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Mathematical Model of Location-Allocation in the Logistics of Relief Goods Response in Emergency Situations (Case Study of Tehran and Suburbs Urban Railway Operation Company)

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Abstract

One of the important logistics strategies to improve performance and reduce relief time is to locate and establish aid distribution centers near vulnerable areas, the presence of these distribution centers in suitable locations can lead to a successful rescue operation, prioritizing according to the current guidelines. The goods needed for relief are from Red Crescent warehouses to relief centers, but after natural disasters, roads and relief routes have been damaged, for this purpose, in this research, the use of rail vehicles and subway infrastructure in Tehran metropolis has been proposed, which in addition to Reducing the response time to the requests of people in need can also solve the problem of blocked routes, and by using the policy of decentralization, we can see an increase in the quality of sending and a reduction in the problems caused by the concentration and accumulation of relief goods. The time and cost of aid delivery has been modeled, and by solving the mathematical model by games software and the input data of a case study, we will locate and select the best aid distribution stations among the candidate stations.

Keywords: Mathematical model, Localization, Allocation of relief goods, Response in emergency situations, Metro.

1 | Introduction

Although crises have always been part of human history, crisis management as a profession and academic discipline is relatively new and still developing [1]. For it to be sustained as a professional and scientific field,

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it requires the continuous development of strategies, tactics, and operational measures [2]. Given that crises account for a significant portion of financial, human, and psychological losses worldwide—and considering that Iran is among the ten most disaster-prone countries globally—crisis management holds a particularly critical position in our country [3]. Despite Iran's extensive experience in dealing with various crises, crisis management as a structured profession and academic field is still in its early stages. However, the existing body of knowledge and experience in this field is substantial enough to allow for the integration of domestic experiences with international best practices [4]. This integration can help formulate and implement effective strategies for crisis planning and management tailored to the specific characteristics and needs of the country.

Integrated urban services management involves a wide range of municipal institutions and organizations, each responsible for providing a particular type of service [5]. Urban services encompass the coordination and implementation of all urban-related issues, aiming to ensure the safety and well-being of citizens [6]. Effective coordination and synergy among all urban service providers create an optimal model for integrated crisis management. Such a model enhances organizational performance during crises by fostering better interaction among critical infrastructure and more efficient emergency response operations [7].

The first 24 to 72 hours following a disaster are crucial for rescue teams and health support units. After this critical window, the potential for effective intervention significantly decreases [8]. Therefore, planning and strategies—especially in response to natural disasters like floods and earthquakes—must be designed to provide maximum coverage within this time frame to minimize casualties [9].

One key aspect of integrated crisis management is strategic decision-making in designing emergency logistics systems, particularly through the location of relief goods distribution centers for affected populations [10]. To optimize these decisions, it is essential to balance the following factors: minimizing shortages of emergency supplies, minimizing transportation time, and maximizing coverage of distribution centers [11].

2 | Problem Definition and Research Objectives

This study focuses on facility location, inventory positioning decisions, and the design of distribution networks within the relief supply chain [11]. Facility location decisions significantly influence the performance of relief operations, as the number and location of distribution centers—and the quantity of relief goods stored at each center—directly impact response time and the costs incurred throughout the relief supply chain [12].

The facility location and inventory decisions examined in this study are influenced by multiple factors, making their integration into a unified approach challenging. On the other hand, the strategic importance of relief and rescue operations during crises from both socio-economic perspectives underlines the necessity of addressing this issue [13].

Due to the complexity and uncertainty of operational environments, establishing efficient and effective relief supply networks remains a major challenge for humanitarian organizations [14–16]. Furthermore, since quantitative methods that specifically address the unique characteristics of relief environments have not yet been widely developed or implemented, humanitarian organizations may rely on outdated or untested approaches for facility location and inventory management [17–19]. This can lead to ineffective responses—such as high costs, duplication and waste of efforts, and resource misallocation—and inefficient operations, including delayed responses and unmet demands [20].

Therefore, the absence of a systematic approach and a decision support framework for relief supply chain design hinders proper evaluation of the responsiveness and performance of humanitarian organizations.

3 | The Problem in the Metro System of Tehran Metropolis

Following an earthquake and the destruction of residential buildings, a large portion of the population typically requires emergency services, particularly temporary shelter, during the first few days [21]. Emergency shelter includes various components such as temporary housing, access to clean drinking water and sanitation, food, healthcare, and security. Providing all of these necessities for such a large population within a few days often exceeds the capabilities of the remaining and potentially damaged infrastructure [21]. Pre-disaster planning is essential to ensure timely and effective decision-making that helps restore normalcy. However, it is also important to consider unexpected shocks and unplanned events.

In its sixth session on October 20, 1999, the National Committee for the Reduction of Natural Disaster Effects—then the highest decision-making body in the field of crisis management—assigned the Tehran Municipality, with support from the Ministry of Interior's Department of Urban Development and in cooperation with relevant ministries and organizations, to prepare a comprehensive crisis management plan for Tehran and present it for approval [22].

The urgency of this matter was also acknowledged by the national government, and on December 6, 1999, the first vice president issued a directive assigning this task to the Tehran Municipality. In response, the Tehran Municipality formed the Crisis Management Coordination Council and, in collaboration with the Japan International Cooperation Agency (JICA), drafted the Comprehensive Crisis Management Plan for Tehran [23]. The plan was approved on May 16, 2005. It examined all aspects of crisis management—including prevention, preparedness, emergency response, and recovery—and proposed practical strategies to reduce potential losses and damages from a major earthquake in Tehran. One of the key components of the plan focuses on improving emergency preparedness [24].

Considering the above, it is evident that with proper planning and feasibility assessments, we can be proactive in facing such unexpected disasters. Since earthquakes are one of the most probable hazards in Tehran, a well-developed emergency logistics plan can enhance the operational effectiveness of relief efforts and significantly reduce potential human casualties.

4 | Research Objectives

One of the major challenges following a large-scale disaster such as an earthquake is determining the optimal locations for relief distribution centers and delivering essential goods to affected areas to meet the victims' basic needs. However, in many cases, roads and transportation routes are damaged and access becomes limited. According to current emergency response protocols in Iran, the priority during the recovery phase is to deliver essential relief supplies from Red Crescent warehouses to the affected regions.

To address the challenge of damaged routes, this study proposes the use of auxiliary rail transport via the metro system in the Tehran metropolis. This approach not only reduces the response time in meeting the demands of those in need but also helps overcome road blockages. Moreover, by adopting a decentralized distribution strategy, the study aims to improve delivery quality and reduce problems related to the concentration and congestion of relief goods.

The relief distribution system in this study includes three main components: suppliers, distribution centers, and demand points. Relief suppliers play a key role in the supply chain by providing the necessary aid items to individuals in the affected areas.

As mentioned, the main goal is to evaluate and select candidate metro stations as relief distribution centers to implement an optimized distribution system. The centers will be selected from among a predefined set of candidate metro stations.

The specific objectives of this study are:

I. To develop a bi-objective mathematical programming model for locating relief distribution centers and managing inventory, aiming to minimize both relief costs and response time.

II. To justify the necessity of establishing relief supply warehouses connected to the metro rail network at metro terminals in Tehran.

III. To determine the number and locations of relief distribution centers, allocate capacity to each, and assign resources to the demand points.

IV. To identify the optimal metro stations for distributing relief goods from among several candidate stations.

V. To analyze and validate the proposed model through a case study using real-world data.

5 | Mathematical Model for Relief Goods Distribution

The foundation of the proposed mathematical model is based on observations and consequences of the most recent earthquake in the Tehran metropolis. Following the earthquake, despite significant casualties and damages, road traffic routes were blocked—a condition that, under more severe circumstances, could greatly disrupt the relief process [19].

Therefore, the mathematical model presented in this study focuses on selecting the optimal relief distribution centers from among a set of candidate metro stations to ensure efficient aid delivery in such emergency situations.

It is worth noting that district 7 of Tehran has been selected as the target area for this study based on the following factors:

I. Availability of 11 metro stations within district 7 provides significant potential for leveraging the urban rail network in comparison to other districts of Tehran.

II. Lower expected damage due to the absence of active fault lines in the region.

III. Ease of access to emergency evacuation centers through emergency road networks facilitates effective distribution from candidate metro stations.

IV. The district has a relatively favorable population density and urban structure.

V. Its central location among surrounding districts (Districts 3, 4, 6, 8, 12, and 13) makes it a strategic hub for supporting relief distribution to neighboring areas.

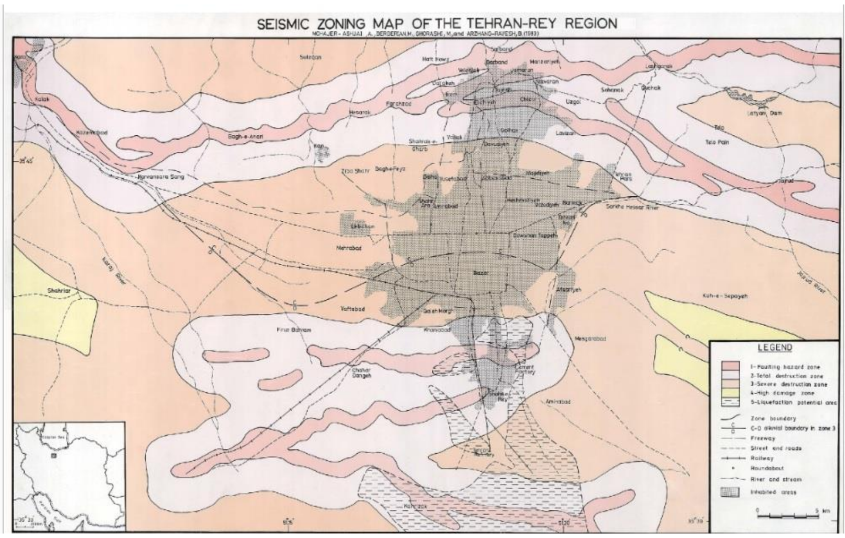

Fig. 1. Main faults of Tehran earthquakes.

Fig. 1, prepared in 1985, illustrates the major seismic fault lines of Tehran. Based on this seismic risk zoning map, the city has been categorized into the following zones:

I. Fault rupture hazard zone.

II. Very severe destruction zone.

III. Severe destruction zone.

IV. High destruction zone.

V. Liquefaction and severe destruction potential zone.

A closer look at this zoning reveals that most of the northern and southern parts of Tehran are at high risk of fault ruptures or severe earthquake-induced destruction. Therefore, to increase the reliability and practical applicability of this research, district 7 of Tehran Municipality has been selected as the candidate area, given its location outside the critical seismic zones.

The relief distribution network used in this study is an extended version of the distribution model designed by Tzeng et al. [11]. This network consists of three hierarchical levels:

I. Supply nodes (Where relief goods are aggregated).

II. Relief distribution centers.

III. Demand points (Locations in need of relief).

The network aims to address the following objectives:

I. Optimal location of relief distribution centers.

II. Strategic planning for transporting relief supplies from supply nodes to distribution centers and from distribution centers to demand points.

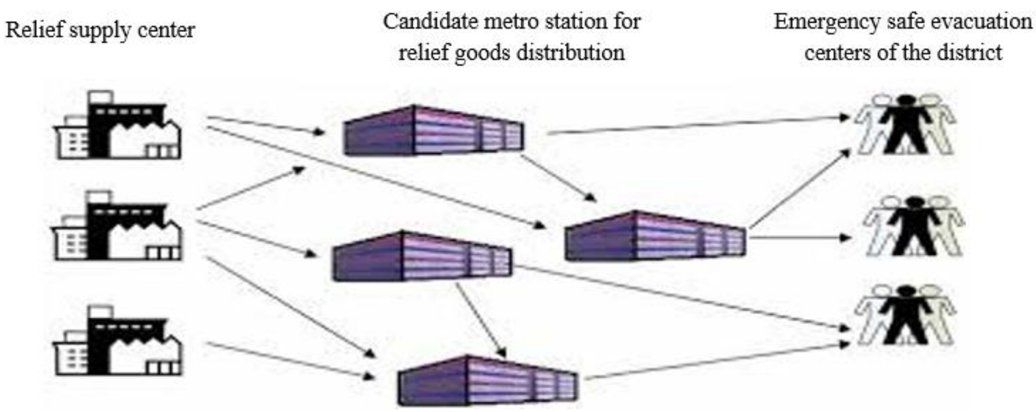

Fig. 2. Schematic diagram of the proposed relief distribution chain in the metro transportation system.

5.1 | Modeling

The model assumptions are as follows:

I. Multiple nodes exist in the network for the supply of relief goods.

II. All data is assumed to be deterministic.

III. The model considers multiple types of relief items (Multi-commodity).

IV. Shortages are allowed and can be backordered in subsequent periods.

V. The target area in this study is district 7 of Tehran Municipality, which includes 11 metro stations.

VI. The hypothetical earthquake scenario assumes that 90% of the survivors in District 7 will require emergency relief for the first 72 hours.

VII. The candidate relief distribution warehouses are forecasted to be the metro stations within District 7.

VIII. All existing passenger trains have the capability to transport relief goods from the designated terminal to the demand area.

IX. Safe emergency evacuation centers for distributing relief goods in district 7 include: Imam Khomeini Mosalla, Shahid Shiroudi Sports Complex, Ghasr Garden Museum, and Azadi Palestine Technical School, based on their location, conditions, and appropriate storage space.

X. The loading and unloading time for goods is considered uniform and has been excluded from the calculations.

5.2|Indices and Sets

Based on the stated assumptions, the model indices and sets are defined as follows:

I. I: Set of supply points (Warehouses at metro transport terminals).

II. J: Set of candidate relief distribution centers (Metro stations).

III. K: Set of safe emergency evacuation centers.

IV. M: Set of relief items.

V. P: Set of time periods.

VI. i: Index for supply points (Warehouses at one of the metro terminals).

VII. j: Index for relief distribution centers (Candidate metro stations).

VIII. k: Index for safe emergency evacuation centers.

IX. m: Index for relief items.

X. p: Index for time periods.

5.3|Parameters

I. Capacity of supply warehouse i for relief item m.

II. Capacity of distribution center j for relief item m.

III. Demand of emergency relief point k for relief item m in period p.

IV. Maximum allowable difference in service level.

V. Construction cost of candidate distribution center j.

VI. Shortage cost of relief item m at emergency relief point k.

VII. Holding cost per unit of relief item m at candidate distribution center j.

VIII. Holding cost per unit of relief item m at emergency relief point k.

IX. Transportation time from distribution center j to emergency relief point k.

X. Transportation time from supply warehouse i to candidate distribution center j.

5.4|Model Variables

X_{ijmp}: The amount of relief item m sent from supply warehouse i to relief distribution center j in time period p.

Y_{jkmp}: The amount of relief item m sent from relief distribution center j to emergency safe evacuation center k in time period p.S_{kmp}.

Inv_{jmp}: The inventory level of relief item m at distribution center j at the end of time period p.

Inv'_{kmp}: The inventory level of relief item m at emergency safe evacuation center k at the end of time period p.

$W_{j\,kp}$: A binary variable indicating whether relief distribution center j serves (1) or does not serve (0) emergency safe evacuation center k during time period p.

U_{ijp}: A binary variable indicating whether supply center i serves (1) or does not serve (0) distribution center j during time period p.

Z_j: A binary variable indicating whether distribution center j is established (1) or not established (0).

5.5 | Objective Functions

This model has two objective functions. The first objective is to minimize the total costs, including establishment costs, inventory holding costs, and shortage costs.

The second objective is to minimize the total relief distribution time. Ultimately, the goal is to achieve a higher level of quality in delivering relief resources under emergency conditions with minimum cost and minimum response time. *Eq. (1)* represents the first objective function—cost minimization.

$$\text{Min} \sum_{k\in K}\sum_{m\in M}\sum_{p\in P} SC_{km}S_{kmp} + \sum_{j\in J}\sum_{m\in M}\sum_{p\in P} IC_{jm}Inv_{jmp} + \sum_{k\in K}\sum_{m\in M}\sum_{p\in P} IC'_{km}Inv'_{kmp} + \sum_{j\in J} EC_jZ_j.$$

Eq. (2) represents the minimization of time as the second objective function.

$$\text{Min} \sum_{j\in J}\sum_{k\in K}\sum_{p\in P} t_{jk}\, W_{j\,kp} + \sum_{i\in I}\sum_{j\in J}\sum_{p\in P} t'_{ij}\, U_{ijp}.$$

5.6 | Constraints

Eq. (3) enforces the flow balance constraint for each relief item m at every distribution center.

$$\sum_{i\in I} X_{ijmp} + Inv_{jm(p-1)} = \sum_{k\in K} Y_{jkmp} + Inv_{jmp}, \text{for all jmp.}$$

Eq. (4) enforces the capacity limit of supply warehouse i for relief item m.

$$\sum_{j\in J}\sum_{p\in P} X_{ijmp} \leq Cap_{i,m}, \text{for all } i, m.$$

Eq. (5) enforces the demand balance constraint at the emergency safe evacuation center k.

$$\sum_{j\in J} Y_{jkmp} + Inv'_{km(p-1)} + S_{kmp} = Dem_{kmp} + Inv'_{kmp} + S_{km(p-1)}, \text{for all } k, m, p.$$

Eq. (6) represents the relationship between the decision variables XijmpX_{ijmp}Xijmp, the quantity of relief item m sent from supply warehouse i to distribution center j in period p, and YjkmpY_{jkmp}Yjkmp, the quantity of relief item m sent from distribution center j to emergency safe evacuation center k in period p.

$$\sum_{i\in I}\sum_{m\in M}\sum_{p\in P} X_{ijmp} + \sum_{k\in K}\sum_{m\in M}\sum_{p\in P} Y_{jkmp} \leq M\, Z_j, \text{for all } j,$$

$$\sum_{m\in M} Y_{jkmp} \leq M\, W_{jkp}, \text{for all } j, k, p,$$

$$\sum_{m\in M} X_{ijmp} \leq M\, U_{ijp}, \text{for all } i, j, p.$$

Eqs. (9) and *(10)* represent the balance of relief distribution between emergency safe evacuation centers k and k'.

The parameter α indicates the maximum allowable difference in the level of service provided.

$$\left|\frac{\sum_j Y_{jkmp}}{Dem_{kmp}} - \frac{\sum_j Y_{jk'mp}}{Dem_{k'mp}}\right| \leq \alpha,$$

$$\alpha \leq \frac{\sum_j Y_{jkmp}}{Dem_{kmp}} - \frac{\sum_j Y_{jk'mp}}{Dem_{k'mp}} \leq \alpha, \text{for all } k, k', m, p,$$

$$\sum_{j \in J} t_{jk} W_{jkp} \leq MaxP, \text{for all } p, k,$$

$$\sum_{i \in I} t'_{ij} U_{ijp} \leq MaxP, \text{for all } j, p,$$

$$\sum_{k \in K} \sum_{m \in M} Y_{jkmp} \leq CA_j, \text{for all } j, p,$$

$$X_{ijmp} \geq 0,$$

$$Y_{jkmp} \geq 0,$$

$$Z_j = \begin{cases} 0, \\ 1, \end{cases}$$

$$W_{jkp} = \begin{cases} 0, \\ 1. \end{cases}$$

6 | Conclusion

In this study, the importance of locating emergency relief distribution centers during crises was first emphasized, and a general layout of the relief supply chain in the metropolis of Tehran was examined. Finally, the proposed model was tested using a case study and implemented in GAMS 24.1 software.

In this mathematical model, the target area was first selected based on logical criteria. Then, using actual household data in the target region and a hypothetical earthquake scenario, the required demand was estimated. In the next step, considering the transportation capacity of the Tehran Urban and Suburban Railway Operation Company and the facilities available in the metro network, warehouses were assumed at metro terminals. Ultimately, using the model, the best candidate metro stations for emergency goods distribution were identified.

Based on the results, the Mosalla, Shahid Haghani (Shahada-ye Haftom-e Tir), Imam Hossein Square, and Shahid Sayad Shirazi stations were selected as the optimal relief distribution centers in District 7 of Tehran Municipality. These stations had zero shortages in distribution and ensured the delivery of relief items with minimal cost and time.

Like other initial models, this model also has some gaps and limitations. Therefore, the following suggestions are proposed for future innovations and improvements to the current model:

I. Similar to most models, this model has not yet been implemented in practice and could be applied in real-world scenarios.

II. By expanding the scope of input data, the model can be solved for a wider data domain using metaheuristic methods.

III. Considering the uncertainty of demand during crises, the problem can be formulated as a dynamic model.

IV. Taking into account heterogeneous capacities in the transportation system can lead to more optimal solutions.

V. The objective functions of the model can be further developed to enhance inter-organizational coordination during crises and to create an integrated structure.

Applying a partial delivery approach may be considered to facilitate relief operations.

Conflict of Interest

The authors declare no competing interests.

Data Availability

The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

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