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OPTIMAL LOGISTICS PLANNING FOR EARTHQUAKE RECOVERY (EXAMPLE OF TEHRAN)

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Disaster relief logistics planning decisions can be divided into two categories: strategic decisions before the crisis, and operational decisions during and after the crisis. One of the strategic challenges in disaster relief logistics planning is the identification of the location of disaster relief warehouses and distribution relief centers, and their inventory levels for each type of relief goods. In the present post-disaster relief process, relief goods are usually provided in distribution relief centers by disaster relief warehouses. The main purpose of this paper is the determination of the required number of disaster relief warehouses and distribution relief centers for providing an optimal relief process in District-1 of Tehran. The proposed approach is based on a mathematical optimization model by considering the augmented epsilon constraint method. To ensure an optimal general solution, a robust two-objective planning model is implemented using GAMS software. The numerical results of the proposed model are provided by combining the humanitarian goal of minimizing the maximum shortage and the economic goal of minimizing relief cost under possible scenarios. To achieve these goals, Mulvey's scenario-based stochastic programming is used to minimize the average cost of relief (economic goal), and Aghezzaf's scenario-based stochastic programming is used to reduce the number of casualties (humanitarian goal) by maximizing the relief efficiency rate. Therefore, the best balance between humanitarian and economic goals is obtained related to the allocated relief budget. Thus, the results of this study help to decrease the costs, as well as accelerate the relief process, and subsequently minimize the casualties in disaster situations.

Keywords: disaster relief logistic planning, humanitarian logistics, robust two-objective planning model, scenario-based optimization, GAMS software, augmented epsilon constraint method

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ОПТИМАЛЬНОЕ ПЛАНИРОВАНИЕ ЛОГИСТИКИ ДЛЯ ЛИКВИДАЦИИ ПОСЛЕДСТВИЙ ЗЕМЛЕТРЯСЕНИЙ (НА ПРИМЕРЕ ТЕГЕРАНА)

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Решения по планированию логистики по оказанию помощи при стихийных бедствиях можно разделить на две категории: стратегические решения до кризиса и оперативные решения во время и после кризиса. Важным стратегическим вопросов при планировании логистики для оказания является определение местоположения складов для оказания помощи при стихийных бедствиях и центров распределения, а также уровня запасов для каждого типа средств оказания помощи. Процесс оказания помощи после стихийных бедствий заключается в том, что товары гуманитарной помощи доставляются в центры распределения через склады. Определение местоположения складов для оказания помощи при стихийных бедствиях и центров распределения помощи, а также уровней их запасов для каждого типа товаров гуманитарной помощи является одним из стратегических вопросов при планировании логистики оказания помощи при стихийных бедствиях. Основная цель этой статьи – определение необходимого количества складов для оказания помощи при стихийных бедствиях и распределительных центров помощи для обеспечения оптимального процесса оказания помощи в районе № 1 Тегерана. Предлагаемый подход основан на математической модели оптимизации с учетом расширенного метода эпсилон-ограничений. Чтобы обеспечить оптимальное универсальное решение, с помощью программного обеспечения GAMS реализована модель планирования с двумя целями. Численные результаты предложенной модели обеспечиваются с учетом как гуманитарной цели минимизации максимального дефицита, так и экономической цели минимизации затрат на оказание помощи при разных возможных сценариях. Для достижения этих целей используется стохастическое программирование Малви на основе сценариев для минимизации средней стоимости помощи (экономическая цель). А для моделирования гуманитарной цели за счет максимизации дефицита помощи используется стохастическое программирование на основе сценариев Агеззафа. Важно отметить, что наилучший баланс между гуманитарными и экономическими целями достигается при помощи выделения бюджетных средств. Таким образом, результаты этого исследования помогают сократить расходы на оказание помощи, а также ускорить процесс оказания самой помощи и минимизировать количество пострадавших.

Ключевые слова: планирование логистики при стихийных бедствиях, гуманитарная логистика, модель планирования с двумя целями, оптимизации на основе сценариев, программное обеспечение GAMS, расширенный метод ограничения эпсилон

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Introduction

A disaster is defined by the Oxford dictionary of disaster management as a "sudden accident or a natural catastrophe that causes great damage or loss of life" [1]. A disaster of moderate scale can easily result in heavy causalities and loss of hundreds of millions of dollars. In fact, high cost is not the only consequence of disasters: social problems, destruction of infrastructure, and other aftermaths of disasters can cause long-lasting adverse consequences in the affected regions [2]. In addition to these direct losses, disasters also have a negative impact on the businesses in the affected areas. Furthermore, because of business failures, economic deterioration impedes their recovery. Disaster management is a cross-disciplinary research field that brings together practitioners and academics, volunteers and professionals, as well as non-governmental organizations, governmental agencies, and international organizations in a common endeavour to coordinate efforts to save lives and reduce loss under difficult working conditions [1]. Since disaster management is a multifaceted process, it is imperative to deploy proper management that optimizes planning and responses. Due to the limitation of resources during and after disaster periods, collaborative efforts at the governmental, private, and community levels are indispensable. In the field of disaster relief, data-driven logistics can reduce the losses both during and after the disaster greatly. Data-driven disaster management is an emerging research area that has undergone considerable progress during the past decade [2]. Its main advantage over traditional disaster management is that it connects different partners and entities in a system, allowing users to find valuable information that makes them aware of the disaster situation and recovery status in real-time. Moreover, the community participants can collaborate to exchange critical information, evaluate the damage, and make practical recovery plans.

Nowadays, data is being generated at a rate as never before. In this digital age, data is constantly being produced and accumulated, and these data help to make major decisions. In order to make better decisions, managerial decisions increasingly rely on data analytics, instead of a leader's "gut instinct" [3]. In recent years, some researchers have developed analytical methods that use data for better decision-making in organizations [4]. Vidgen et al. state that analytical capability mediates between the data that an organization generates and accesses and the value that the organization can derive from the data through actions based on better decisions [5]. While other researchers [6] view management challenges as predominantly covering issues related to privacy, security, governance, and ethical aspects; these challenges also target much broader management, leadership, and decision-making aspects that impact organizational performance. The expanded scope also uses accountability to measure organizational performance [7]. Thereupon, data-driven decisions make or break organizations. This is where the importance of online data visualization becomes operational. Therefore, the importance of data in decision-making is based on data consistency and continuous growth. Data enables organizations to create new opportunities, generate more revenue, anticipate trends, optimize current operations, and generate actionable insights. In this case, data-driven logistics improve the growth of an organization. Consequently, the organization becomes more adaptable. From this perspective, in the case of disaster relief logistics, all around the world, improving disaster management and recovery techniques is one of the national priorities given the possible major toll caused by natural and man-made calamities [2]. Therefore, data-driven disaster management aims at applying advanced data collection and analysis technologies to achieve more effective and responsive disaster management [2]. This research field has undergone considerable progress in the last decade.

The case study of the present work is District-1 in Tehran, Iran. Tehran, as the capital of Iran, is subjected to a significant risk of earthquakes because of geologic faults, which are located around the city (see Fig. 1). The potential risk of earthquakes caused by these faults (Mosha, North of Tehran, South Rey, and other floating faults) illustrates the need for optimal earthquake relief logistics planning to realize the hu-

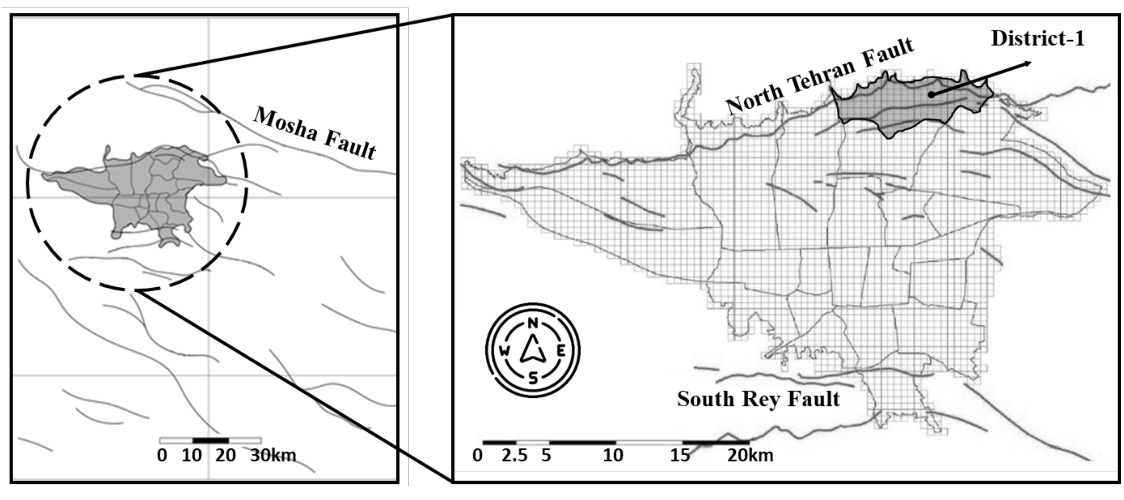

Fig. 1. The map of existing faults around Tehran

manitarian and economic goals mentioned in this work [8]. In particular, District-1 should be considered as a specific area to apply disaster relief logistics plan (DRLP) in the pre- and post-disaster relief process. Especially because this district is located directly on the North Tehran fault and some of the most historical buildings of the last two hundred years of Iran are located there. Furthermore, District-1 has an important role in politics because more than 30 embassies are placed there. The overall information on the topological structure of District-1 is provided in Table 1.

The main purpose of the work is to improve the current process of the disaster relief logistics, which is used in Iran in case of disaster.

Table 1. The geographical and demographic information of District-1, Tehran

Information	Quantity
Population	487508
Area	101 [square km]
Density	4827 [per km^2]
Number of families	166881
Altitude	1800 [m]
Number of zones	10
Number of metro stations	5

The purpose and objectives of the study

Due to importance of strategic pre-disaster issues, the efforts of present study are dedicated to draw an effective organizational chart for the collaborations of governmental and non-governmental organizations. Besides, some of the operational issues related to disaster relief logistics planning (DRLP), including the determination of the number of the disaster relief warehouses (DRWs) and relief distribution centers (RDCs), are studied.

Three interrelated research tasks are the following:

1. Redefinition of the relations between different organs participating in the relief process after a disaster.
2. Improving the disaster relief chart, which is used in case of earthquake.
3. Determination of the adequate number of disaster relief warehouses (DRWs) and relief distribution centers (RDCs) by considering humanitarian and economic goals simultaneously.

Case study

Iran has a high earthquake potential due to its special geological structure. The Iranian plateau is located in the middle of the Alpine-Himalayan tension belt, which has not yet reached its final equilibrium. This causes regular devastating earthquakes in different regions of Iran, in particular Tehran. The national disaster management organization of Iran (NDMO) was established according to the law approved on 15.01.2008 [9]. The national disaster management organization is responsible for creating integrated management in policy-making, planning, and coordination in the fields of implementation and research. Besides, this organization provides a platform for the cooperation of different ministries and organizations. Accordingly, the national disaster management organization is one of the governmental organizations of Iran that operates under the Ministry of Interior of Iran. However, in practice, the performance of this organization is disrupted by parallel governmental or non-governmental organizations. This is due to the political rivalries between the parties, the systematic corruption of the ruling system [10], the efforts of various organizations to obtain financial and non-financial benefits, and finally the intense interest of various institutions to use propaganda to ordinate people's opinions and sentiments in direction of their organiza-

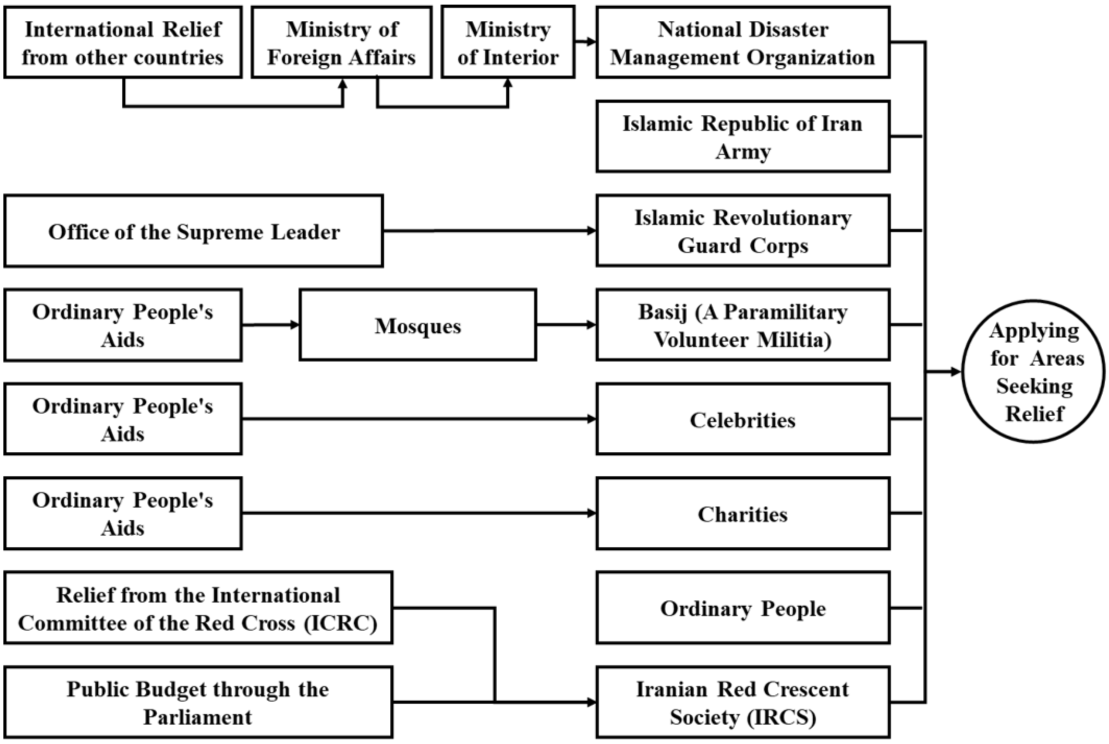

Fig. 2. The current logistics process

tion interests [11]. This organizational parallelism causes major problems in term of disaster management and disrupts the relief process. It also expands the scope of administrative, political, cultural, and social damage. The arising problem of such process includes unorganized relief, low efficiency of the relief process, slow relief process, the possibility of increased casualties in the early hours due to delays in relief, unbalanced relief, increase in operating costs, increase in the criminal behavior of people and organizations due to lack of supervision (theft, money laundering, etc.). Needless to say, for such a corrupt and unorganized system in which all its organs are aware of the existing problems but do not seek to overcome obstacles and problems due to organizational interests, the relief process chart has not been published. However, by monitoring the official sites [9, 12–14] of these organizations and reviewing the news published by them after disasters, the present relief process can be modelled as shown in Fig. 2.

Logistics process description

Disaster relief logistics (DRL) decisions regarding relief goods can be divided into two phases; pre-disaster decisions (strategic planning related to the forecasting and preparation of relief goods) and post-disaster decisions (operational planning related to the distribution of relief goods to the affected areas) [2]. In the event of a disaster, the relief process is usually such that relief goods are delivered to the relief distribution centers (RDCs) through disaster relief warehouses (DRWs). Identification of the location of DRWs and RDCs, and their inventory levels for each type of relief good is one of the strategic issues in Disaster Relief Logistics planning (DRLP). Besides, it should be considered how to allocate the relief from DRWs to RDCs, and cover the affected areas [15]. Furthermore, the operational planning of the supplying and distribution of relief goods depends on the scenarios under which the disaster occurred [16]. Therefore, the DRLP problem can be divided into three main problems; the first is the location of DRWs, the second deals with the management of their inventory, and finally, the third deals with the distribution of relief goods to the applicant areas [17]. In this work, the DRLP procedure is defined by considering economic

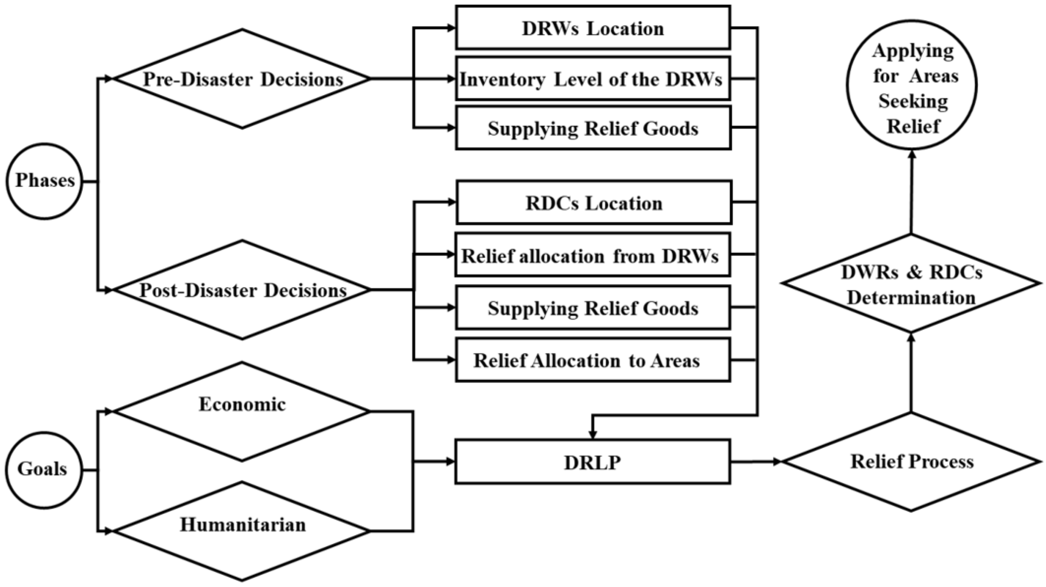

Fig. 3. Decision-making process

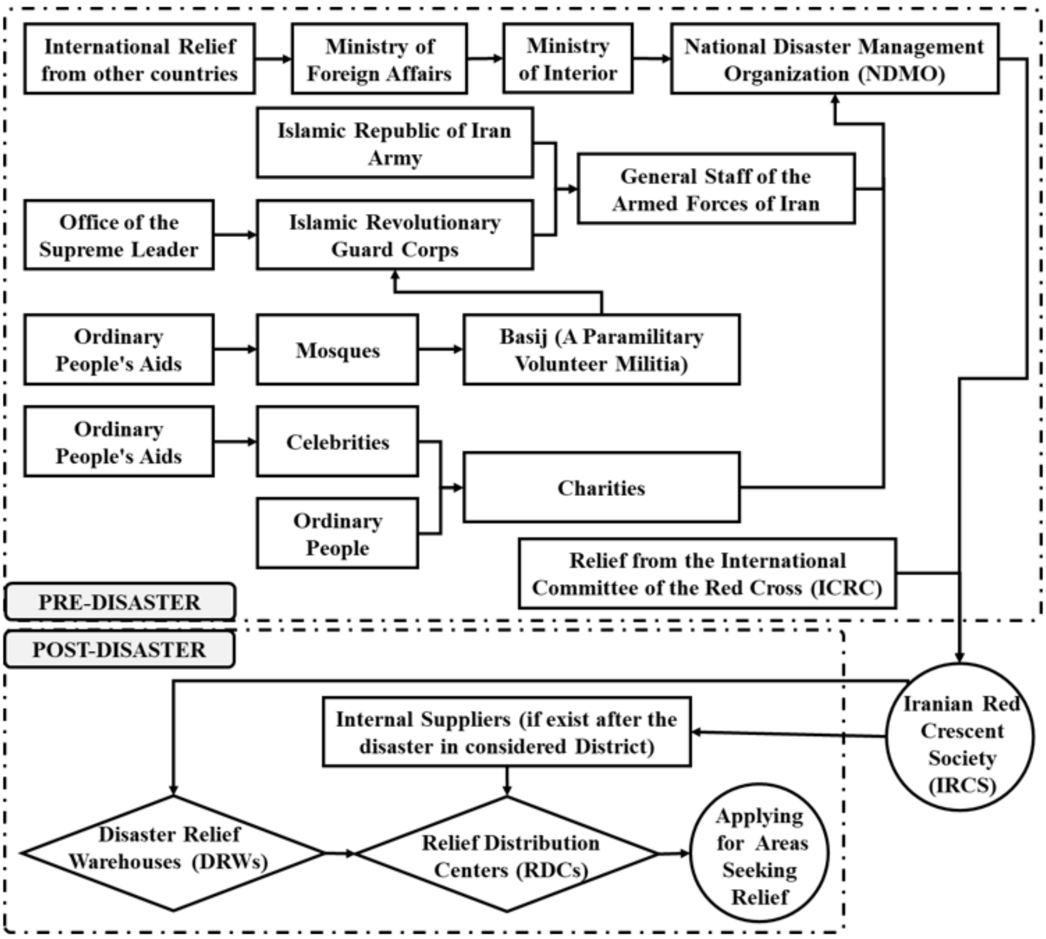

Fig. 4. Proposed logistics process

(decreasing the number of DRWs and RDCs) and humanitarian (increasing the number of DRWs and RDCs) goals simultaneously, which is suggested in the work of [8]. It is worth mentioning, here in this work, the problem is simplified to the determination of the required number of DRWs and RDCs for providing an optimal relief process. This process is illustrated in Fig. 3.

According to the current logistics process (Fig. 2) and proper decision-making process in case of disaster (Fig. 3), this work aims to determine the adequate numbers of DRWs and RDCs. To aim this purpose and improve the process, at first, to keep away from unnecessary parallel functions, which are implemented in reality, the current logistics process should be reconsidered (see Fig. 4). Secondly, to determine the optimum number of DRWs and RDCs in Tehran-District 1, a new two-objective mathematical optimization model, which was provided in the previous work of other researchers [8], is used. As the results of these two steps the optimum numbers of DRWs and RDCs will be defined based on the allocated budget. In particular, the main benefits of the present work include troubleshooting of the following issues: defects in the existing structure and organization, inefficiency of existing rules in different stages of disaster management, lack of transparency in roles, duties, and responsibilities, lack of preparedness to respond to disasters and problems.

Research method

In this work, the proposed approach is based on a mathematical optimization model. For this purpose, a robust two-objective planning model is applied. The reason for using this approach is justified by the uncertain nature of the demand for relief in the disaster relief logistics planning (DRLP). Therefore, two considered parameters include the numbers of DRWs and RDCs which are uncertain at the beginning of the mathematical model and should be assumed by the modeller according to some assumptions. The considered assumptions during modelling and DRLP problem solving are as follows:

– At the beginning of the solution, there are one DRW and one RDC for each zone (10 zones in total),

– Distance between two DRWs, as well as two RDCs, is considered the same,

– After the disaster, if there is an internal supplier of relief goods, the location of the internal supplier will be considered as determined,

– The location of areas seeking relief after the disaster is known and their demand is considered uncertain,

– Delays in receiving relief aids after a disaster are considered to be negligible,

– The basic disaster relief supplies kits include: water, food, the first aid kit (health goods), accommodation tent, and warm clothes (blankets),

– The necessity of all goods is not the same and it is considered by the weight value,

– After the disaster, the amount of deterioration in the contingency reserve of the DRWs is considered negligible,

– RDCs can only distribute relief goods to areas within their coverage radius,

– Before and after the disaster, RDCs keep no relief goods.

The modelling and solving of DRLP are based on the presented algorithm in Fig. 5, in which the humanitarian and economic goals are considered under the possible scenarios [18]. The augmented epsilon constraint method provides the best balance between the economic (decreasing DRWs & RDCs) and humanitarian (increasing DRWs & RDCs) goals. GAMS software is used to implement the proposed model. Furthermore, this software ensures an optimal universal solution. Finally, in order to minimize the average cost of relief (economic goal), Mulvey's scenario-based stochastic programming [19] is used, while Aghezzaf's scenario-based stochastic programming [20] is used to model the humanitarian goal through maximizing relief deficiency.

If it is proposed that (z_s) is target value under the assumed scenario of ($s \in S$), (x_s) is a scenario-dependent variable, (y) is a scenario-independent variable, (c_s, d_s, A_s, K_s, b_s) are optimization problem parameters, (R, q) are the value of definite parameters, and finally (pr_s) is the probability of occurrence of the scenario, then, according to Mulvey's scenario-based stochastic programming, to minimize the average cost of relief, an optimization problem is expressed as follows:

$$\begin{gathered} Min\{Z\} + Var\{Z\} + Penalty = \sum_{s\in S} pr_s * z_s + \lambda \sum_{s\in S} pr_s * \left(z_s - \sum_{s'\in S} pr_{s'} * z_{s'} \right)^2 + \omega \sum_{s\in S} pr_s * \xi_s^2, \\ z_s = c_s * x_s + d_s y \ \forall\, s \in S, \\ A_s x_s + K_s y = b_s + \xi_s \ \forall\, s \in S, \\ Ry = q, \\ y \in Y,\ x_s \geq 0, \end{gathered} \tag{1}$$

where, in the different scenarios, (ξ_s), (ω), and (λ), are perturbation part, model stability coefficient, and factor of significance to the variance of the responses, respectively.

To improve the average performance of the system and reduce response deviations, a penalty component is added to the objective function to prevent overruns, which ensures model stability. Besides, to maximize relief deficiency, according to the Aghezzaf's scenario-based stochastic programming states optimization problems as:

$$\begin{gathered} Min\{Z\} = \gamma\left(Max\left\{ z_s - z_s^* \middle| s \in S \right\} \right) + \mu \sum_{s\in S} pr_s * z_s, \\ z_s = c_s * x_s + d_s y \ \forall\, s \in S, \\ A_s x_s + K_s y = b_s \ \forall\, s \in S, \\ Ry = q, \\ y \in Y,\ x_s \geq 0, \end{gathered} \tag{2}$$

Where, simultaneously, the maximum amount of deficit in all scenarios is minimized with the average deficiency.

Implementation of proposed logistics

As mentioned before, in this work, District-1 of Tehran is considered as a real case study, where the DRLP problem is very important due to the earthquake-prone nature of its geographical location. The relative probabilities of earthquake occurrence, which is shown in Table 2, are extracted from previous researches [18].

Table 2. Possible scenarios [18]

Tehran, District-1	Mosha Fault		North Tehran Fault		South Rey Fault		Other Float Faults	
Earthquake Relative Probability	62%		28%		6%		4%	
Hours of Occurrence	Night	Day	Night	Day	Night	Day	Night	Day
Probability of Occurrence	21%	41%	9%	19%	2%	4%	1%	3%

According to the four introduced faults, Table 2 is arranged by considering the occurrence of an earthquake at night or during the day, which causes different scenarios of injury and the need for help. Therefore, in Table 2, eight different scenarios are stated. The results of the proposed robust optimal planning approach using GAMS software are provided in Table 3. To create this table (Table 3), the number of DRWs and

RDCs at the beginning of calculations are supposed to be 10, corresponding with 10 zones of District-1 (one DRW and RDC for each zone). By using the trial and error method and increasing/decreasing the number of DRWs and RDCs, finally, the optimum numbers of DRWs and RDCs are obtained. In the present work, the optimum numbers of DRWs and RDCs are 13 and 10, respectively. The maximum permissible deviation from the allocated budget is 10 percent, and the relative error of estimated costs for each scenario is provided in Table 3. Therefore, decision-making based on this approach guarantees that the planning for the majority of possible scenarios has been done in the best way and the relief network is in an optimal state. Using these results, disaster managers can make optimal strategic decisions before the disasters and define the number and location of relief warehouses and distribution centers. Consequently, besides the decreasing of relief costs, the relief process will be accelerated, and the lack of relief goods and casualties will be minimized.

Table 3. The comparison of the allocated budget [9, 21] and calculated cost

Scenarios	Probability of occurrence	Allocated budget (AB) [Million $]	Calculated costs (CC) [Million $]	Relative error percentage
Mosha fault- night	21%	1.413	1.49	5.45%
Mosha fault- day	41%	1.15	1.14	0.87%
North Tehran fault- night	9%	1.5	1.624	8.27%
North Tehran fault- day	19%	1.262	1.19	5.71%
South Rey fault- night	2%	0.860	0.94	9.30%
South Rey fault- day	4%	0.771	0.71	7.91%
Other float faults- night	1%	0.767	0.833	8.60%
Other float faults- day	3%	0.662	0.61	7.85%

Conclusion

In recent years, data-driven disaster management is an emerging and interdisciplinary research field that aims at applying advanced data collection and analysis technologies to achieve a more effective and responsive disaster management. In this case, disaster relief logistics planning decisions can be divided into two categories: strategic decisions in the pre-disaster phase and operational decisions, which are implied in the post-disaster phase. In the case of strategic issues before the disaster, the present work provides an effective organizational chart for the collaborations of governmental and non-governmental organizations using the definition of the systematic role of each organization in Iran. Besides, some of the operational issues related to disaster relief logistics planning (DRLP), including the determination of numbers of the disaster relief warehouses (DRWs) and relief distribution centers (RDCs) numbers, are investigated using a two-objective mathematical optimization model, which generally is a scenario-based stochastic programming approach. In this approach, both the humanitarian and economic goals are considered under possible scenarios. The implementation of the proposed model is performed using GAMS software. Thus, due to the study goals, the following results are drawn:

1. The best balance between economic and humanitarian goals is achieved using the perfect epsilon-constraint method.

2. Because of the acceptable performance of the provided approach in terms of such criteria as the numbers of DRWs and RDCs, and the maximum deviation of calculated cost from allocated budget under various scenarios, the obtained numerical results indicate that the approach can be used for disaster relief logistic planning problem solving.

3. The linearity of the proposed model ensures the universal optimization of the results, which are obtained in GAMS software. Therefore, the calculated cost in each scenario is very close to its allocated budget, in particular, when the probability of the scenario is more.

To sum up, in reality before a disaster, decision-makers can make optimal strategic decisions regarding location and inventory of relief warehouses, distribution of relief goods, etc. Thus, this work can decrease the costs of the relief process, as well as accelerate the relief process, and subsequently minimize the casualties in disaster situations.

Directions for further research

To develop the proposed model in this article, for further directions of research, it is suggested to consider the delay/lead time of receiving relief goods due to humanitarian aid in future work. In addition, applying an analysis-based approach to the presented model makes it possible to solve large-scale problems. Therefore, the developed model will be able to direct calculations for problems with more stochastic parameters, also for a wider geographical area within an acceptable time frame.

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