas. Then, quantity flexibility and hybrid fuzzy-stochastic uncertainty is considered in their mathematical model as a novelty. Minimizing the costs of establishing relief centres and transportation costs was the main objective of this research. Eventually, the amount of relief supplies sent to each of the centres was calculated for a hypothetical earthquake in Iran.

Paul and Zhang [16] studied the location and transportation planning in storm situations. Therefore, they provided a two-stage stochastic model to minimize location costs and social costs. Considering the level of service along with the risk in disaster relief supply chain was one of the contributions of their study. The results indicated that funding for lower severity-level supplies is preferred. Paul and Wang [17] presented a robust model for location and determining the capacity of distribution centres during an earthquake. Considering the disruption of distribution centres along with social costs and deprivation costs in scenario-based situation was one of their research contributions. The considered scenarios were about the magnitude of the earthquake. The case study was Northridge region in California, and this region was tested for two recorded earthquakes in 1971 and 1994.

Zhan et al. [18] proposed a stochastic mathematical model for the location and allocation of relief commodities during typhoons. The considered phase is post-disaster. Their main goal was to minimize the amount of unsatisfied demand at the points of demand. A comparison between egalitarianism and utilitarianism in supply chain was their contribution. The case study is intended for Zhejiang Province in China. Voting-Strategy-Coded based on Particle Swarm Optimization has been used to solve the proposed model. Considering the pre-and post-disaster phases simultaneously in the mathematical model along with the demand estimation by simulation method is another advantage of our research. In addition, in our research, the flow of relief commodities and people are considered simultaneously, which in Zhan et al. [18] was not considered.

2.2. Humanitarian relief chain

Arslan et al. [19] formulated a routing-location model for designing a refugee camp network in earthquake conditions. Their contribution was to provide a modified branch-price-and-cut algorithm and cycle-cancelling algorithm to solve their proposed model. Their main goal is to minimize the costs of the whole supply chain. The case study considered a potential earthquake at 244 points in Turkey. The results indicated that with increasing the number of demand points, routing and location costs increase exponentially. One of the priorities of this paper over Arslan et al. [19] is the simultaneous consideration of the pre-and post-disaster phases and the reliability of the routes. In addition, Arslan et al. [19] did not consider the cooperation of members of the relief supply.

Yang et al. [20] presented a dynamic multi-period model for pre -disaster phase management under demand uncertainty. The chance constraint approach has been used to deal with uncertainty parameters. Minimizing pre -disaster costs including the costs of location and storage relief commodities is considered as the objectives of their study. The case study is provided to be the Circum-Bohai Sea Region of China earthquake. A robust optimization approach was used to solve the proposed model. One of the advantages of our research over Yang et al. [20], is the pre -disaster phase in the first level and the post-disaster phase in the second stage which uses a mathematical model. Minimizing the golden time of relief and maximizing the reliability of the routes is another advantage of our research.

Sakiani et al. [21] addressed the inventory management, routing, and dynamic distribution of relief commodities in post-disaster situations. Among the innovations considered was fairness in the distribution of relief commodities. The relief commodities considered were both consumable and durable. A simulated annealing algorithm was used to solve the proposed model and a three-phase systematic approach was used for tuning it. Simultaneous attention to commodities and people in disaster relief as well as demand uncertainty and its estimation are among the priority of our paper over Sakiani et al. [21].

Sharma et al. [22] considered the location and allocation of temporary blood facilities in post-disaster conditions. Their main goal is to minimize response time to hospitals. Their contribution was the use of the Bayesian belief network to prioritize temporary locations. The Tabu search algorithm was used to solve their proposed model. The case study is the Jamshedpur city / Jharkhand State of India earthquake. One of the advantages of our research over Sharma et al. [22] is including the estimation of demand for relief commodities by simulation approach. Also, paying attention to the pre-and post-disaster phases simultaneously and presenting a cooperative mathematical model for routing ambulances is another advantage of our research. The priority of demand according to the type of commodities and demand point is also a novelty that has been considered in our research.

Ghasemi et al. [23] presented a multi-commodity and multi-depot model for locating and allocating distribution centres and hospitals to affected areas. Among their research contributions, considering several types of injured people and the failure rates for distribution centres can be mentioned. Minimizing relief costs and minimizing the shortage of relief commodities under uncertainty (scenario-based) were of the objectives of this research. Finally, the results of the study were provided for a case study with two approaches of NSGA-II and modified Particle Swarm Optimization. Lack of attention to cooperative routing in the disaster relief supply chain as well as pre -disaster decisions such as location in the preparedness phase is among the gaps in the research of Ghasemi et al. [23] which is covered in our research.

Habibi-Kouchaksaraei et al. [24] presented a multi-objective scenario-based model for managing the blood supply chain in disaster situations. In this regard, minimizing costs and maximizing the level of demand satisfaction has been their main contribution. The considered scenarios including the intensity of occurrence and the desired fault are provided. To solve the proposed model, goal programming and robust optimization have been used. The case study was suggested a potential earthquake in Mazandaran / Iran. Among the advantages of our research over Habibi-Kouchaksaraei et al. [24] is the simultaneous consideration of location-routing-inventory decisions. Also, in our research, the demand is estimated using the simulation approach. Additionally, considering the multi-commodity mode and performing the collaborative game in the mathematical model is an added advantage of our research.

Noham and Tzur [25] designed a relief commodities chain after the occurrence of a disaster. The study of the impact of post-disaster decisions on pre -disaster decisions was one of their research contributions. The proposed model was solved in small and medium scale using the exact solution method and in large scale using Tabu search. Finally, the proposed model was solved for a case study based on the information of Geophysical Institute of Israel. Simultaneous consideration of pre-and post-disaster phases and designing location, routing, and allocation decisions are the priority of our research when compared to Noham and Tzur [25].

Toyasaki et al. [26] investigated the horizontal cooperation of humanitarian organizations in managing inventory of relief commodities. Considering a coordination mechanism to determine the share of each organization in stock rationing was of the contribution of their research. The results of the research included determining the policies for the cooperation of different organizations to reduce the relief time. Simulation of the amount of demand for relief commodities along with simultaneous routing, location, and allocation in disaster relief is one of the advantages of our research when compared to Toyasaki et al. [26].

2.3. Cooperative game theory

Akbari et al. [27] presented a collaborative mathematical model for disaster relief management. The allocation of relief commodities and their distribution were among their important decisions. Additionally, uncertainty was considered scenario-based. Their main goals were to minimize the costs of the total supply chain and unsatisfied demand. Finally, the proposed model was solved using robust optimization method. Shapley's results showed that larger coalitions lead to more cost savings.

Cleophas et al. [28] examined collaborative urban transportation. They specifically addressed the impact of horizontal and vertical collaboration, strategic planning, tactical, and operational planning problems, and solution approaches. The results showed that with the change of transportation modes (such as buses, trams, and taxis), the effect of cooperation on routing costs will change.

Molenbruch et al. [29] presented a mathematical model for joint route planning considering horizontal cooperation among dial-a-ride service providers. A large neighbourhood search metaheuristic was used to solve their proposed model. The main purpose of their proposed model was to minimize routing costs. The case study was considered a service provider in Belgium. The costs of the horizontal cooperation scenario are compared with the non-horizontal cooperation scenario, and the results indicated that the costs of the horizontal cooperation scenario are lower.

Nagurney et al. [30] introduced a mathematical model for cooperation among supply chain members in disaster relief operations using the game theory approach. Considering the logistical and financial cooperation between the organizations and considering the costs of purchasing and delivery of relief commodities were of the contributions of their research. In their proposed model, it was possible to purchase relief commodities from local and non-local organizations, with the budget constraint determining the number of purchases from each of them. Finally, the model was solved by the Generalized Nash Equilibrium. Nagurney et al. [30] did not consider routing and location and pre -disaster decisions. Also, their paper does not pay attention to minimizing the golden time of relief, people flow, and demand uncertainty, which our research has covered.

Maharjan and Hanaoka, [31] presented a multi-objective mathematical model in the response phase under uncertainty. Credibility-based fuzzy chance-constrained programming was used to cope with the uncertainty parameters. Minimizing logistics costs and maximizing demand coverage has been the most important goal of their research. Considering different types of relief was one of their research novelties. The case study was the 2015 Nepal Earthquake. The results indicated that either the number of demand points increases, or the number of areas covered decreases. One of the advantages of our research over Maharjan and Hanaoka, [31] is the simultaneous consideration of the routing-location-inventory control problem of relief commodities. Thus, paying attention to the cooperative game between the supply chain players is another priority of the current research.

Tirkolaee et al. [32] designed a robust bi-objective mathematical model for allocation, location, scheduling rescue operations. Their main contribution was to use the learning effect to minimize relief delays. To deal with uncertainty, the multi-choice goal programming approach is used, and the mathematical model is solved using the robust optimization approach. The case study was an earthquake in Mazandaran / Iran province. The results displayed that with increasing uncertainty levels, the amount of relief time increases. One of the advantages of our research over Tirkolaee et al. [32] is including paying attention to pre-and post-disaster decisions simultaneously and cooperative routing using game theory in the post-disaster phase. Considering the reliability of the routes and estimating the demand using the simulation approach is another priority of this research.

Li et al. [33] used the game theory approach to explore the cooperation of organizations in the sustainable humanitarian supply chain. A coordination mechanism was used to connect the supply chain components. Also, evolutionary game model was used to develop the cooperation mechanism. The results indicated that for the design of a proper cooperation mechanism, both the traditional and trust mechanisms should be used.

Estimating the demand for relief commodities by computer simulation, simultaneously considering the flow of commodities and people, and cooperative routing by the game theory is the superiority of our research when compared to Li et al. [33].

Fathalikhani et al. [34] examined the cooperation and competition in disaster relief operations among humanitarian organizations. They presented two mathematical models using game theory. The first model was for the competition of NGOs to raise funds for humanitarian operations and the second model was for the cooperation among NGOs for relief. Considering the impact of the cooperation of NGOs in achieving their social mission successfully is their contribution. The results indicated that cooperation between NGOs and resource sharing between them will greatly help to increase the performance of the NGOs. Considering demand uncertainty before and after the disaster and providing the flow of people and commodities at the same time are the novelties of the proposed paper. Fathalikhani et al. [34] did not consider the location and routing decisions and these decisions are considered in our research. Cavagnini and Morandi [35] presented a novel mathematical model for the cooperative Share-A-Ride Problem (SARP). This paper considers multiple depots and heterogeneous vehicles, and different cooperation levels may be agreed upon by service providers. The results show that cooperation leads to reduced travel times and to improved vehicle occupancy rates, service levels, and profits, which make such a cooperative system even more appealing for service providers.

2.4. Methodology

In this section, the literature related to the methodology used in the research, including exact solutions, heuristic, meta-heuristic and simulation methods, is examined.

Alinaghian et al. [36] presented a mathematical model for locating temporary relief centres as well as routing of air vehicles in post-disaster situations. Their main objective was to minimize the time the last vehicle arrives at the temporary relief centre. Also, the dynamic routing of aerial rescue vehicles is one of their novelties. A heuristic approach based on scatter search was used to solve the model and the proposed approach was compared with the Genetic algorithm. Designing a cooperative game in the routing of ambulances with simultaneous attention to the pre-and post-disaster phases are the advantages of our study over Alinaghian et al. [36].

Loree and Aros-Vera [37] presented a non-linear model for inventory management and facility location in post-disaster situations. The proposed model aimed to minimize location costs, shortage of relief commodities and social costs. The balance between deprivation, facility placement, and logistics costs is their most important novelty. Finally, a heuristic algorithm was proposed for solving the model in large-scale. Presenting a cooperative mathematical model using game theory and the uncertainty of demand for relief commodities are considered as the superiority of our research when compared to Loree and Aros-Vera [37].

Liu et al. [38] designed a mathematical model for logistics management planning in post-disaster conditions. The demand and transportation time uncertainty have been considered as their contributions. Minimizing unsatisfied demand has been their main novelty. Their study provided a case study of the Sichuan Earthquake in Wenchuan country. Their proposed model is solved using the robust optimization approach. The results showed that as demand increases, chain costs and unsatisfied demand increase sharply. One of the priorities of our paper over Liu et al. [38] identified the structure of the interaction of fragile infrastructure during the earthquake. Another fact is the simultaneous study of location-routing-inventory decisions in the mathematical model as illustrated in our research, which in Liu et al. [38] was not considered.

Tavana et al. [39] presented a multi-echelon model for location, routing, and inventory management in the humanitarian supply chain. Their proposed model studied the pre- and post-disaster phases. In the pre -disaster phase, warehouse location and inventory control of relief commodities and in the post-disaster phase, multi-depot routing was investigated. Considering the transportation capacity constraint for routes in the supply chain of perishable relief commodities is one of their novelties. Finally, the model was solved in small scale by Epsilon-constraint approach and in large-scale by NSGA-II; and the results showed the proper performance of the proposed model. Among the advantages of our research over Tavana et al. [39] is the introduction of a cooperative game in the mathematical model, the reliability of the routes, and estimating the number of relief commodities using the simulation approach.

Nagurney et al. [40] presented a mathematical model for the competition of humanitarian organizations to raise funds during the occurrence of a disaster. This research used the Generalized Nash Equilibrium model to calculate the lower bound and upper bound for the demand of relief supplies. Considering a non-cooperative game in the supply chain of perishable relief goods is one of their novelties. The results of the research indicated an increase in the performance of relief operations. Among the advantages of our research over Nagurney et al. [40] presented the demand estimation approach using the simulation approach in both pre-and post-disaster conditions simultaneously. In addition, our research focuses on the reliability of routes and the priority of relief commodities, which Nagurney et al. [40] did not consider.

Camacho-Vallejo et al. [41] presented a new bi-level model for humanitarian logistics management. Considering the countries donating humanitarian aid along with different types of capacities for them was one of their novelties. In their model, the affected country was considered as a leader and humanitarian organizations are considered as a follower. The goal of the leader was to minimize response time and the goal of the follower was to minimize logistics costs. The case study was the Chile earthquake in 2010. The considered game in Camacho-Vallejo et al. [41] was a leader-follower but the considered game in our research is a cooperative approach. Considering routing, location, and inventory control simultaneously, and estimating demand using a simulation approach are other novelties of our research.

Additionally, the details of the recent research in the problem of Location-Routing-Inventory in disaster relief are summarized in Table 1.

The following research opportunities were identified:

- Lack of attention to the cooperation of members of the relief supply chain in reducing the golden time of relief operations.
- Lack of attention to routing-location-inventory-distribution decisions in relief operations simultaneously
- Lack of attention to the pre- and post-disaster phases. Therefore, according to the literature review, it seems necessary to consider strategic decisions before the disaster and operational decisions during the disaster.
- Lack of attention to the multi-commodities and multi-period of the proposed model, as well as the simultaneous flow of relief commodities and the injured in the relief network
- Lack of attention to the identification and impact of critical urban infrastructure on the estimated amount of relief commodities
- In most research, numerical examples are used to prove the proposed model, so it seems necessary to use a real example to prove the efficiency of the proposed model.

Taken together, this research highlights some new points for the first time in this area. The main contributions of this research are outlined as follows:

- Designing a coalition cooperative game to reduce the golden time of relief operations based on customizing the concept of game theory for the disaster relief problem.
- Developing a stochastic mathematical model to integrate routing-location-inventory decisions together in the disaster relief problem.
- Considering the two-stage mathematical model includes pre- and post-disaster decisions simultaneously. In the first stage of the mathematical model, pre -disaster decisions are performed including the location of distribution centres and suppliers, inventory management, and the allocation of relief centres to affected areas. At the second stage, the mathematical model of post-disaster decisions is including cooperative routing for the distribution of relief commodities.
- Presenting a new multi-objective, multi-commodity, and multi-period model according to the flow of commodities and the injured people simultaneously.
- Employing the simulation approach to deal with the uncertainty of the problem: Determining the urban critical infrastructures in the event of an earthquake and investigating their interactions with each other. The performed simulation is based on different scenarios. Finally, the estimated demand value enters the mathematical model as a parameter.
- A customized Multi-Objective Stochastic Fractal Search (SFS) is developed to solve the proposed mathematical programming model.
- Finally, providing a real case study to bring the closer to the problems in the real world: The results of a case study are in cooperative and non-cooperative states that are compared to each other. The amount of synergy caused by the cooperative model is calculated.

3. The problem description

In this research, a four-echelon multi-objective, multi-commodities and multi-period disaster relief chain is considered. This chain includes suppliers, distribution centres, affected areas (with demand for critical and non-critical commodities) and hospitals. The proposed model has two phases; in the first phase, strategic decisions are made on the location of suppliers, distribution centres, and the amount of inventory stored in each of them. In the second phase, vehicle routing is used for distribution of critical commodities from distribution centres to affected areas. Each affected area is served directly by suppliers or by distribution centres within a specified time interval. At the first stage, inventory control and

Table 1
A review of literature on disaster relief.

Author	Number of objective functions (Single/Multi Objective-(SO)/(MO))	Type of objective functions (Cost (C)/ Humanitarian (H))	Cooperative(C)/Non-cooperative game (N)	Planning horizon (Static-(S), Dynamic (D))	Data type (Deterministic (D), Uncertain (U))	Uncertainty sources (Demand (D)/ Supply (S)/ Transportation Network (N))	Optimization method (Deterministic (DtO)/ Stochastic (StO)/ Scenario (Sc)/ Robust (Ro), FuzzyOptimization (F))	Decision-making phases (Pre/ Post Disaster (PR, PO))	Decision types (Pre/Post disaster Location (L-pre, L-pos), Pre-position (PP)/ Allocation (Al) / Network Flow (F)/ Routing (R))						Flow type (People(P)/ Commodities(C))
									L-pre	L-pos	PP	Al	F	R	
Boonmee et al. [14]	SO	C	-	S	DU	D	DtO, StO	PR/PO	*	*			*		-
Torabi et al. [15]	SO	C	-	S	U	D	StO, F	PR			*	*	*		C
Paul and Zhang [16]	SO	C	-	S	U	D	StO	PO		*			*		C
Paul and Wang [17]	SO	C	-	S	U	D, S	Sc, Ro	Pr	*		*	*			C
Zhan et al. [18]	SO	H	-	D	U	D	StO	PO		*		*			C
Arslan et al. [19]	SO	C	-	S	D	-	DtO	PO		*		*		*	-
Yang et al. [20]	SO	C	-	D	U	D	Ro	PR	*		*	*			C
Sakiani et al. [21]	SO	C	-	D	D	-	DtO	PO					*	*	C
Sharma et al. [22]	SO	H	-	D	D	-	DtO	PO		*		*			C
Ghasemi et al. [23]	MO	CH	-	D	U	D	Sc	PO		*		*	*		CP
HabibiKouchaksaraei et al. [24]	MO	CH	-	D	U	D	Ro	PO		*			*		C
Noham and Tzur [25]	SO	H	-	S	U	DS	Sc	PO		*		*	*		C
Toyasaki et al. [26]	SO	C	C	S	D	-	DtO	PO				*	*		C
Akbari et al. [27]	SO	CH	C	S	U	D	Sc,Ro	PO					*	*	C
Cleophas et al. [28]	SO	C	C	S	D	-	Dto	-				*			C
Molenbruch et al. [29]	SO	C	C	S	D	-	Dto	-				*	*		C
Nagurney et al. [30]	SO	C	N	S	D	-	DtO	PO				*	*		C
Maharjan and Hanaoka [31]	MO	CH	-	D	U	D	F	PR/PO		*		*			C
Tirkolaee et al. [32]	MO	H	-	S	U	D	Ro	PO		*		*			C
Li et al. [33]	SO	C	C	S	U	D	Sc	PO				*			-
Fathalikhani et al. [34]	MO	CH	CN	S	D	-	DtO	PO				*	*		C
Cavagnini and Morandi [35]	SO	C	C	S	D	-	DtO	-				*	*		CN
Alinaghian et al. [36]	SO	H	-	D	U	DS	StO	PO		*			*	*	-
Loree and Aros-Vera [37]	SO	H	-	S	D	-	DtO	PO		*			*		C
Liu et al. [38]	SO	C	-	S	U	D	Ro	PO					*		CP
Tavana et al. [39]	MO	CH	-	D	D	-	DtO	PR/PO	*				*	*	C
Nagurney et. al. [40]	SO	C	N	D	D	-	DtO	PO				*			C
Camacho-Vallejo et al. [41]	MO	CH	N	S	D	-	DtO	PO					*		C
This Study	MO	CH	C	D	U	DN	StO, Sc	PR/PO	*	*	*	*	*	*	CP

location of distribution centres and suppliers are carried out in pre -disaster state. At this stage, after determining the location of distribution centres and suppliers, the number of critical commodities sent from the suppliers to the distribution centres is determined. Critical commodities include drinking and non-drinking water, food, and medicine. The amount of shortage of each of these commodities are also determined at this level. Non-critical commodities include blankets and tents. These commodities are transported directly from suppliers to affected areas. The main reason for this is the strict control and monitoring of critical relief commodities. Due to the greater importance of critical commodities than non-critical commodities, the possibility of abuse and hoarding of critical commodities in disaster conditions is very high. Therefore, to prevent the hoarding of critical relief commodities, these commodities are first sent to distribution centres to be distributed in a targeted and fair manner.

The routing problem that is considered at the second stage of the model includes the post-disaster phase. At this phase, since distribution and supply locations are identified in the previous step, routing between distribution centres, affected areas and hospitals is addressed. In this research, a multi-objective mathematical model is used in the second stage. There are several depots (hospitals, distribution centres and suppliers) in the model, and each point will be visited by a vehicle and this vehicle should return to its initial depot after its mission. Here, it is assumed that the depots are run by several owners. Each owner is known as a player who wants to work with other players to reduce transportation time. The kind of cooperation is the use of potential of co-operators' vehicle. Each geographic area is covered by one owner. As such, it will be possible for a vehicle to cover another vehicle's area if there is cooperation. Minimizing transportation time will be done by each coalition. Thus, the time saved by each of the coalitions, which results from the synergy of their cooperation, will be calculated. The coalition m (which consists of $2^N - 1$possible coalitions, N is the number of players) is defined as $S_{\mathrm{m}} \subseteq P$. So, the components of the game are summarized as follows:

- **Players**: Owners of each depot are responsible for covering a geographic area.
- **Cooperation type**: Use of the potential of co-operators' vehicle: The considered coalition relies on the sharing of injured and commodities transportation. Thus the coalition includes sharing the capacity of vehicles carrying the injured and relief commodities.
- **The objective of the game**: Increasing the level of coverage of affected areas and reducing the time of relief.

Therefore, the proposed supply chain structure along with the flow of relief commodities and the affected people in pre-and post-disaster situations is shown in Fig. 1.

3.1. Research methodology

As shown in Fig. 2, the research methodology consists of 6 steps. In the first step, the basic urban infrastructure, which is very fragile at the time of the earthquake, is identified. In the second step, simulation of different scenarios of earthquake occurrence is discussed. The output of this level will be the estimate of the probabilistic parameter of the demand for relief commodities. Estimated parameters will be the input of the third and fourth steps (mathematical modelling). Amount of demand for relief supplies will enter the third step as a probabilistic parameter. In the third step, location-inventory mathematical modelling in pre -disaster phase is examined. At this step, the location of distribution centres, suppliers, as well as the number of commodities stored in distribution centres is specified. The objective is to minimize pre -disaster costs. In the fourth step, a cooperative model for routing in pre -disaster phase will be presented. In this step, routing between located centres and affected areas as well as hospitals will be done. The objective of this step is to minimize the time of relief. The geographic areas covered by the disaster relief organization will be the players involved in this game and minimizing the golden time of the relief will be the payoff of the game. Given that the demand parameter is uncertain in two stage of the model, in the fifth step, Chance Constrained Programming is used to deal with this uncertainty. Finally, in the last step, the proposed model is solved using the exact solution and meta-heuristic approach.

4. Investigating the interaction of basic urban infrastructure at the time of the earthquake

According to Fig. 3, the infrastructure that is affected by an earthquake in a city includes 10 sections. This structure is based on [42–44] and experts' opinion.

Additionally, the destruction of basic urban construction includes gas supply destruction, building collapse, hospital destruction, drainage system destruction, collapse of sewer pipes, offal treatment destruction, functional destruction of the financial institute, electricity supply destruction, telephone destruction, traffic dysfunction based on Fig. 3. The interaction of the above-mentioned infrastructure has ultimately led to the demand for relief commodities. As can be seen, an earthquake can destroy the gas infrastructure. "Gas supply destruction" leads to "no gas supply" (which will result in demand for food) and "gas leak". "Gas leak" leads to "gas station fire" and eventually "fire". The gas station fire will result in demand for needs water. After the fire, there is a possibility of "fire spread" and eventually "urban fire" that can lead to "firefighting action" and "extinguish fire" that will require water, food, and shelter.

One of the other effects of the earthquake is the "collapse of sewer pipes" which results in "sewage inundation", increasing the contagious risk" and "contamination of upstream water" that will require water. Destruction of the electricity infrastructure can also cause" gas station fire "and" no electricity supply" which will result in food demand. Destruction

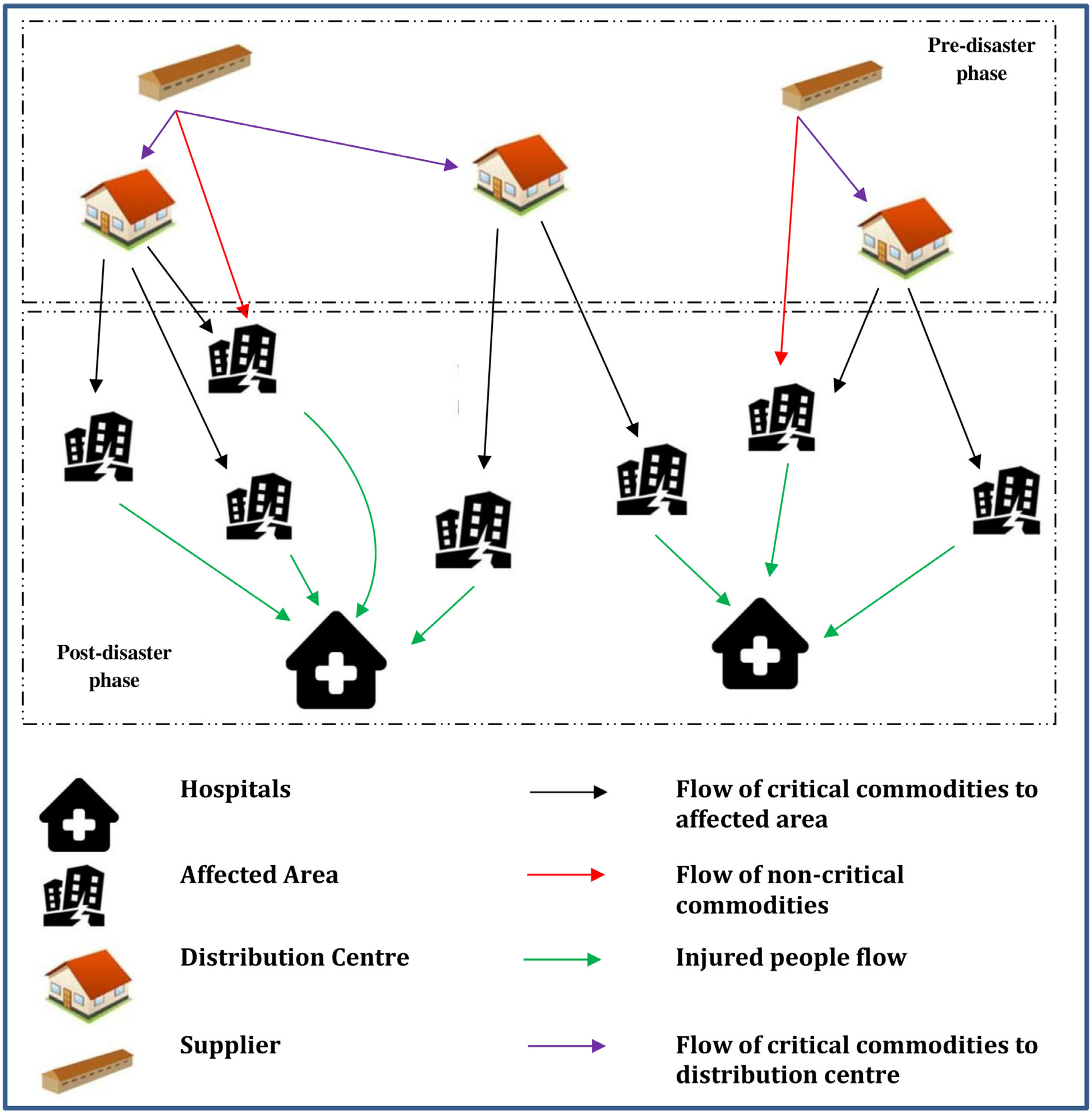

Fig. 1. The structure of the proposed disaster relief supply chain.

of buildings and bridges can also lead to "person died and injured" or "evacuation". There is a need for water, food and medicine for "refugee", and water, food, medicine, and shelter for "refugees without the way to go home".

"Hospital destruction", "telephone line destruction" and "functional downs of financial institute" lead to demand for water, food, medicine, and shelter. The impact of the earthquake on traffic infrastructure includes two parts of "road destruction" and "railway destruction" which in both cases lead to the demand for water, food, medicine, and shelter. "Offal treatment destruction" causes the demand water, food, and medicine, and finally “drainage system destruction" will cause the demand for water.

The structure presented in Fig. 3 is designed to deal with the stochastic behaviour of the problem.

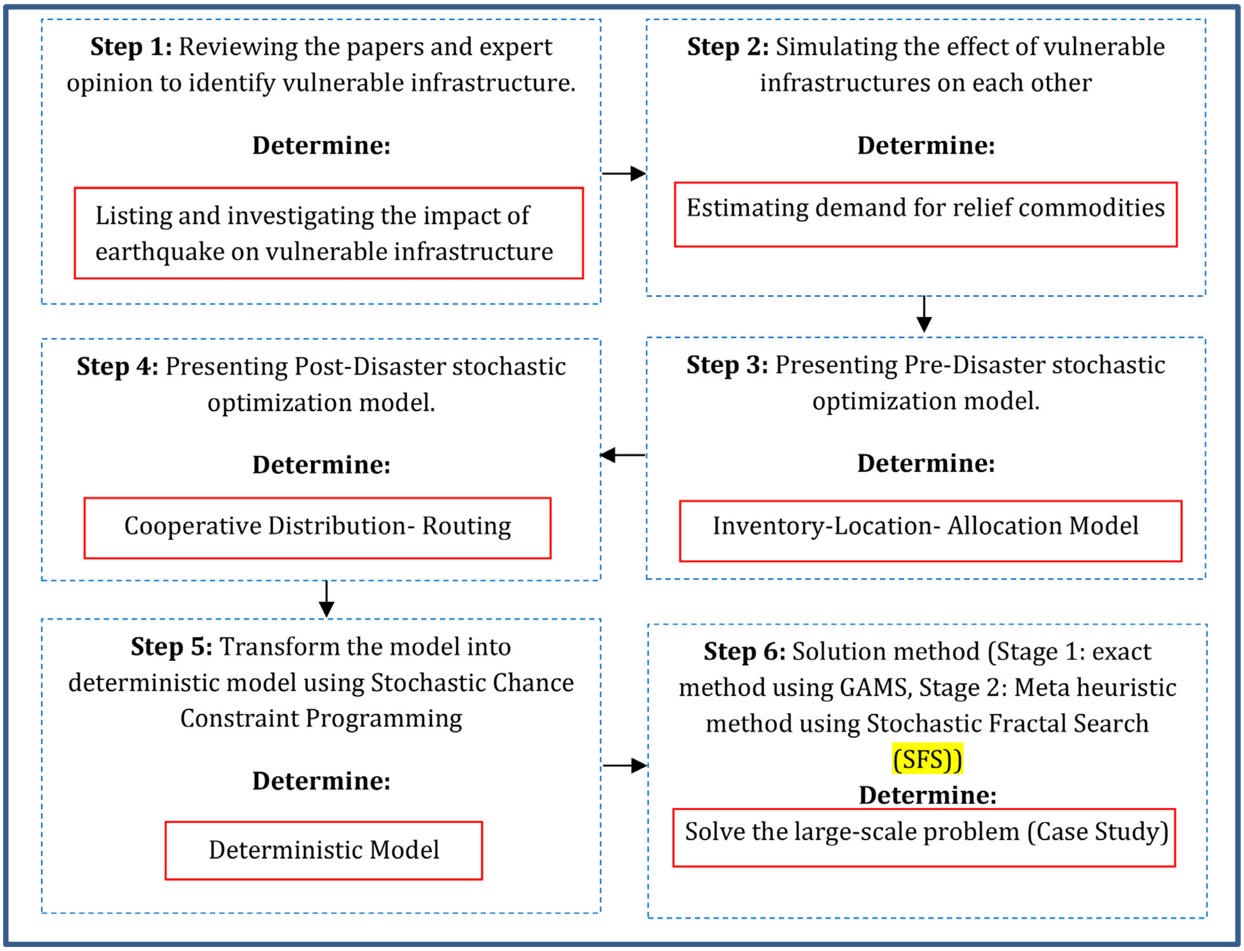

Fig. 2. Research framework.

4.1. Computer simulation modelling

Enterprise Dynamic (ED) software is a user-friendly simulation package that helps users to model problems using 4D Script codes. There are successful uses of ED in literature, including [45,46]. ED software is well responsive in all problems of material handling, transportation, and production process. The atoms in this package can cover all the mentioned processes. ED atoms are designed to implement systems and formed designs in the mind as easily as possible and with the required details in the software. For more details about ED software, see [47].

In this research, an interface is used to link the Microsoft Excel to ED software to extract the simulation output. Also, the observation period is 1000000 seconds, the warm-up period is 100000 seconds, and the simulation method is considered as separate run. Performance measurements (PFMs) are intended to evaluate the effectiveness of the simulation model, including AvgContent (cs) and Avgoutput (cs). The designed layout consists of 49 atoms including a source atom, a sink atom, and 47 server atoms. The four atoms of "food, medicine, shelter and water" are for counting and estimating the demand for relief commodities. The estimated amount of water, food, medicine, and shelter for each injured is 6 litres, 2.5 kilograms, 0.7 kilograms and 0.25, respectively. For example, the 4D Script code for the medicine atom will be as follows:

$$Server\ medicine:\ Trigger\ on\ entry = 0.7 * (AvgContent\ \ (AtomByName([Human\ Injured],\ Model)))$$

For example, the 4D Script codes of the "fire spread" atom are as Eqs. (1)–(9). This code is based on the model of [48]. Hamada [48] developed a model based on the fire spread in urban environments as follows:

B	the number of structures completely burnt in the fire
t	time in minutes
w	wind speed in m / s
δ	hardness rate of the building
a	average structure dimensions in meters

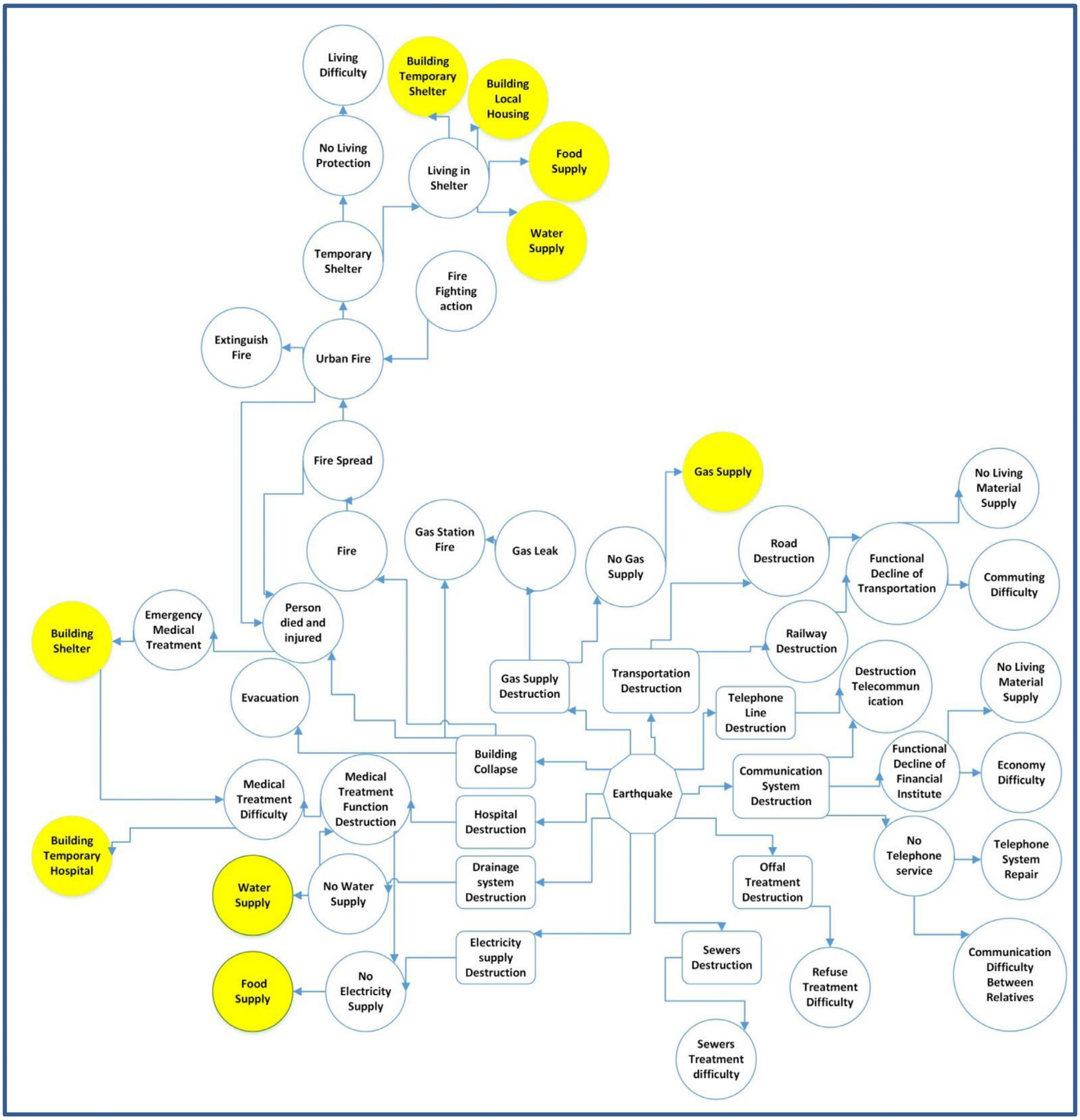

Fig. 3. The structure of the interaction of fragile infrastructure during the earthquake.

c	average building separation in meters
Kr	half the width of the fire from the sides in meters
Kf	the length of fire in the direction of wind blowing in meters
Kp	the length of fire in the opposite direction of the wind blowing in meters
a_i	average dimensions of the structure i
n	number of structures

$$B = \frac{1.5\delta}{a^2} * Kr * (Kf + Kp) \tag{1}$$

$$\delta = \frac{\sum_{i=1}^{n} a_i^2}{Tract\ area} \tag{2}$$

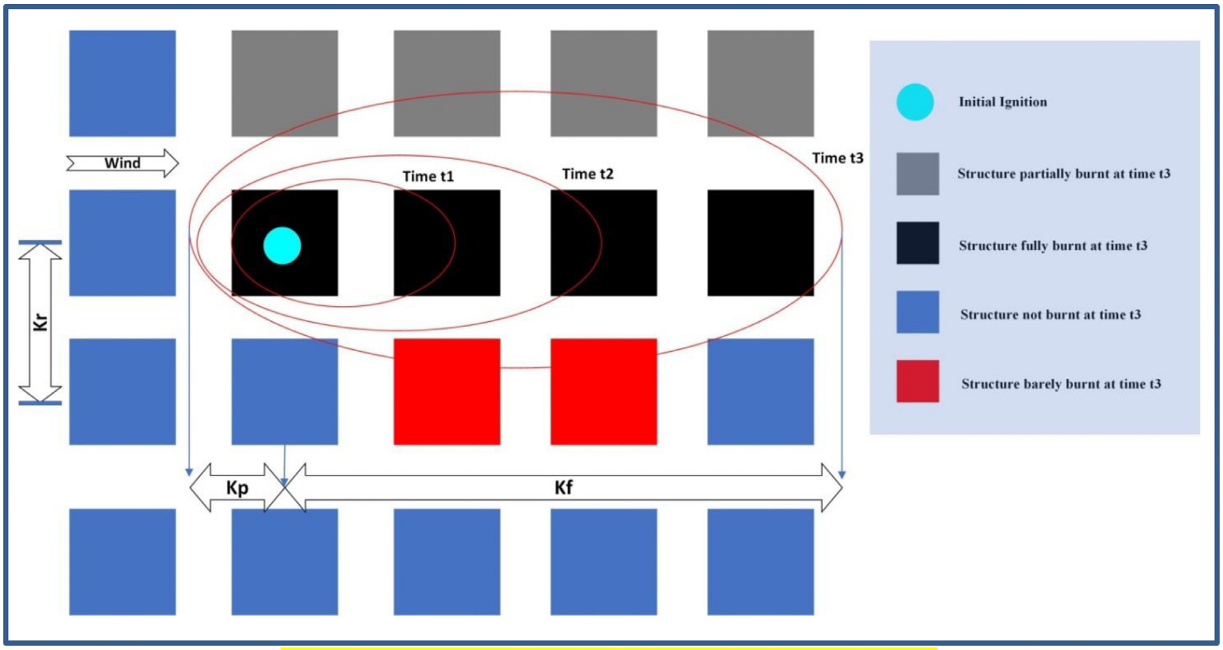

Fig. 4. Estimation of the fire spread during an earthquake.

$$Kr = \left(\frac{a}{2} + c\right) + \frac{(a+c)}{Ts}(t - Ts)Kr \geq 0 \tag{3}$$

$$Kp = \left(\frac{a}{2} + c\right) + \frac{(a+c)}{Tu}(t - Tu)Kp \geq 0 \tag{4}$$

$$Kf = \frac{(a+c)}{Td} * t \tag{5}$$

$$Td = \frac{1}{1.6\left(1 + 0.1w + 0.007w^2\right)}(1 - fb)\left(3 + 0.375a + \frac{8c}{25 + 2.5w}\right) + fb\left(5 + 0.625a + \frac{16c}{25 + 2.5w}\right) \tag{6}$$

$$Tu = \frac{1}{1 + 0.002w^2)}(1 - fb)\left(3 + 0.375a + \frac{8c}{5 + 0.2w}\right) + fb\left(5 + 0.625a + \frac{16c}{5 + 0.2w}\right) \tag{7}$$

$$Ts = \frac{1}{1 + 0.005w^2)}(1 - fb)\left(3 + 0.375a + \frac{8c}{25 + 2.5w}\right) + fb\left(5 + 0.625a + \frac{16d}{25 + 2.5w}\right) \tag{8}$$

$$fb = \frac{\text{Number of fire resistant buildings}}{all\ building} \tag{9}$$

Furthermore, the extent of the fire spread as an oval. Fig. 4 describes to better understand the parameters of “fire spread" atom. The direction of wind with constant speed is shown in Fig. 4. In this figure, based on Hamada [48] model, it is assumed that a city is composed of a series of squares of equal shape and size (plan surface), with equal distances from each other. The length of the plan surface is assumed to be “*a*”, so the area of plan surface is equal to a^2. The building density (δ) is determined according to Eq. (5). The value of 0.35 indicates a high density and 0.1 shows the low density of buildings. The distances between the structures are equal to “*d*”. These distances may include areas such as yards, farms, and alleys.

In real urban fires, the amount of fire spread varies according to the wind speed and the amount of fuel loaded. Therefore, the initial shape of the fire will vary with the final shape. The area of fire is calculated by the length of the fire in the direction of wind blowing plus the length of the fire in the direction of wind blowing (*Kf*+*Kp*) multiplied by the width of the fire from the sides.

5. Mathematical modelling

The assumptions of inventory-location-allocation model in the pre -disaster phase are as follows:

- Pre -disaster inventory-location -allocation model is multi-period, multi-commodities and multi echelon. Supply chain levels include suppliers, distribution centres, affected areas and hospitals.
- There are two types of relief commodities. Critical commodities are sent from suppliers to distribution centres. Non-critical commodities are sent from suppliers to the affected areas. Critical commodities include drinking and non-drinking water, food, and medicine. Non-critical commodities include blankets and tents.
- The parameter$\tilde{b}_{st}{}^{ar}$ has probabilistic distribution. This distribution function is entered into the mathematical model after the estimation in the simulation model. This approach is called simulation-optimization.
- Optimal locations are chosen to establish distribution centres and suppliers from nominated potential locations. Thus, location is considered as a discrete parameter.
- Different levels are considered for the capacity of suppliers. Capacity levels are including small, medium, and large.
- In each scenario, the priority of demand is defined according to the type of commodities and demand point. The lower the value, the higher the priority of the product at the demand point.

In the following, the indices, parameters, and variables of the first stage model are described as follows:

Index

i	index of supplier capacity level $i \in I$
d	index of distribution centres $d \in D$
a	index of demand points (the people affected by the earthquake) $a \in A$
j	index of suppliers $j \in J$
r	index of commodities (including critical and non-critical commodities) $\{CR, RI \in R\}$
s	index of scenarios $s \in S$
t	index of time periods $t \in T$

Parameter

c_{rd}	holding cost for commodity r at distribution centre d
c'_r	cost of shortage of commodity r
c''_{ji}	the cost of opening the supplier j with the capacity level i
c'''_d	the cost of opening the distribution centre d
$O_{st}{}^{ar}$	the priority of demand for commodity r at the demand point a in scenario s and period t
e_d	capacity of distribution centre d
e'_i	supplier capacity at the capacity level i
$I_{st}{}^{jr}$	the inventory level of commodity r in supplier j in scenario s and period t
$\tilde{b}_{st}{}^{ar}$	the demand for commodity r at the demand point a in scenario s and period t (with uncertainty)
δ_r	volume of commodity r
M	a large positive number

Variables

$w_{st}{}^{ji}$	equal to 1 if the supplier j reopens at the capacity level i in the period t and the scenario s, otherwise zero
$k_{st}{}^{ja}$	equal to 1 if the supplier j is allocated to the demand point a in the period t and the scenario s, otherwise zero
$n_{st}{}^{da}$	equal to 1 if the distribution centre d is allocated to the demand point a in the period t and the scenario s, otherwise zero
$n'_{st}{}^{jd}$	equal to 1 if the distribution centre d is allocated to the supplier j in the period t and the scenario s, otherwise zero
f_{dst}	equal to 1 if the distribution centre d opens in the period t and the scenario s, otherwise zero
$l_{st}{}^{jdr}$	the amount of commodity r sent from the supplier j to the distribution centre d in the period t and the scenario s
$l'_{st}{}^{dar}$	the amount of commodity r sent from the distribution centre d to the demand point a in the period t and the scenario s
$l''_{st}{}^{jar}$	the amount of commodity r sent from the supplier j to the demand point a in the period t and the scenario s
$l'''_{st}{}^{dr}$	the amount of commodity r allocated to the distribution centre d in the period t and the scenario s
$I'_{st}{}^{dr}$	the inventory of commodity r at the distribution centre d in the period t and the scenario s
$\pi_{st}{}^{ar}$	the amount of shortage of commodity r sent at the point a in the period t and the scenario s

The pre -disaster mathematical model is formulated as follows:

$$Min \sum_{a\in A}\sum_{r\in R}\sum_{s\in S}\sum_{t\in T} O_{st}{}^{ar} c'_r \pi_{st}{}^{ar} + \sum_{j\in J}\sum_{i\in I}\sum_{s\in S}\sum_{t\in T} c''_{ji} w_{jist} + \sum_{d\in D}\sum_{r\in CR}\sum_{s\in S}\sum_{t\in T} c_{rd} I'_{st}{}^{dr} + \sum_{d\in D}\sum_{s\in S}\sum_{t\in T} c'''_d f_{dst} \tag{10}$$

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$$n_{st}{}^{da} \le f_{dst} \forall d \in D, a \in A, s \in S, t \in T \tag{11}$$

$$\sum_{a\in A}\sum_{r\in RI} l''_{st}{}^{jar} \le M\sum_{a\in A} k_{st}{}^{ja} \forall j\in J, s\in S, t\in T \tag{12}$$

$$\sum_{d\in D} n_{st}{}^{da} + \sum_{j\in L} k_{st}{}^{ja} \ge 1 \forall a\in A, s\in S, t\in T \tag{13}$$

$$\sum_{j\in J}\sum_{r\in CR} l_{st}{}^{jdr} \le M\sum_{a\in A} n_{st}{}^{da} \forall d\in D, s\in S, t\in T \tag{14}$$

$$\tilde{b}_{st}{}^{ar} - \pi_{st}{}^{ar} = \sum_{d\in D} l'_{st}{}^{dar} \forall a\in A, r\in CR, s\in S, t\in T \tag{15}$$

$$\tilde{b}_{st}{}^{ar} - \pi_{st}{}^{ar} = \sum_{j\in J} l''_{st}{}^{jar} \forall a\in A, r\in RI, s\in S, t\in T \tag{16}$$

$$\sum_{r\in R} \delta_r I_{st}{}^{jr} \le \sum_{i\in I} e'_i . w_{jist} \forall j\in J, s\in S, t\in T \tag{17}$$

$$\sum_{r\in CR} \delta_r I'_{st}{}^{dr} \le e_d . f_{dst} \qquad \forall d\in D, s\in S, t\in T \tag{18}$$

$$\sum_{i\in I} w_{jist} \le 1 \qquad \forall j\in J, s\in S, t\in T \tag{19}$$

$$l'''_{st}{}^{dr} . n'_{st}{}^{jd} \le l_{st}{}^{jdr} \qquad \forall j\in J, d\in D, r\in CR, s\in S, t\in T \tag{20}$$

$$l'''_{st}{}^{dr} = \sum_{a=1} n_{st}{}^{da} . \tilde{b}_{st}{}^{ar} \qquad \forall d\in D, r\in CR, s\in S, t\in T \tag{21}$$

$$I'_{s1}{}^{dr} = 0 \qquad \forall d\in D, r\in CR, s\in S \tag{22}$$

$$I'_{st}{}^{dr} + \sum_{a\in A} l'_{st}{}^{dar} = I'_{st-1}{}^{dr} + l_{st}{}^{jdr} \qquad \forall d\in D,\ j\in J, r\in CR, s\in S, \mathrm{t}\neq 1, t\in T \tag{23}$$

$$\sum_{j\in J} n'_{st}{}^{jd} \le w_{st}{}^{ji} \qquad \forall i\in I, s\in S, t\in T \tag{24}$$

$$I'_{st}{}^{dr}, \pi_{st}{}^{ar}, l_{st}{}^{jdr}, l'_{st}{}^{dar}, l''_{st}{}^{jar}, l'''_{st}{}^{dr} \ge 0 \qquad \forall a\in A, r\in R, d\in D,\ j\in J, s\in S, t\in T \tag{25}$$

$$w_{st}{}^{ji}, f_{dst}, n_{st}{}^{da}, n'_{st}{}^{jd}, k_{st}{}^{ja} \in \{0,1\} \qquad \forall a\in A, i\in I,\ j\in J, d\in D, s\in S, t\in T \tag{26}$$

The objective function (10) consists of four terms. The first term minimizes the costs of shortages. In this term, the costs of shortages are multiplied by the number of shortages and the priority of demand for relief commodities. The second term minimizes the cost of establishing suppliers in each period and scenario. The third term minimizes the cost of the inventory holding of stored relief commodities. The fourth term minimizes the cost of establishing distribution centres. Constraints (11) illustrate that the distribution centre can be allocated to the demand points if this centre is already open. Constraints (12) imply that a supplier must first be allocated to points of demand and then can send relief commodities to the demand points. Constraints (13) show at least one distribution centre or supplier must be established. Constraints (14) relate to the allocation and sending of relief supplies from suppliers and distributors to affected areas. Constraints (15) and (16) calculate the number of sent relief commodities from distribution centres to demand points and from suppliers to demand points, respectively. Constraints (17) and (18) indicate the storage capacity of relief commodities in suppliers and distribution centres, respectively. Constraints (19) ensure the establishment of only one level of storage capacity for each supplier in each period. Constraints (20) indicate the amount of non-critical commodities sent from the suppliers to the distribution centres. These constraints also imply that distribution centres must first be established in order to be able to store relief commodities. Constraints (21) calculate the number of relief commodities allocated to distribution centres. Constraints (22) indicate that the initial inventory of distribution centres in the first period is zero. Constraints (23) show the balance between the commodities sent and the number of inventories of distribution centres. Constraints (24) mean that suppliers must be established first, and then distribution centres can allocate demand points. Constraints (25) and (26) show the positive and binary variables of the proposed model, respectively.

The assumptions of the cooperative routing model in post-disaster phase are as follows:

- The amount of demand for relief commodities is stochastic, and this parameter enters the optimization model after computing by simulation model. This approach is called simulation-optimization.
- The availability of routes to evacuate people in the event of a disaster is uncertain. Because of the disaster, a part of the capacity of the hospitals may have been eliminated and infrastructure such as roads may have been destroyed. Therefore, reliability is defined for routes. The route that is more likely to be destroyed is less reliable.
- Each injured person can receive a service from any vehicle.
- The model is multi-period and multi-commodity.
- The time of service to the injured by relief vehicles and relief commodities distribution vehicles in each scenario is the same.
- The game considered in this study is a kind of game without perfect knowledge. The game is without perfect knowledge because players cannot see the entire game in front of them at any given time.
- The game considered in this study is asymmetric. Asymmetric games are often games in which there is not the same strategy set for players in the game.
- The allocation of distribution centres to the demand point is specified in the first level of the mathematical model and its output enters the second level of the mathematical model as a parameter.
- The considered coalition relies on the sharing of injured and commodities transportation. Thus the coalition includes sharing the capacity of vehicles carrying the injured and relief commodities.

The second mathematical model is solved once without considering the coalition and once with considering coalition. Note that in order to avoid increasing the number of pages of the paper, the model has been avoided without considering the coalition. In the second mathematical model, indices and variables are indexed with coalitions. Different coalitions are the input of this model, and the output of the mathematical model is the choice of the best coalition composition. For example, suppose there are three distributors in the suggested problem. In this case, there will be seven ({1},{2},{3},{1,2},{1,3},{2,3},{1,2,3}) possible coalitions that the model will be solved for each coalition. Finally, the model will decide which coalition has the best value of the objective function. For more information on mathematical modelling considering coalition, you can refer to [49]. Therefore, the indices, parameters, and variables of the second stage model are described as follows:

Sets

$A_{[C_m]}$ set of the people affected by the earthquake or demand points in the coalition C_m
$D_{[C_m]}$ set of distribution centres in the coalition C_m
$H_{[C_m]}$ set of hospitals in the coalition C_m
$V_{[C_m]}$ set of vehicles of relief commodities in the coalition C_m
$V'_{[C_m]}$ set of vehicles for transporting the injured in the coalition C_m
P set of depot owners (players)

Indices

r index of relief commodities (including critical and non-critical commodities) {CR, RI $\in R$}
s index of scenarios
t index of time periods
v index of vehicles of relief commodities $v \in V_{[C_m]}$
v' index of vehicles for transporting the injured $v' \in V'_{[C_m]}$

Parameter

ρ_{vrt} capacity of vehicle v for the commodity r in period t
ρ'_{ht} capacity of hospital h in period t
$\rho''_{av'ht}$ capacity of vehicle v' for transporting the injured from demand point a to the hospital h in period t
$\tilde{b}_{st}{}^{ar}$ demand for commodity r at the demand point a in scenario s and period t (with uncertainty)
α_{at} service time to demand point a in period t
β_{ast} the end of the time window at the demand point a in scenario s and period t
M a large positive number
Γ_{ast} the number of injured people requesting treatment at the demand point a in scenario s and period t
$r_{st}{}^{da}$ reliability of transportation from distribution centre d to demand point a in scenario s and period t
$r'_{st}{}^{ha}$ reliability of transportation from hospital h to demand point a in scenario s and period t
$r''_{st}{}^{aa'}$ reliability of transportation from demand point a to demand point a' in scenario s and period t
s_{ast} the start of the time window at the demand point a in scenario s and period t
$\eta_{st}{}^{ad}$ time interval between distribution centre d and demand point a in scenario s and period t
$\eta'_{st}{}^{ah}$ time interval between hospital h and demand point a in scenario s and period t
$\eta''_{st}{}^{a'a}$ time interval between demand points a and a' in scenario s and period t
$\zeta_{st}{}^{da}$ equal to 1 if the distribution centre d is allocated to the demand point a in scenario s and period t; otherwise, zero (derived from the first stage model)

Variables

$z_{dvst}^{[C_m]}$ the return time of the relief vehicle v to the distribution centre d in the scenario s, period t and the coalition C_m

${z'}_{hv'st}^{[C_m]}$ the return time of the relief vehicle v' to the hospital h in the scenario s, period t and the coalition C_m

$g_{ahst}^{[C_m]}$ the number of the injured transported from the demand point a to the hospital h in the scenario, period t and the coalition C_m

$q_{dvst}^{[C_m]}$ time of movement from the distribution centre d by the vehicle v in the scenario s, period t and the coalition C_m

${q'}_{hv'st}^{[C_m]}$ time of movement from the hospital h by the vehicle v' in the scenario s, period t and the coalition C_m

$\psi_{avst}^{[C_m]}$ time of arrival of the vehicle v to the demand point a in the scenario s, period t and the coalition C_m

${u_{avst}}^{[C_m]}$ this variable is used to prevent sub-tours for commodity transportation vehicles. The amount of cumulative estimated demand for the vehicle v after visiting the demand point a in the scenario s, period t and the coalition C_m

${u'}_{av'st}^{[C_m]}$ this variable is used to prevent sub-tours for the injured transportation vehicles. The amount of cumulative estimated demand for the vehicle after visiting the demand point a in the scenario s, period t and the coalition C_m

${x^{(1)}}_{vst_{[C_m]}}^{0ad}$ equal to 1 if the demand point a is the first point in the scenario s and the coalition C_m that is visited after the distribution centre d by the vehicle v in the period t, otherwise zero

${x^{(2)}}_{vst_{[C_m]}}^{a0d}$ equal to 1 if the demand point a is the last point in the scenario s and the coalition C_m that is visited before the distribution centre d by the vehicle v in the period t, otherwise zero

${x^{(3)}}_{vst_{[C_m]}}^{a'ad}$ equal to 1 if the demand point a is visited after the point $a'$and then the distribution centre d by the vehicle v in the scenario s, period t and the coalition C_m, otherwise zero

${x^{(4)}}_{v'st_{[C_m]}}^{0ah}$ equal to 1 if the demand point a is the first point in the scenario s and the coalition C_m that is visited after the hospital h by the vehicle v' in the period t, otherwise zero

${x^{(5)}}_{v'st_{[C_m]}}^{a0h}$ equal to 1 if the demand point a is the last point in the scenario s and the coalition C_m that is visited before the hospital by the vehicle v' in the period t, otherwise zero

${x^{(6)}}_{v'st_{[C_m]}}^{a'ah}$ equal to 1 if the demand point a is visited after the point $a'$and then the hospital h by the vehicle v in the scenario s, period t and the coalition C_m , otherwise zero

$y_{hast}^{[C_m]}$ equal to 1 if the hospital h is allocated to the demand point a in the scenario s, period t and the coalition C_m , otherwise zero

Thus, the cooperative post-disaster mathematical model is formulated as follows:

$$z_1 = Min \sum_{d\in D_{[C_m]}} \sum_{v'\in V'_{[C_m]}} \sum_{v\in V_{[C_m]}} \sum_{s\in S} \sum_{t\in T} \sum_{C_m} z_{dvst}^{[C_m]} + {z'}_{hv'st}^{[C_m]} \tag{27}$$

$$\begin{aligned} z_2 = Max &\sum_{a\in A_{[C_m]}} \sum_{a'\in A_{[C_m]}} \sum_{d\in D_{[C_m]}} \sum_{h\in H_{[C_m]}} \sum_{v\in V_{[C_m]}} \sum_{v'\in V'_{[C_m]}} \sum_{s\in S} \sum_{t\in T} \sum_{C_m} {r''}_{st}^{aa'} \left({x^{(3)}}_{vst_{[C_m]}}^{a'ad} + {x^{(6)}}_{v'st_{[C_m]}}^{a'ah} \right) + \\ &\sum_{a\in A_{[C_m]}} \sum_{d\in D_{[C_m]}} \sum_{h\in H_{[C_m]}} \sum_{v\in V_{[C_m]}} \sum_{v'\in V'_{[C_m]}} \sum_{s\in S} \sum_{t\in T} \sum_{C_m} \left[{r_{st}}^{da} \left({x^{(1)}}_{vst_{[C_m]}}^{0ad} + {x^{(2)}}_{vst_{[C_m]}}^{a0d} \right) + {r'}_{st}^{ha} \left({x^{(4)}}_{v'st_{[C_m]}}^{0ah} + {x^{(5)}}_{v'st_{[C_m]}}^{a0h} \right) \right] \end{aligned} \tag{28}$$

St.

$$\sum_{a\in A_{[C_m]}} {x^{(1)}}_{vst_{[C_m]}}^{0ad} = \sum_{a\in A_{[C_m]}} {x^{(2)}}_{vst_{[C_m]}}^{a0d} \qquad \forall d \in D_{[C_m]}, v \in V_{[C_m]}, s \in S, t \in T \tag{29}$$

$$\sum_{a\in A_{[C_m]}} {x^{(4)}}_{v'st_{[C_m]}}^{0ah} = \sum_{a\in A_{[C_m]}} {x^{(5)}}_{v'st_{[C_m]}}^{a0h} \qquad \forall h \in H_{[C_m]}, v' \in V'_{[C_m]}, s \in S, t \in T \tag{30}$$

$$\sum_{a'\in A_{[C_m]}\cup\{0\},\ a\neq a'} {x^{(3)}}_{vst_{[C_m]}}^{a'ad} = {\zeta_{st}}^{da} \qquad \forall d \in D_{[C_m]}, v \in V_{[C_m]}, s \in S, t \in T \tag{31}$$

$$\sum_{a\in A_{[C_m]}\cup\{0\}, a\neq a'} {x^{(6)}}_{v'st_{[C_m]}}^{a'ah} = y_{hast}^{[C_m]} \qquad \forall h \in H_{[C_m]}, v' \in V'_{[C_m]}, s \in S, t \in T \tag{32}$$

$$\tilde{b}_{st}^{\,ar} \le u_{avst}^{[C_m]} \le \rho_{vrt} \qquad \forall r \in R, a \in A_{[C_m]}, v \in V_{[C_m]}, s \in S, t \in T \tag{33}$$

$$u_{avst}^{[C_m]} - u_{a'vst}^{[C_m]} + \rho_{vrt} \sum_{d\in D_{[C_m]}} {x^{(3)}}_{vst_{[C_m]}}^{a'ad} \le \rho_{vrt} - \tilde{b}_{st}^{\,ar} \qquad \forall r \in R, a, a' \in A_{[C_m]}, v \in V_{[C_m]}, s \in S, t \in T \tag{34}$$

$$\Gamma_{\mathrm{ast}} \le {u'}_{av'st}^{[C_m]} \le \rho''_{av'ht} \qquad \forall h \in H_{[C_m]}, a \in A_{[C_m]}, v' \in V'_{[C_m]}, s \in S, t \in T \tag{35}$$

$$ {u'}_{av'st}^{[C_m]} - {u'}_{a'v'st}^{[C_m]} + \rho''_{av'ht} \sum_{h\in H_{[C_m]}} {x^{(6)}}_{v'st_{[C_m]}}^{a'ah} \le \rho''_{av'ht} - \Gamma_{\mathrm{ast}} \qquad \forall a, a' \in A_{[C_m]}, v' \in V'_{[C_m]}, s \in S, t \in T \tag{36}$$

$$\psi_{avst}^{[C_m]} \geq s_{ast} \qquad \forall a \in A_{[C_m]}, v \in V_{[C_m]}, s \in S, t \in T \tag{37}$$

$$\psi_{avst}^{[C_m]} \leq \beta_{ast} - \alpha_{at} \qquad \forall a \in A_{[C_m]},\ v \in V_{[C_m]}, s \in S, t \in T \tag{38}$$

$$-M\left(1 - x^{(3)}{}_{vst_{[C_m]}}^{a'ad}\right) - \left(\psi_{avst}^{[C_m]} - \psi_{a'vst}^{[C_m]} - \alpha_{a't} - \eta''{}_{st}{}^{a'a}\right) \leq 0 \qquad \forall d \in D_{[C_m]}, \forall a', a \in A_{[C_m]}, v \in V_{[C_m]}, s \in S, t \in T \tag{39}$$

$$M\left(1 - x^{(3)}{}_{vst_{[C_m]}}^{a'ad}\right) - \left(\psi_{avst}^{[C_m]} - \psi_{a'vst}^{[C_m]} - \alpha_{a't} - \eta''{}_{st}{}^{a'a}\right) \geq 0 \qquad \forall d \in D_{[C_m]}, \forall a', a \in A_{[C_m]}, v \in V_{[C_m]}, s \in S, t \in T \tag{40}$$

$$-M\left(1 - x^{(1)}{}_{vst_{[C_m]}}^{0ad}\right) - \left(\psi_{avst}^{[C_m]} - q_{dvst}^{[C_m]} - \eta_{st}{}^{ad}\right) \leq 0 \qquad \forall d \in D_{[C_m]}, a \in A_{[C_m]}, v \in V_{[C_m]}, s \in S, t \in T \tag{41}$$

$$M\left(1 - x^{(1)}{}_{vst_{[C_m]}}^{0ad}\right) - \left(\psi_{avst}^{[C_m]} - q_{dvst}^{[C_m]} - \eta_{st}{}^{ad}\right) \geq 0 \qquad \forall d \in D_{[C_m]}, a \in A_{[C_m]}, v \in V_{[C_m]}, s \in S, t \in T \tag{42}$$

$$-M\left(1 - x^{(2)}{}_{vst_{[C_m]}}^{a0d}\right) - \left(z_{dvst}^{[C_m]} - \psi_{avst}^{[C_m]} - \alpha_{at} - \eta_{st}{}^{ad}\right) \leq 0 \qquad \forall d \in D_{[C_m]}, a \in A_{[C_m]}, v \in V_{[C_m]}, s \in S, t \in T \tag{43}$$

$$M\left(1 - x^{(2)}{}_{vst_{[C_m]}}^{a0d}\right) - \left(z_{dvst}^{[C_m]} - \psi_{avst}^{[C_m]} - \alpha_{at} - \eta_{st}{}^{ad}\right) \geq 0 \qquad \forall d \in D_{[C_m]}, a \in A_{[C_m]}, v \in V_{[C_m]}, s \in S, t \in T \tag{44}$$

$$-M\left(1 - x^{(6)}{}_{v'st_{[C_m]}}^{a'ah}\right) - \left(\psi_{av'st}^{[C_m]} - \psi_{a'v'st}^{[C_m]} - \alpha_{a't} - \eta''{}_{st}{}^{a'a}\right) \leq 0 \qquad \forall h \in H_{[C_m]}, a', a \in A_{[C_m]}, v' \in V'_{[C_m]}, s \in S, t \in T \tag{45}$$

$$M\left(1 - x^{(6)}{}_{v'st_{[C_m]}}^{a'ah}\right) - \left(\psi_{av'st}^{[C_m]} - \psi_{a'v'st}^{[C_m]} - \alpha_{a't} - \eta''{}_{st}{}^{a'a}\right) \geq 0 \qquad \forall h \in H_{[C_m]}, a', a \in A_{[C_m]}, v' \in V'_{[C_m]}, s \in S, t \in T \tag{46}$$

$$-M\left(1 - x^{(4)}{}_{v'st_{[C_m]}}^{0ah}\right) - \left(\psi_{av'st}^{[C_m]} - q'_{hv'st}{}^{[C_m]} - \eta'{}_{st}{}^{ah}\right) \leq 0 \qquad \forall h \in H_{[C_m]}, a \in A_{[C_m]}, v' \in V'_{[C_m]}, t \in T \tag{47}$$

$$M\left(1 - x^{(4)}{}_{v'st_{[C_m]}}^{0ah}\right) - \left(\psi_{av'st}^{[C_m]} - q'_{hv'st}{}^{[C_m]} - \eta'{}_{st}{}^{ah}\right) \geq 0 \qquad \forall h \in H_{[C_m]}, a \in A_{[C_m]}, v' \in V'_{[C_m]}, s \in S, t \in T \tag{48}$$

$$-M\left(1 - x^{(5)}{}_{v'st_{[C_m]}}^{a0h}\right) - \left(z'_{hv'st}{}^{[C_m]} - \psi_{av'st}^{[C_m]} - \alpha_{at} - \eta'{}_{st}{}^{ah}\right) \leq 0 \qquad \forall h \in H_{[C_m]}, a \in A_{[C_m]}, v' \in V'_{[C_m]}, s \in S, t \in T \tag{49}$$

$$M\left(1 - x^{(5)}{}_{v'st_{[C_m]}}^{a0h}\right) - \left(z'_{hv'st}{}^{[C_m]} - \psi_{av'st}^{[C_m]} - \alpha_{at} - \eta'{}_{st}{}^{ah}\right) \geq 0 \qquad \forall h \in H_{[C_m]}, a \in A_{[C_m]}, v' \in V'_{[C_m]}, s \in S, t \in T \tag{50}$$

$$g_{ahst}^{[C_m]} \leq \sum_{v'=1} \rho''_{av'ht} \qquad \forall h \in H_{[C_m]}, a \in A_{[C_m]}, s \in S, t \in T \tag{51}$$

$$\sum_{a=1} g_{ahst}^{[C_m]} \leq \rho'_{ht} \qquad \forall h \in H_{[C_m]}, s \in S, t \in T \tag{52}$$

$$\sum_{h=1} g_{ahst}^{[C_m]} = \Gamma_{\mathrm{ast}} \qquad \forall a \in A_{[C_m]}, s \in S, t \in T \tag{53}$$

$$x^{(1)}{}_{vst_{[C_m]}}^{0ad},\ x^{(2)}{}_{vst_{[C_m]}}^{a0d},\ x^{(3)}{}_{vst_{[C_m]}}^{a'ad},\ x^{(4)}{}_{v'st_{[C_m]}}^{0ah},$$
$$x^{(5)}{}_{v'st_{[C_m]}}^{a0h},\ x^{(6)}{}_{v'st_{[C_m]}}^{a'ah},\ y_{hast}^{[C_m]},\in\{0,1\} \qquad \forall d\in D_{[C_m]}, a,a'\in A_{[C_m]}, v\in V_{[C_m]}, v'\in V'_{[C_m]}, h\in H_{[C_m]}\ t\in T \tag{54}$$

$$z_{dvst}^{[C_m]}, {z'_{hv'st}}^{[C_m]}, g_{ahst}^{[C_m]}, q_{dvst}^{[C_m]}, {q'_{hv'st}}^{[C_m]}, \psi_{avst}^{[C_m]},$$
$$u_{avst}^{[C_m]}, {u'_{av'st}}^{[C_m]}\geq 0 \qquad \forall d\in D_{[C_m]}, a\in A_{[C_m]}, v\in V_{[C_m]}, v'\in V'_{[C_m]}, h\in H_{[C_m]}\ t\in T \tag{55}$$

The objective function (27) describes the minimization of relief time in all coalitions. The relief time is equal to the return time of all relief vehicles and vehicles carrying the injured. The objective function (28) is to maximize the reliability of routes between distribution centres and between distribution centres and affected areas in all coalitions. This objective function maximizes the reliability of the routes between the point of demand to the point of other demand, distribution centres to the point of demand, and hospitals to the point of demand, respectively. Constraints (29) show the route from distribution centres to demand points in the coalition state. Constraints (30) show the route from the hospital to the demand points in the coalition state. Constraints (31) define the relationship between allocation and routing variables. These constraints indicate that if a distribution centre is allocated to a demand centre, the route must be allocated to them. Constraints (32) show the route of vehicles from the demand points to the hospital in the coalition state. These constraints implies that if a hospital is allocated to a demand centre, a route must be allocated to them. Constraints (33) and (34) are related to the elimination of sub-tours for distribution vehicles in the coalition state. Constraints (35) and (36) are related to the elimination of sub-tours in the coalition state for the vehicles that transport the injured. Constraints (37) represent the time of entry in the time window for each demand point in each period and in each coalition. These constraints demonstrate that the arrival time must be larger than the beginning of the time window. Constraints (38) are the constraints of exit from the time window. These constraints show that the arrival time must be less than the difference between the completion of the window time and the service time. Constraints (39)–(50) show the schedule of vehicles in the coalition state. In fact, constraints (39)–(44) show the schedule of vehicles for transporting relief commodities and constraints (45)–(50) show the schedule of vehicles for transporting the injured. Constraints (51) show the transportation capacity of the injured people in the coalition state. These constraints mean that the number of injured transferred from demand points to hospitals must be less than the capacity of the vehicles. Constraints (52) ensure that, in the coalition state, the number of the injured transported to the hospital is not higher than the capacity of the hospital. Constraints (53) indicate that the total number of people transferred from demand points to hospitals is equal to the number of injured people requesting treatment at the demand. Also, these constraints implies that all injured people should be transported to the hospital in the coalition state. Constraints (54) represent the binary variables of the model. Constraints (55) represent the positive variables of the model.

5.1. The process of converting the stochastic model into deterministic model

In this research, the chance constrained programming approach has been used for converting the proposed model into the deterministic state. Considering that the second stage of the model (routing model) is two-objective, to deal with the uncertainty, chance constrained programming and goal programming approaches are used simultaneously. For more information on how to convert a stochastic model into deterministic state using these two approaches, refer to [50].

Now according to the above-mentioned approaches, the constraints (15), (16), and (21) of the first stage of the model will be converted to the deterministic state as follows.

$$\left[E({b_{st}}^{ar})+\varphi^{-1}(1-\alpha_i)\sqrt{Var({b_{st}}^{ar})}\right]-{\pi_{st}}^{ar}=\sum_{d\in D}{l'_{st}}^{dar} \qquad \forall a\in A, r\in CR, s\in S, t\in T \tag{56}$$

$$\left[E({b_{st}}^{ar})+\varphi^{-1}(1-\alpha_i)\sqrt{Var({b_{st}}^{ar})}\right]-{\pi_{st}}^{ar}=\sum_{j\in J}{l''_{st}}^{jar} \qquad \forall a\in A, r\in RI, s\in S, t\in T \tag{57}$$

$${l'''_{st}}^{dr}=\sum_{a=1}{n_{st}}^{da}.\left[E({b_{st}}^{ar})+\varphi^{-1}(1-\alpha_i)\sqrt{Var({b_{st}}^{ar})}\right] \qquad \forall d\in D, r\in CR, s\in S, t\in T \tag{58}$$

Also, the constraints (33) and (34) of the second stage of the model will be converted to the deterministic state as follows.

$$\left[E({b_{st}}^{ar})+\varphi^{-1}(1-\alpha_i)\sqrt{Var({b_{st}}^{ar})}\right]\leq {u_{avst}}^{[C_m]}\leq \rho_{vrt} \qquad \forall r\in R, a\in A_{[C_m]}, v\in V_{[C_m]}, s\in S, t\in T \tag{59}$$

$$u_{avst}^{[C_m]}-u_{a'vst}^{[C_m]}+\rho_{vrt}\sum_{d\in D_{[C_m]}}x^{(3)}{}_{vst_{[C_m]}}^{a'ad}$$
$$\leq \rho_{vrt}-\left[E({b_{st}}^{ar})+\varphi^{-1}(1-\alpha_i)\sqrt{Var({b_{st}}^{ar})}\right] \qquad \forall r\in R, a,a'\in A_{[C_m]}, v\in V_{[C_m]}, s\in S, t\in T \tag{60}$$

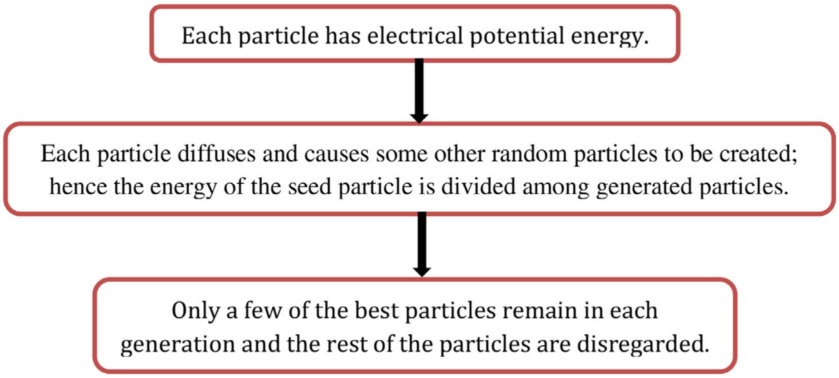

Fig. 5. The flowchart of the traits of fractals in the MOSFS.

6. Solution method

In this section, two solution approaches are used in this study. The first approach is the Epsilon-Constraint Algorithm. The second approach is SFS algorithm.

6.1. Epsilon-constraint algorithm

Due to the single objective of the first stage model, this model has been solved by GAMS 28.2.0 and BARON solver. Also due to the multi-objective of the second stage model, this model has been solved using Epsilon- Constraint algorithm [51,52]. In Epsilon-Constraint algorithm, one of the objective functions will be selected to be optimized and the other objective functions will act as the constraints. The general form of this algorithm is as follows:

$$\begin{aligned} & \min f_j(x) j \in \{1, \ldots, k\} \\ & s.t. \\ & \quad f_i(x) \le \varepsilon_i, \forall i \in \{1, \ldots, k\}, i \ne j \\ & \quad x \in S \end{aligned} \tag{61}$$

where, S is the feasible solution space, and ε_i is the upper bound of i-th objective function. Also $f_j(x) j \in \{1, \ldots, k\}$is the j-th objective func tion chosen to be optimized. For more information about this method, you can refer to [53–55].

6.2. Multi-objective stochastic fractal search (MOSFS) algorithm

In this section, the MOSFS algorithm is provided by [56] for the first time which utilizes Diffusion-Limited Aggregation (DLA). This algorithm is based on a basic mathematical concept which is called "fractal." Fractal is a feature in an object which causes self-similarity. DLA is one of the most commonly employed approaches to create fractal-shaped objects. In this regard, MOSFS is one of the population-based and stochastic optimization techniques and is inspired by the natural phenomenon of fractal growth. This algorithm is based on the theory of potential and the phenomenon of fractal growth and according to three basic physical laws to search the problem space. The MOSFS algorithm is superior to other successful algorithms in previous research based on several criteria including convergence speed, success rate, and computation time in solving problems with different sizes [57]. The flowchart of the traits of fractals in the MOSFS is shown in Fig. 5.

In the MOSFS, there are two main phases that contain the first is the diffusion phase (exploitation) and the second is the update phase (exploration). In terms of the diffusion process, according to the concept of fractals, the algorithm employs what's named a diffusion process by producing new points after taking a random walk step. This phase raises the chance of finding the global minima as well as prevents being trapped in the local minima. Hence, the algorithm simulates how a point in the group updates its position based on the position of other points in the group in the second phase. Unlike the first process in fractal that causes a dramatic rise in the number of participating points, a static diffusion phase for MOSFS is considered. As the best-generated particle from the diffusing phase is the only particle that is considered, and the rest of the particles are discarded. Additionally, for the efficient exploration of the problem space, MOSFS utilizes some random approaches as updating phases. In other words, the updating phase conducts diversification (exploration) in MOSFS. The update process is the process of creating a new solution through mixing with other solutions randomly, this is performed through two update steps, the first step involves element-wise updates, while the second update step is just a weighted sum of multiple vectors in the population. For more details about the MOSFS algorithm and multi-objective SFS refers to some references that contain [56–58].

In the following, the definition of the chromosome, the multi-objective MOSFS operators, stopping criterion, and constraint handling are discussed. An important point is that the first stage of the proposed model has been solved using the

Table 2
Parameters set in the MOSFS.

Start point	Maximum energy	Population Size	Max iteration	Maximum Diffusion Number	Remaining points	Distributed Energy
5	2500(joule)	80	100	10	0.01	99%

GAMS software. Also, because the second stage of the proposed model is NP-hard and multi-objective, it has been solved using the multi-objective MOSFS algorithm.

The multi-section chromosome, cross-over and mutation presented in this study are shown in Supplementary material due to the limitation of pages. In this study, two types of stop criteria are considered for the algorithm. If either of these two states occurs, the algorithm will stop. These two states are as follows:

- Stop after a specified number of iterations without improvement of the solution.
- Stop after reaching a specified number of iterations (maximum iteration)

Then, the input values of the MOSFS are provided in Table 2, which includes the start point, maximum energy, population size, max iteration, maximum diffusion number, remaining points, and distributed energy. Accordingly, this algorithm is implemented by MATLAB 2020b Software on a PC with 6 GHz RAM.

Many constraints are satisfied with the definition of chromosomes, but for the rest of the constraints, the penalty strategy is used. For example, calculating the number of violations of constraints (51) and (52) is given here. The number of penalties for constraints is given as Eqs. (62) and (63):

$$A_c = O^{51}_{hast} = \max_{\forall h,a,s,t}\left\{0, g^{[C_m]}_{ahst} - \sum_{v'=1}\rho''_{av'ht}\right\} \forall c = 1,2 \tag{62}$$

$$B_c = O^{52}_{hst} = \max_{\forall h,s,t}\left\{0, \sum_{a=1} g^{[C_m]}_{ahst} - \rho'_{ht}\right\} \qquad \forall c = 1,2 \tag{63}$$

where index C shows the number of objective functions and A_c and B_c are fixed penalties of cth objective functions. Also, O^{51}_{hast} and O^{52}_{hst} indicate fixed penalties of constraints 51 and 52. Additionally, $\rho''_{av'ht}$and $\rho'_{ht}$are the parameters of the second model and $g^{[C_m]}_{ahst}$ is the variable of the second model.

The total amount of violation of chromosomes is calculated from the sum of their individual violations according to the Eq. (64):

$$Violation_c = (A_c + B_c) * iteration \tag{64}$$

where $Violation_c$ demonstrates the total penalties of the mathematical model for the cth objective function and *iteration* is the iteration number of the algorithm.

It should be noted that in Eq. (64), the amount of penalty is fixed and will vary according to the number of iterations. Therefore, the final value of objective functions for the chromosomes suffering the penalty is Eq. (65):

$$f_c = f_c + penalty * Violation_c \qquad \forall c = 1,2 \tag{65}$$

where f_c shows the dynamic final penalty of the objective function c.

6.3. Numerical examples

This section describes the benchmark functions used to compare the proposed algorithms. Benchmark functions are groups of functions that can be used to test the performance of any optimization problem, unimodal or multimodal, constrained or unconstrained, with continuous or discrete variables. Since the benchmark functions existing in the literature are not available for the proposed model due to its novelty, a specific approach is required to design the test problems that can investigate the velocity of convergence, robustness, precision, and performance of the proposed algorithms. In this paper, a set of test problems in different sizes were designed to investigate and compare the proposed procedures. Ten experiment problems are divided into two classifications i.e., small sizes (1 to 10) and medium sizes (11 to 20). The sizes of the problem instances are introduced in Table 3.

On the other hand, the comparison of methods in the term of multi-objective model is difficult. Therefore, many researchers have suggested several metrics to evaluate the quality of Pareto fronts for the meta-heuristic [58]. Next, two assessment metrics including Mean Ideal Distance (MID) and Spacing Metric (SM) have been used in this paper.

- **MID:** The goal of the MID is the distance between the Pareto optimal solutions. This metric is formulated based on Eq. (66).

$$MID = \frac{\sum_i^n \sqrt{\left(\frac{f_{1i} - f_1^{best}}{f^{\max}_{1,total} - f^{\min}_{1,total}}\right)^2 + \left(\frac{f_{2i} - f_2^{best}}{f^{\max}_{2,total} - f^{\min}_{2,total}}\right)^2}}{n} \tag{66}$$

Table 3
The samples for experiment problems.

No	Problem size	Affected area	Distribution centre	Hospital	No	Problem size	Affected area	Distribution centre	Hospital
1	small	2	1	1	11	medium	8	3	7
2	small	2	2	1	12	medium	9	3	7
3	small	3	1	2	13	medium	9	3	8
4	small	3	2	2	14	medium	10	2	8
5	small	4	1	3	15	medium	10	3	8
6	small	4	2	3	16	medium	11	4	8
7	small	5	2	4	17	medium	11	5	8
8	small	6	2	5	18	medium	12	5	9
9	small	6	3	6	19	medium	12	5	10
10	Small	7	3	6	20	medium	13	5	11

Table 4
The outcomes of assessment metrics of the proposed methods.

No.	Epsilon-constraint					MOSFS approach Error						
	First OBJ	Second OBJ	SM	MID	Time(s)	First OBJ	Second OBJ	SM	MID	Time(s)	First OBJ error %	Second OBJ error %
1	124.8	1.74	0	0	2	124.8	1.74	0	0	2	0	0
2	126.5	1.79	0	0	2	126.5	1.79	0	0	2	0	0
3	128.6	1.83	0	0	2	128.6	1.83	0	0	2	0	0
4	129.3	1.76	0	0	17	130.2	1.76	0	0	4	0.6	0
5	131.8	1.47	0	0	26	131.8	1.47	0	0	6	0	0
6	132.1	1.89	0.08	6.51	33	134.1	1.88	0.09	6.66	4	1.4	0.5
7	132.3	2.08	0.08	6.55	52	135.8	1.99	0.10	6.68	7	2.5	4.3
8	132.9	1.7	0.09	6.60	93	136.1	1.65	0.12	6.69	9	2.3	2.9
9	134.0	2.76	0.15	6.71	142	137.7	2.71	0.18	6.73	14	2.6	1.8
10	138.2	2.89	0.14	6.60	571	140.3	2.86	0.16	6.70	18	1.4	1.0
11	2362.3	3.37	0.13	6.64	1351	2371.5	3.33	0.16	6.68	23	0.3	1.1
12	2379.7	3.49	0.22	6.73	2875	2386.4	3.21	0.26	6.77	26	0.2	0.8
13	2396.6	3.56	0.16	6.71	3412	2402.1	3.54	0.24	0.75	29	0.2	0.5
14	2418.8	3.64	0.14	6.70	3742	2426.0	3.60	0.19	6.75	32	0.2	1.0
15	2425.4	3.71	0.16	6.75	4376	2432.2	3.67	0.20	6.79	36	0.2	0.1
16	2437.5	3.89	0.17	6.78	4981	2443.2	3.75	0.21	6.84	38	0.2	3.5
17	2449.6	3.94	0.15	6.80	5220	2456.6	3.89	0.19	6.85	40	0.2	1.2
18	2561.3	4.12	0.15	6.83	6412	2572.9	3.99	0.20	6.87	41	0.4	3.1
19	2570.0	4.18	0.17	6.83	7730	2578.5	4.09	0.19	6.88	42	0.3	2.1
20	2581.1	4.23	0.19	6.86	8912	2589.2	4.15	0.20	6.89	45	0.3	1.8

where f_{ji} indicates the value of jth objective for the ith solution in Pareto frontier and $f_{j,total}^{min}$ and $f_{j,total}^{max}$ illustrate the minimum and maximum amounts of the ith objective between solutions in Pareto frontier. In addition, n represents the number of Pareto solutions. Low values of this metric indicate high performance and quality.

- **SM:** The SM demonstrates the uniformity of the spread of the non-dominated set of solutions. The SM metric is computed according to Eq. (67).

$$SM = \frac{\sum_{i=1}^{n-1} \left| d_i - \bar{d} \right|}{(n-1)\,\bar{d}} \tag{67}$$

where $\bar{d}$ indicates the average Euclidean distance and d_i is the Euclidean distance between two adjacent Pareto solutions. Lower values of SM indicate higher efficiency. Hence, when SM is close to zero, the distance among all the adjacent solutions will be equal.

The performance of suggested methods is investigated by assessment metrics i.e. MID and SM are as the comparison metrics for attained Pareto sets under each experiment problem. Then, the outcomes are provided in Table 4.

The first and second objective functions as well as the solution time are the output of GAMS and MATLAB. The MID and SM metrics were also calculated using Eqs. (66) and (67), and the errors values were computed as a percentage. For example in Table 4 the errors of the 20th Pareto point were calculated as: Objective 1 error: [(2589.2-2581.1)/2589.2]*100=0.3%, Objective 2 error: [(4.23-4.15)/4.23]*100=1.8%. As shown in Table 4, the average MID value for the Epsilon-Constraint method and MOSFS algorithm is 5.03 and 4.77, respectively. Therefore, the results indicate the accuracy of the algorithm in terms of this criterion. The average value of SM is 0.109 for the epsilon constraint and 0.134 for the MOSFS algorithm. As can be seen, the mean value of SM for the two methods of Epsilon constraint and MOSFS is very close to each other and zero. Examination of the computational time also shows that with increasing the sizes of the problem, the computational time of the Epsilon-Constraint approach increases sharply, while the computational time of the MOSFS has a much slower speed

Table 5
The case study scenarios.

Scenario	Richter
Mosha Fault-night	6-10
Mosha Fault-day	6-10
North Tehran Fault-night	6-10
North Tehran Fault-day	6-10
South Ray Fault-night	6-10
South Ray Fault-day	6-10
Floating Fault-night	6-10
Floating Fault-day	6-10

Table 6
Set of suppliers of relief commodities (first stage parameters).

No	Region Number	Suppliers	Establishment Cost $			Storage Capacity(m^3)		
			Small	Medium	Large	Small	Medium	Large
1	1	Ozgol Base	10000	30000	50000	50000	100000	200000
2	2	Sa'adat Abad Base	10000	30000	50000	50000	100000	200000
3	3	Vali Asr Base	10000	30000	50000	50000	100000	200000
4	4	Vafadar Base	10000	30000	50000	50000	100000	200000

with an average of 21 seconds. Therefore, according to this criterion, the proposed meta-heuristic solution approach can be trusted. Therefore, according to the above explanations, the results of MOSFS for large-scale problem solving (case study) can be trusted.

7. Case study

In this research, the efficiency of the proposed model is tested by the real-life data of a case study (including the ten regions of the district 1 of Tehran city). District 1 of Tehran is in the heights of Tehran, with an area of 49.6 km^2 and has the population of nearly 487000 people. The massive number of made and half-made buildings will close the region^{\prime}s population to 500000 soon.

In the case study, 8 distribution centres are considered. The costs of establishing Farmanieh, Evin, and Golab Darreh distribution centres are $ 50,000, $ 55,000, and $ 50,000, respectively. The establishment costs of distribution centres of the Jamaran, Araj, and Tajrish are $ 60,000, $ 50,000, and $ 55,000, respectively. The establishment costs of Chizar and Ozgol distribution centres are $ 7,000. The storage capacities of Farmanieh, Evin, and Golab Darreh distribution centres are 400,000, 500,000, and 500,000 cubic meters, respectively. The storage capacities of Jamaran, Araj, and Tajrish distribution centres are 500,000, 300,000, and 400,000 cubic meters, respectively. Finally, the storage capacities of Chizar and Ozgol distribution centres are 500,000 and 600,000 cubic meters.

The case study is a 7-magnitude earthquake in the scenario of South Ray^{\prime}s fault during the day. Various studies considered various scenarios for disaster relief operations at the time of the earthquake. In this research, the approach of Khojasteh and Macit [59] has been used for scenario selection. Hence, the scenarios considered in the case study are provided in Table 5. The magnitude scale shown in the table has the accuracy of 0.1. Therefore, considering the existence of 4 faults (Masha, north of Tehran, south of Ray, floating), two types of occurrence time (day and night) and 41 earthquake intensity scenarios (6-10 Richter scale), 328 scenarios are investigated. It should be noted that since the scenarios are defined based on the time, place, and severity of the earthquake, due to the unpredictability of the time, place, and severity of the earthquake, according to decision-makers, the possibility of all scenarios occurring is considered equal. Therefore, there is no weighting of scenarios in the objective function. The designed scenarios will affect the estimated amount of relief commodities (in the simulation approach). Thus, each scenario has its own amount of demand. Parameters and variables of the two stage of the proposed mathematical model will also affected by the scenarios. For example, each scenario will destroy the communication routes due to the severity of the occurrence and will affect the reliability of the routes. Moreover, suppliers of relief commodities for district 1 are shown in Table 6.

The time interval between hospitals and demand points in minutes is provided in Table 7.

7.1. Computational results

In this sub-section, the results of the simulation for a 7-magnitude earthquake during the day are shown in Fig. 6. This figure shows the estimation of distribution functions of relief commodities. As can be seen, the distribution functions are drinking water Weibull (0.982), non-drinking water 3-parameter Lognormal (0.979), medicine Exponential (0.985), food loglogistic (0.970), tent Smallest Extreme value (0.955) and blanket Normal (0.970).

Table 7
Time interval between hospital $\boldsymbol{h}$ and demand point $\boldsymbol{a}$ (second stage parameter).

No.	Affected AreaHospital	Taleqani	Shohada Tajrish	baqiyatallah	Farhangian	Nur Afshar	505 Artesh	Mahak	Daneshvari	Akhtar	Chamran
1	Hesar Buali	30	35	18	48	40	50	30	75	60	65
2	Farmanieh	45	80	65	20	57	54	21	65	18	64
3	Evin	25	50	80	85	45	60	56	72	52	70
4	Velenjak	51	42	90	53	42	20	25	80	40	60
5	Zafaranieh	60	20	50	30	58	64	85	35	45	63
6	Darband	45	79	84	58	100	72	95	29	80	60
7	Emamzadeh Qasem	90	93	50	54	54	87	74	54	30	51
8	Dezashib	84	20	65	93	96	120	110	100	93	120
9	Jamaran	60	60	85	50	40	50	64	81	60	37
10	Niavaran	50	70	45	50	82	95	80	140	38	37
11	Kashanak	81	56	72	52	70	30	40	50	61	72
12	Dar Abad	61	30	80	50	60	61	81	82	62	54
13	Ferdows Park	51	85	35	45	63	64	84	35	72	76
14	Tajrish	37	80	29	40	80	50	64	95	79	26
15	Qeytarieh	45	48	65	54	30	20	57	54	20	30
16	Chizar	62	80	90	76	35	85	30	60	85	54
17	Hekmat	30	100	72	95	50	53	42	30	53	37
18	Araj	50	54	87	74	65	30	58	64	30	80
19	Ozgol	90	96	120	110	55	40	30	50	60	85

Table 8
Allocation of affected areas to distribution centres (the variable$\boldsymbol{z}_{dast}$).

No	Distribution Centres	Affected Area
1	d_1: Farmanieh Base	a_1: Hesar Buali
		a_2: Farmanieh
2	d_2: Evin Base	a_3: Velenjak
		a_4: Zafaranieh
		a_5: Evin
		a_6: Emamzadeh Qasem
3	d_3: Araj Base	a_7: Darband
		a_8: Dezashib
		a_9: Jamaran
		a_{10}: Niavaran
		a_{11}: Kashanak
4	d_4: Tajrish Base	a_{12}: Ferdows Park
		a_{13}: Tajrish
		a_{14}: Qeitarieh
		a_{15}: Dar Abad
5	d_5: Ozgol Base	a_{16}: Chizar
		a_{17}: Hekmat
		a_{18}: Araj
		a_{19}: Ozgol

To evaluate the validity of the model, the flows of each synapse are run for each infrastructure. The next step in verifying the validity of the model is to investigate the boundary values. In this approach, the zero-magnitude and 10-magnitude scenarios enter the system, and the behaviour of the system is monitored. Fig. 7 is a comparison between the results achieved and the values obtained from the real system. According to this figure, considering the normality and the 95% confidence interval, it can be concluded that the proposed model is an accurate example of the real system performance. This figure is the results of hypothesis testing of H_0: $\mu = \mu_0$ against H_1: $\mu \neq \mu_0$. The value of $\mu_0$is the expected value of the estimated parameter. As can be seen, the amount of drinking water, non-drinking water, medicine, food, tents, and blankets is respectively estimated to be 96, 92, 94, 96, 93 and 95 percent like the real system. So, according to the simulation results, the proposed model can be trusted, and it can be concluded that the proposed model shows an accurate estimate of the performance of the real system.

Then, the first stage of the proposed model is solved using the GAMS software. After solving the first stage model, Farmanieh base, Evin base, Araj base, Tajrish base and Ozgol Base were selected as distribution centres (variable s_{dst}). Also, after solving the first stage model, allocation of distribution centres to the affected areas will be determined (variablez_{dast}). Table 8 provides the result of solving the first stage model. For example, the Farmanieh base is allocated to Hesar Buali and Farmanieh region and Evin base to Velenjak, Zafaranieh, Evin and Emamzadeh Qasem region.

Table 9 shows the routing of distribution vehicles of relief commodities. For example, in the sixth coalition, the first distributor goes to the affected areas two, one, four, and six, respectively, and finally returns to the distribution centre. Also, the second distributor will return to the distribution centre after visiting the affected areas five and three.

Table 9
Routing of distribution vehicles of relief commodities.

	Route 1	Route 2	Route 3	Route 4	Route 5
$\mathbf{s}_1 = \{1\}$	$d_1 - a_2 - a_1 - d_1$	-	-	-	-
$\mathbf{s}_2 = \{2\}$	-	$d_2 - a_5 - a_4 - a_3 - a_6 - d_2$	-	-	-
$\mathbf{s}_3 = \{3\}$	-	-	$d_3 - a_7 - a_8 - a_{10} - a_{11} - a_9 - d_3$	-	-
$\mathbf{s}_4 = \{4\}$	-	-	-	$d_4 - a_{14} - a_{12} - a_{13} - a_{15} - d_4$	-
$\mathbf{s}_5 = \{5\}$	-	-	-	-	$d_5 - a_{16} - a_{17} - a_{19} - a_{18} - d_5$
$\mathbf{s}_6 = \{1, 2\}$	$d_1 - a_2 - a_1 - a_4 - a_6 - d_1$	$d_2 - a_5 - a_3 - d_2$	-	-	-
$\mathbf{s}_7 = \{1, 3\}$	$d_1 - a_2 - a_7 - a_{10} - d_1$	-	$d_3 - a_1 - a_8 - a_9 - a_{11} - d_3$	-	-
$\mathbf{s}_8 = \{1, 4\}$	$d_1 - a_2 - a_{12} - a_{13} - d_1$	-	-	$d_4 - a_{14} - a_1 - a_{15} - d_4$	-
$\mathbf{s}_9 = \{1, 5\}$	$d_1 - a_2 - a_{17} - a_{16} - d_1$	-	-	-	$d_5 - a_{19} - a_1 - a_{18} - d_5$
$\mathbf{s}_{10} = \{2, 3\}$	-	$d_2 - a_5 - a_{10} - a_6 - a_7 - d_2$	$d_3 - a_8 - a_4 - a_3 - a_{11} - a_9 - d_3$	-	-
$\mathbf{s}_{11} = \{2, 4\}$	-	$d_2 - a_3 - a_5 - a_{14} - a_{12} - d_2$	-	$d_4 - a_6 - a_4 - a_{15} - a_{13} - a_{16} - d_4$	-
$\mathbf{s}_{12} = \{2, 5\}$	-	$d_2 - a_{19} - a_4 - a_{16} - a_6 - d_2$	-	-	$d_5 - a_5 - a_{17} - a_{18} - a_3 - d_5$
$\mathbf{s}_{13} = \{3, 4\}$	-	-	$d_3 - a_{15} - a_8 - a_7 - a_{11} - a_{14} - d_3$	$d_4 - a_{10} - a_{12} - a_{13} - a_9 - d_4$	-
$\mathbf{s}_{14} = \{3, 5\}$	-	-	$d_3 - a_7 - a_{16} - a_{17} - a_9 - a_{18} - d_3$	-	$d_5 - a_8 - a_{11} - a_{10} - a_{19} - d_5$
$\mathbf{s}_{15} = \{4, 5\}$	-	-	-	$d_4 - a_{13} - a_{12} - a_{17} - a_{15} - d_4$	$d_5 - a_{14} - a_{16} - a_{19} - a_{18} - d_5$
$\mathbf{s}_{16} = \{1, 2, 3\}$	$d_1 - a_2 - a_{10} - a_{11} - d_1$	$d_2 - a_1 - a_3 - a_4 - d_2$	$d_3 - a_7 - a_6 - a_8 - a_5 - a_9 - d_3$	-	-
$\mathbf{s}_{17} = \{1, 2, 4\}$	$d_1 - a_2 - a_6 - a_{13} - d_1$	$d_2 - a_4 - a_{15} - d_2$	-	$d_4 - a_{14} - a_5 - a_{12} - a_1 - d_4$	-
$\mathbf{s}_{18} = \{1, 2, 5\}$	$d_1 - a_5 - a_4 - a_1 - d_1$	$d_2 - a_2 - a_{17} - a_{19} - a_3 - d_2$	-	-	$d_5 - a_{16} - a_6 - a_{18} - d_5$
$\mathbf{s}_{19} = \{1, 3, 4\}$	$d_1 - a_{14} - a_2 - a_{15} - d_1$	-	$d_3 - a_1 - a_7 - a_8 - a_{10} - a_9 - d_3$	$d_4 - a_{12} - a_{11} - a_{13} - -d_4$	-
$\mathbf{s}_{20} = \{1, 3, 5\}$	$d_1 - a_8 - a_{10} - a_{11} - d_1$	-	$d_3 - a_7 - a_2 - a_{16} - a_{17} - a_9 - d_3$	-	$d_5 - a_1 - a_{19} - a_{18} - d_5$
$\mathbf{s}_{21} = \{1, 4, 5\}$	$d_1 - a_2 - a_1 - a_{17} - a_{19} - d_1$	-	-	$d_4 - a_{12} - a_{13} - a_{15} - d_4$	$d_5 - a_{14} - a_{16} - a_{18} - d_5$
$\mathbf{s}_{22} = \{2, 3, 4\}$	-	$d_2 - a_5 - a_{12} - a_{13} - d_2$	$d_3 - a_6 - a_{10} - a_{11} - a_4 - a_3 - a_9 - d_3$	$d_4 - a_{15} - a_7 - a_8 - a_{14} - d_4$	-
$\mathbf{s}_{23} = \{2, 3, 5\}$	-	$d_2 - a_5 - a_7 - a_4 - a_3 - d_2$	$d_3 - a_8 - a_{10} - a_{11} - a_{17} - a_{19} - a_9 - d_3$	-	$d_5 - a_{16} - a_{18} - a_6 - d_5$
$\mathbf{s}_{24} = \{3, 4, 5\}$	-	-	$d_3 - a_{17} - a_{15} - a_{12} - a_{11} - a_{10} - a_9 - d_3$	$d_4 - a_8 - a_{13} - a_{16} - -a_7 - d_4$	$d_5 - a_{14} - a_{19} - a_{18} - d_5$
$\mathbf{s}_{25} = \{1, 2, 3, 4\}$	$d_1 - a_{12} - a_1 - d_1$	$d_2 - a_2 - a_4 - a_3 - d_2$	$d_3 - a_5 - a_7 - a_8 - a_{14} - a_{13} - a_9 - d_3$	$d_4 - a_{10} - a_{11} - a_{15} - a_6 - d_4$	-
$\mathbf{s}_{26} = \{1, 2, 3, 5\}$	$d_1 - a_2 - a_1 - a_4 - a_3 - d_1$	$d_2 - a_8 - a_{10} - a_6 - d_2$	$d_3 - a_{16} - a_{17} - a_{19} - a_{11} - a_9 - d_3$	-	$d_5 - a_5 - a_7 - a_{18} - d_5$
$\mathbf{s}_{27} = \{1, 2, 4, 5\}$	$d_1 - a_2 - a_1 - a_5 - d_1$	$d_2 - a_3 - a_{12} - a_{13} - a_4 - d_2$	-	$d_4 - a_{14} - a_6 - a_{15} - d_4$	$d_5 - a_{16} - a_{17} - a_{19} - a_{18} - d_5$
$\mathbf{s}_{28} = \{1, 2, 3, 5\}$	$d_1 - a_1 - a_7 - a_{17} - a_8 - d_1$	$d_2 - a_5 - a_4 - a_6 - d_2$	$d_3 - a_2 - a_{10} - a_{16} - a_{19} - a_{11} - a_9 - d_3$	-	$d_5 - a_3 - a_{18} - d_5$
$\mathbf{s}_{29} = \{2, 3, 4, 5\}$	-	$d_2 - a_{15} - a_4 - a_3 - a_6 - d_2$	$d_3 - a_{16} - a_{17} - a_{13} - a_5 - a_{14} - d_3$	$d_4 - a_7 - a_8 - a_{10} - a_{11} - a_{12} - d_4$	$d_5 - a_{19} - a_{18} - a_9 - d_5$
$\mathbf{s}_{30} = \{1, 2, 4, 3, 5\}$	$d_1 - a_2 - a_{19} - a_{16} - a_1 - d_1$	$d_2 - a_6 - a_{17} - a_{12} - a_{13} - d_2$	$d_3 - a_5 - a_4 - a_3 - a_{11} - a_9 - d_3$	$d_4 - a_{14} - a_{15} - d_4$	$d_5 - a_7 - a_8 - a_{10} - a_{18} - d_5$

Table 10
Characteristics of the routes.

Coalition	Route 1		Route 2		Route 3		Route 4		Route 5	
	Travel Time	Reliability	Travel Time	Reliability	Travel Time	Reliability	Travel Time	Reliability	Travel Time	Reliability
$\boldsymbol{s}_1 = \{1\}$	515618	2.39	-	-	-	-	-	-	-	-
$\boldsymbol{s}_2 = \{2\}$	-	-	515625	2.14	-	-	-	-	-	-
$\boldsymbol{s}_3 = \{3\}$	-	-	-	-	515731	2.31	-	-	-	-
$\boldsymbol{s}_4 = \{4\}$	-	-	-	-	-	-	515598	2.08	-	-
$\boldsymbol{s}_5 = \{5\}$	-	-	-	-	-	-	-	-	515658	2.25
$\boldsymbol{s}_6 = \{1, 2\}$	305432	2.98	210278	3.05	-	-	-	-	-	-
$\boldsymbol{s}_7 = \{1, 3\}$	250793	2.36	-	-	264865	2.41	-	-	-	-
$\boldsymbol{s}_8 = \{1, 4\}$	258408	2.55	-	-	-	-	257361	1.97	-	-
$\boldsymbol{s}_9 = \{1, 5\}$	227922	1.99	-	-	-	-	-	-	287665	2.27
$\boldsymbol{s}_{10} = \{2, 3\}$	214723	2.10	-	-	300894	2.03	-	-	-	-
$\boldsymbol{s}_{11} = \{2, 4\}$	-	-	247909	2.50	-	-	266756	2.00	-	-
$\boldsymbol{s}_{12} = \{2, 5\}$	-	-	205931	2.14	-	-	-	-	309716	1.89
$\boldsymbol{s}_{13} = \{3, 4\}$	-	-	-	-	218584	2.41	297207	2.53	-	-
$\boldsymbol{s}_{14} = \{3, 5\}$	-	-	-	-	315874	2.55	-	-	199736	2.47
$\boldsymbol{s}_{15} = \{4, 5\}$	-	-	-	-	-	-	318464	1.88	197246	2.36
$\boldsymbol{s}_{16} = \{1, 2, 3\}$	171900	2.67	113570	2.89	210430	3.04	-	-	-	-
$\boldsymbol{s}_{17} = \{1, 2, 4\}$	186707	2. 84	143688	3.11	-	-	185205	2.75	-	-
$\boldsymbol{s}_{18} = \{1, 2, 5\}$	154687	2.77	200198	2.94	-	-	-	-	160714	2.89
$\boldsymbol{s}_{19} = \{1, 3, 4\}$	183502	3.17	-	-	192557	3.00	139604	2.80	-	-
$\boldsymbol{s}_{20} = \{1, 3, 5\}$	115941	2.16	-	-	201307	2.98	-	-	198402	2.50
$\boldsymbol{s}_{21} = \{1, 4, 5\}$	197233	2.15	-	-	-	-	148420	2.27	169957	3.08
$\boldsymbol{s}_{22} = \{2, 3, 4\}$	-	-	182325	2.67	198416	2.09	-	-	134959	3.11
$\boldsymbol{s}_{23} = \{2, 3, 5\}$	-	-	167788	2.22	173391	2.75	-	-	174505	3.14
$\boldsymbol{s}_{24} = \{3, 4, 5\}$	-	-	-	-	204097	2.68	156090	2.45	155479	3.02
$\boldsymbol{s}_{25} = \{1, 2, 3, 4\}$	101769	3.14	121308	3.15	150112	3.15	142515	2.95	-	-
$\boldsymbol{s}_{26} = \{1, 2, 3, 5\}$	128803	2.80	123486	2.86	-	-	144516	3.12	118825	3.05
$\boldsymbol{s}_{27} = \{1, 2, 4, 5\}$	122135	3.03	130568	2.96	-	-	127209	3.24	135736	3.32
$\boldsymbol{s}_{28} = \{1, 3, 4, 5\}$	110764	2.84	-	-	135962	3.21	132966	3.08	135933	2.90
$\boldsymbol{s}_{29} = \{2, 3, 4, 5\}$	-	-	125500	3.31	116818	3.14	113598	3.35	109762	3.07
$\boldsymbol{s}_{30} = \{1, 2, 4, 3, 5\}$	126219	2.98	135140	3.07	118308	3.00	124021	2.79	103478	3.15

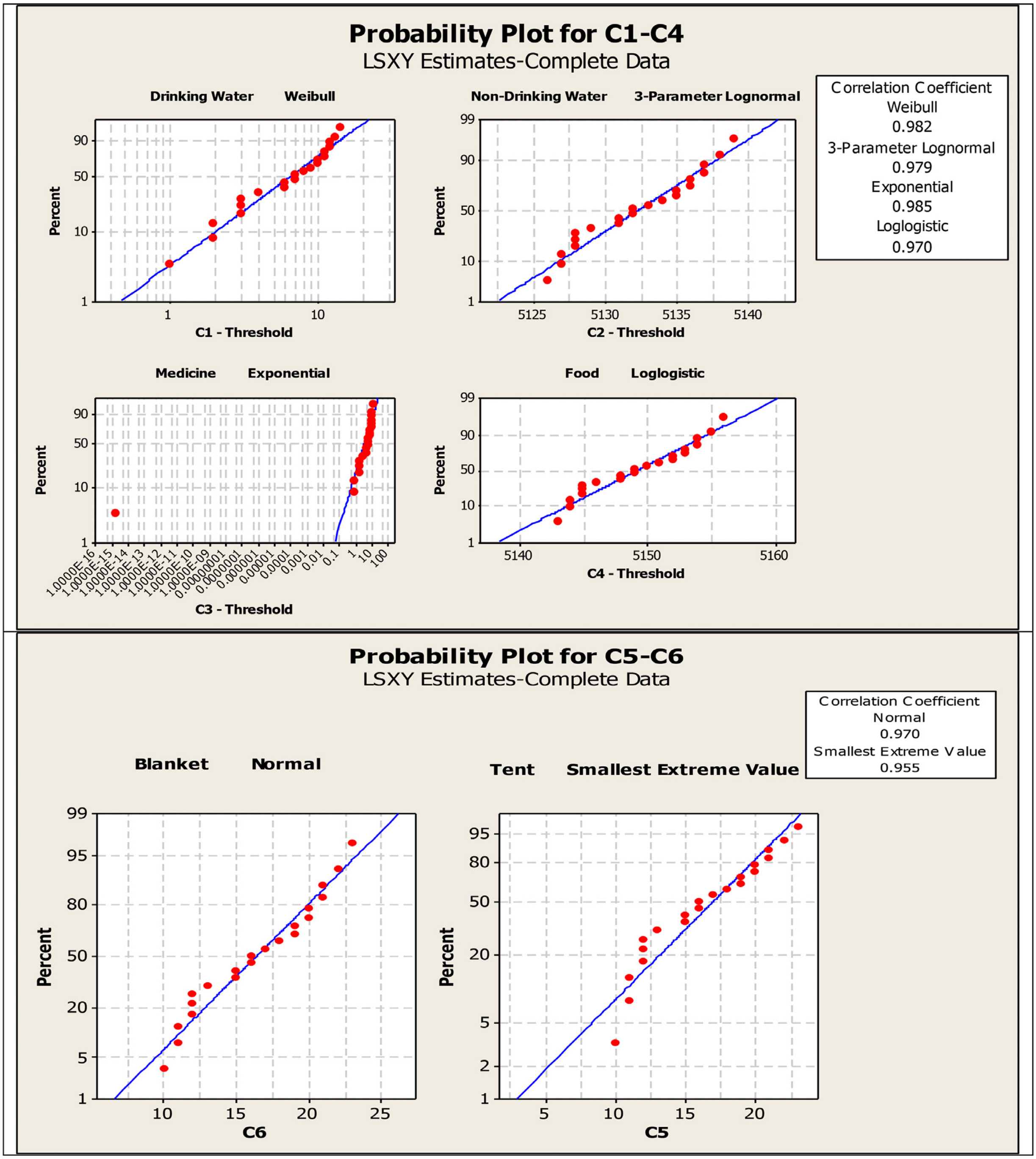

Fig. 6. Estimation of distribution functions of relief commodities.

Table 10 shows the characteristics of routes in each coalition. Characteristics of the routes are based on travel time on each route and route reliability. For instance, as can be seen in coalition 29, the travel times of routes 2, 3, 4, and 5 are 125500, 116818, 113598, and 109762 seconds, respectively. Also, the reliability of routes 2, 3, 4, and 5 in coalition 29 is 3.31, 3.14, 3.35, and 3.07 units.

In the following, after estimating the distribution functions of relief commodities and reporting the decision variables, synergy and saving value are described.

To solve the second stage, at first all players are considered as independent. Then the multi-player coalition model will be solved. When the optimal objective function for each coalition scenario is smaller than the sum of the optimal objective

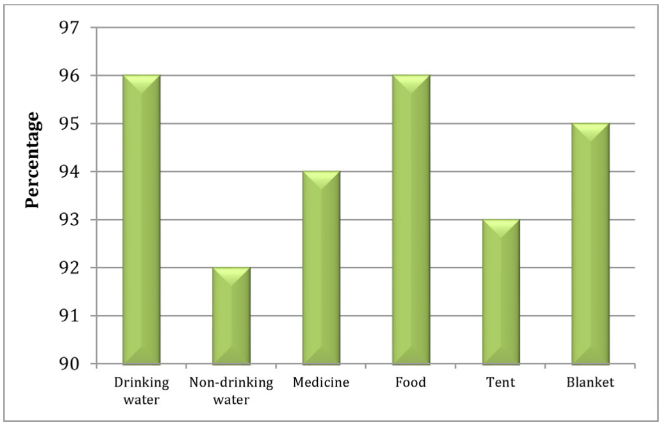

Fig. 7. A 95% confidence interval for results obtained by simulation and real system.

functions of individuals, players are motivated to work together. Therefore, according to Eq. (68):

$$z_1(s_m) \le \sum_{p \in s_m} z_1(\{p\}) \tag{68}$$

The amount of time saving is also shown in Eq. (69):

$$TS(s_m) = \sum_{p \in s_m} z_1(\{p\}) - z_1(s_m) \tag{69}$$

Relief time saving $TS(s_m)$ is the difference between the total of individual objective functions and the coalition objective function. Depending on the cooperation between players in different coalitions, the level of synergy in relief time can change. This synergy can be defined as Eq. (70).

$$SYNERGY(s_m) = \frac{z_1(s_m)}{\sum_{p \in s_m} z_1(\{p\})} \tag{70}$$

After describing synergy and saving value, the definition of Shapley value is as follows:

For an N-player cooperative game, Shapley calculates the average payoff of each player from the coalitions. $S_i^*$is equal to the payoff of the player i if it joins the coalition c. Therefore, the value of a player for a coalition is defined by Eq. (71).

$$\{V(C) - V(C - (i))\} \tag{71}$$

The value of Shapley is also calculated from Eq. (69). So that, N is the total number of players, k is the number of players in the coalition and $\frac{(k-1)!(N-K)!}{N!}$ is the probability of occurrence of each coalition. The value of Shapley S_i^*can determine the power of the player i to be sensitive and his ability to win a coalition.

$$S_i^* = \sum_{c \in N, i \in C} \frac{(k-1)!(N-K)!}{N!} \{V(C) - V(C - (i))\} \tag{72}$$

After describing Shapley value, the definition of Core value is as follows:

The concept of Core of a game was first introduced by Gillies [60]. This value of a game consists of a set or set of points. In other words, Core is an imputation set resulting from a game coalition, so that none of the existing imputations in that set is dominated by another imputation. Therefore,u'_i, from a Core in the normal space, represents a proportion of the value of its cooperation value in the game. A Core of R solution points for a cooperative game is defined according to Eq. (73):

$$R = Core = \left\{ U' \in Mif \sum_{i \in C} u'_i \ge v'(c) \to C \subset N \right\} \tag{73}$$

Table 11 shows the amount of synergy of the objective functions (second stage model), the value of the Shapley and the Core. As can be seen, the amount of savings from the coalition $s_7 = \{1, 3\}$ is equal to 55199.11 and its synergy is equal to 0.15, and the highest amount of synergy is 0.44 for the coalitions $s_{27} = \{1, 2, 4, 5\}$ and $s_{29} = \{2, 3, 4, 5\}$. Also, the total coalition with an amount of savings of 374401.4 has the synergy of 0.42. Each player has a different value in the coalition. For example, if the player 1 joins the coalition $s_{10} = \{2, 3\}$, 144495.7 seconds will be reduced; if it joins the coalition $s_{11} = \{2, 4\}$, 139687.7 seconds will be reduced; and if it joins the coalition $s_{13} = \{3, 4\}$ 165148.8 seconds of the relief time will be reduced. Also, the value of the second objective function due to the coalition $s_{13} = \{3, 4\}$ is 22.9 and its synergy value is 0.62.

Table 11
Synergy, shapely and core value.

Coalition	$TC_1(S_m)$	Saving of first objective function	Synergy of the first objective function	$TC_2(S_m)$	Synergy of the second objective function	Shapely	Max(core)
$s_1 = \{1\}$	178452.34	0	0	30.4	0	9.4936	8.9612
$s_2 = \{2\}$	178434.51	0	0	31.02	0	9.1934	10.0142
$s_3 = \{3\}$	177561.02	0	0	33.1	0	8.4234	8.9410
$s_4 = \{4\}$	179211.00	0	0	28.5	0	9.2967	8.9147
$s_5 = \{5\}$	176360.55	0	0	27.1	0	9.1070	8.9014
$s_6 = \{1, 2\}$	285530.05	71356.8	0.19	20.3	0.66	6.778	6.8217
$s_7 = \{1, 3\}$	300814.25	55199.11	0.15	18.2	0.71	5.3618	5.7054
$s_8 = \{1, 4\}$	268242.54	89420.8	0.25	21.0	0.64	5.6621	5.0541
$s_9 = \{1, 5\}$	225313.08	129499.8	0.36	23.7	0.58	5.6428	6.0164
$s_{10} = \{2, 3\}$	267916.80	88078.73	0.24	21.5	0.66	4.0091	4.0355
$s_{11} = \{2, 4\}$	285409.65	72235.86	0.20	20.8	0.65	6.9661	7.2450
$s_{12} = \{2, 5\}$	292413.00	62382.06	0.17	19.4	0.66	5.4674	5.1049
$s_{13} = \{3, 4\}$	244700.20	112071.8	0.31	22.9	0.62	5.6482	5.5620
$s_{14} = \{3, 5\}$	310318.61	43602.96	0.12	17.4	0.71	5.3420	5.8651
$s_{15} = \{4, 5\}$	274892.14	80679.41	0.22	21.1	0.62	5.9412	6.1857
$s_{16} = \{1, 2, 3\}$	389952.15	144495.7	0.27	13.5	0.85	3.2541	2.7088
$s_{17} = \{1, 2, 4\}$	396410.55	139687.3	0.26	13.0	0.85	3.6798	3.4310
$s_{18} = \{1, 2, 5\}$	363518.99	169728.4	0.31	14.6	0.83	3.1102	2.9550
$s_{19} = \{1, 3, 4\}$	370075.55	165148.8	0.30	14.0	0.84	3.5640	3.7250
$s_{20} = \{1, 3, 5\}$	365230.00	167143.9	0.31	14.3	0.84	3.9954	4.0044
$s_{21} = \{1, 4, 5\}$	379250.11	154773.8	0.28	13.8	0.83	3.6419	3.3025
$s_{22} = \{2, 3, 4\}$	356500.100	178706.4	0.33	15.9	0.82	3.8834	4.1024
$s_{23} = \{2, 3, 5\}$	387218.35	145137.7	0.27	13.7	0.84	3.4361	3.1000
$s_{24} = \{3, 4, 5\}$	344342.22	188790.4	0.35	16.3	0.81	3.3470	3.6481
$s_{25} = \{1, 2, 3, 4\}$	401268.14	312390.7	0.43	8.8	0.94	1.8626	2.5417
$s_{26} = \{1, 2, 3, 5\}$	418642.44	292166	0.41	8.0	0.93	1.7870	2.0154
$s_{27} = \{1, 2, 4, 5\}$	395530.08	316928.3	0.44	9.6	0.91	2.0100	1.6224
$s_{28} = \{1, 3, 4, 5\}$	404577.98	307006.9	0.43	8.5	0.92	2.5554	1.1547
$s_{29} = \{2, 3, 4, 5\}$	392234.55	319332.5	0.44	9.8	0.94	1.3499	1.4675
$s_{30} = \{1, 2, 4, 3, 5\}$	515618.07	374401.4	0.42	6.7	0.93	2.9840	2.5431

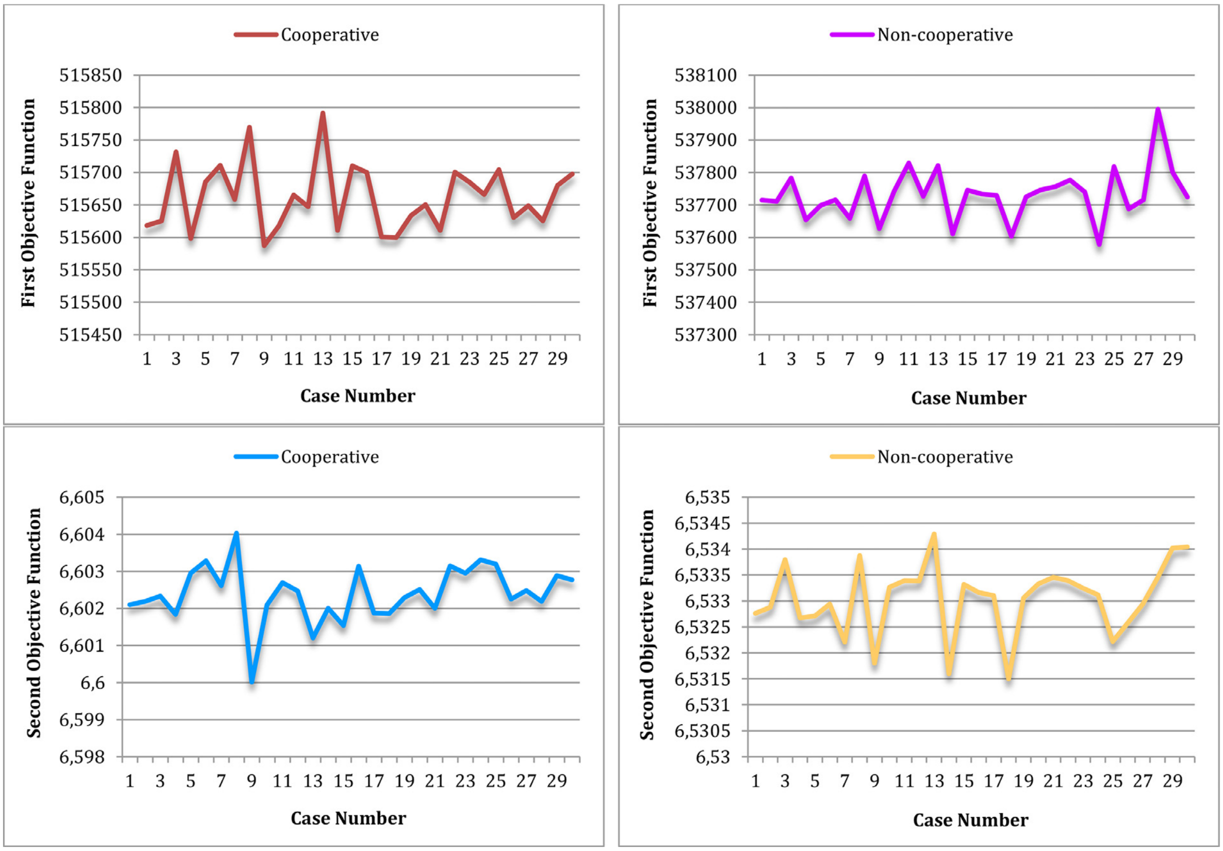

Fig. 8. Comparison of cooperative and non-cooperative state.

As Table 11 shows, the more coalitions go forward (groups with more players), the more the synergy of relief operations will increase. According to this chart, the coalition $s_{29} = \{2, 3, 4, 5\}$means the cooperation of four distributors of 2, 3, 4 and 5 has the synergy of 0.44 for the first objective function and 0.94 for the second objective function. Therefore, the coalition is the 29 is the best coalition of all possible coalitions. The ascending trend of the chart also indicates that an increase in the number of players will also reduce the amount of relief time and will make the vehicles to choose more reliable routes.

Fig. 8 shows the comparison of the first objective function in the cooperative and non-cooperative states. In this figure, 30 Pareto points are shown. This comparison is between the total coalition and non-cooperative state. Red points show the value of the first objective function and the blue points indicate the value of the second objective function. As can be seen, the relief time in cooperative state in almost all cases is better than non-cooperative state. The average objective function in cooperative state for Pareto points is 515662 seconds and for non-cooperative state it is 537731.89 seconds. Therefore, the results of the comparison of the first objective function in cooperative and non-cooperative states indicates that the averagely, 22069.89 seconds is saved in cooperative state comparing to the non-cooperative state.

Also, the investigation of the second objective function indicates that the average reliability of the cooperative state is 6.602408 and for non-cooperative state, it is 6.533052. Therefore, the cooperative state has had 0.069356 units of improvement in the reliability of the routes compared to the non-cooperative state.

7.2. Managerial insights

If there is a national disaster, the public sector will be involved. A national disaster means that high-magnitude earthquakes occur simultaneously in one or more cities or provinces. Therefore, organizations such as the Ministry of Interior (disaster Management Organization), Ministry of Commerce (for the location of the suppliers and storage centres and distribution of relief commodities), Ministry of Health (for the location of the relief commodities and ambulance centres), Ministry of Roads (to remove the roadblocks in the event of a breakdown), and the Ministry of Energy (to discuss energy such as water, gas, and electricity) will be involved. Specifically, the following organizations can be among the beneficiaries of this research including (1) Rescue Organization, (2) disaster Management Organization, (3) Red Crescent Organization, (4) Fire Department, (5) Hospitals, (6) Blood Transfusion Organization, etc. Logistics and evacuation operations are important measures to respond to the earthquake and the correct implementation of these measures can have significant effects on the casualties caused by the earthquake. In this situation, the discussion of cooperation in the relief supply chain seems more and more necessary. Therefore, in this paper, a cooperative model for the location-routing-allocation-distribution problem of relief commodities is developed. The cooperation of supply chain members can minimize the golden time of relief. A comparison of cooperative and non-cooperative mode in this study also indicates that considering the cooperation of the relief time of 22069.89 seconds is less than the non-cooperative mode. Also, in the cooperative mode, the reliability of the system has increased by 0.069356 units. In addition, minimizing relief time and maximizing system reliability can help managers make operational decisions to reduce the loss of life and property caused by an earthquake.

Among the advantages of the proposed model over others in the literature are summarized as follows:

- Considering a cooperative mathematical model using game theory to minimize the golden time of relief.
- Applying simultaneous routing-location-inventory decisions in the disaster relief supply chain
- Designing a two-stage mathematical model for simultaneous pre -disaster and post-disaster decisions, so in the first stage pre -disaster decisions and in the second stage post-disaster decisions are made.
- In previous studies, only the flow of people or the flow of commodities has been considered, but in this study, the simultaneous flow of people and commodities has been considered.
- In other studies, the impact of critical urban infrastructure on the estimated amount of relief commodities has not been considered. In this research, considering the critical urban infrastructure, the amount of demand for relief commodities is simulated.
- Providing a real case study to compare with cooperative and non-cooperative scenarios.

Another important issue that has been addressed in this research is the simulation of fragile urban infrastructure and the estimation of the required relief commodities. Although in small events where there is usually a shortage of relief supplies, disaster managers can do this planning to an acceptable level. But if the dimensions of the event become larger and go beyond a small area, in other words, it becomes a disaster. They cannot do proper planning alone. Therefore, estimating relief commodities can give a strategic view to the relevant managers so that they can make strategic decisions before the disaster and operational decisions after the disaster with more efficiency and lower costs. Also, pre -disaster decisions such as inventory-location-allocation helps the managers to tackle the disaster. The periodicity of these decisions leads to careful planning in each period. According to the inventory decisions that have periodic in nature, managers require careful monitoring in each period. Moreover, by identifying the stored inventory and the allocation of the centres, managers can effectively control this process. In addition, routing decisions and how supply chain components work together make managers more familiar with their tasks. Also, determining the reliability of the routes allows managers to choose the best routes and the least risky routes when routing. Thus, they can minimize the golden time of relief by cooperating effectively.

The average relief time in cooperative state for is 515,662 seconds and for non-cooperative state it is 537,731.89 seconds. Therefore, the results of the comparison of the first objective function in cooperative and non-cooperative states indicates that the averagely, 22,069.89 seconds is saved in cooperative state comparing to the non-cooperative state. Also, the investigation of the second objective function indicates that the average reliability of the cooperative state is 6.602408 and for non-cooperative state, it is 6.533052. Therefore, the cooperative state has had 0.069356 units of improvement in the reliability of the routes compared to the non-cooperative state. Also, the supply chain costs for the case study are $ 8,256,134. Coalition 29 is also the best coalition with distributors of 2, 3, 4, and 5 with a synergy of 0.44 for the first objective function and 0.94 for the second objective function.

To run and solve the proposed model, GAMS, MATLAB, and ED software are needed. Access to a powerful computer system with high RAM and CPU is also essential for running software. Additionally, an expert user to run and analyse software output is required. The results of the research should be reported to the beneficiaries of the research including the disaster Relief Organization, the Ministry of Health, hospitals, etc., during a meeting.

The limitations of this study are including as follows:

- There is no accurate data on transportation costs. In this research, estimates of costs by provided by drivers and the Ministry of Roads were utilized.
- Based on that there are no precise data on air infrastructure such as airports, so this research has not paid much attention to simulating the amount of demand required for this infrastructure.
- To solve the simulation and mathematical model, GAMS, MATLAB, and ED software are needed. Then, for implementation of this software requires access to a powerful computer system with high RAM and CPU.

8. Conclusion and future works

The management of disaster relief logistics is a very complex problem, involving aspects like inventory management and distribution planning, and subject to high degrees of uncertainty. The reduction of waiting times while increasing service levels and keeping costs to a minimum are usually the main objectives when facing a disaster, which gives an idea of the complexity involved. This is why the application of the appropriate mathematical modelling tools can represent a powerful decision-making support system to assist managers and engineers in this task.

In this research, a new two-stage mathematical model for relief logistics network management is developed. The considered network includes affected areas, suppliers, distribution centres, and hospitals. The proposed model includes the pre-and post-disaster phases. Since the information about the requirements at the time of disaster is not available before the occurrence of the disaster, the model is considered as a two-stage model. Hence, in the first stage, the location, and the amount of inventory in the distribution centres are addressed. Also, in the second stage, the routing of the relief vehicles and the distribution of the relief commodities for the affected area are performed. Since there are some uncertainties at the disaster time, the model is considered under uncertainty to be closer to real-world conditions. In addition, uncertainty based on the definition of different scenarios is provided.

The simulation performance is represented by the distribution function of relief commodities. Therefore, distribution functions of tent, medicine, non-drinking water, food, drinking water and blanket are normal with the correlation coefficient of 0.945, 0.982, 0.900, 0.978, 0.951 and 0.975. As evident, the amount of drinking water, non-drinking water, medicine, food, tents, and blankets is respectively estimated to be 96, 92, 94, 96, 93 and 95 percent like the real system. Also, the comparison between simulation results and the obtained value from the real system indicates the accurate performance of the implemented model. Considering the normality and the 95% confidence interval, it can be concluded that the proposed model provided an accurate example of the real system performance.

Therefore, to solve the model, an exact method and a meta-heuristic algorithm called MOSFS are used. Next, the value of synergy resulting from the cooperation is calculated. In the first objective function, the amount of saved coalition $s_7 = \{1, 3\}$ is equal to 55,199.11 and the value of synergy is equal to 0.15, and the maximum synergy value is 0.44 for the coalitions $s_{27} = \{1, 2, 4, 5\}$ and $s_{29} = \{2, 3, 4, 5\}$. Also, the total coalition with an amount of savings of 374,401.4 has the synergy of 0.42. According to second objective function, the amount of saved coalition $s_{13} = \{3, 4\}$is equal to 38.7 and its synergy value is 0.62. The results indicate that the coalition $s_{29} = \{2, 3, 4, 5\}$ means the collaboration of four distributors of 2, 3, 4 and 5 with a synergy of 0.44 for the first objective function and 0.94 for the second objective function. Moreover, the coalition 29 is the best coalition of all possible coalitions.

This paper suggests some work for future studies. The model could be utilized and implemented for disasters with lesser advanced speed and human-made disasters such as wars, drought, and famine. Interested scholars can investigate other disaster management phases simultaneously, such as the phases of reconstruction and prevention. Next, they can add new constraints on relief personnel such as work shifts as well as can be considered the interactive and cascading effects of disasters on each other, such as a state in which an earthquake leads to a tsunami. Finally, new heuristics and metaheuristics can be investigated.

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