# A prepositioning model for prioritized demand points considering lateral transshipment

*Mohsen Anvari*
Department of Industrial Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran
*Alireza Anvari*
Department of Industrial Engineering and Management, Gachsaran Branch, Islamic Azad University, Gachsaran, Iran, and
*Omid Boyer*
Department of Industrial Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran

**Abstract**

**Purpose** – This paper aims to examine the integration of lateral transshipment and road vulnerability into the humanitarian relief chain in light of affected area priority to address equitable distribution and assess the impact of various parameters on the total average inflated distance traveled per relief item.

**Design/methodology/approach** – After identifying comprehensive critical criteria and subcriteria, a hybrid multi-criteria decision-making framework was applied to obtain the demand points' weight and ranking in a real-life earthquake scenario. Direct shipment and lateral transshipment models were then presented and compared. The developed mathematical models are formulated as mixed-integer programming models, considering facility location, inventory prepositioning, road vulnerability and quantity of lateral transshipment.

**Findings** – The study found that the use of prioritization criteria and subcriteria, in conjunction with lateral transshipment and road vulnerability, resulted in a more equitable distribution of relief items by reducing the total average inflated distance traveled per relief item.

**Research limitations/implications** – To the best of the authors' knowledge, this study is one of the first research on equity in humanitarian response through prioritization of demand points. It also bridges the gap between two areas that are typically treated separately: multi-criteria decision-making and humanitarian logistics.

**Practical implications** – This is the first scholarly work in Shiraz focused on the equitable distribution system by prioritization of demand points and assigning relief items to them after the occurrence of a medium-scale earthquake scenario considering lateral transshipment in the upper echelon.

**Originality/value** – The paper clarifies how to prioritize demand points to promote equity in humanitarian logistics when the authors have faced multiple factors (i.e. location of relief distribution centers, inventory level, distance, lateral transshipment and road vulnerability) simultaneously.

**Keywords** Lateral transshipment, Demand points, Disaster, Facility location, Humanitarian logistics

**Paper type** Case study

**An executive summary for managers and executive readers can be found at the end of this article.**

## 1. Introduction

Many people are affected by natural disasters yearly, and how to respond effectively to emergencies has become an important issue worldwide (Gad-el-Hak, 2008). Vital issues in such severe disasters are how to react quickly and plan responses to minimize the consequences of these natural disasters (Kovács and Spens, 2007). The large scale of these natural disasters has addressed the need for effective supply chain management. According to the World Health Organization, a catastrophe is any occurrence that results in widespread devastation, loss of life, human suffering and a breakdown in health services on a large enough scale to warrant the involvement of humanitarian organizations. Humanitarian logistics (HL) has, as a result, garnered the interest of several scholars in recent years. Therefore, the HL program is the core of any relief operation. A sufficient amount of resources must be distributed in this network to reduce casualties, and HL would be used after a disaster in a limited time (Bozorgi-Amiri and Khorsi, 2016).

Coordination and collaboration are commonly used synonymously in humanitarian organizations (Russell, 2005). Coordination is essential for supply chain management in humanitarian relief chains that respond to disasters causing deaths, shortages and damages. Organizations need to coordinate with each other to provide aid and reconstruction to the affected people, as no single organization can handle the situation alone. Coordination involves various forms of interorganizational collaboration that range from common

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Journal of Humanitarian Logistics and Supply Chain Management
13/4 (2023) 433–455
Emerald Publishing Limited [ISSN 2042-6747]
[DOI 10.1108/JHLSCM-01-2023-0005]



Received 25 January 2023
Revised 8 June 2023
Accepted 4 July 2023

goals to negotiated agreements while preserving partners' independence. These organizations frequently coordinate and pool resources to achieve these goals. There are two categories of coordination: vertical and horizontal (Schulz and Blecken, 2010). Vertical coordination refers to the coordination with upstream or downstream activities, for instance, coordinating with a transportation company by a traditional nongovernment organization (NGO) (Balcik *et al.*, 2010).

According to Thomas and Kopczak (2005), Van Wassenhove (2006) and Schulz (2009), horizontal coordination between humanitarian organizations is increasingly seen as a practical and efficient way to manage the processes of humanitarian preparedness, response and recovery in challenging and dynamic environments. For example, horizontal coordination occurs when two NGOs coordinate to deliver relief goods and/or services (Balcik *et al.*, 2010). While vertical coordination entails organizations at different levels collaborating, horizontal coordination entails organizations at similar levels of the humanitarian response chain sharing skills and resources (Schulz and Blecken, 2010). Horizontal coordination mechanisms are transforming how humanitarian organizations jointly do capacity building, warehouse management and emergency delivery worldwide. For more efficient and effective relief, humanitarian organizations use horizontal coordination for fundraising, procurement, transportation and stock storage.

Additionally, more adaptable systems enable lateral transshipments (LTs), a type of horizontal coordination in which inventory is shared among organizations at the same level in the supply chain. Organizations can handle fluctuations in demand and prevent shortages of goods by LTs (Evers, 1997). This also results in a more balanced inventory system (Diks and de Kok, 1996). LT is especially beneficial in crowded areas where the centers are close to each other and far from the main depot (Hw Stanger *et al.*, 2013; Wang *et al.*, 2021). In contrast to the horizontal coordination of stock management in private sectors, humanitarian sectors use LT as a borrowing and loaning scheme without any monetary transfer between humanitarian organizations.

Most people concur that vital goods should be distributed fairly and equitably. Decision-making in humanitarian operations is influenced by equity or fairness, which is a key issue in economics in general. According to Gralla *et al.* (2014), equity is the fairness achieved by distributing goods in a way that does not systematically disadvantage any of the affected areas. Gutjahr and Nolz (2016) noted that the metric of equity, which measures the fair distribution among survivors, differed in publications. The weight or significance of the demand point is an important factor for equity in HL. Preparedness strategies involve making decisions before rare events occur, which leads to inherent decision-making challenges regarding optimization strategies during preparedness. Hence, different criteria and subcriteria that reflect each demand point's vulnerability to a disaster (e.g. earthquake) should be used to prioritize all the demand points (DPs). DPs with higher priority scores carry higher vulnerability and risk, and delivering relief items to the points assures equity.

The objective of the research is to discuss the implementation of equity in decision-making by using multi-criteria decision-making (MCDM) techniques for relief operations and how relief distribution centers (RDCs) can use LT to coordinate horizontally in responding to DPs. It also presents a real case study to show the applicability and positive impact of the proposed methodology on a relief prepositioning problem. This research uses MCDM techniques to rank every DP based on its urgency and importance. Then, it applies a mathematical programming model to optimize the delivery of relief supplies to the highest priority DPs and minimize the total average inflated distance traveled. Therefore, in this study, a novel hybrid MCDM framework defined by coupling the ordinal priority approach (OPA) and the VIseKriterijumska Optimizacija I Kompromisno Resenje in Serbian (VIKOR) method (Opricovic, 1994, 1998; Opricovic and Tzeng, 2002). VIKOR method is applied to ranking the alternatives with conflicting and compromising multi-criteria according to the weight calculated using the OPA method. In this study, LT is considered as a solution to increase the ability to meet higher-priority demand and decrease distance. Therefore, while most studies focused on considering LT in commercial logistics, two mathematical models developed considering direct shipment (DS) and LT in HL, integrated with facility location, inventory level, road vulnerability, distance and prioritization with no cost consideration. To the best of our knowledge, no simultaneous analysis has been conducted on the use of the MCDM framework and LT for demand prioritization to address equity in HL.

To support this exploration, the continuation of this article is arranged as follows: the following Section 2 of this paper will focus on the relevant literature. Section 3 defines the problem more precisely and describes related systems. In Section 4, decision-making techniques are presented. Section 5 presents the formulations of direct and LT mathematical models. Section 6 presents the case study's findings. Section 7 presents managerial insights. Finally, Section 8 presents the paper's conclusion and explores potential future research.

## 2. Literature review

Recent years have seen an exciting rise in HL. The term "disaster logistics" refers to the coordination of supplies to distribute aid in the aftermath of a catastrophic event (i.e. affected people) (Sheu, 2007). Studies of HL have mainly concentrated on the two phases of preparedness and response Altay and Green (2006). This section compares more relevant literature by studying mathematical and conceptual models. As a result, the literature is presented in three sections: prepositioning, demand prioritization and LT.

### 2.1 Prepositioning

Emergency management during disasters can be divided into four phases: mitigation, preparedness, response and recovery (McLoughlin, 1985; Van Wassenhove, 2006; Bullock *et al.*, 2017). Emergency logistics issues involve the preparedness and response phases. The main optimization strategies prior to disasters are the location of facilities, prepositioning of relief supplies and resource allocation. The response phase focuses on victim relocation, casualty transportation, resource adjustment and route optimization (Tomasini and Van Wassenhove, 2009). Prepositioning is the main topic of most papers in the preparedness phase. Prepositioning assets and supplies before disasters is a well-known and challenging problem for researchers (Sabbaghtorkan *et al.*, 2020). This issue was initially studied by Psaraftis *et al.* (1986) for oil spills disaster management, and later Akkihal (2006) applied it to the concept of HL.

Locating the relief warehouses and determining the quantity of prepositioned relief items are the two main decisions of the relief prepositioning problem in the HL (Balcik and Beamon, 2008). Their major decisions determine the classification of papers in this category: location optimization, allocation optimization and joint location–allocation optimization (Liu *et al.*, 2021). The goal of location optimization papers is to determine the best locations for prepositioned facilities (An *et al.*, 2015; Hong *et al.*, 2015; Charles *et al.*, 2016; Liu *et al.*, 2021). As opposed to demands or evacuees, the inventory of relief supplies that are stored in fixed locations is the main concern of allocation papers (Dufour *et al.*, 2018; Ulusan and Ergun, 2021). In other papers, such as Rawls and Turnquist (2010), Tofighi *et al.* (2016), Elçi and Noyan (2018) and Torabi *et al.* (2018), location and allocation strategies are jointly optimized across the board.

In prepositioning research, the primary goals often involve reducing the expenses associated with establishing relief centers and transportation (Galindo and Batta, 2013; Khayal *et al.*, 2015; Lin *et al.*, 2012), as well as decreasing unsatisfied demand and overall costs (Rawls and Turnquist, 2010, 2011, 2012; Moreno *et al.*, 2018; Haghgoo *et al.*, 2022; Wang *et al.*, 2022a, 2022b). Other objectives include reducing commodity procurement costs and average response time while increasing responsiveness (Duran *et al.*, 2011; Klibi *et al.*, 2018), minimizing the total cost, time and distance traveled (Abazari *et al.*, 2021), reducing maximum response time and unmet demand (Afshar and Haghani, 2012) and decreasing unsatisfied demand and total cost while increasing responsiveness (Rezaei-Malek and Tavakkoli-Moghaddam, 2014: Rezaei-Malek *et al.*, 2016a, 2016b; Bozorgi-Amiri and Khorsi, 2016). Additionally, Huang *et al.* (2012) outlined efficiency, efficacy and equity as types of objective functions for relief routing. The facility location problem can also be addressed in conjunction with vehicle routing, as demonstrated by Ukkusuri and Yushimito (2008).

Thus, a prepositioning mathematical model is presented. To be more specific, these decisions involve choosing the locations and number of RDCs and the inventory level of relief items. Furthermore, to consider equity in the objective function, the priority score is presented while minimizing the total average inflated distance traveled per relief item.

### 2.2 Demand prioritization of affected area

Finding out what counts as a fair distribution and how to support it with reasonable and universal principles has been remarkably hard for the literature on philosophy and decision theory. The long-standing debate between utilitarianism, which prioritizes the "greatest good for the greatest number of people" and often overlooks equity concerns, and various theories of justice that provide a rational basis for equity considerations, can be traced back to classical utilitarianism (Gutjahr and Fischer, 2018). Developed by Bentham (1789) and his student Mill (1863), classical utilitarianism was challenged by authors such as Rawls (1971), Nozick (1974) and Nagel (1995), who argued for the importance of justice as a separate criterion and developed their unique theories of "fair" distribution and processes.

Some researchers in the field of HL have begun to incorporate considerations of equity into their quantitative decision-making models. The most prevalent way of addressing equity is to ensure that every demand node is reachable from a supply node within a certain limit of time or distance (Beraldi and Bruni, 2009; Zhan and Liu, 2011; Elçi *et al.*, 2018). Moreover, there are several approaches to representing equity. Hong *et al.* (2015) introduced local probabilistic constraints to ensure fair service distribution at the regional level and meet demand within each region. Mostajabdaveh *et al.* (2019) included the Gini mean absolute difference of distances in their objective. Alem *et al.* (2022) also used Gini to model equity based on the Lorenz curve. Lin *et al.* (2012) viewed equity as the maximum difference in penalties. Ortuño *et al.* (2011) included the fair distribution of goods in a lexicographical goal programming formulation for humanitarian aid distribution in a related model. Vitoriano *et al.* (2011) and Ransikarbum and Mason (2016) used a goal programming approach and addressed equity by maximizing the minimum percentage of demand met using a maximin approach. Tzeng *et al.* (2007) and Huang *et al.* (2012) pursued similar approaches.

To address equity, Tofighi *et al.* (2016) minimized the maximum weighted distribution time, while Sun *et al.* (2014) considered the maximal travel distance to the assigned hospital as a second objective function in a bi-objective optimization model. Alem *et al.* (2021) used the social vulnerability index to prioritize areas with higher vulnerability. They dealt with prioritization via weighted sums. Lin *et al.* (2011) proposed a comprehensive logistics model for the supply of prioritized items in the response phase of a disaster, using a maximin approach to represent equity.

Consequently, the priority of different DPs is one of the main input data affecting the main decisions of relief prepositioning problems. Accordingly, to ensure that limited resources are assigned in a way that is equitable and meets the needs of those who are the most vulnerable, each DP needs to be prioritized based on various criteria and subcriteria to decrease the casualties. In this regard, Rivera-Royero *et al.* (2016) discussed emergency supplies distribution. To meet demand, they created a dynamic model that prioritized the response based on the DP urgency during a planning horizon. Sheu (2007), for instance, outlined the distribution of an emergency logistics strategy for meeting the immediate relief needs of the impacted communities within three days of the vital rescue period. He and Jung (2018) examined determining the priority of disaster-damaged areas. Following the establishment of four criteria used in a real-world case study.

However, previous studies clearly show the lack of implementation of MCDM techniques to prioritize the vulnerability of DPs and address equity. Moreover, it is important to emphasize modeling equity and using criteria that decision-makers can easily understand. Different DPs have typically different priorities considering their vulnerability degrees and their actual damages postdisaster (Sheu, 2010). A wide range of criteria and subcriteria have been used to assess the vulnerability of different DPs. For example, Fariborz (2001), Rezaei-Malek *et al.* (2019) and Tofighi *et al.* (2016) considered seismicity as a criterion, and Yariyan *et al.* (2020) treated the seismicity aspect (SA) as a subcriterion, while Sheu (2010) and Cai *et al.* (2011) ignored it completely. Similarly, the texture aspect (TA) was only considered by Fariborz (2001), Rezaei-Malek *et al.* (2019) and Yariyan *et al.* (2020), while public open space was only considered by Tofighi *et al.* (2016) and Yariyan *et al.* (2020). Also, this paper provides a more detailed and clear analysis by dividing some of the existing criteria into more specific subcriteria. For instance, emergency services are split into four subcriteria. The road network is split into three subcriteria. Public open space is split into three subcriteria. The demographic is split into three subcriteria. Socioeconomic is split into three subcriteria.

Moreover, two main types of data have been used to estimate how likely earthquakes are to happen in seismic hazard models: faults that have been mapped and earthquakes that have happened before (Rhoades *et al.*, 2017; Zhang *et al.*, 2023). Mapped faults show where and how faults are shaped in a certain area, which helps to calculate the possibility of seismic activity. Previous earthquakes are also useful, as they show which areas are more prone to seismic activity. Therefore, the inclusion of a new criterion called background aspects (BA) has been proposed based on previous research in earthquake occurrence prediction and forecasting and opinions gathered from Crisis Management Center of Shiraz Municipality (CMCS) Experts and previous earthquake prediction research. BA is comprised of historical points (HP) and the density of earthquake occurrence points (DE).

Hence, in the current study, eight criteria and 20 subcriteria were presented to include all the relevant criteria and subcriteria to prioritize DPs. This study considered SA, TA, emergency services aspects (EA), road network aspects (RA), public open space aspects (PA), demographic aspects (DA), socioeconomics aspects (CA) and BA as the criteria. And the 20 subcriteria include the distance from causative faults (DF), worn-out urban texture (UT), hospital (H), clinic (C), fire stations (FS), red crescent centers (RC), primary network (PN), secondary network (SN), neighborhood network (NN), the green space of city roads (GR), stadiums and open spaces (SO), local and regional parks (LP), population density (PD), family density (FD), the elderly population (EP), income level of people (IP), political importance (PO), economic role (ER), HP and DE.

### 2.3 Lateral transshipment in humanitarian logistics

When there is a stock-out, lateral and emergency shipments are made to replenish the inventory. In the field of commercial logistics, the practice of LT is well-researched. Most research on commercial LT focuses on low-demand and high-value commodities (Wang *et al.*, 2021). For example, Wong *et al.* (2006) proposed a continuous review model for repairable spare parts with two locations. Meissner and Senicheva (2018) applied an approximate dynamic programming model to a periodic review system with multiple locations and transshipment opportunities. Van Wijk *et al.* (2019) analyzed the optimal transshipment policies for a two-location problem with multiple demand classes.

In contrast to commercial logistics, HL are primarily concerned with meeting an increase in demand for relief supplies. These supplies can include bottled water, tents, food and other items. However, there is a dearth of writings about LT in the field of HL. Some studies have applied LT to HL contexts and shown its benefits. The work of Lodree *et al.* (2012) exemplifies the use of LT in the field of HL. Rottkemper *et al.* (2012) developed a mathematical transshipment model for inventory relocation and distribution under uncertainty. Reyes *et al.* (2013) used a simulation model to show that LT improves inventory management efficiency in disaster relief. Hw Stanger *et al.* (2013) illustrated the real-life advantages of LT for blood transfusion between UK hospitals using case studies and surveys. Mulyono and Ishida (2014) proposed a logistics and inventory model based on probabilistic cellular automata for emergency relief and validated it with data from an eruption on Sinabung Mountain in 2013. Caunhye *et al.* (2016) presented a location-routing model with transshipment for integrated preparedness and response planning under uncertainty. Ozkapici *et al.* (2016) found optimal locations for disaster relief centers in Istanbul using an intermodal model that incorporates maritime transportation with LT opportunities. Baskaya *et al.* (2017) compared DS, LT and maritime LT models for Istanbul and found that models with LT performed better than DS, considering road vulnerability and facility location, inventory level and LT quantity. Coskun *et al.* (2019) studied the prepositioning decisions of relief organizations using a mathematical model that accounts for coordination among organizations. Wang *et al.* (2021) designed a model that considers LT opportunities and facility location and allocation decisions under uncertainty and applied it to the Gulf Coast region of the USA, showing that LT is more cost-effective and flexible than DS. Wang *et al.* (2022a, 2022b) formulated a distribution robust optimization model that integrates facility location, inventory prepositioning, vehicle routing and LT decisions for disaster relief logistics planning. They used a case study of storms in the southeastern US to demonstrate the practicality of their model and showed that it outperforms the traditional stochastic programming model.

Inspired by the emergency nature of LT decisions in commercial logistics, HL can also leverage LT to reduce the distress of those in need. LT in HL can offer benefits such as lower travel distance and casualties, better resource utilization and flexibility and more effective supply delivery to high-priority locations in a disaster. Therefore, LT is a valuable method for distributing supplies in a disaster situation. Table 1 illustrates the brief related literature of HL.

### 2.4 Research distinction

As discussed above, prepositioning mathematical models have been proposed to address the preparedness and response decisions of HL. Moreover, in the HL literature, different approaches have been used to address equity. Nevertheless, there is a lack of application of MCDM techniques and comprehensive criteria and subcriteria for equitable distribution to DPs in HL planning with LT integration. To fill these research gaps, we developed two mathematical programming models to incorporate equity and LT into the HL. The objective is to minimize the total average inflated distance traveled to DPs considering the corresponding priority score. Therefore, DPs are prioritized by MCDM techniques to achieve equity in humanitarian response. Furthermore, this paper compares mathematical models with and without LT integration and determines the optimal decisions for prepositioned RDCs, inventory levels and distribution of prioritized relief items. Another major objective is to assess how LT in HL can enhance flexibility, reduce travel distance and optimize resource utilization. The relief items can be transported directly from RDCs to DPs or through other RDCs. Our model considers the

**Table 1** Comparing the developed model and related literature

| Relevant studies | Facility location | Inventory level | Distance | Transshipment | MCDM* | Road vulnerability | Case study |
|---|---|---|---|---|---|---|---|
| Lodree *et al.* (2012) | ✓ | ✓ | | ✓ | | | ✓ |
| Rottkemper *et al.* (2012) | | ✓ | | ✓ | | | ✓ |
| Reyes *et al.* (2013) | | ✓ | | ✓ | | | |
| Hw Stanger *et al.* (2013) | | ✓ | | ✓ | | | ✓ |
| Mulyono and Ishida (2014) | | ✓ | | ✓ | | | ✓ |
| Bozorgi-Amiri and Khorsi (2016) | ✓ | ✓ | | | | | ✓ |
| Caunhye *et al.* (2016) | ✓ | ✓ | | ✓ | | | |
| Ozkapici *et al.* (2016) | | | | ✓ | | ✓ | ✓ |
| Rivera-Royero *et al.* (2016) | | ✓ | | | | | ✓ |
| Baskaya *et al.* (2017) | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ |
| He and Jung (2018) | | | | | | | ✓ |
| Klibi *et al.* (2018) | ✓ | ✓ | | | | | ✓ |
| Moreno *et al.* (2018) | ✓ | ✓ | | | | | ✓ |
| Coskun *et al.* (2019) | | ✓ | | ✓ | | | ✓ |
| Rezaei-Malek *et al.* (2019) | ✓ | ✓ | | | | | ✓ |
| Abazari *et al.* (2021) | ✓ | ✓ | | | | ✓ | |
| Haghgoo *et al.* (2022) | ✓ | ✓ | | ✓ | | | |
| Wang *et al.* (2021) | ✓ | ✓ | ✓ | ✓ | | | ✓ |
| Wang *et al.* (2022a, 2022b) | ✓ | ✓ | | ✓ | | | ✓ |
| Wang *et al.* (2022a, 2022b) | ✓ | ✓ | ✓ | ✓ | | | ✓ |
| Present work | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

**Note:** *Addressing equity through the MCDM approach
**Source:** Table created by authors

location of distribution centers, inventory level, distance, transshipment, prioritization and road vulnerability to make the mathematical model more realistic.

## 3. Problem description

In this section, we provide an overview of how we have incorporated MCDM techniques into our mathematical models for an equitable relief item distribution system. We also outline the data sources and assumptions that have been used in our proposed system with LT integration. Furthermore, we discuss the link between MCDM techniques and mathematical models.

Decision-makers face challenges in estimating the nature and impact of a disaster before it happens. They also need to plan how to respond and deliver relief items quickly and effectively. One of the key inputs for the relief prepositioning problem is the priority score of DPs. An HL network should consider these priorities when locating relief warehouses and prepositioning relief items. This way, the relief items are distributed to the DPs according to their needs, and the equity of the HL network is improved. Different DPs may have different priorities based on their vulnerability and damage levels. To deal with the complexity of the problem, the management process should consider the relevant criteria and subcriteria. This paper uses the proposed classification (see Table 2) to determine the priority of each neighborhood. Then, it applies a hybrid MCDM framework (OPA–VIKOR) to obtain the weight and ranking of the DPs in a real-life earthquake. The outcome is a decision tree shown in Figure 1.

OPA is a new MCDM method that can handle incomplete data and individual or group decision-making. Collecting data in MCDM problems is an ongoing concern, and experts may become confused when comparing alternatives using complicated approaches with precise values. To prevent mistakes, the input data should be simple. Aggregation methods in MCDM can lead to wrong decisions, so OPA uses a linear programming approach that does not require normalization, averaging methods or pairwise decision matrices. Moreover, experts can only comment on the attributes and alternatives for which they have sufficient knowledge and experience, and their priority is determined by their experience and knowledge. This allows decision-makers to incorporate their knowledge into the model. Combining OPA with VIKOR allows decision-makers to assign relative importance values to alternatives based on their preferences. VIKOR is a simple MCDM method that assesses proximity to ideal and anti-ideal possibilities simultaneously. It provides a reasonable option for decision-makers based on the greatest group advantage and minimal individual regret. VIKOR uses linear normalization, and normalized values do not depend on the evaluation unit of a criterion. The advantage of VIKOR is that it can determine a compromise solution that reflects the attitude of most decision-makers.

Furthermore, the priorities of DPs are incorporated into the mathematical models. The models suggest a two-echelon system for distributing relief items. This system includes RDCs at the upper echelon and prioritized DP locations for aid at the lower echelon, as shown in Figure 2. In this system, each DP is serviced by only one RDC, with supplies transported directly as needed. This mode of shipment is referred to as DS and is represented by a solid line. LT, an example of horizontal coordination between relief facilities, is also possible and is illustrated by dotted lines. LT allows organizations to manage demand variability and

Journal of Humanitarian Logistics and Supply Chain Management
Volume 13 · Number 4 · 2023 · 433–455

**Table 2** Criteria and subcriteria for the prioritization of DPs

| Criteria | Subcriteria | Scholars |
|---|---|---|
| **Seismicity aspect (SA)** | Distance from causative faults (DF) | Fariborz (2001), Tofighi *et al.* (2016), Rezaei-Malek *et al*. (2019), Yariyan *et al.* (2020) |
| **Texture aspect (TA)** | Worn-out urban texture (UT) | Fariborz (2001), Rezaei-Malek *et al*. (2019), Yariyan *et al.* (2020) |
| **Emergency services aspects (EA)** | Hospital (H) | Fariborz (2001), Rezaei-Malek *et al*. (2019) |
| | Clinic (C) | |
| | Fire stations (FS) | |
| | Red crescent centers (RC) | |
| **Road network aspects (RA)** | Primary network (PN) | Fariborz (2001), Tofighi *et al.* (2016), Rezaei-Malek *et al*. (2019) |
| | Secondary network (SN) | |
| | Neighborhood network (NN) | |
| **Public open space aspects (PA)** | The green space of city roads (GR) | Tofighi *et al.* (2016), Yariyan *et al.* (2020) |
| | Stadiums and open spaces (SO) | |
| | Local and regional parks (LP) | |
| **Demographic aspects (DA)** | Population density (PD) | Sheu (2010), Cai *et al.* (2011), Tofighi *et al.* (2016), Rezaei-Malek *et al*. (2019), Yariyan *et al.* (2020) |
| | Family density (FD) | |
| | Elderly population (EP) | |
| **Socioeconomics aspects (CA)** | Income level of people (IP) | Fariborz (2001), Rezaei-Malek *et al*. (2019) |
| | Political importance (PO) | |
| | Economic role (ER) | |
| **Background aspects (BA)** | Historical points of the earthquake (HP) | Rhoades *et al.* (2017), Zhang *et al.* (2023), CMCS Experts |
| | Density of earthquake occurrence points (DE) | |

**Source:** Table created by authors

stockouts. Each RDC can engage in LT with only one of its neighboring RDCs. Each family of three people receives one standard "relief item package" containing bottles of water and food cans. It is assumed that all demands are met and that RDCs are transparent about their inventory positions with other RDCs. Additionally, the capacity of vehicles used for deliveries is assumed to be sufficient. For computational simplicity, the DP for each neighborhood in District No. Seven of Shiraz [1] is considered to be the center of that neighborhood.

Figure 3 illustrates two primary areas of study: MCDM techniques and mathematical programming models. To achieve equitable distribution, the connection between MCDM techniques and mathematical modeling is mutually beneficial. MCDM techniques provide essential information for creating the objective function of mathematical models, while mathematical models assist decision-makers in making informed choices by determining the optimal delivery of resources based on priorities identified through MCDM techniques.

## 4. Decision-making techniques

Methods of decision-making can assist decision-makers in determining the optimal alternative by applying specific criteria to the evaluation of alternatives. There have been many suggestions made for MCDM methods, each appropriate for a different circumstance. The current research uses the distance-based VIKOR approach, with criteria weights generated by the OPA method, which excels when presented with a decision matrix rather than a pair-wise comparison matrix. Finally, the VIKOR method is used to identify the optimal solutions.

### 4.1. Ordinal priority approach

In the MCDM theory, OPA represents a significant advancement. This technique was first presented by Ataei *et al.* (2020). As well as supporting individual and group decision-making, the OPA can also determine the weight of experts, criteria and alternatives. This study focuses just on the weight of the criteria. In the present investigation, the original OPA was used to determine the weight of the criteria. Table 3 presents the sets, indices and variables of the OPA's core model required for its use. The steps involved in the OPA are discussed in more detail in the following section. According to Ataei *et al.* (2020) and Mahmoudi *et al.* (2021), the OPA consists of the following steps:

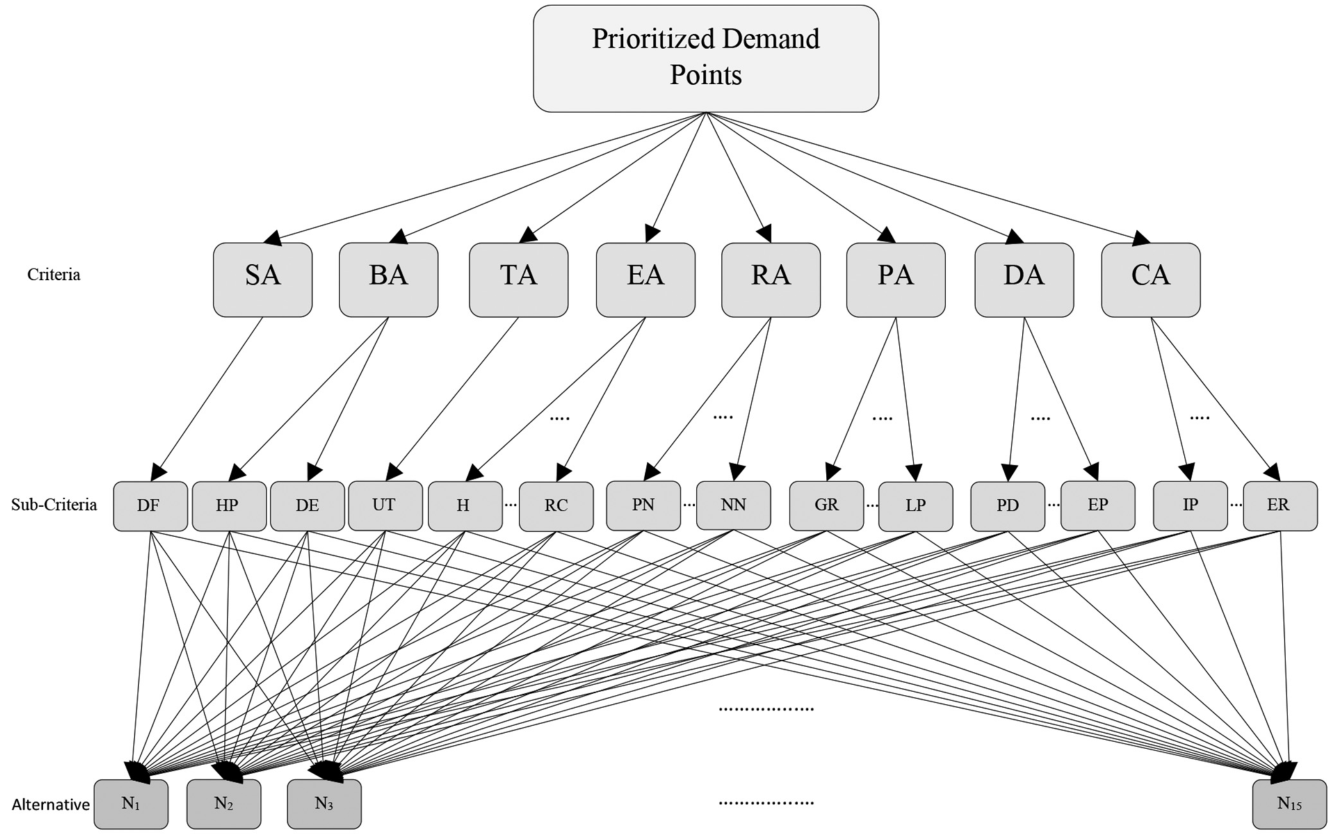
*Step 1*: Criteria specification is the initial step of the OPA. Decision-maker determines the criteria based on the requirements. Criteria are essential to the decision-making process in any circumstance.

*Step 2*: Identifying the experts to collect the required data. In addition, experts should be ranked according to their experience or some other significant factor by the decision-maker.

*Step 3*: Criteria play a crucial role in decision-making. In the next stage, criteria should be ranked based on experts' opinions.

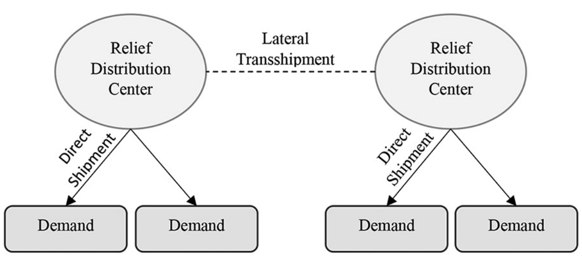
*Step 4*: For every criterion, alternatives should be ranked by experts. This is a crucial stage for the outcome; consequently, the expert(s) sufficient knowledge is needed. The rankings of alternatives might range from 1 to $m$ for each criterion.

**Figure 1** Decision tree for prioritizing DPs




**Source:** Figure created by authors

**Figure 2** Flow of relief items in the distribution system




**Source:** Figure created by authors

*Step 5:* Finally, using information from the preceding steps, Model (1) is constructed:

$$
\begin{aligned}
& MaxZ \\
& S.t: \\
& Z \leq i\left(j\left(r\left(W_{ijk}^{r} - W_{ijk}^{r+1}\right)\right)\right) && \forall i,j,k \text{ and } r \\
& Z \leq ijm W_{ijk}^{m} && \forall i,j \text{ and } k \\
& \sum_{i=1}^{p}\sum_{j=1}^{n}\sum_{k=1}^{m} W_{ijk} = 1 \\
& W_{ijk} \geq 0 && \forall i,j \text{ and } k \\
& Where\ Z: Unrestrictedinsign
\end{aligned}
\tag{1}
$$

Once Model (1) has been solved, the value of $W_{ijk}$ for each alternative can be derived and is shown in equation (2):

$$\left(W_{ijk}^{(1)}, W_{ijk}^{(2)}, \ldots, W_{ijk}^{(m)}\right) \quad \forall i, j, k \tag{2}$$

*Step 6:* It is possible to determine the weight of the alternatives by applying equation (3), which is based on the values that were acquired in Step 5:

$$W_k = \sum_{i=1}^{p}\sum_{j=1}^{n} W_{ijk}\ \forall k \tag{3}$$

The weights of the criteria can be calculated using equation (4):

$$W_j = \sum_{i=1}^{p}\sum_{k=1}^{m} W_{ijk}\ \forall j \tag{4}$$

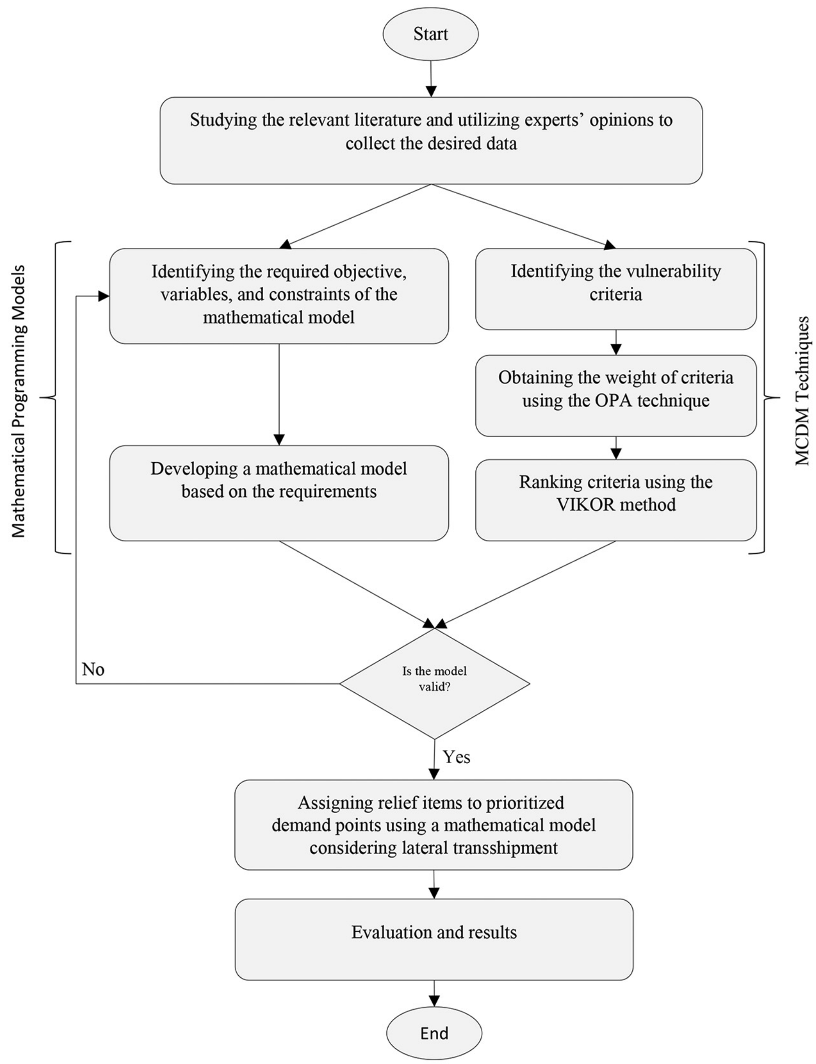
Experts' weights can be calculated using equation (5) if the MCDM problem involves group decision-making:

$$W_i = \sum_{j=1}^{n}\sum_{k=1}^{m} W_{ijk}\ \forall i \tag{5}$$

## 4.2. VIseKriterijumska Optimizacija I Kompromisno Resenje

The compromise ranking method, called the VIKOR method, lets us figure out different ways to decide and choose a compromise solution, even if the evaluation criteria are in conflict. Distances from ideal and anti-ideal points are used for evaluating solutions

**Figure 3** Research flowchart




**Source:** Figure created by authors

(variants). The comprehensive indicator, the maximum weighted distance from this point and the weighted average distance from the ideal solution are all determined for each decision-making variant. The variants are ranked using the values obtained in this manner, resulting in three rankings (Opricovic and Tzeng, 2004). The steps of the VIKOR method are presented:

*Step 1:* Create the decision matrix $(x_{ij})_{m\times n}$ based on the criteria and alternatives, where "$n$" stands for criteria and "$m$" stands for alternatives, and quantify the indicators shown in equation (6). For instance, the $x_{21}$ is related to the second alternative and the first criterion:

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{21} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{6}$$

Note that the VIKOR cannot calculate the weight of criteria, so the decision-maker should provide the weight of criteria as input. Equation (7) demonstrates the weight vector. The weights in this analysis were calculated using the OPA technique:

$$W = [w_1, w_2, w_3] \tag{7}$$

*Step 2:* The matrix is then normalized to form a new matrix using the norm normalization method:

$$F = [f_{ij}]_{m\times n} \tag{8}$$

where:

$$f_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \quad i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, n \tag{9}$$

$$f_{ij} = \frac{\frac{1}{x_{ij}}}{\sqrt{\sum_{i=1}^{m} \left(\frac{1}{x_{ij}}\right)^2}} \quad i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, n \tag{10}$$

and $x_{ij}$ represents the alternative $i$ performance concerning criterion $j$. Keep in mind that if negative indicators are

**Table 3** OPA sets, indices and variables

| **Sets** | |
|---|---|
| ***I*** | Set of experts $\forall i \in I$ |
| ***J*** | Set of criteria $\forall j \in J$ |
| ***K*** | Set of alternatives $\forall k \in K$ |
| **Indices** | |
| ***i*** | Index of the experts (1, . . ., *p*) |
| ***j*** | Index of preference of the criteria (1, . . ., *n*) |
| ***k*** | Index of the alternatives (1, . . ., *m*) |
| **Variables** | |
| ***Z*** | Objective function |
| $W_{ijk}^{r}$ | Weight (importance) of *k*th alternatives based on *j*th criterion by *i*th expert at *r*th rank |
| **Parameters** | |
| ***i*** | Rank of expert *i* |
| ***j*** | Rank of criterion *j* |
| ***r*** | Rank of alternative *k* |

**Source:** Table adapted from Ataei *et al.* (2020) and Mahmoudi *et al.* (2021)

normalized using equation (10), they are considered positive. Following is the normalized decision matrix:

$$F = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{21} & \cdots & f_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{m1} & f_{m2} & \cdots & f_{mn} \end{bmatrix} \tag{11}$$

*Step 3:* Find the positive-ideal and negative-ideal answers. ($f^+$) and ($f^-$) represent the best and worst alternatives, respectively:

$$f^+ = \left\{ \left(\max f_{ij} | j \in \mathcal{J}\right) or \left(min f_{ij} | j \in \mathcal{J}'\right) | i = 1, 2, \ldots, m \right\} = \left\{ f_1^+, f_2^+, \ldots, f_j^+, \ldots, f_n^+ \right\} \tag{12}$$

$$f^- = \left\{ \left(\min f_{ij} | j \in \mathcal{J}\right) or \left(max f_{ij} | j \in \mathcal{J}'\right) | i = 1, 2, \ldots, m \right\} = \{ f_1^-, f_2^-, \ldots, f_j^-, \ldots, f_n^- \} \tag{13}$$

where $\mathcal{J} = \{j = 1, 2, \ldots, n \mid f_{ij}$, *a larger response is desired*$\}$
and $\mathcal{J}' = \{j = 1, 2, \ldots, n \mid f_{ij}$, *a smaller response is desired*$\}$

*Step 4:* Calculate both utility and regret measures. The utility and regret measures for every alternative are given as follows:

$$S_i = \sum_{j=1}^{n} W_j \frac{\left(f_j^+ - f_{ij}\right)}{\left(f_j^+ - f_j^-\right)} \tag{14}$$

$$R_i = max \left[ w_j \frac{\left(f_j^+ - f_{ij}\right)}{\left(f_j^+ - f_j^-\right)} \right] \tag{15}$$

where $w_j$ represents the weight of criterion $j$ and $S_i$ and $R_i$ stand in for the utility and regret measures.

*Step 5*: Determining the VIKOR index using equation (16):

$$Q_i = v\left[\frac{S_i - S^+}{S^- - S^+}\right] + (1 - v)\left[\frac{R_i - R^+}{R^- - R^+}\right] \tag{16}$$

where $Q_i$ represents the VIKOR value of alternative $i$, $i = 1, \ldots, m$; $S^+ = minS_i$, $S^- = maxS_i$, $R^+ = minR_i$, $R^- = MaxR_i$ and the maximum group utility's weight is "$v$," which is typically set to 0.5 (Opricovic, 1994, 1998; Tong *et al.*, 2007).

*Step 6*: Sort and rank the alternatives based on $R$, $S$ and $Q$ values. The best solution is the alternative that results in the lowest possible VIKOR value. At this step, the following procedure is followed:

- At first, the alternatives are arranged in three columns in the order of indicators $R$, $S$ and $Q$ in ascending order.
- If an alternative rank first in all three indicators, this alternative will be the best.
- If condition number 2 is not satisfied, select the first and second rank of the $Q$ column and check the condition below:

$$Q(A_2) - Q(A_1) \geq \frac{1}{m-1} \quad m: number\ of\ alternatives \tag{17}$$

where $A_1$ is the alternative with the first position in $S$ or/and $R$, and $A_2$ is the second-positioned alternative in the ranking list of $Q$. If the condition is satisfied and $A_1$ is ranked best by $S$ or/and $R$, then $A_1$ is ranked first; otherwise, both $A_1$ and $A_2$ are the best alternatives.

- If condition number 3 is not satisfied, the following relationship continues until it is satisfied:

$$Q(A_k) - Q(A_1) \geq \frac{1}{m-1} \tag{18}$$

where $k$ is the rank of the last alternative in which condition three is not fulfilled. In this case, alternative $A_1$ to $A_{k-1}$ are the best alternatives.

## 5. Proposed mathematical model

The DS and LT between RDCs are formulated and described in this section.

### 5.1 Direct shipment model

First, a DS mathematical model with no LT is developed. Two-stage mixed integer programming can be used to model the DS. Prepositioning relief supplies and the size and location of RDCs are three critical elements in the first stage of the decision-making process. Considering the demands of the future is essential when making these decisions. Second-stage decision variables focus on the relief supplies distribution in light of particular DPs. The following is a presentation of the notations for the model of DS.

*Sets:*

$I$ = Set of RDCs $i \in I$; and
$\mathcal{J}$ = Set of DPs $j \in \mathcal{J}$.

*Parameters:*

$N$ = quantity of relief items required at each DP;
$P$ = maximum number of RDCs to open;

$G$ = a big number;
$c_i$ = capacity of RDCs;
$pr_j$ = priority of demand at location $j$;
$d_j$ = number of people affected at location $j$;
$v_{ij}$ = vulnerability factor between RDC $i$ and DP $j$;
$R$ = maximum distance for a relief item to travel; and
$r_{ij}$ = distance between RDC $i$ and DP $j$.

*Decision variables:*
$q_i$ = quantity of relief items held at RDC $i$;
$y_i$ = 1, if the RDC $i$ is opened; otherwise, 0;
$X_{ij}$ = quantity of relief item sent to DP $j$ from RDC $i$; and
$m_{ij}$ = 1, if DP $j$ is assigned to RDC $i$; otherwise, 0.

Consequently, the comprehensive model for DS is as follows:

$$Min(F) = \frac{\sum_i \sum_j X_{ij} r_{ij}(1-pr_j)(1+v_{ij})}{\sum_j (d_j N)} \tag{19}$$

Subject to:

$$\sum_i X_{ij} \geq d_j N \quad j \in \mathcal{J} \tag{20}$$

$$\sum_j X_{ij} \leq q_i \quad i \in I \tag{21}$$

$$r_{ij}(1+v_{ij}) m_{ij} \leq R \quad i \in I, j \in \mathcal{J} \tag{22}$$

$$\sum_i y_i \leq P \tag{23}$$

$$\sum_i m_{ij} = 1 \quad j \in \mathcal{J} \tag{24}$$

$$\sum_j m_{ij} \leq G y_i \quad i \in I \tag{25}$$

$$X_{ij} \leq G m_{ij} \quad i \in I, j \in \mathcal{J} \tag{26}$$

$$q_i \leq y_i c_i N \quad i \in I \tag{27}$$

$$\sum_i q_i \leq \left\{\sum_j d_j\right\} N \times 1.01 \tag{28}$$

$$X_{ij}, q_i \geq 0 \quad i \in I, j \in \mathcal{J} \tag{29}$$

$$y_i, m_{ij} \in \{0,1\} \quad i \in I, j \in \mathcal{J} \tag{30}$$

The objective function (19) aims to minimize the total average inflated distance traveled per relief item while taking into account the priority of DPs. The objective is weighted by a parameter $pr_j \in [0,1]$ that represents the priority of each DP $j \in \mathcal{J}$. Since the objective function is minimizing, the priority parameter needs to be subtracted from one [i.e. $(1 - pr_j)$] to minimize the needs of DPs with higher significance. Also, the original distance of a route $r_{ij}$ is inflated here by the vulnerability of that route $v_{ij} \in [0,1]$ using [*Inflated distance* = *Original distance* × (1 + *Vulnerability*)] equation. Next, mentioned terms are multiplied by the quantity of relief item $X_{ij}$ sent from RDC $i$ to DP $j$; therefore, the risk and priority of shipment in that route are obtained. Finally, it is divided by the number of relief items the affected people need; thus, the total average inflated distance traveled per relief item sent is obtained based on priority. The satisfaction of demand at every DP is guaranteed by constraint (20). As a result of constraint (21), relief items sent do not surpass the storage capacity of RDC $i$. Constraint (22) states that relief items cannot be transferred more than $R$. Constraint (23) determines the maximum relief center that can be operated. Constraints (24)–(26) ensure that every DP can be assigned to precisely one RDC. If the RDC is opened, then the DP can be assigned there. Relief centers cannot send relief items to the DP unless they are assigned to that relief center. Constraint (27) determines the upper bound of relief items in relief facilities. Constraint (28) assumes that all demands can be met with 101% of available resources, ensuring demands are met. Constraints (29) and (30) define restrictions on decision variables.

### 5.2 Lateral transshipment model

Taking into account the application of LT to the model, a new index, parameters and decision variables are defined below:

*Sets:*
$I'$ = Set of transshipment points $i' \in I$.

*Parameters:*
$v_{i'j}$ = vulnerability factor between RDC $i'$ and DP $j$;
$v_{ii'}$ = vulnerability factor between RDCs $i$ and $i'$;
$r_{i'j}$ = distance between RDC $i'$ and DP $j$; and
$r_{ii'}$ = distance between RDCs $i$ and $i'$.

*Decision variables:*
$Xb_{ii'j}$ = quantity of relief item sent to DP $j$ from RDC $i$ through RDC $i'$;
$f_{ii'}$ = 1, if RDCs $i$ and $i'$ engage in LT; otherwise, 0; and
$t_{ii'j}$ = 1, if RDCs $i$ and $i'$ engage in LT for DP $j$; otherwise, 0.

Then the complete LT model is formulated as below:

$$Min(\mathrm{F}) = \frac{\sum_i \sum_j X_{ij} r_{ij}(1-pr_j)(1+v_{ij}) + \sum_i \sum_{i'} \sum_j Xb_{ii'j}(1-pr_j)\left(r_{i'j}(1+v_{i'j}) + r_{ii'}(1+v_{ii'})\right)}{\sum_j (d_j N)} \tag{31}$$

Subject to (22)–(28), and:

$$\sum_i X_{ij} + \sum_i \sum_{i'} Xb_{ii'j} \geq d_j N \quad j \in \mathcal{J} \tag{32}$$

$$\left(r_{ii'}(1+v_{ii'}) + r_{i'j}(1+v_{i'j})\right) t_{ii'j} \leq R \quad i \in I, i' \in I, j \in \mathcal{J}, i \neq i' \tag{33}$$

$$\sum_j X_{ij} + \sum_{i'} \sum_j Xb_{ii'j} \leq q_i \quad i \in I, i \neq i' \tag{34}$$

$$\sum_i f_{ii'} \leq 1 \quad i' \in I, i \neq i' \tag{35}$$

$$Xb_{ii'j} \leq Gt_{ii'j} \quad i \in I, i' \in I, j \in \mathcal{J}, i \neq i' \tag{36}$$

$$\sum_j \sum_{i'} t_{ii'j} \leq Gy_i \quad i = I, i \neq i' \tag{37}$$

$$\sum_i \sum_{i} t_{ii'j} \leq Gy_{i'} \quad i' = I, i \neq i' \tag{38}$$

$$\sum_i t_{ii'j} \leq m_{i'j} \quad i' \in I, j \in \mathcal{J}, i \neq i' \tag{39}$$

$$\sum_j t_{ii'j} \leq Gf_{ii'} \quad i \in I, i' \in I, i \neq i' \tag{40}$$

$$X_{ij}, Xb_{ii'j}, q_i \geq 0 \quad i \in I, i' \in I, j \in \mathcal{J}, i \neq i' \tag{41}$$

$$y_i, m_{ij}, t_{ii'j}, f_{ii'} \in \{0, 1\} \quad i \in I, i' \in I, j \in \mathcal{J}, i \neq i' \tag{42}$$

The total average inflated distance traveled by each relief item is minimized based on DP priority in the objective function (31), considering both DS and LT. In fact, equation (31) is the same as equation (19) in addition to the consideration of LT. Again, the objective is weighted by a parameter $pr_j \in [0,1]$ that represents the priority of each DP $j \in \mathcal{J}$, and this parameter is applied for DS and LT. In the first term inflated distance of DS is obtained by multiplying the distance $r_{ij}$, between RDC $i$ and DP $j$, by the vulnerability rate $(1 + v_{ij})$ between RDC $i$ and DP $j$. After that, the inflated distance is multiplied by the quantity of relief item $X_{ij}$ sent from RDC $i$ to DP $j$; therefore, the risk and priority of DS in that route are obtained. Furthermore, the inflated distance of LT is calculated by multiplying the distance $r_{i'j}$, between RDC $i'$ and DP $j$ to the vulnerability rate $(1 + v_{i'j})$ between RDC $i'$ and DP $j$; and also by multiplying the distance $r_{ii'}$, between RDC $i$ and RDC $i'$ to the vulnerability rate $(1 + v_{ii'})$ between RDC $i'$ and RDC $i$. Then, the inflated distance is multiplied by the quantity of relief item $Xb_{ii'j}$ sent from RDC $i$ through RDC $i'$ to DP $j$; therefore, the risk and priority of LT in that route are calculated. After all, all the terms are divided by the number of relief items the affected people need; thus, the total average inflated distance traveled per relief item sent is obtained based on the priority while considering vulnerability and LT. In constraint (32), the demand of each location is met by DS or LT. Constraint (33) limits the distance traveled by $R$. Constraint (34) indicates that the opened RDC capacity for assigned demands is sufficient. Constraint (35) limits each RDC to participate in LTs with only one neighbor RDC. Constraint (36) states that sending relief items is impossible until two RDCs participate in LT. Constraints (37) and (38) guarantee LT is only allowed for opened RDCs. Constraint (39) assures LT is engaged while using neighbor RDC to satisfy the assigned demand to that RDC. Constraint (40) ensures relief items can only be transferred if two RDCs engage in LT. Decision variables are restricted by Constraints (41) and (42).

## 6. Case study: plausible earthquake in Shiraz

Shiraz, the capital of Fars Province and the most populous city in Iran's southern region with a population of about 1,699,000 is the country's fifth most populous metropolis and a hub for politics, business and culture. Besides being one of the most populous cities in Iran, Shiraz is also one of the most disaster-prone cities. An earthquake is one of the most damaging natural calamities, causing substantial financial damage and terrible casualties.

Shiraz experienced one earthquake of magnitude 6.3, 39 earthquakes between 5.0 and 6.0, 337 earthquakes between 4.0 and 5.0, 594 earthquakes between 3.0 and 4.0, 767 earthquakes between 2.0 and 3.0 and 15 earthquakes occurred with magnitudes lower than 2.0 between January 1, 2002, and October 6, 2022, as reported by volcano discovery on www.volcanodiscovery.com. There were 1,753 earthquakes, with an annual average of 88 quakes (most quakes are felt at magnitudes greater than 2.0).

Geographically and geologically, Shiraz is situated on a natural spread with multiple active faults. The most active faults are Sabzposhan, Kohenjan, Sarvestan and Karehbas, and the main fault in District No. Seven of Shiraz is Soltan fault with a length of 45 km (see Figure 4). Table 4 lists the most significant active faults in and around Shiraz.

### 6.1 Input data

The source of the majority of the data used in this investigation was gathered from CMCS, the municipal yearbook of Shiraz Ganjehi and Norouzi Khatiri (2021), and the geographic information system (GIS) from the work of Abdolazimi *et al.* (2022) research. This section describes the system's data types and the methods for updating them. In this case, District No. Seven of Shiraz is considered. District No. Seven includes 15 neighborhoods, and each neighborhood has a different priority. Eleven nodes are selected as potential RDCs based on the review with experts of CMCS of Shiraz, as shown in Figure 5. These nodes' indices and related location names are listed in Table 5. For each neighborhood, the neighborhood center point is obtained as a DP to simplify the complexity of the calculation.

The number of affected individuals is calculated to be 25,667 for the most likely earthquake scenario expressed by CMCS experts, and the total facility distribution centers capacity is assumed to meet the total demand in the 15 neighborhoods of District No. Seven of Shiraz. Each neighborhood is evaluated by experts based on GIS maps and data-driven from the municipality of Shiraz, like DA and CA.

Additionally, related to several editions of Iran's seismic building code (Standard No. 2800–15 of Iran), three-time periods for building codes have been considered to estimate the damage number of damaged buildings. The construction year of a building has been used to define three categories of building codes: precode, moderate code and high code, which relate to buildings constructed prior to 1991, between 1991 and 2014 and after 2014, respectively Sadeghi *et al.* (2017). Structures are categorized by their earthquake-resistance features, construction year, height and materials used. Consequently, the potential number of heavily, moderately and partially damaged structures in each neighborhood is determined. The building taxonomy of Shiraz is presented in Table 6.

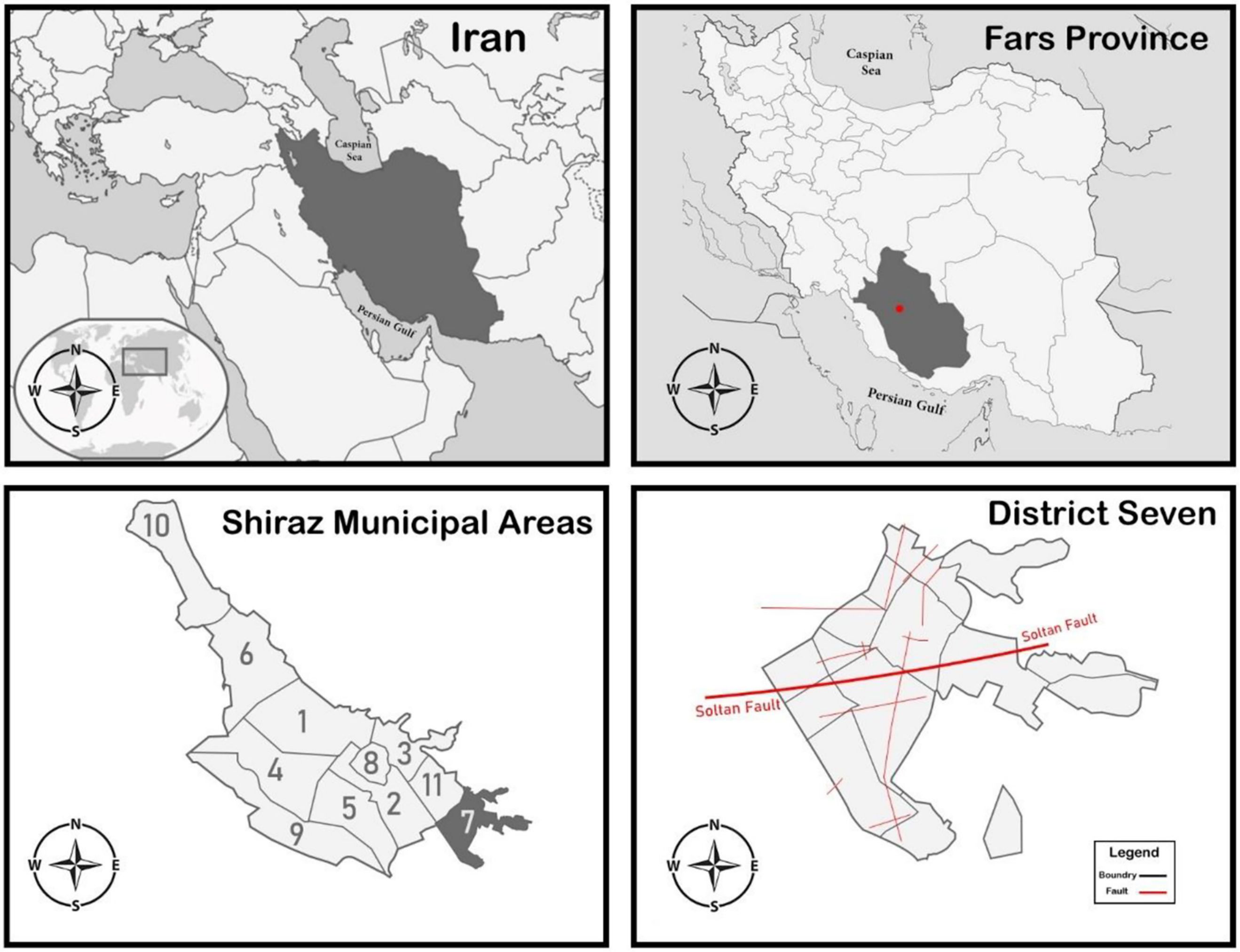
The average number of residents in a building is determined using equation (43) for each district:

$$A = \frac{\textit{Population of district}}{\textit{Number of buildings in the district}} \tag{43}$$

The Shiraz municipal yearbook was the source for the demographic data that was used in the preceding formulation.

Journal of Humanitarian Logistics and Supply Chain Management
Volume 13 · Number 4 · 2023 · 433–455

**Figure 4** Case study




**Source:** Figure adapted from the Shiraz Municipal Yearbook (2019), and the Geological Survey and Mineral Exploratory of Iran, available at https://gsi.ir/en

**Table 4** Principal active faults in and around Shiraz

| No. | Fault | Length (km) | Observation magnitude |
|---|---|---|---|
| 1 | Sabzposhan | 51 | 6.5, 6.2, 6.2, 4.2, 4 |
| 2 | Kohenjan | 75 | 6.5, 6.2, 6.2, 4.2, 4 |
| 3 | Sarvestan | 75 | 7.5, 6.4, 5, 4.6, 4.3, 4.2, 4 |
| 4 | Karehbas | 63 | 4.7, 4.1, 4.1 |
| 5 | Mishvan | 55 | 4.5, 4.4 |
| 6 | Goam | 32 | 5, 4.9, 4.7, 4.4, 4.3 |
| 7 | Bazin | 23 | 4.3 |
| 8 | Soltan | 45 | 4.4 |
| 9 | Kovar | 53 | 5.2, 4.8, 4.6, 4.5 |
| 10 | Shorab | 70 | 4.8, 4.4 |
| 11 | Rahdar | 72 | 6.3, 5.2, 5.1, 4.9, 4.6, 4.5, 4.3, 4.2 |

**Source:** Table adapted from Amiri *et al.* (2014)

Using Formula (44), the number of earthquake victims in each neighborhood is determined, where $H$, $M$ and $P$ correlate to the number of severely, moderately and partially damaged structures, respectively:

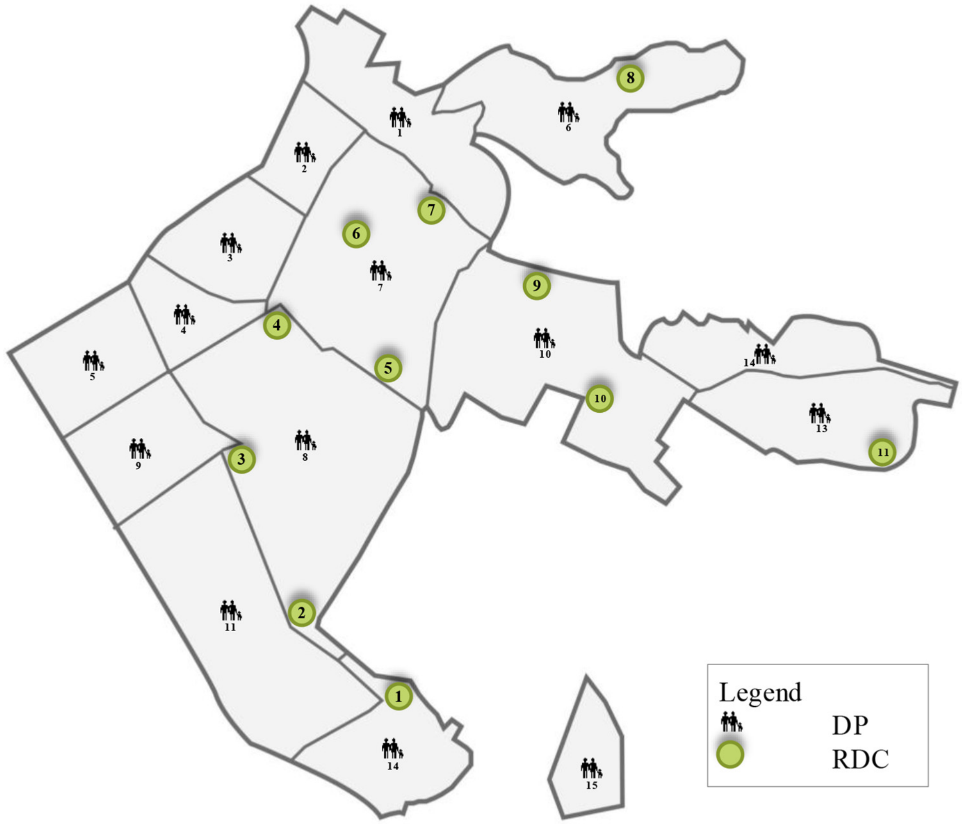
$$Number\ of\ affected\ people = A * (100\%H + 50\%M + 10\%P) \tag{44}$$

The Formula (45) determines the number of relief supplies required in each neighborhood. Statistically, a family of three will benefit from the one relief item shipped out since the family density is almost three in each neighborhood. Consequently, the formulation requires that the value be multiplied by 0.30:

$$Relief\ items\ required = 0.3 * Number\ of\ affected\ people\ in\ that\ neighborhood \tag{45}$$

Google Maps™ is used to obtain the distances between RDCs as well as between RDCs and DPs. The shortest distance is then selected between two points. Horner and Widener (2011) concluded that network disruption levels increased the average distance after a disaster. Based on Horner and Widener (2011) and Baskaya *et al.* (2017), we inflate the actual distance of a route by its vulnerability, which ranges from 0 to 1, with 1 representing the most vulnerable instance. The emergency road network proposed by Ganjehi and Norouzi Khatiri (2021) is used to determine the vulnerability coefficient of each road. The road

**Figure 5** Candidate RDCs




**Source:** Figure adapted from Shiraz Municipal yearbook (2019)

**Table 5** Node indices and the municipality code of neighborhood (DP)

| Index | Municipal code | Index | Municipal code | Index | Municipal code |
|---|---|---|---|---|---|
| 1 | 119 | 6 | 131 | 11 | 140 |
| 2 | 120 | 7 | 132 | 12 | 142 |
| 3 | 121 | 8 | 133 | 13 | 143 |
| 4 | 122 | 9 | 134 | 14 | 144 |
| 5 | 123 | 10 | 139 | 15 | 148 |

**Source:** Table adapted from Shiraz Municipality (2019)

system is overlaid with the proposed emergency network. They evaluated the vulnerability of roads by using road length, hazardous land use, transportation construction, population density, buildings vulnerability, safety and volume of the population on the road at a moderate level. Afterward, the vulnerable rate of routes is considered in a range of 0 to 1 and provided in Table 7.

It is assumed that a relief item can travel a distance of up to 5 km, which guarantees the DPs can be serviced by a single RDC regardless of location.

Each household of three receives one "relief item package," which contains a set of standardized aid items. Bottled water and food cans are included in this shipment. It is assumed that RDCs share correct information about their inventory level with each other and that the vehicle capacity is sufficient.

### 6.2 Calculating the weight of criteria using ordinal priority approach

The current research exposes the OPA approach to obtain the weight of each criterion, which allows managers to develop a decision-making tool to evaluate criteria meritoriously. The study used the data listed in Table 8 to run the OPA model, as shown in equation (1).

The OPA was executed as per the steps mentioned before. After solving the OPA model, the criteria weights were obtained using equation (4). Later, they were utilized in the VIKOR method to rank the alternatives. Figure 6 demonstrates the weights of the criteria.

Overall, the CA stands out as the best criterion, followed by the DA, CA and PA, as shown in Figure 6. Therefore, these criteria are the four most influential factors among

**Table 6** Basis for seismic design levels' definition

| Type of structure | Steel (MRF and BF) and concrete (MRF and SW) | | | | | | | | | Masonry (All) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bldg. code | High-code (H) | | | Moderate-code (M) | | | Pre-code (P) | | | High-code (H) | | Moderate-code (M) | | Pre-code (P) | |
| **No. of stories** | 1 to 3 stories | 4 to 7 stories | More than 8 stories | 1 to 3 stories | 4 to 7 stories | More than 8 stories | 1 to 3 stories | 4 to 7 stories | More than 8 stories | 1 to 2 stories | More than 3 stories | 1 to 2 stories | More than 3 stories | 1 to 2 stories | More than 3 stories |
| **Label** | H_1_3 | H_4_7 | H_8 | M_1_3 | M_4_7 | M_8 | P-1_3 | P_4_7 | P_8 | H_1_2 | H_3 | M_1_2 | M_3 | P_1_2 | P_3 |

**Source:** Table adapted from Sadeghi *et al.* (2017)

twenty factors in disaster situations based on the seven experts.

### 6.3 Ranking of alternatives using VIseKriterijumska Optimizacija I Kompromisno Resenje

This method is one of the well-known methods in the MCDM process, which can be used in MCDM problems with conflicting criteria. Furthermore, the utility and regret measures are considered simultaneously when the experiment is carried out.

First, the decision matrix is formed using equation (6) (see Table 9), and the positive-ideal ($f^+$) and negative-ideal ($f^-$) values are determined using equations (12) and (13). In the next step, the utility and regret measures are calculated using equations (14) and (15). Finally, $Q$ values are calculated by combining the values obtained from the previous steps using equation (16). The final result is shown in Table 10.

### 6.4 Results of direct shipment and lateral transshipment models

A case study based on the execution of the models as well as the derived solution approach for an anticipated earthquake in District No. Seven of Shiraz is given. Parameters were set to the same values in both the DS and LT models in GAMS 24.0.1 and the models were solved in about 2 s and 10 s, respectively, using the commercial solver CPLEX 12.5. This allowed us to examine the impact of LT on the result. The numerical experiments were executed in a Windows 8.1 environment on a laptop with an Intel i7-4510U processor and 8 GB of RAM.

We begin by comparing and contrasting the results obtained from the DS and LT models. As can be seen in Table 11, there is variation in both distribution flows and opened RDCs numbers by the two models.

To guarantee that one RDC services every DP within the maximum travel distance, seven RDCs are opened and dispersed widely across the network. In addition, it is essential to find a balance between the demand for relief packages and the number of packages provided while selecting RDCs. For instance, nodes 4, 5 and 6 are selected as relief distributer, and since the demand estimation in mentioned nodes is higher than the rest, the inventory level is relatively higher than other nodes. The total value of the objective function for this solution is 1,336 kilometers. The results of DS decision variables are summarized in Table 12.

Under the second-stage decisions, relief items are supplied via DS or LT. Entirely nine RDCs opened, and seven RDCs are the same as in DS (see Table 13). The nearest storage facilities usually service the DPs. A total of five LT activities occurred. This solution's overall objective function value is 0.921 km, which is decreased by 68.94%.

The meager usage rate of RDCs 1 and 10 in both shipments indicates that establishing RDCs here would not be prudent, but RDCs must be established here to satisfy the demand of the adjacent DPs. In addition, this demonstrates that the flexibility of prepositioning and distribution of relief items can be increased by using LT.

Furthermore, the results of DS and LT models are evaluated and contrasted for varying numbers of RDCs and the maximum allowed distance traveled. DS and LT models are solved for diverse RDCs, ranging from 1 to 11. We find that allowing relief items to travel up to their maximum allowed distance does not affect the location of RDCs or the LT percentage. Consequently, it is assumed that the maximum

**Table 7** Vulnerability coefficient of the route in a medium earthquake of District no. 7

| Road | Vul. rate | Road | Vul. rate | Road | Vul. rate | Road | Vul. rate | Road | Vul. rate |
|---|---|---|---|---|---|---|---|---|---|
| 1–2 | 0.11 | 7–8 | 0.27 | 13–14 | 0 | 19–20 | 0.12 | 12–20 | 0 |
| 2–3 | 0 | 8–9 | 0.25 | 14–15 | 0.08 | 1–16 | 0.87 | 11–20 | 0.12 |
| 3–4 | 0.32 | 9–10 | 0.5 | 15–16 | 0.4 | 2–17 | 0 | 3–21 | 0.95 |
| 4–5 | 0.2 | 10–11 | 0.65 | 16–17 | 0 | 15–18 | 0.7 | 17–21 | 0 |
| 5–6 | 0.62 | 11–12 | 0.88 | 17–18 | 0 | 15–19 | 1 | 18–22 | 0.36 |
| 6–7 | 0.3 | 12–13 | 0.9 | 18–19 | 0.09 | 14–20 | 0.95 | 19–23 | 0.37 |
| 21–22 | 0.58 | 22–23 | 0.75 | 24–25 | 0.75 | 25–26 | 0.75 | 23–26 | 0.75 |
| 10–23 | 0.25 | 4–24 | 0.85 | 21–24 | 0.13 | 6–24 | 0 | 22–25 | 0.38 |

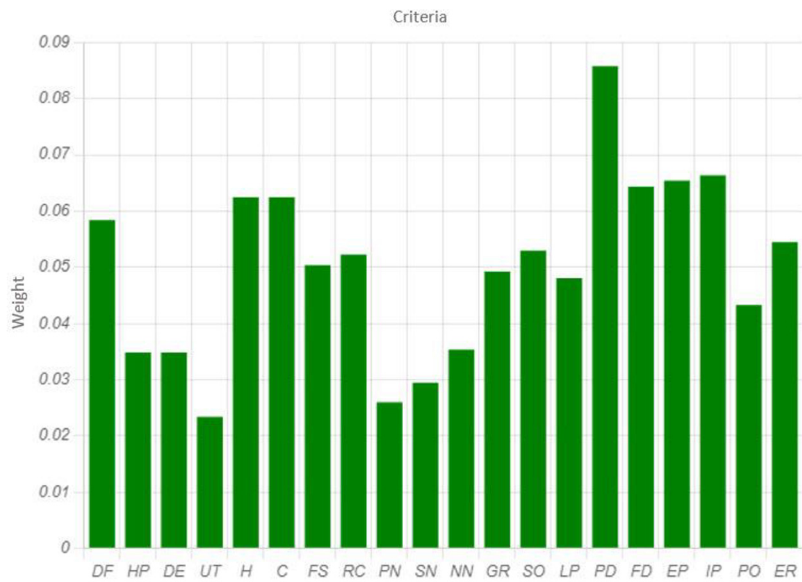
**Source:** Table adapted from Ganjehi and Norouzi Khatiri (2021)

**Table 8** Relative importance of the criteria of seven experts ($E_n$)

| Expert \ Criterion | DF | HP | DE | UT | H | C | FS | RC | PN | SN | NN | GR | SO | LP | PD | FD | EP | IP | PO | ER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $E_1$ | 6 | 7 | 7 | 5 | 3 | 3 | 4 | 4 | 8 | 9 | 9 | 12 | 10 | 11 | 1 | 2 | 2 | 15 | 13 | 14 |
| $E_2$ | 1 | 4 | 4 | 5 | 3 | 3 | 3 | 3 | 6 | 6 | 6 | 8 | 7 | 7 | 2 | 2 | 2 | 10 | 9 | 10 |
| $E_3$ | 10 | 11 | 11 | 9 | 1 | 1 | 3 | 2 | 4 | 12 | 12 | 13 | 13 | 5 | 8 | 8 | 8 | 14 | 6 | 7 |
| $E_4$ | 2 | 4 | 9 | 5 | 3 | 3 | 3 | 3 | 6 | 8 | 8 | 9 | 9 | 7 | 1 | 1 | 1 | 10 | 12 | 11 |
| $E_5$ | 10 | 9 | 3 | 8 | 4 | 4 | 4 | 4 | 3 | 2 | 1 | 6 | 6 | 6 | 5 | 5 | 5 | 11 | 7 | 7 |
| $E_6$ | 2 | 3 | 3 | 4 | 1 | 1 | 1 | 1 | 5 | 5 | 5 | 6 | 6 | 6 | 1 | 1 | 1 | 9 | 7 | 8 |
| $E_7$ | 9 | 1 | 1 | 8 | 10 | 10 | 10 | 10 | 11 | 12 | 12 | 14 | 15 | 13 | 4 | 3 | 2 | 7 | 5 | 6 |

**Source:** Table created by authors

**Figure 6** Weight of criteria using OPA




**Source:** Figure created by authors

**Table 9** Aggregated decision matrix of experts

| Neighborhood (alternative) \ Criterion | DF | HP | DE | UT | H | C | FS | RC | PN | SN | NN | GR | SO | LP | PD | FD | EP | IP | PO | ER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N_1$ | 9.00 | 3.64 | 4.88 | 6.67 | 5.00 | 4.65 | 7.69 | 7.00 | 5.00 | 5.25 | 5.44 | 5.25 | 5.25 | 9.00 | 3.23 | 5.25 | 6.67 | 3.00 | 3.23 | 5.25 |
| $N_2$ | 8.68 | 1.17 | 3.47 | 3.39 | 6.36 | 7.70 | 8.08 | 9.00 | 7.26 | 9.00 | 9.00 | 3.23 | 8.68 | 3.23 | 9.00 | 5.00 | 7.00 | 4.65 | 7.00 | 7.26 |
| $N_3$ | 5.25 | 1.37 | 1.17 | 5.91 | 6.67 | 8.28 | 7.80 | 8.68 | 7.52 | 8.38 | 8.68 | 3.39 | 7.69 | 4.65 | 8.68 | 5.25 | 7.52 | 9.00 | 7.26 | 5.25 |
| $N_4$ | 3.00 | 5.00 | 3.47 | 1.37 | 6.06 | 8.68 | 8.38 | 8.38 | 5.00 | 9.00 | 8.38 | 3.23 | 7.26 | 9.00 | 8.38 | 3.23 | 5.00 | 5.25 | 5.25 | 7.00 |
| $N_5$ | 2.89 | 6.67 | 6.43 | 1.47 | 2.56 | 7.98 | 7.00 | 9.00 | 9.00 | 8.68 | 8.28 | 3.39 | 7.00 | 3.23 | 7.98 | 7.00 | 7.00 | 9.00 | 7.26 | 7.00 |
| $N_6$ | 3.00 | 1.17 | 3.47 | 4.65 | 2.76 | 8.38 | 3.00 | 5.25 | 3.23 | 3.00 | 6.67 | 3.73 | 5.00 | 1.37 | 7.00 | 5.00 | 5.00 | 3.82 | 1.00 | 3.00 |
| $N_7$ | 1.37 | 1.37 | 1.17 | 1.26 | 6.92 | 6.20 | 6.67 | 5.25 | 6.43 | 6.67 | 6.36 | 3.47 | 7.00 | 5.00 | 5.25 | 4.65 | 5.25 | 5.00 | 3.23 | 5.50 |
| $N_8$ | 1.17 | 5.25 | 5.25 | 8.38 | 3.97 | 5.00 | 7.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.25 | 5.25 | 5.25 | 5.00 | 7.00 | 5.00 | 5.00 | 5.25 | 3.47 |
| $N_9$ | 1.37 | 6.67 | 1.60 | 1.47 | 3.00 | 6.67 | 5.25 | 7.98 | 9.00 | 9.00 | 7.00 | 3.73 | 6.92 | 7.00 | 6.67 | 5.00 | 8.68 | 8.68 | 7.26 | 5.25 |
| $N_{10}$ | 3.00 | 1.17 | 1.72 | 3.00 | 8.68 | 5.25 | 3.23 | 3.00 | 4.88 | 7.00 | 8.68 | 3.00 | 3.23 | 8.68 | 5.00 | 4.65 | 4.65 | 3.23 | 3.23 | 3.47 |
| $N_{11}$ | 5.25 | 5.50 | 1.17 | 1.47 | 1.17 | 3.00 | 9.00 | 3.23 | 9.00 | 8.68 | 5.00 | 3.47 | 1.00 | 5.00 | 3.23 | 5.00 | 7.00 | 5.25 | 8.68 | 7.26 |
| $N_{12}$ | 5.25 | 1.00 | 5.25 | 1.00 | 6.67 | 3.23 | 1.17 | 1.00 | 3.00 | 3.23 | 3.23 | 3.00 | 1.17 | 3.00 | 8.68 | 5.25 | 1.26 | 3.23 | 3.23 | 1.37 |
| $N_{13}$ | 4.88 | 1.37 | 3.47 | 3.64 | 7.00 | 3.00 | 1.00 | 1.37 | 3.47 | 1.17 | 9.00 | 3.92 | 1.17 | 3.23 | 7.26 | 5.25 | 1.17 | 3.39 | 3.64 | 1.37 |
| $N_{14}$ | 8.38 | 1.00 | 1.60 | 1.37 | 1.17 | 1.17 | 9.00 | 1.26 | 9.00 | 6.36 | 3.23 | 3.23 | 1.37 | 1.37 | 3.23 | 9.00 | 3.23 | 7.00 | 9.00 | 9.00 |
| $N_{15}$ | 6.67 | 7.26 | 5.50 | 1.17 | 1.00 | 1.00 | 3.00 | 1.60 | 5.50 | 5.25 | 7.00 | 3.00 | 1.00 | 1.00 | 1.17 | 7.26 | 5.25 | 1.00 | 7.00 | 5.50 |

**Source:** Table created by authors

distance traveled per relief item is the same when comparing the models. It is recommended that at least four relief facilities be established, as shown in Figure 7, to allow for the required LT between the facilities.

In the DS problem, the objective function reaches its optimal value of 1,336 kilometers, which is an increase of 0.415 km compared with the average distance traveled in the LT problem. The average distance traveled for each relief item under the LT model is consistently equal to or superior to the result of the DS model, demonstrating that the LT model is a relaxation of the DS model. The value of the average distance traveled by DS for the maximum number of RDCs from 7 to 11 is the same, and we have the same result. Therefore, only seven RDCs have been opened. In the LT model, the average distance traveled for the maximum number of RDCs from 9 to 11 is the same; therefore, only nine RDCs are opened.

Additionally, the amount of LT drops due to the rise in relief facilities (see Figure 8) because each DP is served by its nearest RDC, so there is no need for LT consideration. LT is used when at least four RDCs open. In other words, when the inventory of the RDC is insufficient to satisfy the vicinity DP's demand, that inventory shortage will be supplied by another nearest RDC with a sufficient amount of relief items, which means utilization of LT. Therefore, as more RDCs open, there

**Table 10** Utility and regret measures and VIKOR index of neighborhoods

| Neighborhood (alternative) | Si | Ri | Qi | Rank |
|---|---|---|---|---|
| $N_1$ | 0.38542 | 0.047893 | 0.052455 | 1 |
| $N_2$ | 0.354812 | 0.0857 | 0.5 | 8 |
| $N_3$ | 0.421739 | 0.082226 | 0.568756 | 10 |
| $N_4$ | 0.369845 | 0.078875 | 0.435501 | 5 |
| $N_5$ | 0.531272 | 0.074572 | 0.655244 | 14 |
| $N_6$ | 0.577652 | 0.06381 | 0.592396 | 11 |
| $N_7$ | 0.429134 | 0.056917 | 0.246719 | 3 |
| $N_8$ | 0.55232 | 0.0584 | 0.477436 | 6 |
| $N_9$ | 0.500313 | 0.0654 | 0.480885 | 7 |
| $N_{10}$ | 0.452155 | 0.0492 | 0.184111 | 2 |
| $N_{11}$ | 0.483191 | 0.06102 | 0.393614 | 4 |
| $N_{12}$ | 0.646573 | 0.082226 | 0.954059 | 15 |
| $N_{13}$ | 0.577415 | 0.066611 | 0.629028 | 13 |
| $N_{14}$ | 0.521265 | 0.0643 | 0.502243 | 9 |
| $N_{15}$ | 0.599883 | 0.0624 | 0.611846 | 12 |

**Notes:** Overall, neighborhoods 1, 10, 7 and 11 have the highest priorities and neighborhoods 12, 5, 13 and 15 have the least
**Source:** Table created by authors

**Table 11** Flows of DS and LT mathematical models

| DS model flows | LT model flows |
|---|---|
| **(1,15)** | (1,15) |
| **(2,14)** | (2,14) |
| **(2,11)** | (2,11) |
| **(4,5)** | (5,8) |
| **(5,4)** | (5,9) |
| **(5,7)** | (6,7) |
| **(5,8)** | (9,2) |
| **(5,9)** | (10,10) |
| **(6,1)** | (10,2) |
| **(6,3)** | (10,13) |
| **(7,2)** | (5,4,3) |
| **(10,6)** | (5,4,4) |
| **(10,10)** | (5,4,5) |
| **(10,12)** | (10,9,1) |
| **(10,13)** | (10,9,6) |

**Notes:** In the DS model, the two numbers represent the original RDC and demand point. In the LT model, the three numbers present the original RDC, transshipment point and demand point
**Source:** Table created by authors

**Table 12** DS decision variables result

| Node | Facility size | $q_i$ | Space utilization |
|---|---|---|---|
| 1 | 300 | 26 | 8.6 |
| 2 | 3,000 | 531 | 17.7 |
| 4 | 950 | 261 | 27.47 |
| 5 | 8,000 | 2,225 | 27.81 |
| 6 | 3,500 | 1,157 | 33.05 |
| 7 | 1,000 | 215 | 21.5 |
| 10 | 65,000 | 2,081 | 3.2 |

**Source:** Table created by authors

**Table 13** LT decision variable result

| Node | Facility size | $q_i$ | Space utilization |
|---|---|---|---|
| 1 | 300 | 26 | 8.6 |
| 2 | 3,000 | 530 | 17.6 |
| 4 | 950 | 317 | 33.36 |
| 5 | 8,000 | 1,420 | 17.75 |
| 6 | 3,500 | 1,167 | 33.34 |
| 7 | 1,000 | 334 | 33.4 |
| 8 | 1,000 | 334 | 33.4 |
| 9 | 1,000 | 215 | 21.5 |
| 10 | 65,000 | 2,149 | 3.3 |

**Source:** Table created by authors

would be more opportunities for DPs to be assigned to the nearest RDC with sufficient inventory levels to satisfy their demand. Furthermore, when the number of RDCs decreases, and may capacity of one RDC is not sufficient to satisfy the assigned DP; therefore, more than one RDCs engage in the supply flow.

## 7. Managerial insights

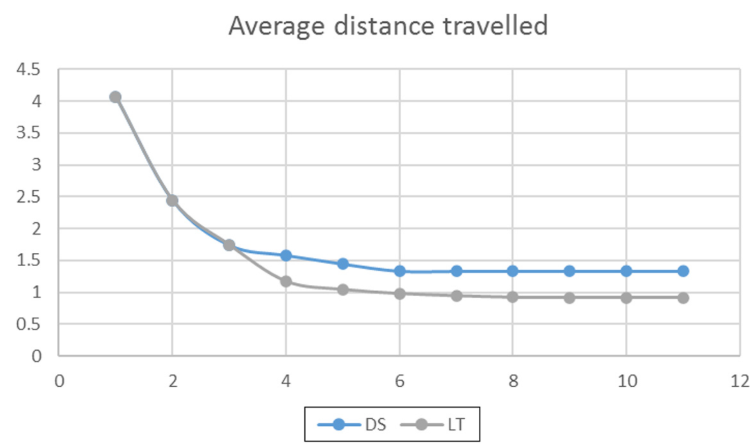
At the strategic level, decisions about the predisaster phase involve locating warehouses for prepositioning relief items and determining their required quantity. These decisions set up the HL network for a long planning horizon and rely on information that is stable over time. For instance, in an area prone to disasters, factors such as SA, TA, EA, RA, PA, DA, CA and BA do not vary much. Hence, the priority score of DPs can help decision-makers design a more equitable HL network for the strategic level of disaster management.

In addition, our research emphasizes the significance of efficient coordination and communication among various RDCs in HL. By using LT, relief items can be distributed more easily. When disaster managers implement horizontal coordination in the HL network, LT can decrease the distance required to deliver relief items to DPs. Additionally, decision-makers can use LT to foster horizontal coordination, improve centralized decision-making and synchronize distribution flow and inventory activities.

The results also suggest that RDCs with low utilization space levels should only be opened to meet the demand of their assigned surrounding area. As more RDCs open, DPs have more opportunities to be assigned to the nearest RDC with sufficient inventory levels. Therefore, decision- and policy-makers should focus on expanding/decentralizing the RDC network by building and operating smaller, more numerous RDCs. This will fully use space and decrease the risk and average distance from RDCs to destinations. This is because LT promotes coordination and strengthens relationships between organizations. Collaboration through LT can build a more resilient supply chain that can withstand disruptions and crises. By sharing resources and capacity, the flow of relief items can be maintained even when one part of the chain is affected by a disaster or conflict.

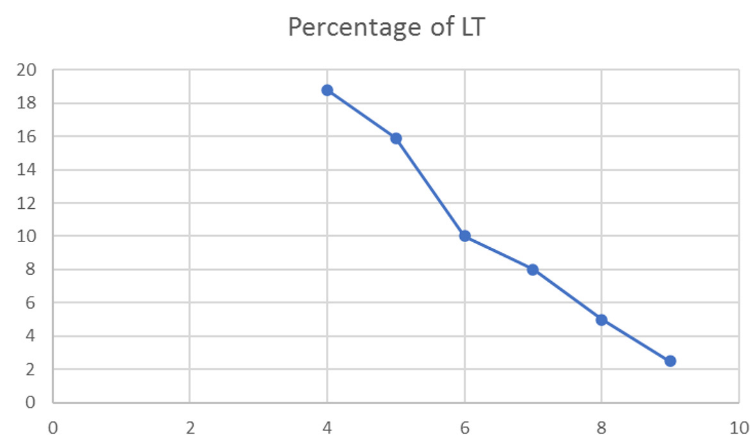
Furthermore, road vulnerability can help policy-makers design a humanitarian response network that adapts to changing road conditions after a disaster. By examining the factors that affect road vulnerability, such as road length, land use, construction, population density, building vulnerability, safety and traffic

**Figure 7** Average distance traveled in DS and LT models




**Source:** Figure created by authors

**Figure 8** Percentage of LT utilization




**Source:** Figure created by authors

volume, managers can identify and address the weaknesses of the roads and plan better strategies for delivering aid.

In this regard, we proposed an MCDM framework to prioritize DPs before a potential earthquake based on conventional and new criteria and subcriteria. The significance of this approach is demonstrated through the use of relief prepositioning models, as well as the consideration of road vulnerability and LT options. Our results show that incorporating LT and road vulnerability into optimization models for equitably delivering relief items can significantly reduce the average distance in the network. Therefore, we strongly recommend considering DP priorities, road vulnerability and LT when designing a HL network.

## 8. Conclusion

Today, the humanitarian supply chain plays an important role in helping people and governments to reduce postdisaster damage. Shiraz is the most populous city in the south of Iran, with a population of 1,699,000 that is exposed to 11 active faults in and around it and has experienced 1,753 earthquakes in the past 20 years. This paper presented hybrid decision-making by integrating OPA and VIKOR techniques to prioritize DPs and addressed equity under a medium-scale earthquake for 15 neighborhoods (15 DPs) of District No. Seven of Shiraz. So, the priority of DPs considered when designing networks for relief prepositioning to minimize casualties in disaster situations. In this regard, essential criteria (i.e. SA, TA, EA, RA, PA, DA, CA and BA) were chosen based on a survey of the relevant literature and expert interviews. HP and DE, as BA, were added by consulting with CMCS experts based on Rhoades *et al.* (2017) and Zhang *et al.* (2023) research.

In the developed model, initially, the weights of the criteria were specified using the OPA approach. After that, the VIKOR technique was used to rank the 15 DPs. According to the findings, EA, DA, CA, RA, BA, SA and TA have a higher impact on the affected area in descending order. Therefore, when designing a network for relief prepositioning, such a classification system would allow for a more systematic and standardized approach to assessing vulnerability, which can be useful for comparing different locations and identifying areas that may require more attention or resources. The main data source of the study was obtained from CMCS, the municipal yearbook of Shiraz Ganjehi and Norouzi Khatiri (2021) and Abdolazimi *et al.* (2022) research.

In this study, the developed mathematical models minimize the total average inflated distance traveled per relief item considering the obtained prioritized DPs for both models and considers the LT strategy in the upper echelon (between RDCs) for the second model in the relief operations. Also, road vulnerability is considered as the inflation concept in the model. It is the first time the case has been analyzed from the perspectives of the location of RDCs, inventory level, distance, LT, equity, prioritization (using MCDM techniques) and road vulnerability in the mathematical models simultaneously. Using a real-world scenario, the DS and LT models are developed and compared for District No. Seven of Shiraz. By comparing DS with LT. It is shown that the LT solution, as an example of horizontal coordination, is more adaptable than DS, and the average distance traveled per the relief item in the model with LT is much lower than the distance traveled in the model, considering DS by a 68.94% reduction. Also, by increasing the number of opened RDCs, the percentage of LT will decrease. In other words, as more RDCs open, more opportunities for DPs to be assigned to the nearest RDC with sufficient inventory levels to satisfy their demand. In Shiraz case, at least four RDCs should be opened to let the LT be engaged in the distribution. The results also provided that RDCs with deficient utilization space levels could not be opened unless to cover the demand of the surrounding area assigned to that center. The low utilization rate of RDCs 1 and 10 indicates the undesirability but the necessity of locating mentioned RDCs. The nodes provide supplies to DPs intending to decrease distance and casualties. The capability and application of this developed model are not seen in past and mostly related studies (Baskaya *et al.*, 2017; Wang *et al.*, 2021, 2022a, 2022b), which indicates the innovation of this research. The importance and use of this research are that; since life is immeasurably valuable and putting a price on human life does not make sense in HL, engaged RDCs with low utilization rates must be opened, while in commercial logistics, alternative solutions could be applied.

Potential future research can be broken down into two directions. First, further realistic considerations should be made to apply the created model. For example, the variety of vehicles used, their respective carrying capacities, and the weight and volume of each relief item sent to DPs can be investigated. Besides that, prioritization can be made for different types of relief items. Furthermore, the urgency of DPs may fluctuate in real-time as the rescue operation develops. Second, this study conducts a case study for 11 RDCs and 15 DPs. Nevertheless, when the scale of the problem increases, it is better to develop an efficient algorithm for a large-scale problem with stochastic parameters.

## Note

1 Shiraz is the capital of Fars Province in Iran and is divided into 11 districts based on the municipality division and district Seven, due to its closeness to various faults, was selected for the case study.

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## Further reading

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### About the authors

**Mohsen Anvari** has a master's degree from I.A.U. Najafabad branch, and a bachelor's degree from I.A.U, Shiraz branch, all in Industrial Engineering. His areas of interest include Supply Chain Management, Humanitarian Logistics, TQM, Operations Research and MCDM.

**Alireza Anvari** is currently an Assistant Professor at I.A.U., Gachsaran branch. He obtained his PhD in Industrial Engineering from the University of Putra Malaysia. His research interests focus on Lean Manufacturing, Agility, Knowledge Management, TQM and MCDM. Alireza Anvari is the corresponding author and can be contacted at: anvar.ali67@gmail.com

**Omid Boyer** is currently an Assistant Professor at I.A.U., Najafabad branch. He obtained his PhD in Industrial Engineering from the University of Putra Malaysia. His areas of interest include Mathematical Models Optimization, Logistic and Supply Chain and Project Management.

## Executive summary

The study emphasizes the significance of multi-criteria decision-making (MCDM) techniques, lateral transshipment (LT) and road vulnerability in minimizing total average inflated distance while ensuring fair distribution to demand points (DPs). Despite this, there is a lack of implementation of MCDM techniques in humanitarian logistics (HL) literature to address equity. To tackle this issue, the study proposes the adoption of MCDM techniques to prioritize demand and bring equity in humanitarian response by linking LT and road vulnerability to demand prioritization in HL.

To prioritize the demand points, a comprehensive set of criteria and subcriteria were identified (Table 2). Each demand point was then ranked based on its weight using these criteria and subcriteria. In this study, the OPA–VIKOR techniques were used. The VIKOR technique was used to rank the demand points based on the weight of the criteria and subcriteria obtained by the OPA technique. As a result, the priority score of each demand point was determined.

To optimize the priority score, two mathematical models were formulated as mixed-integer programming models, with and without the integration of LT. The distribution system in the model consisted of two echelons: the upper echelon, which includes relief distribution centers (RDCs) that use the LT as an example of horizontal coordination and the lower echelon, which includes DPs. The objective was to minimize the total average inflated distance traveled per relief item.

This research presented a real-life case study to showcase the practicality of the proposed methodology and its positive influence on achieving equitable distribution. Section 6 can be referred to for inspiration on how the framework has been applied in the case study and to assess the integration and application of MCDM techniques, LT and road vulnerability for an equitable distribution system in HL. The use of comprehensive criteria for prioritizing disaster-prone areas is crucial as it helps managers to accurately evaluate the situation. As the results showed, the integration of the priority score of DPs and LT significantly reduces the distance, leading to a more equitable and responsive distribution system after a disaster.