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Relief Logistics Network Design for Facility Location and Flow Allocation under Environmental Considerations

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ABSTRACT

Objective: This paper develops a single-objective and a bi-objective mixed-integer linear programming model to optimize the post-earthquake relief logistics network involving transfer points, hospitals, and relief centers in Tehran, Iran. The primary aim is to minimize the total time required to transfer injured individuals through the system, while the bi-objective model additionally minimizes penalties for failing to transfer casualties due to capacity shortages.

Methodology: The methodology involves formulating location-allocation models in which demand points, transfer points, hospitals, and relief centers are represented by specific capacity and travel-time parameters. The models are applied to two earthquake scenarios in south-central Tehran: a magnitude-6 event with lower casualties and selective facility activation, and a magnitude-7 event requiring full capacity utilization and a 30% assumed increase in hospital capacity.

Results: The model's effectiveness in optimizing the relief network is demonstrated. For the magnitude-6 scenario, the model selects 10 transfer points, 15 hospitals, and 25 relief centers to minimize total transfer time. For the magnitude-7 scenario, utilizing all available facilities, the model optimally allocates casualties despite severe capacity constraints.

Conclusion: The proposed models offer a practical decision-support tool for designing efficient humanitarian supply chains in earthquake-prone urban areas. They underscore the necessity of pre-disaster planning, including establishing transfer points with triage and outpatient capabilities, increasing hospital surge capacity, and ensuring public awareness to direct casualties to designated transfer points.

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Introduction

Iran is one of the most earthquake-prone countries in the world, located along the active Alpine-Himalayan seismic belt. As the largest city in Iran, Tehran is particularly vulnerable, with several major fault lines running through the urban area (Amani et al., 2025a). The high population density, aging infrastructure, and concentrated distribution of essential facilities in Tehran make the city susceptible to severe damage and a large number of casualties in the event of a major earthquake. In the aftermath of an earthquake, the provision of timely and effective relief efforts is crucial to minimize loss of life and alleviate human suffering (Ghasemi et al., 2022). However, the management of disaster relief logistics in Tehran faces several challenges (Wang et al., 2021). One of the key issues is the limited capacity of the city's medical infrastructure, with a mismatch between the number of potential casualties and the available hospital beds and treatment facilities (Kebriyaii et al., 2021). This often leads to overcrowding in hospitals and disruption of the treatment process, as the injured are transported directly to the medical centers (Sheikholeslami & Zarrinpoor, 2023).

To address this problem, the concept of transfer points has been introduced, where the injured are first transported to designated facilities for screening, triage, and initial treatment before being sent to hospitals (Gralla & Goentzel, 2018). However, the design and operation of these transfer points, as well as the broader relief logistics network, must consider not only logistical efficiency but also the environmental impact of the relief efforts (Desi-Nezhad et al., 2022; Sheikholeslami & Zarrinpoor, 2023). The environmental footprint of disaster relief operations, including the transportation of the injured, the operation of transfer points and hospitals, and the management of medical waste and supplies, can be substantial (Özdamar & Ertem, 2015a). Mitigating this environmental impact is crucial for ensuring the long-term sustainability of disaster response efforts and aligning with global sustainability goals (Boostani et al., 2021).

One of the emerging approaches to optimizing disaster response is the integration of transfer points with alternative transportation methods (G. Wang, 2024). For instance, in high-casualty incidents such as earthquakes or mass traffic accidents, the initial transport of injured individuals by ambulances to transfer points allows for effective triage and screening before dispatching only the critically injured to hospitals (Amani et al., 2025b). Additionally, utilizing helicopters or specialized emergency transport vehicles for severe cases can significantly reduce response time and enhance survival rates (Q. Wang et al., 2024; Xu et al., 2024). However, the feasibility of such a system depends on well-structured facility location planning and an optimized allocation of resources to balance efficiency, equity, and sustainability (Zhang et al., 2022).

Another significant challenge in Tehran's disaster logistics network is the imbalance in the distribution of medical centers relative to the area's most at risk of earthquake damage. Many high-risk districts lack adequate medical infrastructure, creating a bottleneck in emergency response (Aliakbari et al., 2022). To address this, a structured system of relief centers and reverse logistics facilities can enhance the overall effectiveness of disaster management. Reverse logistics in humanitarian operations includes the collection and recycling of medical waste, unused resources, and temporary shelters, thereby reducing environmental burdens and promoting resource efficiency (Xu et al., 2024; Zhang et al., 2022). Integrating such practices into the relief logistics network can contribute to both immediate disaster response and long-term sustainability.

This paper presents a bi-objective optimization model that addresses both the timely and effective transportation of the injured and the minimization of the environmental impact of the relief logistics network. The model considers the multiple locations of transfer points, hospitals, relief centers, and recycling/reverse logistics facilities, along with the optimal allocation of the injured flow. By incorporating sustainability and circular economy principles into the design of relief logistics, the proposed approach aims to enhance the resilience and environmental responsibility of disaster response in Tehran and other earthquake-prone regions.

Literature Background

The field of humanitarian logistics and disaster response has been extensively studied, with a particular focus on facility location optimization, resource allocation, and transportation planning (Ghasemi et al., 2022). Numerous studies have explored mathematical modeling techniques to enhance the efficiency of emergency logistics networks. For instance, (Madani Saatchi et al., 2021)introduced a dynamic relief-demand management model to optimize the allocation of emergency supplies in large-scale disasters. Similarly, (Abazari et al., 2021) examined the role of hybrid transportation networks in reducing response time and improving accessibility in disaster-stricken areas. These studies emphasize the importance of efficient logistics planning to minimize casualties and ensure timely medical intervention. Furthermore, multi-objective optimization approaches have gained increasing attention in disaster logistics research, as they allow decision-makers to balance conflicting priorities, such as minimizing response time while reducing costs or environmental impacts (Li et al., 2023).

Despite the extensive research on disaster relief logistics, relatively few studies have incorporated environmental sustainability into the design of emergency response networks (Nayeem & Lee, 2021; Zhang et al., 2022). Traditional models primarily focus on time efficiency and cost minimization without addressing the environmental footprint of relief operations. However, recent research has highlighted the need for integrating sustainability principles, such as carbon footprint reduction and reverse logistics, into disaster response strategies (F. Akbari et al., 2022). Reverse logistics, in particular, plays a crucial role in post-disaster waste management by facilitating the collection, recycling, and redistribution of unused resources (Abazari et al., 2022). By combining sustainable logistics practices with advanced optimization models, researchers can help develop resilient, environmentally responsible disaster response frameworks (V. Akbari & Sayarshad, 2022). The proposed study builds upon these insights by introducing a bi-objective optimization model that simultaneously minimizes response time and environmental impact, addressing a critical gap in the existing literature (Yin et al., 2024).

The problem of the location of the transfer point, which is part of the problem of location, was introduced into the literature (Balcik & Beamon, 2005; Berman et al., 2007; Özdamar & Ertem, 2015b; Vahdani et al., 2018). Then, various methods of presenting and solving the model at the level and network with maximum-minimum and minimum approaches were presented (Berman et al., 2008a). Then, the types of transfer point mathematical models were classified into three general modes of transfer point location, multiple transfer point location, and multiple transfer point location and facilities location problems (Berman et al., 2008b). Sasaki et al. (2008) provided an accurate solution to the minimum-maximum transmission point location in the network. Hosseini Joo and Bashiri (2009) presented the model of the possible location of transfer points. Hosseini Joo and Bashiri (2011) developed their possible model by considering several demand points. Mahmoudian et al. (2010) have presented two innovative algorithms to solve the transfer point problem. Kalantari et al. (2014) presented a fuzzy model without a nonlinear restriction on the transfer point location and investigated its analytical solution. Kalantari et al. (2014) present a rule-based algorithm for the practical solution of the fuzzy model of transfer point location. Mohammadi et al. (2015) have studied the function of the limited chance location model of the transfer point with a case study of Tehran Region One (Dastyar et al., 2018). Merakl and Yaman (2016) developed a sustainable transfer point location model that accounts for uncertain demand. McDougall and Otero (2017) review the location model for the transfer point that sends goods from the warehouse to the customer airborne. Yousefli et al. (2018) have presented a possible model for locating the transfer point and solving it using a rule.

Table 1. Summarizing the literature

References	Research Objective	Type of Model	Type of Objective Function	Case Study
Balcik and Beamon (2020)	Develop a distribution network design model for humanitarian relief chains	Multi-objective mixed-integer programming	Minimize total cost, maximize responsiveness	Not specified
Berman et al. (2020)	Introduce the transfer point location problem in disaster relief	Single-objective location model	Minimize total travel time	Hypothetical network
Özdamar and Ertem (2021)	Review models, solutions, and enabling technologies in humanitarian logistics	Review paper	N/A	N/A
Vahdani et al. (2021)	Develop a two-stage multi-objective location-routing-inventory model for humanitarian logistics network design	Multi-objective mixed-integer programming	Minimize total cost, maximize service level	Tehran, Iran
Hosseinijou and Bashiri (2022)	Present a stochastic model for the transfer point location problem	Stochastic programming	Minimize maximum travel time	Hypothetical network
Hosseinijou and Bashiri (2022)	Extend the stochastic transfer point location model to consider multiple demand points	Stochastic programming	Minimize maximum travel time	Hypothetical network
Kalantari, Yousefli et al. (2022)	Propose a fuzzy transfer point location problem model	Fuzzy programming	Minimize travel time	Hypothetical network
Kalantari, Badiee et al. (2023)	Develop a rule-based algorithm to solve the fuzzy transfer point location model	Fuzzy programming	Minimize travel time	Hypothetical network
Mohammadi et al. (2023)	Study the function of the limited chance transfer point location model	Stochastic programming	Minimize total travel time	Tehran, Iran (Region 1)
Meraklı and Yaman (2024)	Develop a sustainable transfer point location model with uncertain demand	Robust optimization	Minimize total cost	Hypothetical network

Table 1 provides an overview of the existing literature on the transfer point location problem and humanitarian logistics network design, including the research objectives, types of mathematical models, objective functions, and case studies. The table highlights the diversity of approaches used in the literature, as well as the focus on logistical efficiency and cost minimization, with limited consideration of sustainability and environmental impact. This provides a context for the proposed research, which aims to address the environmental footprint of earthquake relief logistics through a bi-objective optimization approach.

Materials and Methods

In this paper, the model for locating optimal transfer points and allocating them to facilities is investigated. The injured are taken to the transfer point by ambulance or by citizens. The injured are classified into three colors: red, yellow, and green at the transfer point. Red indicates a severe injury and requires special medical care; yellow indicates lower levels, and green indicates first aid and outpatient treatment. Only the severely injured are sent to the hospital by helicopter, and in the absence of capacity, by ambulance. Therefore, other relief centers have been envisaged to meet the medical needs, which will be activated in times of disaster. The injured in yellow are taken to ambulances. If the injured are in critical condition and turn red, they will be sent to the hospital by ambulance. First aid and outpatient services are provided to the green injured at the transfer point, and they are removed from the relief process. The desired relief chain is shown in Figure 1.

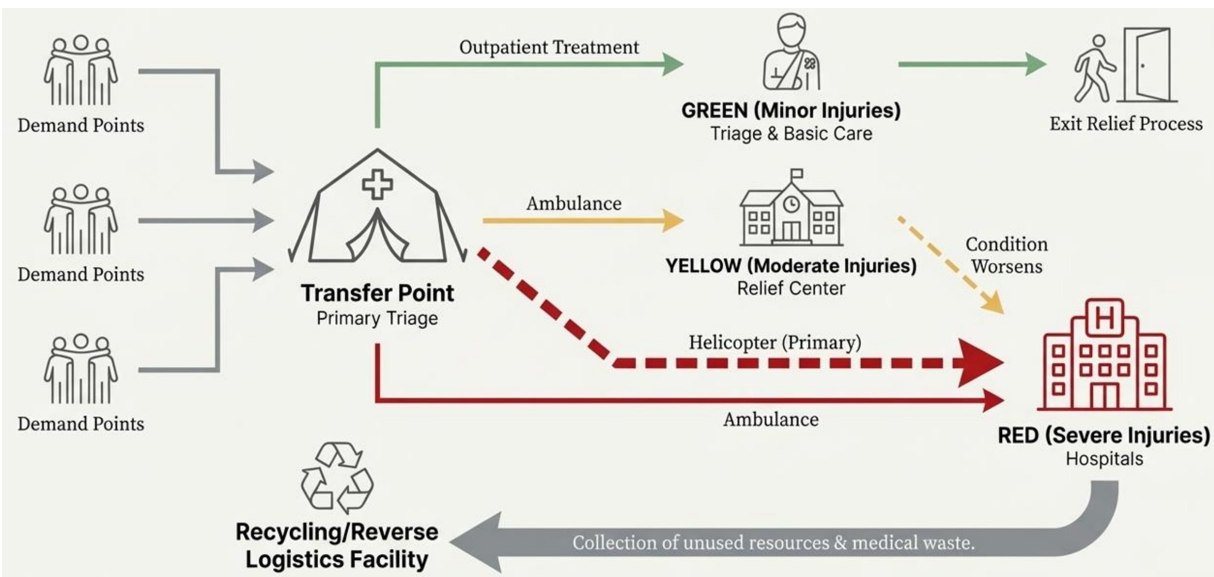

Figure 1. Designed a relief chain

In this paper, two models are presented. One is a one-purpose model to minimize the time spent serving the injured, and the other is a two-purpose model to minimize the penalty for failing to provide service during the service process. The models are solved by selecting a limited number of transfer points, relief centers, and hospitals for milder earthquakes with a low number of injured, and by using all transfer points, relief centers, and hospitals for severe earthquakes with a high number of injured. The results are compared. This study investigates the optimal location of transfer points and the allocation of facilities to injured individuals in disaster scenarios. The injured are transported to transfer points by ambulance or by citizens, where they are classified into three categories:

- Red (severe injury requiring urgent medical care)
- Yellow (moderate injury)
- Green (minor injuries requiring first aid and outpatient treatment)

Only red casualties are sent to hospitals by helicopter or ambulance if capacity is available. Other relief centers are activated to meet medical needs during disasters. Yellow casualties are taken to relief centers by ambulance, and if their condition worsens to red, they are sent to hospitals. Green casualties receive first aid at transfer points and exit the relief process. The research process is illustrated in Figure 2.

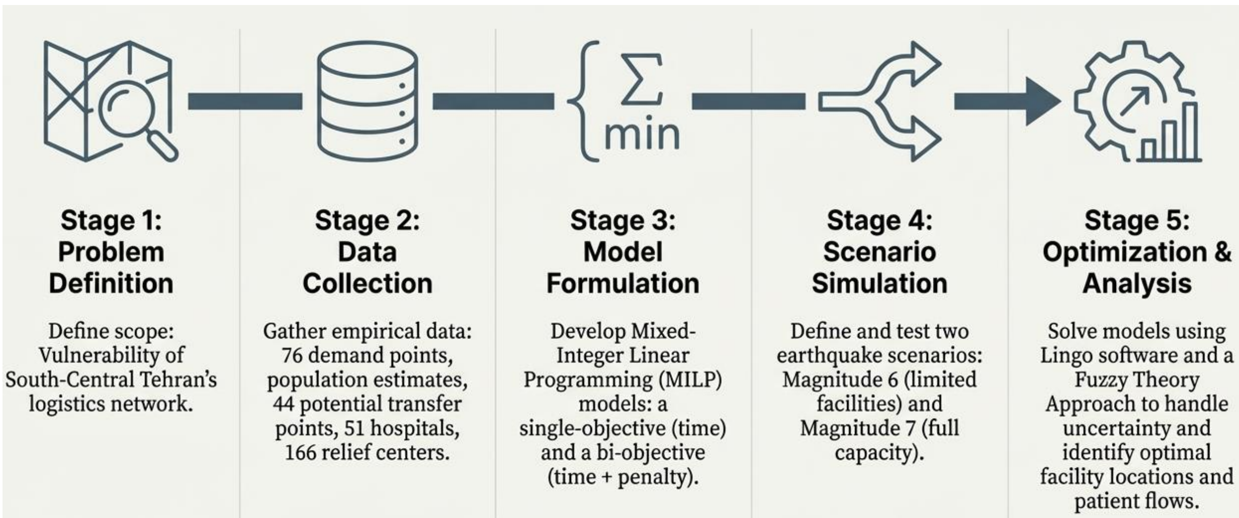

Figure 2. The research multi-stage process

The single objective model

Indices, parameters, and variables of the single-objective model are presented below.

Indices	**Description**
i	Index of demand
j	Index of transfer points
k	Index of hospitals
l	Index of relief center
m	Index for earthquake magnitude scenario

Parameters	**Description**
DT_{im}	The amount of demand (injured) the entire demand area i under the earthquake scenario m.
β_{Rm}	The ratio of red casualties to total casualties is the same for yellow and green β_Y, β_G for scenario m
β_{YR}	The proportion of yellow injured who turn red at the relief center
t_{ij}	Travel time between two points i and j, as well as t_{jk} ، t_{jl} ، t_{lk}

α	Reduction coefficient of travel time from the point of transfer to the hospital
CAP_k	Hospital capacity k
$CAP.AMB_j$	Transmission point ambulance capacity j, $CAP.HELI_j$ Helicopter capacity and $CAP.OT_j$ Outpatient treatment capacity
$CAP.HRC_l$	The medical capacity of the relief center l and $CAP.ARC_l$ the capacity of its ambulance
P	The number of transfer points to choose from, as well as the facilitation and relief center Q, S

Variables	**Description**
x_{ij}	The number of injured sent from the point of demand i to the point of transfer j
R_j	The number of reds injured at the transfer point j, the same for yellow and green Y_j ‹ G_j
RH_{jk}	Number of reds injured sent by helicopter from transfer point j to hospital k
RA_{jk}	Number of reds injured sent by ambulance from transfer point j to hospital k
YA_{jl}	Number of yellow injured sent by ambulance from transfer point j to hospital l
YR_{lk}	Number of reds injured sent by ambulance from transfer point l to hospital k
W_k	equal to one if node k is selected as a hospital; Otherwise, equal to zero
Z_j	equal to one if the node j is selected as a transfer point; Otherwise, equal to zero
U_l	equal to one if node l is chosen as a relief center; Otherwise, equal to zero

The single-objective model focuses solely on minimizing the transfer point. The characteristic of this mathematical model is presented in Figure 3.

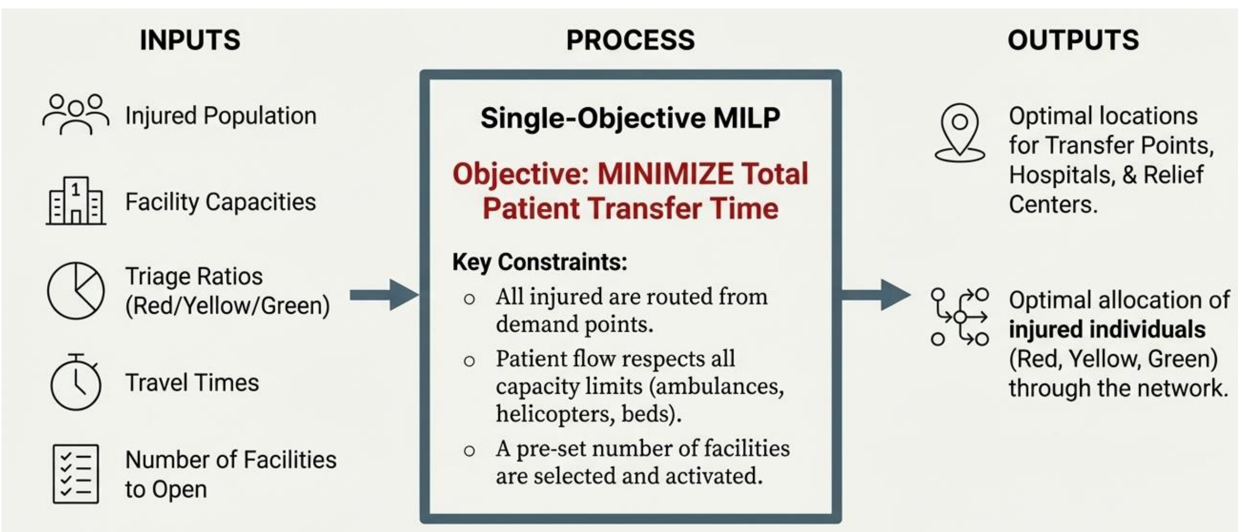

Figure 3. The single objective model characteristic

The mathematical form of this model is as follows:

$$MIN \sum_i \sum_j t_{ij} * x_{ij} + \sum_j \sum_k (t_{jk} * RH_{jk} * \alpha + t_{jk} * RA_{jk}) + \sum_j \sum_l t_{jl} * YA_{jl} + \sum_l \sum_k t_{lk} * YR_{lk} \quad (1)$$

S.t

$\sum_i x_{ij} = DT_i$	$\forall i \in I$	(2)
$Y_j = \sum_l YA_{jl}$	$\forall j \in J$	(3)
$R_j = \sum_k (RH_{jk} + RA_{jk})$	$\forall j \in J$	(4)
$\beta_{YR} * \sum_j YA_{jl} = \sum_k YR_{lk}$	$\forall l \in L$	(5)
$\beta_G * \sum_i x_{ij} = G_j$	$\forall j \in J$	(6)
$\beta_R * \sum_i x_{ij} = R_j$	$\forall j \in J$	(7)
$\beta_Y * \sum_i x_{ij} = Y_j$	$\forall j \in J$	(8)
$\beta_G + \beta_R + \beta_Y = 1$		(9)
$\sum_j RH_{jk} + \sum_j RA_{jk} + \sum_l YR_{lk} \leq CAP_k * W_k$	$\forall k \in K$	(10)
$Y_j + R_j \leq (CAP.AMB_j + CAP.HELI_j) * Z_j$	$\forall j \in J$	(11)
$\sum_k RH_{jk} \leq CAP.HELI_j * Z_j$	$\forall j \in J$	(12)
$G_j \leq CAP.OT_j * Z_j$	$\forall j \in J$	(13)
$\sum_j YA_{jl} \leq CAP.HRC_l * U_l$	$\forall l \in L$	(14)
$\sum_k YR_{lk} \leq CAP.ARC_l * U_l$	$\forall l \in L$	(15)
$\sum_j Z_j = P$		(16)
$\sum_l U_l = S$		(17)
$\sum_k W_k = Q$		(18)
$x_{ij}, RH_{jk}, RA_{jk}, YA_{jl}, YR_{lk} \geq 0$ and integer	$\forall i \in I$ $\forall j \in J$ $\forall k \in K$ $\forall l \in L$	(19)
$Z_j, W_k, U_l \in \{0,1\}$	$\forall j \in J$	(20)

Equation 1 represents the objective function of minimizing the total time required to transfer the affected people to the transfer point, hospital, and relief centers (Aliakbari et al., 2022). Equation 2 indicates that all injured demand points should be sent to different transfer points (Seyyedi et al., 2019). Equation 3 indicates that all yellow-injured individuals transferred to a transfer point are sent to a relief center (Seyyedi et al, 2019). Equation 4 indicates that all red-injured patients transferred to a transfer point are sent to the hospital by helicopter or ambulance (Seyyedi et al, 2019). Equation 5 indicates that all red-injured individuals are sent to a hospital or a relief center (Vahdani et al., 2018). Equations 6, 7, and 8 calculate the number of green, red, and yellow injured at a point of transmission, respectively (Developed by Authors). Equation 9 indicates that the sum of the proportions of the injured with different colors should be equal to 1

(Seyyedi et al, 2019). Equations 12 to 15 indicate that the total number of injured sent to transfer points, hospitals, and relief centers should be less than the capacity to hold or send them if the desired point is selected (Xu et al, 2024). Equations 16, 17, and 18 specify the required numbers of transfer points, relief centers, and hospitals (Xu et al., 2024). Equations 19 and 20 specify the range of variables (Developed by Authors).

The bi-objective model

The bi-objective model introduces a crucial trade-off between time and unmet need. The characteristic of this mathematical model is presented in Figure 4.

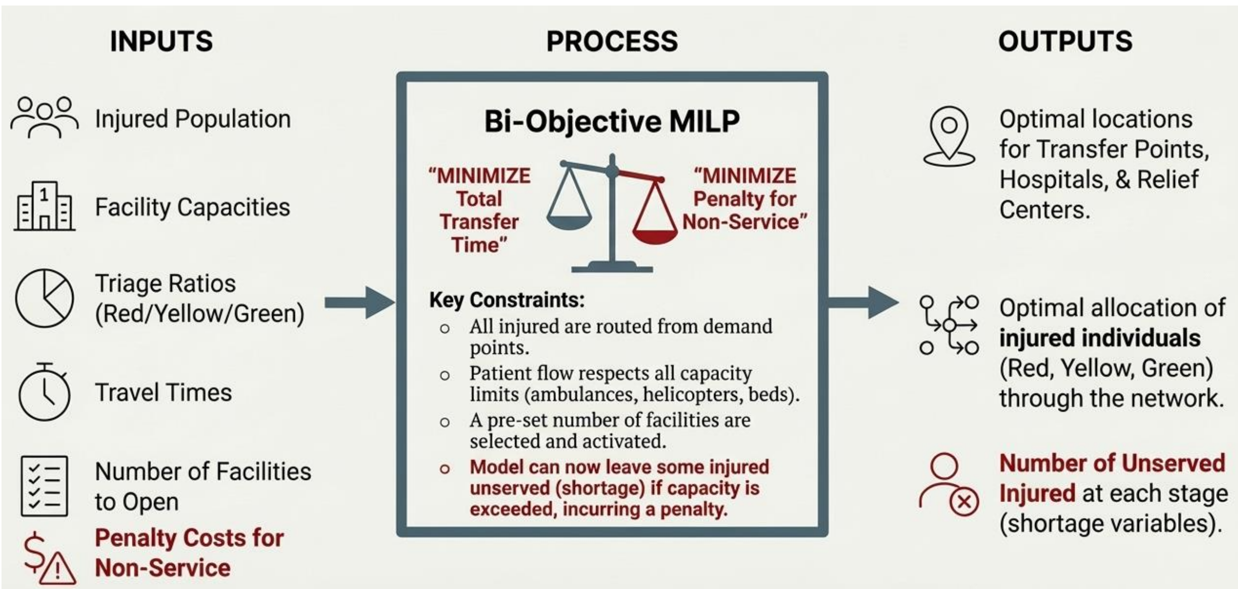

Figure 4. The bi-objective model characteristic

In addition to the parameters and variables of the single-objective model, the following items are included.

Parameters	Description
CX	Cost of not sending the injured from the point of demand to the point of transfer
CYR	Cost of not sending the injured red from the relief center to the hospital
CY	Cost of not sending the yellow injured person from the transfer point to the hospital
CR	Cost of not sending the injured red from the point of transfer to the hospital

Variables	Description
KX_i	Number of injured not sent to the point of transfer from the point of demand i
KYR_l	Number of injured Reds not sent to hospital from the relief center l
KY_j	Number of yellow injured not sent to hospital from transfer point j
KR_j	Number of red casualties not sent to hospital from the transfer point j

Although the worst-case scenario should always be considered in disaster relief, some of the injured may not receive prompt care due to limited facilities and budget constraints. Therefore, the lowest cost of living is significant. Because the delay in serving the injured red and green will have different life consequences. Therefore, a bi-objective model with the second objective of minimizing the penalty due to shortage is presented. Shortage indicates a lack of service at the right time.

$$minZ_1 = \sum_i \sum_j t_{ij} * x_{ij} + \sum_j \sum_k (t_{jk} * RH_{jk} * \alpha + t_{jk} * RA_{jk}) + \sum_j \sum_l t_{jl} * YA_{jl} + \sum_l \sum_k t_{lk} * YR_{lk} \quad (21)$$

$$minZ_2 = \sum_i (CX * KX_i) + \sum_l (CYR * KYR_l) + \sum_j (CY * KY_j + CR * KR_j) \quad (22)$$

s.t

$$\sum_i x_{ij} + KX_i = DT_i \qquad \forall\, i \in I \quad (23)$$

$$Y_j = \sum_l YA_{jl} + KY_j \qquad \forall\, j \in J \quad (24)$$

$$R_j = \sum_k (RH_{jk} + RA_{jk}) + \sum_l RAL_{jl} + KR_j \qquad \forall\, j \in J \quad (25)$$

$$\beta_{YR} * \sum_j YA_{jl} = \sum_k YR_{lk} + KYR_{lk} \qquad \forall\, l \in L \quad (26)$$

$$\beta_G * \sum_i x_{ij} = G_j \qquad \forall\, j \in J \quad (27)$$

$$\beta_R * \sum_i x_{ij} = R_j \qquad \forall\, j \in J \quad (28)$$

$$\beta_Y * \sum_i x_{ij} = Y_j \qquad \forall\, j \in J \quad (29)$$

$$\beta_G + \beta_R + \beta_Y = 1 \quad (30)$$

$$\sum_j RH_{jk} + \sum_j RA_{jk} + \sum_l YR_{lk} \leq CAP_k * W_k \qquad \forall\, k \in K \quad (31)$$

$$Y_j + R_j \leq (CAP.AMB_j + CAP.HELI_j) * Z_j \qquad \forall\, j \in J \quad (32)$$

$$\sum_k RH_{jk} \leq CAP.HELI_j * Z_j \qquad \forall\, j \in J \quad (33)$$

$$G_j \leq CAP.OT_j * Z_j \qquad \forall\, j \in J \quad (34)$$

$$\sum_j YA_{jl} \leq CAP.HRC_l * U_l \qquad \forall\, l \in L \quad (35)$$

$$\sum_k YR_{lk} \leq CAP.ARC_l * U_l \qquad \forall\, l \in L \quad (36)$$

$$\sum_j Z_j = P \quad (37)$$

$$\sum_l U_l = S \quad (38)$$

$$\sum_k W_k = Q \quad (39)$$

$$x_{ij}, RH_{jk}, RA_{jk}, YA_{jl}, YR_{lk} \geq 0 \text{ and integer} \qquad \forall\, i \in I,\ \forall\, j \in J,\ \forall\, k \in K,\ \forall\, l \in L \quad (40)$$

$$Z_j, W_k, U_l \in \{0,1\} \qquad \forall\, j \in J \quad (41)$$

$$KX_i, KYR_l, KY_j, KR_j \geq 0 \text{ and integer} \qquad \forall\, i \in I \quad \forall\, j \in J \quad \forall\, l \in L \qquad (42)$$

Equation 21 represents the objective function of minimizing the total time required to transfer the injured to the transfer point, hospital, and relief centers (Desi-Nezhad et al., 2022). Equation 22 represents the objective function of reducing the cost of shortages due to the non-dispatch of injured in various parts of the relief process (Akbari et al, 2022). Equation 23 indicates that all injured points are either sent to different transfer points or remain at the transfer point as shortages (Seyyedi et al., 2019). Equation 24 indicates that all yellow-injured individuals transferred to a transfer point are either sent to a relief center or remain deficient at the transfer point (Seyyedi et al, 2019). Equation 25 indicates that all red casualties transferred to a transfer point are transported to the hospital by helicopter or ambulance or remain deficient at the transfer point (Beigi et al, 2020). Equation 26 indicates that all red-injured are sent to a hospital or a relief center, or remain in the relief center in short supply (Beigi et al., 2020). Equations 27, 28, and 29 calculate the number of green, red, and yellow injured at a point of transmission, respectively (Developed by Authors). Equation 30 indicates that the sum of the proportions of the injured with different colors should be equal to 1 (Seyyedi et al, 2019). Equations 31 to 36 indicate that the total number of injured sent to transfer points, hospitals, and relief centers should be less than the capacity to hold or send them if the desired point is selected (Xu et al, 2024). Equations 37, 38, and 39 specify the number of transfer points, relief centers, and hospitals required (Xu et al, 2024). Equations 40-42 specify the range of variables (Developed by Authors).

The Fuzzy Theory Approach is applied in the Solution Method section to handle uncertainties inherent in the earthquake disaster scenario. Since many input parameters, such as casualty numbers, travel times, and hospital capacities, are uncertain or imprecise, fuzzy logic provides an effective way to model them. Fuzzy variables are defined for key factors such as casualty severity (e.g., low, medium, high) and travel time (e.g., short, medium, long). Membership functions are used to represent these fuzzy sets, enabling a flexible and realistic representation of imprecise data. Fuzzy constraints and objectives are then integrated into the optimization model, enabling decision-making under uncertainty (Ghasemi et al., 2022).

In this approach, fuzzy decision rules are utilized to guide resource allocation and prioritization during the disaster response, such as determining which casualties should be transferred first based on available resources (Amani et al., 2025a). The optimization problem is formulated as a fuzzy mathematical program, with defuzzification applied to convert the fuzzy results into actionable, crisp values. This procedure was presented in Figure 5.

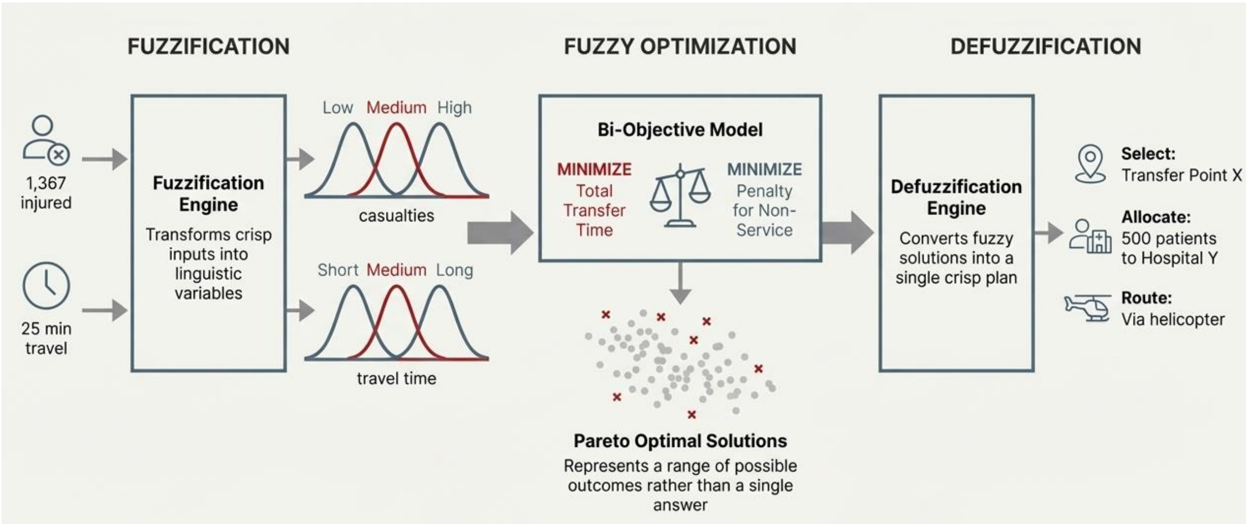

Figure 5. Research a solution approach to manage the problem uncertainty

This enables practical decision-making in real-world settings where precise data is often unavailable and improves overall response efficiency by accounting for the inherent uncertainty in disaster management scenarios.

Results

In this section, to evaluate the model's performance, areas 10, 11, 12, 16, 17, and 19 of Tehran, which constitute the south-central part of the city, have been selected. The south-central part of Tehran is shown in Figure 6.

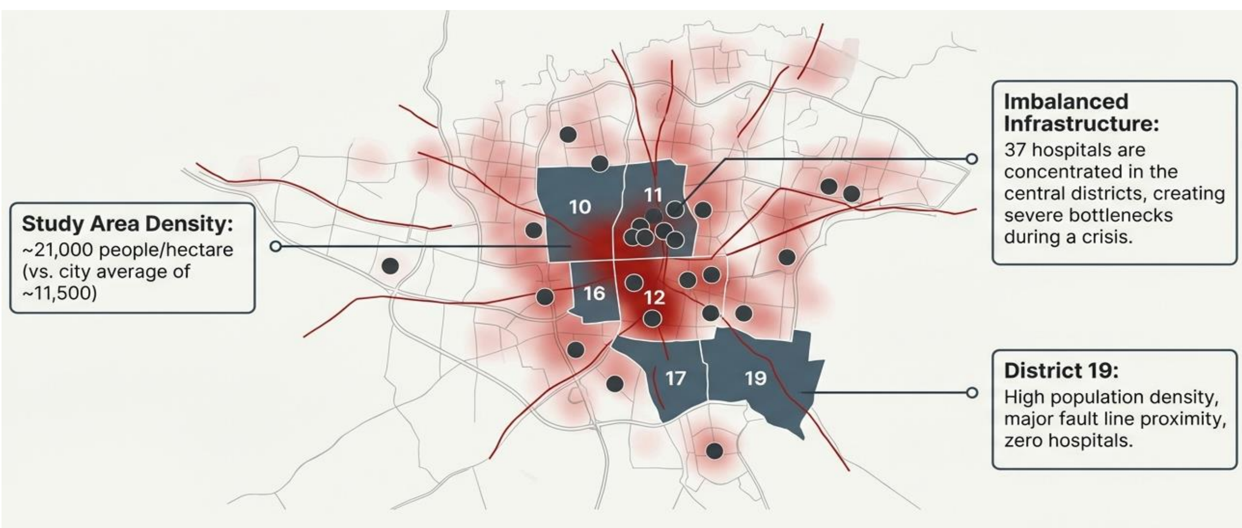

Figure 6. Map of research case study

The selected areas form an interconnected area of the city of Tehran. These areas have a very high population density. The average population density in Tehran is about 11,500 people per hectare, while the average population density of these six areas is about 21,000 people per hectare. On the other hand, their urban structures are old and worn out. In fact, due to the erosion of buildings and narrow streets and alleys, relief activities and transportation of the injured in these areas are much more complicated than in other areas. The demand at each demand point is the product of the area's population and its vulnerability. The degree of vulnerability depends on 1) the severity of the disaster, 2) the type of disaster, and 3) the area's texture. The severity of the disaster also depends on three factors: the magnitude of the earthquake in terms of Richter, the depth, and the location of the earthquake (Karimi, 2012).

In this research, areas are divided into 76 sections by district. Each neighborhood represents a demand point. The estimated injuries in each district are based on a magnitude six earthquake with fewer injuries and a magnitude seven earthquake with more injuries. Information from the Disaster Management Organization was used to estimate the number of injuries. Table 1 shows the number of districts and the estimated results of the injured.

Table 1. Demand points and the number of injured people

No.	Demand Points (DP)	Region	Population of DP	Injured estimation – Scenario 1	Injured estimation – Scenario 1
1	North salsabil	10	34178	1367	273
2	Sheikh hadi	11	19378	968	193
3	harandi	12	26371	2241	448
4	khazaneh	16	42635	3410	682
...	...	...	...	...	...
76	North khani abad	19	26744	1872	374
	sum		1707837	108964	

Forty-four locations in these areas were considered as transfer points. These areas should provide helicopter landing zones and facilities for outpatient and emergency medical services, and they should have adequate access and be known to residents so that the general public understands the address and how to reach it. The names and characteristics of several predicted areas are presented in Table 2.

Table 2. The capacity of demand points

No.	Transfer point location	Region	Ambulance capacity	Helicopter capacity	Outpatient treatment capacity
1	Meqdad district	10	1600	300	1500
2	Baharan Park	17	1300	100	1400
3	University of Tehran	11	1500	300	1500
...	....	....	...	....	....
44	Velayat Park	19	1550	200	1500
	Sum		65350	8750	63150

There are 51 hospitals in the designated area. One of the problems in providing relief is the lack of proper distribution of hospitals in the city of Tehran: there is no hospital in district 19, and there are only two hospitals in district 17, while 37 hospitals are in districts 11 and 12, which are the central districts of Tehran. Therefore, during disasters, the influx of the wounded into central areas will create many problems. For example, the information of some hospitals in these areas is presented in Table 3.

Table 3. The capacity of hospitals

No.	Hospital Name	Region	Capacity
1	Madaen	11	144
2	ziaeeyan	17	155
3	Sina	12	625
...	...	...	...
51	Valieasr	16	365
	Sum		10839

As is well known, the capacity of hospitals in these areas is approximately 0.1 times the volume of injuries during the 7.0-magnitude earthquake, underscoring the importance of screening the injured. So that if all the injured rush to the hospitals, along with their companions, the relief process will be completely interrupted. This demonstrates pre-disaster training for citizens to work with aid workers, the absence of congestion in medical centers, and the generalization of transfer points. Due to limited hospital capacity, 166 relief centers are planned to provide services during the earthquake. These centers are selected from schools and school complexes where several schools are located next to each other, stadiums, shrines, and newly built mosques that have the space and facilities to serve as temporary relief centers. For example, information on some of the envisaged relief centers is presented in Table 4.

Table 4. Estimated relief centers and their capacity

No.	Relief center	Region	Holding capacity	Ambulance Capacity
1	Azadi Sport Complex	10	400	25
2	Beheshti school	11	400	25
3	Emamzade hasan	17	400	25
...	...	...	...	...
51	Fani university	19	400	25
	Sum		66400	4150

The road routes on the map were used to calculate distances between points. To calculate the distance from the transfer point to the hospital, a direct distance was used. For simplicity, the ratio of the mean direct distance to the road distance was calculated, and the alpha coefficient was affected. In other words, the alpha coefficient indicates that an increase in vehicle speed is associated with a shorter route.

The presented models are solved in two modes. For the first case, the model is solved by assuming a six-magnitude earthquake with fewer injuries and selecting ten transfer points, 15 hospitals, and 25 relief centers. In other words, only transfer points, relief centers, and selected hospitals are activated. Therefore, the hospitals' actual capacity is used. The proportion of red injuries is increased due to hospitals' greater capacity. The seriously injured can be transferred to the hospital whenever possible.

For the second case, a 7-magnitude earthquake and a severe catastrophe are assumed, and it is necessary to use all the capacity of the projected facilities. Even the capacity of existing hospitals must be increased by 30% to meet 10% of the injured. Of course, there is a limit to the impossibility of accepting the injured by air transfer in all hospitals. Therefore, it is necessary to create air admission for all hospitals for this assumption to be applicable. Finally, given that the second model has two purposes, the methods of solving multi-objective models must determine the answers to the problem. In this paper, the fuzzy approach is used to solve multi-objective models. Of course, to avoid prolonging the article, only the optimal Pareto solutions of the second model in the case of a 6-magnitude earthquake are presented. Solving a single-objective model, six magnitude earthquakes, the problem of location and optimal allocation of injured flow are as follows:

Select ten transfer points and 15 hospitals, and 25 relief centers. The ratio of red, yellow, and green injuries from the total injured is 0.2, 0.45, and 0.35, respectively. The proportion of injured who change position from yellow to red at the relief center. 0.03. The alpha speed-increase coefficient is 0.2. The model was solved using Lingo, and the final value of the objective function was 0.2820267e08.

Figure 3 shows the allocation of Jamalzadeh, Jomhouri, North and South Salsabil, Eskandari, Horr, Special, and Khorramshahr neighborhoods to the transfer point Heydarnia Stadium and its allocation to hospitals and relief centers on the map of Tehran. The demand points may be closer to the hospital than the transfer point, but it is necessary to prevent the transfer of the injured directly.

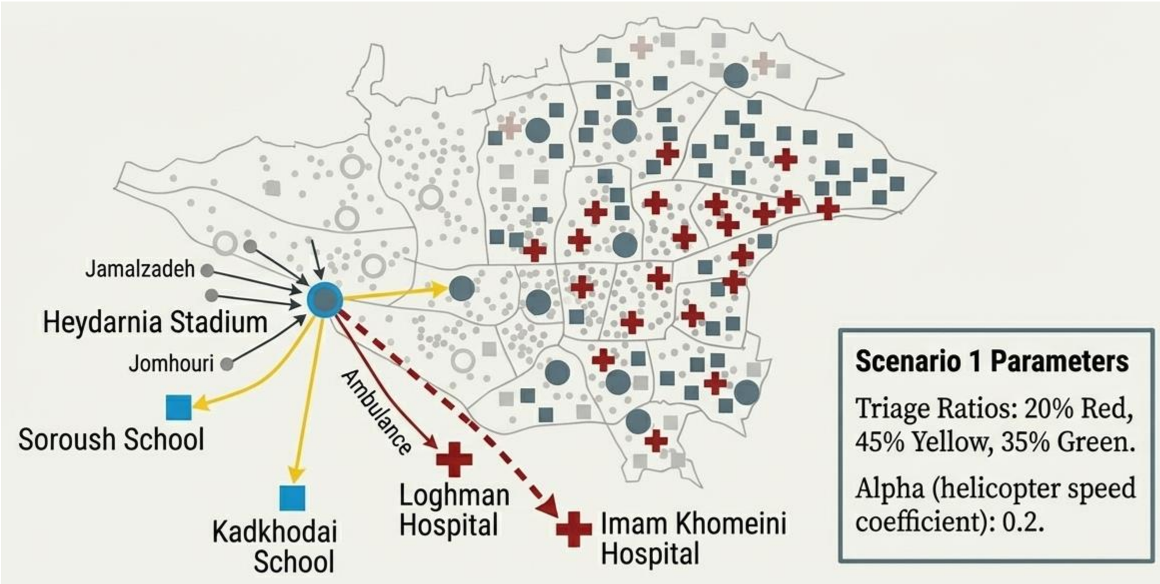

Figure 7. Findings for scenario 1

Use of all planned transfer points, relief centers, and hospitals (allocation issue). The proportion of red, yellow, and green injured from the total injured is 0.1, 0.55, and 0.35, respectively. 30% increase in the capacity of existing hospitals to respond to 10% of the injured. The ratio of injured people who change position from yellow to red in the relief center Alpha speed increase coefficient is equal to 0.2. Table 5 presents two examples of the answers obtained by solving the allocation model, which has been unable to provide all solutions due to the length of the table.

Table 6. The optimal solution of single objective model- Scenario 2

No.	Demand points	Transfer point	Hospital	Relief center	Hospital
1	South karon (818) South zanjan (1232) Hashemi (872)	Fire-fighting mail station	Imamkhomeini (292 helocupter)	Jeihon complex (400)	Shahriar
				Toos (400)	Shahriar
				Ezabadi school (8)	Meimanat
				Farzanegan school (400)	Shahriar
				Fazel school (400)	Babak
2	Hashemi (864) Jey (1828)	Malekashtar complex	Meimanat (96 ambulance (Azadi (23 ambulance) Omid (18 ambulance) Madaen (78 ambulance)	Ezabadi school (7)	Meimanat
				Ghods school (400)	Meimanat
				Farhangsara (400)	Azadi
				Abotaleb school (204)	Babak
				Alzahra school (400)	Meimanat
...	...	...	...	...	...

The fuzzy theory approach was used as follows:

$$
\begin{aligned}
&\max w_1\alpha_1 + w_2\alpha_2 \\
&\text{s.t} \\
&z_1 \le z_1^- + (1-\alpha_1)(z_1^+ - z_1^-) \\
&z_2 \le z_2^- + (1-\alpha_2)(z_2^+ - z_2^-) \\
&w_1 + w_2 = 1 \\
&0 \le \alpha_1 \le 1 \\
&0 \le \alpha_2 \le 1 \\
&w_1 \ge 0 \\
&w_2 \ge 0
\end{aligned}
$$

z^-represents the best possible answer for the minimum type objective functions, and z^+ represents the worst possible answer for the minimum type objective functions. Equation 43 indicates the maximization of the desirability of α, and relations 44 and 45 satisfy the level of desirability. The value is between 0 and 1, with 1 indicating complete desirability for the objective function and 0 indicating non-desirability.

The problem parameters, as well as the location and allocation mode of the single-objective model, are set. In addition, penalty parameters are predicted. Pareto-optimal solutions obtained by varying the weights of the objective functions are presented in Table 6. The names of the points have been omitted to prevent the table from becoming large. By changing the weight of the target functions, the answers in all three sections of the selection of transfer points, hospitals, and relief centers, and the amounts and volumes of their allocation change. Therefore, the decision-maker will have a more accurate understanding of the results of his decision in different situations.

Table 6. Pareto results in a different scenario

Weight	Transfer Point	Hospital	Relief Center
W1= 0/1 W2= 0/9	9-12-14-16-19-25-28-29-32-40	1-4-6-13-14-15-16-17-23-30-44-45-48-49	8-9-15-16-17-18-37-48-49-50-53-54-67-68-84-114-115-118-119-120-122-129-135-150-151
W1= 0/3 W2= 0/7	9-14-16-19-25-28-39-32-36-40	2-3-4-5-14-15-16-18-30-45-46-47-48-50-51	16-18-23-37-38-49-50-66-67-68-84-102-110-115-116-120-121-122-127-129-135-140-150-151-165
W1= 0/5 W2= 0/5	7-22-14-16-19-25-29-32-36-40	2-3-5-6-14-15-16-17-18-3-36-46-47-50-51	16-17-18-37-38-48-50-53-54-67-68-71-72-107-114-115-118-121-127-135-144-150-151-164-165
W1= 0/7 W2= 0/3	9-12-14-16-19-25-29-32-36-40	2-3-5-13-14-15-16-18-45-46-47-48-49-50-51	16-17-18-36-37-49-50-53-54-57-67-68-1 70-84-114-115-118-121-129-135-144-150-151-163-165
W1= 0/9 W2= 0/1	6-7-13-14-16-25-29-32-33-41	2-4-5-6-9-13-14-16-17-18-38-46-50-51	4-18-19-22-23-31-35-37-38-42-50-61-67-98-115-118-121-125-129-134-135-140-145-157-161

The bi-objective model reveals the trade-off between speed and service coverage, as shown in Figure 8.

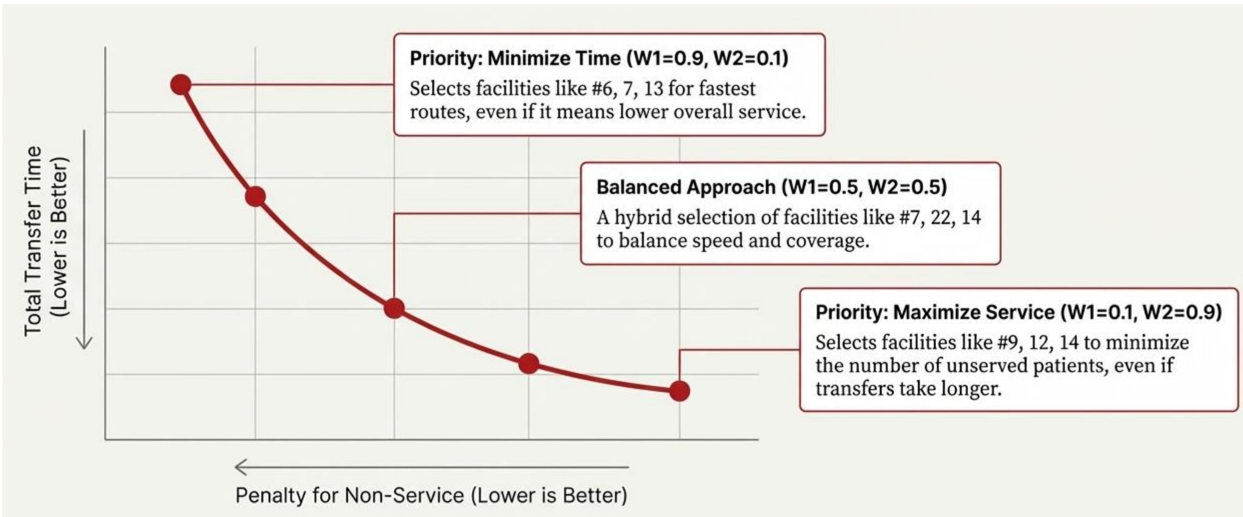

Figure 8. The bi-objective model trade-off

Figure 8 empowers decision makers to choose a strategy that aligns with their specific priorities and resource constraints.

Discussion

Given current estimates of the number of injured in severe earthquakes, hospital capacity will certainly not be sufficient, and a solution must be devised to help the injured. This article proposes the establishment of facilities at transfer points and relief centers, so that at the transfer points, it is possible to screen the injured based on the triage system and provide outpatient treatment services (Y. Wang et al., 2021). Lack of proper distribution of hospitals in Tehran is another problem identified in a case study and has not been considered in previous articles. There are no hospitals in some areas, and the ones that are located in the city center are in the city center. This relief effort will face many challenges, including the influx of people into these areas after the crisis. It is also essential to address this situation, not to accept the injured directly at the hospital, and to train citizens to attend the transfer points. In previous articles, transfer capacity at unlimited transfer points is often considered.

In contrast, helicopter transfers are limited due to the country's economic conditions; the number of relief helicopters is low, and infrastructure is not available. For this reason, a limited capacity for helicopter transport was considered in this paper. The rest of the transfer was done by ambulance (Gralla & Goentzel, 2018). The models were solved for two states: 6- and 7-magnitude earthquakes. In addition to the deterioration of buildings and the inadequate urban structure, due to citizens' lack of education, the number of injuries in earthquakes in Tehran will be higher than the global average. In the light earthquake of 1396 in Tehran, one person was killed, and several others were injured while fleeing. In the event of a magnitude 7 earthquake, the capacity of existing hospitals must be increased by 30% to accommodate 10% of the injured population, requiring the purchase of hospital beds and other equipment. Also, some hospitals are specialized and should be prepared to shift to general treatment during a disaster (Özdamar & Ertem, 2015a).

One of the key innovations of this research is the incorporation of sustainability and circular-economy principles into the design of the relief logistics network. The environmental impact of disaster relief operations, including the transportation of the injured, the operation of transfer points and hospitals, and the management of medical waste and supplies, can be substantial. By minimizing the carbon emissions, energy consumption, and resource depletion associated with these activities, the proposed bi-objective optimization approach can help mitigate the overall environmental footprint of the relief efforts. Furthermore, the integration of reverse logistics facilities into the model enables the collection and processing of unused medical supplies, equipment, and other resources, promoting the circularity of the relief logistics system (Desi-Nezhad et al., 2022). This can not only reduce waste and environmental impact but also enhance the efficiency and resilience of the disaster response by ensuring the availability of critical resources during future emergencies (Zhang et al., 2022). Beigi et al. (2020) determined the volume of flow between demand points and emergency resettlement sites, clinics, and hospitals. The objective function of the mathematical model was to minimize the expected total transfer time for people, taking into account the coefficient of fines for the later transmission of affected persons to the treatment centers. Given the accidental nature of natural disasters, uncertainty in this study is modeled as a scenario. In this study, the probability of occurrence of different scenarios, the probability of injury in each area in different scenarios, the classification of injured persons, and the limited reception capacity at resettlement and treatment centers were considered. This research used fuzzy programming for managing the uncertain parameters. Our findings align with those of Safari and Jalali (2020) in optimizing the needs of affected people. Their results showed that the need for nutrition and food, evacuation of the affected groups from the accident site, and access to drinking water are the most important needs of the victims during the earthquake.

The methodology and solution methods presented in this research play a crucial role in enhancing the effectiveness of earthquake relief logistics. By combining optimization techniques with fuzzy logic, the methodology provides a structured approach to addressing the complexity and uncertainties involved in disaster response. The optimization model ensures that resources such as medical supplies, transportation, and personnel are allocated efficiently, reducing delays and maximizing the impact of each decision. This structured approach helps minimize response time and ensure that critical areas affected by the earthquake receive immediate attention. Considering multiple factors, such as casualty severity, hospital capacity, and travel time, further improves decision-making, enabling a more comprehensive and adaptable relief effort.

The integration of fuzzy logic into solution methods offers significant benefits for managing uncertainty inherent to real-world disaster scenarios. Earthquake relief efforts often involve incomplete or imprecise data, such as estimated casualties or unpredictable road conditions. By using fuzzy theory, the model can incorporate these uncertainties into the decision-making process, providing more realistic and flexible solutions. This approach allows relief teams to make decisions based on approximate data, adjusting dynamically as more information becomes available. Overall, the combination of a robust optimization model and fuzzy logic not only streamlines the relief operations but also enhances the overall resilience and responsiveness of earthquake logistics, thereby contributing to more effective disaster mitigation and recovery efforts.

Conclusion

This paper presents mixed-integer mathematical planning models with single- and bi-objective approaches for multiple locations of transfer points, hospitals, relief centers, and recycling/reverse logistics facilities, as well as for the optimal allocation of injured flow. The main objective is to mitigate the environmental footprint of earthquake relief logistics operations in Tehran, Iran, while ensuring timely and effective service to the injured population. A case study was conducted in the south-central regions of Tehran, which includes regions 10, 11, 12, 16, 17, and 19, to evaluate the model's efficiency. One of the model's main assumptions is that injured individuals are screened at transfer points. Also, due to air transfer restrictions, dual air and ground transportation is provided to transport the injured. The unbalanced distribution of hospitals across the city will also pose a problem during disaster relief.

The presented models were solved in two modes: 6-magnitude and 7-magnitude earthquakes, using Lingo 17 software. In the six-magnitude earthquake, the optimal location and allocation of 10 transfer points, 15 hospitals, and 25 relief centers were considered, with the results presented in single- and two-objective modes. In the seven-magnitude earthquake, all available facilities were used. In other words, the model became an allocation issue, in which case one important assumption is a 30% increase in hospital capacity to respond to 10% of the injured. Provision of emergency facilities and equipment for hospitals, and the storage of essential supplies and medicines, such as food, heating equipment, and first aid, in areas of demand, relief centers, and hospitals, is necessary. Predicting helicopter pads in hospitals and transfer points is also an important relief issue. The results show the model's real-world efficiency, which can serve as a guide for decision-makers planning crisis management, but should be implemented across the city of Tehran as a whole.

Theoretical implications

The proposed research contributes to the existing literature on humanitarian logistics and disaster relief operations in several ways. Firstly, it integrates sustainability and circular economy principles into the design of the relief logistics network, a novel approach compared to the predominant focus on logistical efficiency and cost minimization in previous studies. By introducing a third objective function to minimize the environmental impact, the model addresses an important gap in the literature.

Secondly, incorporating reverse logistics facilities and activities into the optimization model expands the scope of the relief logistics network beyond traditional transportation and the allocation of injured people. This enables the recycling and reuse of critical resources, enhancing the overall resilience and circularity of the disaster response system.

Thirdly, the case study-based approach, focusing on the highly vulnerable and densely populated regions of Tehran, provides valuable insights into the practical challenges and constraints faced in earthquake-prone urban centers. The model's ability to address the unbalanced distribution of hospitals and the need for screening and outpatient treatment at transfer points contributes to the theoretical understanding of disaster relief logistics in complex environments.

Managerial implications

From a managerial perspective, the findings of this research can guide decision-makers and planners in developing sustainable and resilient disaster response strategies. The optimization models can be used to identify optimal locations for transfer points, hospitals, relief centers, and recycling/reverse logistics facilities, while accounting for both logistical efficiency and environmental impact.

The insights gained from the model can also inform investment decisions and infrastructure planning, such as allocating resources for helicopter landing pads, enhancing hospital capacity, and establishing reverse logistics processing centers. Additionally, the emphasis on screening and outpatient treatment at transfer points can improve coordination and the utilization of medical resources during disaster relief operations.

Limitations and future direction

While the proposed research offers a comprehensive approach to mitigating the environmental footprint of earthquake relief logistics, it is not without limitations. The case study is limited to the south-central regions of Tehran, and generalizing the findings to other geographic contexts may require further validation and adaptation of the model. Additionally, the model does not account for the dynamic and stochastic nature of disaster events, which can affect resource availability and the evolving needs of the affected population. Incorporating uncertainty and real-time information into the decision-making process could be an area for future research.

Future studies could also explore integrating other sustainability dimensions, such as social and economic factors, into the design of the relief logistics network. Additionally, the development of decision support tools and simulation-based approaches could enhance the practical implementation and adoption of the proposed optimization models by disaster management authorities and humanitarian organizations.

Author Contributions

For research articles with multiple authors, a short paragraph outlining their individual contributions must be included. The following statements should be used: "Conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript."

All authors contributed equally to the conceptualization of the article and writing of the original and subsequent drafts.

Data Availability Statement

Data available on request from the authors.

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Ethical considerations

The authors avoided data fabrication, falsification, and plagiarism, as well as any form of misconduct.

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Conflict of interest

The authors declare no conflict of interest.

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