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A Mathematical Model for the Relief Logistics in Humanitarian Supply Chain

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A B S T R A C T

Objective: The coordination of relief supply chain actions following a crisis is undeniable and necessitates proper management and appropriate resource allocation to affected areas, especially due to the increasing occurrence of natural disasters such as floods, storms, and destructive earthquakes. The aim of this study is to design an integrated humanitarian supply chain system, considering the relationships among various components of the rescue and relief supply chain.
Methodology: This research innovates over previous studies by proposing a five-level model comprising suppliers, warehouses, distributors, affected areas, and shelters within the supply chain; it also includes the location of relief warehouses and support facilities with an integrated dynamic model. Two categories of decisions are considered: the first involves selecting locations for regional warehouses from candidate sites and the quantity of pre-stocked inventory in them, and the second involves designing the distribution network and relief items, determining the flow of goods within it.
Findings: The first objective of this issue is to minimize the construction costs of regional warehouses in Tehran under various scenarios, and the second objective is to minimize the costs of supply, maintenance of goods in regional warehouses; minimize the costs of sending and maintaining goods in the central warehouse; minimize the costs related to sending goods to demand points, and minimize the costs related to leftover goods in each region at the end of each period.
Conclusion: The results show that the designed model optimizes the logistics costs of relief and rescue.
Keywords: *Relief logistics, unforeseen incidents, crisis management, humanitarian supply chain, resource allocation.*

1 Introduction

According to the statistics from the Research Institute for Disasters and Natural Calamities (2015), natural disasters such as earthquakes, floods, storms, and droughts afflict various parts of the world every year. Studies indicate that Iran ranks among the top ten disaster-prone countries in the world. Unfortunately, out of the 40 types of recognized global disasters, 31 are likely to occur in Iran, with earthquakes, floods, and droughts causing the most damage to our country. It is reported that approximately 83% of Iran's population resides in areas with a high to very high risk of earthquakes, and 50% are at risk of flooding (Sadeghi Moghadam et al., 2018; Sadeghi Moghadam et al., 2019).

Today, due to population growth, the financial and human losses resulting from natural and unnatural crises have become a global concern (Bozorgi-Amiri et al., 2017; Olivares Aguila, 2018; Van Wassenhove & Pedraza Martinez, 2012). Tansil and Alpan (2010) define supply chain management as encompassing all activities that link suppliers, manufacturers, distributors, and customers to ensure goods are delivered in the right quantities and at the right time, aiming to minimize system costs and maximize customer service levels (Nazarian-Jashnabadi et al., 2023; Sahafzadeh & Haghighi, 2023; Zhang et al., 2023). Humanitarian supply chain is defined as the process of planning, implementing, controlling efficiently, and storing goods and services, as well as related information from the point of origin to the point of consumption, to alleviate the suffering of vulnerable people (Asadi et al., 2018; Salehi-Tadi & KHani, 2017; Zhang et al., 2019).

The humanitarian supply chain in emergency management plays a key role in saving lives, transporting victims to emergency centers, evacuating the homeless from disaster areas, and meeting the needs of people in crisis situations. Today, natural and human-made disasters such as earthquakes, floods, landslides, volcanic eruptions, terrorist attacks, coups, etc., are constantly reported in global news. While natural disasters cannot be stopped, the severity and damage they cause can be mitigated. Therefore, prevention and proper allocation of rescue and relief resources and how to deal with these incidents are of great importance (McLachlin & Larson, 2011).

In natural disasters, the urgent need of the injured for essential goods often exacerbates the crisis. Thus, the location of distribution warehouses and their establishment in areas that expedite relief is crucial (Kabra & Ramesh, 2015; Sadeghi Moghadam et al., 2018; Yadav & Barve, 2016). Around the world, the number and severity of incidents, natural disasters, and unexpected events are increasing significantly. Relief logistics operations must be planned to enable quick and appropriate responses after a crisis occurs and to minimize the impact of these disasters (Blecken, 2010; Talaie et al., 2019).

Every year, natural crises such as Hurricane Michael (2018), Hurricane Matthew (2016), Hurricane Sandy (2012), the March 11 Japan earthquake (2011) with 1,500 victims; the Chile earthquake (2008) that led to a tsunami and the death of 700 people; Hurricane Katrina (2005); Hurricane Charley (2004), and more occur worldwide. In Iran, natural crises such as floods in Golestan, Lorestan, Shiraz, Khuzestan, Mazandaran, Kermanshah, Qom, and Tehran (Spring 2019); the Sarpol-e Zahab earthquake (2017 and 2018); the Sistan and Baluchestan flood (2016); the floods in Mazandaran and Semnan (2014); the floods in the cities of Behshahr, Ghaemshahr, Sari, and Babol (2012); the Qom province flood (2009); the Firoozabad Fars and Zarand Kerman earthquake (2004) resulted in 612 deaths; the Bam earthquake (Winter 2003) led to the death of 41,000 people; the devastating floods in Golestan province (2001 and 2002); the Masouleh flood (1998); the Birjand earthquake (1997) with 1,500 deaths; the Rudbar and Manjil earthquake (1990) resulted in 35,000 deaths; the Tajrish flood (1987); the Sirch, Kerman earthquake (1981) with 1,300 deaths occur; according to statistics, about 21 major earthquakes have occurred in Iran over the last 100 years, the largest being the 7.8 magnitude earthquake in Saravan (2013) that resulted in 2,000 deaths (Ahmadvand & Azad, 2019; Sadeghi Moghadam et al., 2019).

The goal of this article is to design a mathematical model for the humanitarian supply chain to enhance the efficiency of resource allocation methods in emergency response operations to unforeseen incidents. This study proposes alternative methods for meeting the immediate long-term needs of unforeseen events.

The innovations of this research, considering the literature review and gaps between existing models and the lack of an integrated model for the supply chain of emergency victim care from the incident site to shelters, include the following features of the designed model:

Considering the impact of communications between suppliers, distributors, and distribution centers.

Incorporating a five-level supply chain consisting of suppliers, raw material warehouses, distributors, disaster-affected areas, and shelters.

The multi-stage nature of the designed model, which in the initial and secondary phases involves selecting locations for regional warehouses from candidate points and the amount of pre-stocked inventory stored in them, and decisions of the second phase include designing the distribution network and relief items, determining the flow of goods within it.

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Allocating disaster-affected areas to warehouses to concentrate the distribution of raw materials and relief items to the injured and disaster-affected areas.

Implementing the designed model in the metropolis of Tehran, which, given its high population relative to other provinces in Iran, involves greater potential casualties and crisis management complexities.

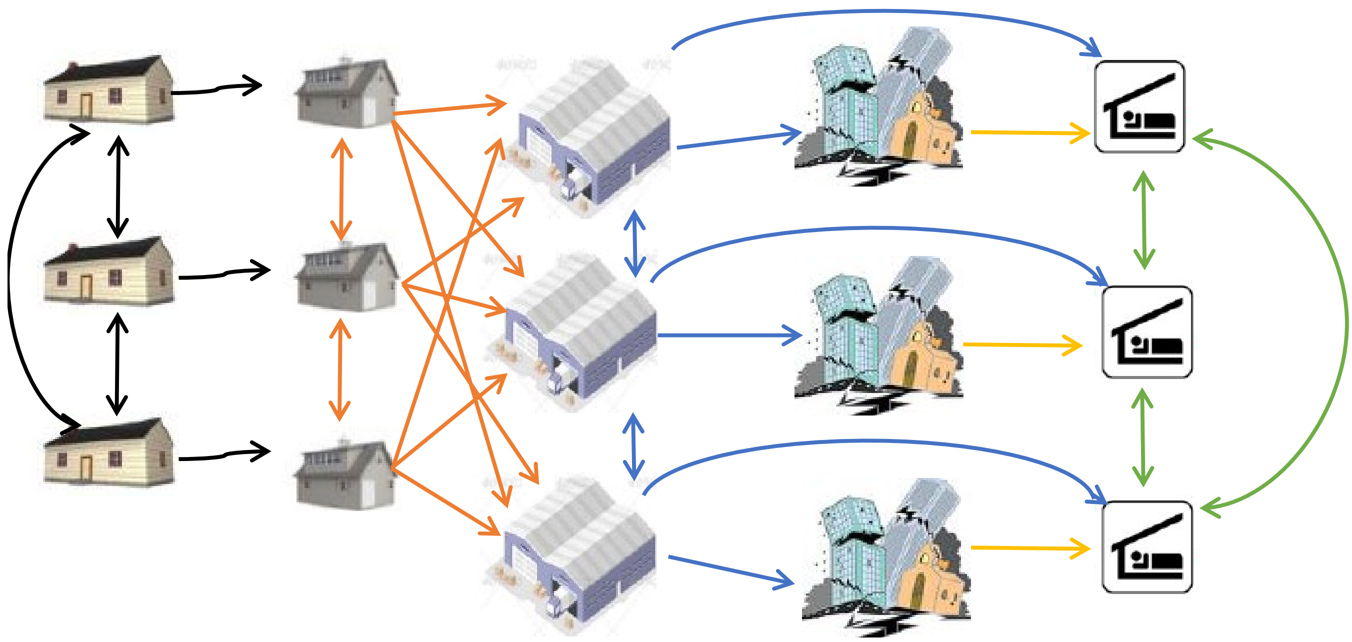
2 Methods and Materials

2.1 Methodology

The objective of this research is to design a humanitarian supply chain system for emergency relief. The innovation of this study compared to other research is the consideration of a five-level model including suppliers, central warehouses, distributors, affected areas, and shelters in the supply chain; the location of relief warehouses and support facilities is presented with a proposed integrated dynamic model. This model considers two categories of decisions: the first involves selecting locations for regional warehouses from candidate sites and the amount of pre-stocked inventory at these locations, and the second involves designing the distribution network and relief items and determining the flow of goods within it. An overview of the proposed model is shown in Figure 1.

Figure 1

Overview of Proposed Model



2.2 Research Assumptions

The assumptions for the current research model are as follows:

Time plays a vital role in crisis management. Post-crisis phase planning faces variable supply and demand that is time-dependent. Therefore, the presented model is considered over five periods or 120 hours after the crisis.

The demand for relief items over the planning horizon is uncertain and depends on various factors such as the intensity and effects of disasters. This uncertain variable is modeled using a set of discrete scenarios, each with a specified probability of occurrence.

Cost parameters of the relief supply chain, such as transportation, shortage, and holding costs, are considered parametrically and dependent on the scenario in the general model. In the case study used, all these parameters are assumed to be constant throughout the planning horizon.

The presented model is five-level and considers internal communications between each level except for the affected areas.

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The model is multi-commodity, and each relief item has a specified volume and different costs for procurement, shortage, and storage.

In addition to holding costs for relief items in warehouses during the post-crisis planning horizon, holding costs for items remaining in affected areas are also considered; these surplus items transported to one damaged area might cause shortages in other areas.

Demand points (affected areas) and the location of the central warehouse are specified. Potential locations for constructing supplier warehouses are also determined.

The model considers the connections between raw material warehouses, suppliers, distributors, and shelters.

After the disaster, there is the possibility of exchange between shelters.

In each time period, each affected area can only receive relief items from one central warehouse, meaning there is a single assignment per affected area.

Time periods are considered one day long. Therefore, due to the short distances between them, shipping and receiving goods between central warehouses occur within the same time period, and delivery time between central warehouses is not considered.

In the victim rescue phase of the incident, only relocation to the nearest shelter is considered.

In the post-crisis phase, each central warehouse can receive its needs from another central warehouse or supply the needs of one or more other central warehouses. In other words, bilateral relationships between central warehouses exist.

Transportation of relief items between the central warehouse and distributors, among distributors themselves, and between central warehouses and affected areas is only possible by road, while transportation between distributor warehouses and shelters is only possible by air.

Relief items are sent to affected areas from distributors; therefore, for affected areas with a hospital, relief packages are sent. It is also assumed that areas without a hospital send their wounded to neighboring areas at a predetermined rate. Therefore, the needs of areas without a hospital are aggregated in areas that have hospitals.

2.3 *Mathematical Model*

In this section, the sets, parameters, decision variables, objective function, and constraints of the model will be described.

Sets and Indices

The sets and indices used in the model are as follows:

I: Set of candidate points for constructing central warehouses (I);

J: Set of demand points (affected areas and shelters) (J);

K: Set of available emergency and relief goods in the chain (K);

T: Planning horizon (T);

S: Set of scenarios (S);

A: Set of affected points (A);

Z: Set of candidate points for constructing shelters (Z).

Table 1 displays the parameters used in the model.

Table 1

Parameters of the Relief Logistics Model

Mathematical Symbol	Parameter Description
gi	Cost of setting up central warehouse i
Ps	Probability of scenario s occurring
volk	Volume of item k
capi	Capacity of supplier warehouse i (based on volume)
capc	Capacity of central warehouse (based on volume)
Capd	Capacity of distributor d (based on volume)
LRA	Transportation capacity between central warehouse i and affected area j (based on the volume of goods) under scenario s in time period t
LRR	Coefficient of usable transportation capacity between supplier warehouses i and under scenario s in time period t
LRZ	Transportation capacity between distributors i and shelter z (based on the volume of goods) under scenario s in time period t
Holding Cost	Holding cost of item k for one time period
Utilization Coefficient	Coefficient of the amount of item k that remains usable in central warehouse i under scenario s
Demand	Demand at point j for relief package k in period t under scenario s
SCOk	Initial inventory of central warehouse for item k in the pre-disaster phase
TRR	Variable cost of sending one unit of item k from central warehouses i under scenario s in time period t

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TGC	Variable cost of sending one unit of item k from supplier warehouses to central warehouse under scenario s in time period t
TCR	Variable cost of sending one unit of item k from the central warehouse to distributors i under scenario s in time period t
TRZ	Variable cost of sending one unit of item k from distributors i to shelter j under scenario s in time period t
TRA	Variable cost of sending one unit of item k from distributors i to affected areas j under scenario s in time period t
PenaltyZ	Penalty cost per unit shortage of item k at demand point of shelter j related to time period t under scenario s
PenaltyD	Penalty cost per unit shortage of item k at demand point of affected areas j related to time period t under scenario s

Table 2 shows the decision variables of the model for relief logistics in unforeseen incidents.

Table 2

Decision Variables of the Relief Logistics Model

Mathematical Symbol	Parameter Description
SPreik	Pre-disaster inventory of item k at supplier warehouse i
SPrejk	Pre-disaster inventory of item k at central warehouse j
SPrelk	Pre-disaster inventory of item k at distributor warehouse l
RDi	Binary decision variable indicating the establishment of distributors at candidate point i
RCi	Binary decision variable indicating the establishment of a central warehouse at candidate point i
RZi	Binary decision variable indicating the establishment of a shelter at candidate point i
FSCR	Quantity of item k sent from supplier warehouses to central warehouse i in time period t under scenario s
FCR	Quantity of item k sent from central warehouse to distributors i in time period t under scenario s
FRZ	Quantity of item k sent from distributors to shelter in time period t under scenario s
FRA	Quantity of item k sent from distributors to affected areas in time period t under scenario s
LRR	Binary decision variable indicating a two-way connection between two central warehouses i and in each time period t
SR	Inventory of item k in central warehouse i at the end of period t under scenario s
SS	Inventory of item k in supplier warehouses i at the end of period t under scenario s
SD	Inventory of item k in distributor warehouses i at the end of period t under scenario s
FRSC	Quantity of item k sent from supplier i to central warehouse j in time period t under scenario s
FRCD	Quantity of item k sent from central warehouse i to distributors j in time period t under scenario s
FGDA	Quantity of item k sent from distributors j to affected area A in time period t under scenario s
FGDZ	Quantity of item k sent from distributors j to shelter Z in time period t under scenario s
SC	Inventory of item k in central warehouse at the end of period t under scenario s
SS	Inventory of item k in supplier warehouse at the end of period t under scenario s
SD	Inventory of item k in distributors at the end of period t under scenario s
DU	Unmet demand quantity of relief package k at demand point j at the end of period t under scenario s

2.4 *Objective Functions*

Due to the two-stage nature of the problem, the objective functions are separately introduced in two steps.

2.4.1 *First Step Objective Function*

$$\boldsymbol{min\, f} = \sum \boldsymbol{g_i} \times \boldsymbol{RD_i} \times \boldsymbol{RC_i} \times \boldsymbol{RZ_i} + \boldsymbol{E(Q(x,s,w))} \quad (1)$$

Equation 1 minimizes the total cost of constructing distributors' warehouses, central warehouses, and shelters plus the expected probability of scenario occurrences.

In the first phase of the objective function, holding costs for pre-stocked inventories are not considered. Since in the constraints related to central warehouses, supplier warehouses, and the construction of shelters, the amount of pre-stocked inventory is connected to the amount of inventory held at the end of the first period of the planning horizon, the model prevents the creation of holding costs in the first period in central warehouses by avoiding overstocking in the preparation phase. For example, if the capacity of central warehouses is 2000 units and we do not consider pre-stocked inventory for central and distributor warehouses, the model seems to use all the warehouse capacity and apparently pays no holding cost. However, if in the first period, a demand for 200 units from one of the regions is shipped, 1800 units will remain in inventory at the end of the first period. Consequently, the model avoids overstocking pre-inventory beyond the necessary amount to prevent incurring holding costs at the end of the first period.

2.4.2 *Second Step Objective Function*

$$E(Q(X,S,\omega)) = \sum_s P_s \times [C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 + C_9 + C_{10}] \quad (2)$$

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Equation 2 is the objective function for the second step, written to minimize the costs of the supply chain for relief, including the following components:

$$C_1 = \sum_{t=1}^{T}\sum_i(\sum_k h_k \times SS_{i\,k}^{st} + \sum_{i'\neq i}\sum_k FSCR_{i\,k}^{st} \times TGC_{i\,j_k}^{st}) \quad (3)$$

This component of the objective function (Equation 3) relates to the supply and holding costs for supplier warehouses.

$$C_2 = \sum_{t=1}^{T}\sum_i(\sum_k h_k \times SR_{i\,k}^{st} + \sum_{i'\neq i}\sum_k FCR_{i\,k}^{st} \times TCR_{i\,j_k}^{st}) \quad (4)$$

This component of the objective function (Equation 4) relates to the supply and holding costs for central warehouses.

$$C_3 = \sum_{t=1}^{T}\sum_i(\sum_k h_k \times SD_{i\,k}^{st} + \sum_{i'\neq i}\sum_k FRZ_{i\,i'k}^{st} \times TRZ_{i\,jk}^{st} + \sum_{i'\neq i}\sum_k FRA_{i\,i'k}^{st} \times TRA_{i\,jk}^{st}) \quad (5)$$

This component of the objective function (Equation 5) relates to the supply and holding costs for distributor warehouses.

$$C_4 = \sum_{t=1}^{T}\sum_i\sum_j\sum_k FSCR_{i\,k}^{st} \times TGC_{i\,jk}^{st} \quad (6)$$

This component of the objective function (Equation 6) relates to the transportation costs for goods from supplier warehouses.

$$C_5 = \sum_{t=1}^{T}\sum_i\sum_j\sum_k FCR_{i\,k}^{st} \times TCR_{i\,jk}^{st} \quad (7)$$

This component of the objective function (Equation 7) relates to the transportation costs for goods from central warehouses.

$$C_6 = \sum_{t=1}^{T}\sum_i\sum_j\sum_k FRZ_{i\,i'k}^{st} \times TRZ_{i\,jk}^{st} \quad (8)$$

This component of the objective function (Equation 8) relates to the transportation costs for goods from distributors to shelters.

$$C_7 = \sum_{t=1}^{T}\sum_i\sum_j\sum_k FRA_{i\,i'k}^{st} \times TRA_{i\,jk}^{st} \quad (9)$$

This component of the objective function (Equation 9) relates to the transportation costs for goods from distributors to affected areas.

$$C_8 = \sum_{t=1}^{T}\sum_j\sum_k DU_{jk}^{st} \times PenaltyZ_{jk}^{st} \quad (10)$$

This component of the objective function (Equation 10) pertains to the costs of unmet goods in shelters.

$$C_9 = \sum_{t=1}^{T}\sum_j\sum_k DU_{jk}^{st} \times PenaltyD_{jk}^{st} \quad (11)$$

This component of the objective function (Equation 11) pertains to the costs of unmet goods in affected areas.

$$C_{10} = \sum_{t=1}^{T}\sum_j\sum_k SZ_{jk}^{st} \times h_k \quad (12)$$

This component of the objective function (Equation 12) represents the costs related to leftover goods in each region at the end of each period.

2.5 Constraints of the Five-Level Relief Logistics Model

The model constraints can be categorized as follows:

$$\sum_k SPre_{ik}.Vol_k \leq cap_i.RD_i \quad (13)$$

This constraint ensures that there is no allocation of goods to supplier warehouses and adheres to the capacity of each warehouse per item (based on volume).

$$\sum_k SPre_{jk}.Vol_k \leq cap_c.RC_i \quad (14)$$

This constraint ensures that there is no allocation of goods to the central warehouse and adheres to the capacity of each warehouse per item (based on volume).

$$\sum_k SPre_{lk}.Vol_k \leq cap_d.RZ_i \quad (15)$$

This constraint ensures that there is no allocation of goods to shelters and adheres to the capacity of each shelter per item (based on volume).

2.5.1 Supplier Warehouse Constraints

$$SS_{i\,k}^{st} = avail_i^s.SPre_{ik} + \sum_{i'\neq i} FSCR_{i\,k}^{st} - FCR_{i\,k}^{st} - FSCR_{i\,k}^{st} \quad (16)$$

For the first step, balance constraints are written as Equations 16, 17, and 18, where the initial inventory of supplier warehouses, central warehouses, and distributor warehouses is the same as the pre-stocked inventory saved in the pre-crisis phase, only a portion of which is accessible and some of which is lost due to earthquake damage.

2.5.2 Central Warehouse Constraints

$$SC_{i\,k}^{st} = avail_i^s.SPre_{jk} + \sum_{i'\neq i} FCR_{i\,k}^{st} - FSCR_{i\,k}^{st} \quad (17)$$

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2.5.3 Constraint related to distributors

$$SD_{i\ k}^{st} = avail_i^s . S\,Pr\,e_{lk} + \sum_{i' \neq i} FRZ_{i\ i'\ k}^{st} - FCR_{i\ k}^{st} + FRA_{i\ i'\ k}^{st} - FCR_{i\ k}^{st} \quad (18)$$

3 Findings and Results

The information presented in this research is extracted from the final report on the seismic micro-zoning of Tehran, conducted at the request of the Government of the Islamic Republic of Iran through cooperation with the Government of Japan in 2002.

The objectives of the study include:

Preparation of seismic micro-zoning maps as a fundamental tool for the preparation of urban and regional crisis prevention plans in Tehran;

Presentation of predictions of human and financial damages in the event of an earthquake;

Recommendations for reducing the impact of the crisis caused by the earthquake.

Proposed Earthquake Scenarios for Tehran and the Probability of Each

According to information provided by JICA, four Japanese models for earthquakes have been considered: the Rey fault model, the North Tehran fault model, the Masha fault model, and the floating mode. In this research, based on the four models and different hours of the day, four scenarios are defined.

3.1 Estimation of Injuries and Human and Financial Damages

Based on historical data, the number of casualties during the day is one-quarter (25%) of the ratio at night. These results are based on experience from past earthquakes in Iran. In this research, human casualties in daytime earthquakes are estimated using the same relationship from nighttime human casualty data. Thus, the number of casualties is obtained for both day and night. According to experts in this field, four scenarios are assumed, and one-third of the number of casualties in each region under each scenario exists as injured, of which only a portion is transferred to hospitals for treatment in each region and under each scenario. This risk scale for each area (30% risk number) and multiplying it by the number of injured determines the number of victims needing hospital treatment.

3.2 Calculation of Demand for Relief Items

Relief items are divided into four groups: food items (drinking water, canned goods, food packages, and bread); life necessities (tents, blankets, carpets, clothing, heating/cooling devices); medical needs (first aid, medications and IVs, medical supplies, counseling and psychiatric services for disaster victims); hygiene needs (showers, portable toilets, sewage disposal, and trash bins). The required quantity of each item for different areas is calculated such that only one life necessity item (such as tents) is delivered once to each family whose home is destroyed; therefore, it is assumed that under each scenario, there is a need for life necessity items like tents according to the number of destroyed buildings in each area and only during the first time period. Based on crisis management principles, the need for food and life necessities for disaster victims is addressed within 48 hours of the first 120 hours after the crisis. Assuming that on average four people live in each building, the number of human victims needing relief items under each scenario can be estimated by multiplying the number four by the number of destroyed buildings. Each day, a water ration and two meals are considered for homeless individuals, and one medical (relief) package for the injured. In this research, the 22 zones of Tehran and the set of potential regional (central) warehouses, including 14 warehouses, are considered.

3.3 Results of Solving the Proposed Five-Level Relief Logistics Model

In this section, the computational results from solving the proposed model with the presented case study are discussed. The mathematical model was coded in GAMS version 24.1.2 and executed on a computer with 64 GB of memory, a 2.3 GHz central processing unit, and running a 32-bit version of Windows 7, taking 28 minutes to run.

Values of Decision Variables for the First and Second Steps

After running the model, the decision variables for the first stage are presented in Table 3. As can be seen, points 2, 4, 6, 9, 11, 13, and 14 have been selected for the construction of central warehouses. Also, the values of some decisions for the first and second steps are shown below:

Table 3

Values of First Step Decision Variables

Constructed Warehouse	Pre-stock of Food Items	Pre-stock of Life Necessities	Pre-stock of Medical Needs	Pre-stock of Hygiene Needs
2	25693	-	12836	15771
4	17638	-	10298	18369
6	14759	25718	-	12478
9	10557	23610	-	36258
11	9236	10258	14893	-
13	8500	9874	16247	-

Table 4

Amount of Relief Items Transferred from Suppliers to Central Warehouses Under Scenarios in the Second Step

Scenario	Food Items Pre-stock	Life Necessities Pre-stock	Medical Needs Pre-stock	Hygiene Needs Pre-stock
1	35147	-	-	35186
2	5639	-	16870	-
3	-	34781	-	-
4	58987	-	12543	-

Table 5

Amount of Relief Items Transferred from Central Warehouses to Distribution Centers Under Scenarios in All Steps

Scenario	Food Items Pre-stock	Life Necessities Pre-stock	Medical Needs Pre-stock	Hygiene Needs Pre-stock
1	25147	-	-	23114
2	3541	-	14852	-
3	-	30258	-	-
4	42517	-	10247	-

Table 6

Amount of Relief Items Transferred from Distribution Centers to Affected Areas Under Scenarios in All Steps

Scenario	Food Items Pre-stock	Life Necessities Pre-stock	Medical Needs Pre-stock	Hygiene Needs Pre-stock
1	-	3214	-	14271
2	25147	-	10234	-
3	-	27416	-	-
4	49523	-	9761	-

Table 7

Amount of Relief Items Transferred from Distribution Centers to Shelters Under All Scenarios in All Steps

Scenario	Food Items Pre-stock	Life Necessities Pre-stock	Medical Needs Pre-stock	Hygiene Needs Pre-stock
1	12471	-	-	16471
2	10824	-	10239	-
3	-	35695	-	-
4	4176	-	11347	-

3.4 Sensitivity Analysis of the Proposed Model

In this section, the model's sensitivity to parameters such as post-crisis transportation cost, shortage cost, warehouse construction cost, and the amount of pre-stock in central warehouses is examined. Sensitivity analysis is conducted with 5 coefficients as described in Table 8. Coefficients of 0.5, 1, and 1.2 have also been used for demand analysis.

The results from the sensitivity analysis regarding changes in demand and the number of constructed warehouses are observed in Table 9 and Table 10, showing

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the relationship between changes in pre-stock in central warehouses and the number of constructed warehouses.

Table 8

Coefficients Used for Sensitivity Analysis

Row	1	2	3	4	5
Coefficients for Sensitivity Analysis	1	1.2	1.4	2	3

Table 9

Relationship Between Changes in Demand and Number of Constructed Warehouses

Sensitivity Analysis Coefficient	1	1.4	2
Number of Constructed Warehouses	6	10	12
Pre-stock of Food Items	4587139	5832150	7859321
Pre-stock of Life Necessities	5825365	7125631	8639813
Pre-stock of Medical Needs	3547	4521	3852
Pre-stock of Hygiene Needs	41287	368821	35417
Total Pre-stock	10457338	13331123	16538403

Table 10

Relationship Between Changes in Pre-stock of Central Warehouses and Number of Constructed Warehouses

Sensitivity Analysis Coefficient	0.5	1	1.2
Number of Constructed Warehouses	13	10	8
Pre-stock of Food Items	3214735	4159821	7963157
Pre-stock of Life Necessities	4157823	6217585	9314726
Pre-stock of Medical Needs	2514	3241	4210
Pre-stock of Hygiene Needs	3269	421963	51247
Total Pre-stock	7378341	10802610	17333340

4 Discussion and Conclusion

The occurrence of natural and human disasters such as earthquakes, floods, volcanic eruptions, and others are on the rise worldwide, including in Iran. The extent and severity of these disasters and their effects are such that they cause significant harm to people's lives and property, and this has led to considerable global attention to addressing these disasters. Given the population growth in Tehran as the capital and other major cities of the country, and the earthquake-prone nature of many urban and rural areas in Iran (including the capital, which has recently faced increased density), the occurrence of earthquakes, floods, and other unforeseen incidents can cause significant damage and fatalities, potentially halting urban and national development. Since the nature of natural disasters like earthquakes is unpredictable and carries a great deal of environmental uncertainty, the issue of the humanitarian supply chain and rescue becomes more complicated, extensive, and in need of a logistics network design to supply food and relief items as a primary concern before these unforeseen incidents occur.

In this research, a two-stage stochastic model for an integrated rescue logistics in five levels; suppliers, central warehouses, distributors, affected areas, and shelters has been presented. Supply chain activities for relief are temporally divided into two phases: pre-disaster or preparedness, and post-disaster or response. In the preparedness phase, a four-level relief supply chain including supplier warehouses, central warehouse, distributor warehouses, and shelter construction sites existed, where optimal locations for the establishment of central warehouses, distribution, and shelters, and optimal decisions for the amount of pre-stocked inventory in each warehouse were determined. Including central warehouses in the distribution network for relief items increased the speed and effectiveness of post-crisis phase activities, or in other words, enhanced the response capability of the crisis management system. Also, the location of shelters and the anticipation of relief items after the disaster in the designed

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model increased the supply confidence of these items to avoid shortages and surprises for relief forces and reduced the time to aid affected individuals.

For gathering information for the case study, the final report of Tehran micro-zoning prepared by the JICA group in 2002 was consulted, and after reviewing and updating its data with the population data of 2018, the most comprehensive estimate of the damages from a potential earthquake in Tehran was obtained. According to the case study data, dividing the 24-hour day into work (18 hours) and non-work (8 hours) periods, a total of four earthquake scenarios were used. Relief items were considered in four categories: food items (drinking water, canned goods, food packages, and bread); life necessities (tents, blankets, carpets, clothing, heating/cooling devices); medical needs (first aid, medications and IVs, medical supplies, counseling and psychiatric services to victims); and hygiene needs (mobile showers, portable toilets, sewage disposal, and trash bins). Ultimately, the model presented was solved with real data from the damages of the major Tehran earthquake, and after analysis, the model's efficiency in different conditions was evaluated.

The results of this research align with the findings of other studies (from a theoretical perspective), (Kabra & Ramesh, 2015; McLachlin & Larson, 2011; Yadav & Barve, 2016). Practical recommendations derived from the findings of this research include:

Given the results, life necessities such as tents, blankets, carpets, clothing, heating/cooling devices, due to the highest demand as per the designed model, it is recommended that national crisis managers and decision-making bodies pay special attention to the provision of these items.

In the first scenario (Ray Fault) and the second scenario (North Tehran Fault), the pre-stocked inventory of hygiene needs (mobile showers, portable toilets, sewage disposal, and trash bins), according to the designed model, achieved the highest quantity from suppliers to central warehouses, and it is recommended that crisis managers focus more on these items in that area.

In the third scenario (Masha Fault), it is recommended that crisis managers focus on pre-stocking life necessities (tents, blankets, carpets, clothing, heating/cooling devices).

In the fourth scenario (floating model), it is recommended that crisis managers focus on pre-stocking food items (drinking water, canned goods, food packages, and bread).

Senior crisis management officials are advised to use simulation and leverage experts in earthquake-prone and disaster-prone areas of the country to pursue potential damages and needs before, during, and after earthquakes more vigorously and with greater force, and to provide necessary facilities for optimal management of affairs.

With a review of the literature on relief logistics, future researchers are advised to design the model by adding planning for transferring victims to hospitals and considering the distribution areas of relief items, taking into account adding the model to six levels and calculating the appropriate time and place for constructing emergency hospitals and transferring potential victims after a crisis.

Authors' Contributions

All authors have contributed significantly to the research process and the development of the manuscript.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were observed.

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