A two-phase model for resilient hub and mobile distribution centers location

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CHRONICLE	ABSTRACT
	Hub location is crucial for resilient and uninterrupted supply chain operations, particularly during disruptions or unforeseen events. In this paper, we propose a resilience hub location framework for Third Party Logistics (3PL) companies with two key objectives: optimizing demand flows and establishing a resilient network capable of with-standing sudden disruptions. The study aims to identify the key criteria that contribute to the successful implementation of the resilient center. The proposed structure utilizes a two-phase decision-making methodology. The first phase presents a new Multi-Criteria Decision-Making (MCDM) approach called SWARA-EDAS method that evaluates and ranks potential locations based on resiliency criteria. The second phase proposes an optimization model to determine the optimal hub location. To illustrate the approach, a real-world case study of a 3PL company in Tehran is included. Due to the absence of precise demand data in the case study, a novel clustering approach is proposed to estimate the demand flow. Each cluster can be considered as a distinct demand point, and a clustering analysis involving 122 regions within Tehran is conducted, taking into account various factors such as population, economic index, accessibility to the Internet, and the number of business units. To enhance the resiliency of the network, mobile distribution centers are also deployed. These mobile centers not only provide flexibility but also serve as backup capabilities in the event of a disruption or failure at the fixed hub. The proposed structure offers practical in-sights for 3PL companies seeking to implement a resilient network structure.

1. Introduction

Hubs play a crucial role in logistic networks by facilitating the switching, transshipment, and sorting of commodities in complex distribution networks involving multiple sources and destinations (Alumur & Kara, 2008). These hubs efficiently consolidate commodity flow from the same source and then redistribute them through various streams to reach the intended destination. By leveraging economies of scale, hubs effectively reduce transportation distances between origin and destination nodes (Farahani et al., 2013).

The establishment of a hub is typically a strategic decision that requires substantial investment, considerable social and human capital engagement, and also a significant amount of time to integrate into the transportation network (Vieira & Luna, 2016). Due to the considerable investment at stake, it is crucial to consider resiliency criteria for the hub location, to get the least impact of disruption and unforeseen events. The importance of resilience in the face of supply chain disruptions cannot be understated (Ambulkar et al., 2015). During the COVID-19 pandemic, disruptions in the supply chain, particularly those related to distribution centers, had a significant impact on supply chain operations and performance (Zheng et al., 2022).

The study by Zsidisin and Wagner (2010) emphasizes that while redundant supply chain practices can offer a company extra time to recover from disruptions, there are associated costs with this strategy, suggesting that innovative solutions for distribution centers can provide a cost-effective solution to enhance resilience. Mobile Distribution Centers (DCs) could be considered as an innovative and adaptive approach to stand against the concept of "Hub Paradox[1]" (Liu et al., 2022). In fact, mobile DCs play a crucial role in enhancing the resilience of a supply chain network. Firstly, mobile DCs provide a level of flexibility and adaptability that is essential in responding to disruptions (Faugère et al., 2020), (Satish Natarajan, 2020). They can be strategically positioned and relocated as needed, allowing for quick adjustments and rerouting of logistics operations in the face of unforeseen events such as natural disasters or transportation disruptions. This ensures that the logistics center can continue its operations and maintain the flow of goods even in challenging circumstances.

Additionally, mobile DCs contribute to the network's resilience by providing redundancy and backup capabilities. In the event of a disruption or failure at a fixed logistics hub, the mobile DCs can quickly step in and continue operations, minimizing downtime and ensuring the continuity of services. This redundancy not only helps mitigate the impact of disruptions on customers but also provides a safety net for the logistics center itself, reducing the risk of significant financial losses or reputational damage.

This paper seeks to develop a resilient framework for third-party logistics providers. The proposed framework utilizes a two-phase decision-making methodology. In the initial phase, an innovative MCDM approach known as the SWARA-EDAS method is employed to assess the value of potential locations, considering resiliency criteria. In the subsequent phase, an optimization model is presented to determine the optimal location for the hub. Additionally, to enhance network resilience, the deployment and the location of mobile distribution centers within the clusters is proposed.

It is important to note that the proposed framework is implemented in a third-party logistics company located in Tehran. However, due to the substantial customer base and the unavailability of precise data, we propose a novel clustering approach in 122 regions of Tehran to estimate customer demand using the suggested clustering method.

In summary, this paper makes three significant contributions:

- Developing an innovative two-phase methodology that combines a Multi-Criteria Decision-Making approach using SWARA-EDAS, and a mathematical model for determining resilient hub locations.
- Introducing a novel clustering approach to analyze 122 regions within the selected case study.
- Developing a model for the deployment of mobile distribution centers within clusters of the selected 3Pl company.

The subsequent sections of this paper are organized as follows: Section 2 presents a comprehensive review of the most relevant studies. In Section 3, we propose a two-phase decision-making methodology. The initial phase employs a hybrid SWARA-EDAS method, which is an MCDM approach, to evaluate the potential locations based on resiliency criteria. The subsequent phase introduces an optimization model for determining the optimal hub location. In Section 4, we introduce a clustering approach to estimate customer demands. In section 5, we identify the locations of mobile DCs in our case study conducted in Iran. Finally, in Section 6, we conclude the paper by summarizing our findings and providing suggestions for future research.

2. Literature Review

Extensive research has been conducted on the hub location problem in the literature, leading to the identification of various classification criteria. These criteria include the number of hubs, the selection process for candidate locations, the objective function, and the hub's capacity. The initial exploration of this domain was introduced by (O'kelly, 1986) . Furthermore, Hsieh and Kao (2019) have extensively studied the hub location problem and its different variations, and interested readers are encouraged to refer to their work. However, the practical implementation of resilient hub locations, especially in the face of disruption like natural hazards, presents some challenges. Although, the idea of "resilience hubs" has recently emerged to aid communities in facing challenges and enhancing their well-being during disasters and normal conditions. Recently Ciriaco and Wong (2022) offered an initial conceptual comprehension of resilience hubs, particularly their transportation requirements, by conducting a thorough literature review. In this context, (Kulkarni et al., 2021) suggested using an integer programming to create solution approaches for designing hyperconnected networks that can withstand unanticipated disruptions on a large scale.

In another study, Kulkarni et al. (2022) proposed two approaches for designing resilient hyperconnected logistics hub networks in the context of resilient parcel delivery networks. These approaches were motivated by new opportunities introduced by the Physical Internet. The first approach involves multiple shortest paths, while the second approach involves multiple shortest edge-disjoint paths. To address computational tractability issues, the authors developed a metaheuristic algorithm. A comprehensive study about future direction of supply chain resilience is presented by Katsaliaki et al. (2021) that eager readers are referred to.

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[1] The hub paradox in supply chain and distribution refers to the tension between the benefits of centralization and the risks of disruption.

In order to enhance the review of the relevant literature, a summary of recent papers in the similar field as our research has been provided in Table 1.

Table 1
Summarized literature review

Row	Reference	Novelty	Methodology
1	(Ciriaco & Wong, 2022)	Conceptual understanding of resilience hubs and their transportation needs	Conceptual analysis
2	(Maharjan & Kato, 2022)	Reviewing existing literature on Resilient supply chain network design and proposing a new classification for quantitative resilience measures.	A systematic literature review
3	(Aldrighetti et al., 2021)	Focus on the costs associated with resilience and disruptions in supply chain network design models	Systematic literature review
4	(López-Castro & Solano-Charris, 2021)	Integration of resilience and sustainability criteria in the supply chain network design	Systematic Literature Review
5	(Kulkarni et al., 2022)	The proposal of solution methodologies based on integer programming for the establishment of logistics hubs and the connection of origin-destination pairs.	Graph-theoretic measures
6	(Zhalechian et al., 2018)	Designs a bi-objective reliable logistics network based on a hub location problem	Hybrid solution approach
7	(Gkanatsas & Krikke, 2020)	Overview of quantitative modelling approaches for resilient 3PL supply chain network designs	Systematic literature review
8	(Özmen & Aydoğan, 2020)	A three-stage methodology of BWM2 –EDAS3	Three-stage approach that includes criteria determination, weighting, and ranking.
9	(Pahwa & Jaller, 2023)	Introduces the R44 Last Mile Distribution Resilience Triangle Framework	Performance-based qualitative-cumquantitative domain-agnostic framework.
10	(Saffari et al., 2023)	A novel multi-objective model for resilient, sustainable, and responsive forward/reverse logistics network design by cionsidering horizontal collaboration.	A multi-objective algorithm with a new aggregation approach
11	(Maharjan & Kato, 2022)	Providing a comprehensive review of recent literature on resilient supply chain network design	Systematic literature review
12	(Sundarakani et al., 2021)	Examining the feasibility of establishing or relocating distribution facilities within the global supply chain, by considering factors such as costs, fulfillment capabilities, trade uncertainties, and risks, with the aim of achieving a resilient and sustainable supply chain.	Robust Optimisation and Mixed Integer Linear Programming (ROMILP) model
13	(Yu et al., 2017)	Developing risk-averse optimization models for an uncapacitated facility location problem with random facility disruptions.	Mixed-integer nonlinear programming
14	(Lu & Cheng, 2021)	Introducing a budgeted uncertainty set that effectively encompasses both disruptions in facilities and uncertain customer demand resulting from the failures of adjacent facilities.	Three two-stage robust optimization formulations
15	(N. Wang et al., 2023)	Considering a four-tier supply chain network and focuses on optimizing supply chain resilience by determining the inventory quantity of each material before disruptions, and locating temporary distribution centers,	Mixed integer linear programming model using LHS[5], SAA[6], and SR[7] methods

[2] Best–Worst Method
[3] Evaluation based on Distance from Average Solution
[4] Robustness, Redundancy, Resourcefulness, and Rapidity
[5] Latin Hypercube Sampling
[6] Sample Average Approximation
[7] Scenario Reduction

It is important to highlight that the majority of studies in the field of resiliency, particularly concerning resilient hubs, primarily concentrate on their role as emergency centers, providing assistance to communities before, during, and after disasters. While some research has been conducted on the design of resilient networks within the realm of business logistics (see Table 1), To our understanding, there exists a significant lack of thorough research regarding resilient hub locations within the logistics industry. Therefore, we propose an innovative structure that considers the resiliency criteria for determining the hub location. Additionally, we consider the incorporation of mobile DCs as a flexible approach to bolster network resiliency. Although, Faugère et al. (2020) proposed a mobile access hub structure for parcel delivery, it does not account for the relocation of mobile centers to fixed hubs, and its focus is more aligned with sustainability rather than resilience. Generally, the objective of this study is to propose a resilient structure for hubs and mobile DCs within a 3PL system. Given the strategic nature of hub location decisions and the substantial investments required, our aim is to design a distribution network that can effectively withstand disruptions. To achieve this, by using the hybrid SWARA-EDAS method, we initially assess and prioritize the critical criteria for establishing a resilient hub that is least vulnerable to disruptions. Considering the resilience criteria, we ascertain the optimal location for a logistics hub within a specific case study. Additionally, we identify the appropriate locations for mobile DCs that function as adaptable and also backup consolidation and deconsolidation centers, thereby enhancing the resilience of the network.

The subsequent section presents a proposed two-phase decision-making methodology for determining the resilient location of the hub.

3. Hub Location: A Two-Phase Decision-Making Methodology

3.1 Phase One: Hybrid SWARA- EDAS Method

This methodology comprises three key parts. First, a comprehensive literature review is conducted to identify relevant and essential criteria for locating a resilience hub in a supply chain. The second part introduces the SWARA (Step-wise Weight Assessment Ratio Analysis) method, which is utilized to assign weights to the identified criteria based on their significance. This allows for a systematic assessment of their relative importance. The third part employs the EDAS (Evaluation based on Distance from Average Solution) method, which scores and ranks potential hub locations using the weighted criteria. The SWARA-EDAS method offers substantial advantages in evaluating potential locations for hubs and distribution centers in terms of resiliency. The SWARA component enables the decision maker to select, evaluate, and weigh the indicators, while the EDAS method considers both positive and negative deviations from an average solution, making it effective in balanced decision-making. The adaptability of the SWARA-EDAS method in facilitating informed decision-making even with estimated data has been demonstrated in various applications such as supplier selection, personnel selection in the aviation industry, and evaluation of supply chain management (Dahooie et al., 2020; Kurnaz et al., 2023). Additionally, the SWARA method has been found to be simpler to comprehend with fewer pair comparisons than similar methods such as AHP and ANP, making it a practical choice in decision-making processes (Mostafaeipour et al., 2020). In addition, the integration of fuzzy SWARA and EDAS methods has been shown to increase the accuracy of risk analysis, particularly in the context of turnaround project risk assessment in upstream oil process industries (Moniri et al., 2021). These references collectively support the effectiveness and practical applicability of the SWARA-EDAS method in multi-criteria decision-making for evaluating locations in terms of resiliency.

In the subsequent sections, each part of the methodology will be explained in detail, providing a comprehensive understanding of the approach.

3.1.1 Identified Criteria for Selecting a Resilience Hub Location

The identification of criteria for locating a resilience hub in a supply chain is a crucial step in ensuring the resilience and continuity of supply chains, particularly in the face of disruptions or unexpected events. Through an extensive literature review and analysis of existing studies, industry reports, and best practices in supply chain management and disaster resilience, we have identified seven criteria that play a significant role in locating a resilient hub center. It is essential to understand the rationale behind each criterion and its contribution to the resilience of hub locations. Below, we expand on the rationale and significance of each criterion selected for assessing location resilience:

Land Cost and Availability: The cost and availability of land are pivotal factors in the establishment of hubs and distribution centers. Affordable and accessible land offers flexibility for operational expansion or modifications in response to emergencies or evolving needs. This criterion also involves evaluating land in areas less vulnerable to disasters, thereby enhancing resilience and reducing potential disruption risks (Pu et al., 2023).

Accessibility to Transportation Infrastructure: Proximity to highways, ports, or airports is crucial for maintaining supply chain flow, especially during disruptions. Reliable access to diverse transportation modes and routes is a cornerstone of resilience, enabling quick rerouting of goods and maintaining operational continuity in crisis scenarios (Pettit et al., 2019).

Accessibility to Transport Terminals: The ease of reaching major transport terminals, particularly for small-sized shipments, is essential for rapid response capabilities during disruptions. This criterion focuses on the location's connectivity with key logistic nodes, ensuring efficient material flow under varying circumstances (Remko, 2020).

Geographical Situation and Environmental Safety: The geographical location's inherent characteristics, such as its proximity to disaster-prone areas or major transportation routes, are crucial in mitigating the impact of potential disasters. A location's environmental safety influences its vulnerability to disruptions and shapes its recovery strategies post-disruption (Brandon-Jones et al., 2014).

Availability of Labor: The presence of a skilled workforce is vital for effective operation and swift recovery following disruptions (Jakubicek & Woudsma, 2011). Labor availability impacts the ability to maintain operational efficiency during normal conditions and enhances the capacity for rapid response and recovery in crisis situations.

The Urban Fabric of the Location: The existing urban infrastructure and surroundings, including facilities, services, and amenities, significantly contribute to a location's resilience (Çakmak et al., 2021). A robust urban fabric supports logistical operations by providing additional resources and capabilities, especially critical during emergency responses.

Communications System: Effective communication infrastructure is indispensable in resilience-building (Ciriaco & Wong, 2022). Timely information dissemination and efficient communication channels are key during disruptions, aiding in quick decision-making and coordination among various stakeholders.

Table 2 summarizes the key criteria for selecting resilient hub locations. The table serves as a quick reference, outlining each criterion's importance and source, facilitating easier application in decision-making.

Table 2
Criteria for Locating a Disaster Resilience Hub in a Supply Chain

Index	Criteria	Brief Explanation	Source
C_1	Land cost and availability	Refers to the cost and availability of suitable land for establishing a hub and distribution center.	(Sopha et al., 2016), (Chou et al., 2008) , (Stević et al., 2018), (Alam, 2013) (Pourmohammadreza & Jokar, 2023) (Pu et al., 2023)
C_2	Accessibility to transportation infrastructure	Considers the proximity and ease of access to transportation infrastructure, such as highways, ports, or airports.	(Sopha et al., 2016), (Stević et al., 2018), (Uyanik et al., 2020), (Erkayman et al., 2011), (Pettit et al., 2019)
C_3	Accessibility to the transport terminals	Focuses on the proximity and ease of access to major transportation terminals, such as rail or container terminals for small-sized shipments.	Based on the expert team's idea of the selected company, (Remko, 2020)
C_4	Geographical situation and environmental safety of the location	Takes into account the geographical characteristics of the location, such as its proximity to potential disaster-prone areas or transportation routes.	(Sopha et al., 2016), (Uyanik et al., 2020), (Erbaş et al., 2018) , (Witkowski et al., 2018), (Tadić et al., 2014), (B. Wang et al., 2014)
C_5	Availability of labor	Considers the availability of skilled labor or workforce in the area, which is crucial for operating the center effectively.	(Jakubicek & Woudsma, 2011), (Maharjan & Hanaoka, 2019)
C_6	The urban fabric of the location	Refers to the existing urban infrastructure and surroundings of the location, including facilities, services, and amenities.	(Sopha et al., 2016), (Chou et al., 2008), (Stević et al., 2018), (Uyanik et al., 2020), (Çakmak et al., 2021)
C_7	Communications system	Effective communication and timely dissemination of information in case of disruptions or disasters.	(Ciriaco & Wong, 2022), (USDN, n.d.)

By incorporating these criteria into our proposed framework, we aim to provide a comprehensive approach for 3PL companies to evaluate and select suitable locations for their hubs and distribution centers. This approach will enable them to optimize their supply chain operations, mitigate risks, and enhance their ability to respond and recover from unexpected disruptions.

This study employs a hybrid MCDM approach, integrating the SWARA and EDAS methods. This innovative hybrid methodology, developed as the main framework of our research, has been previously utilized in only one other study for practical application in house plan shape evaluation (Juodagalvienė et al., 2023). The current study leverages the robustness of the EDAS method to derive stable answers, and the flexibility of SWARA to evaluate criteria based on policy-based strategy and perspective.

3.1.2 SWARA Method

The SWARA method is employed in the first phase of the process, aiming to ascertain the weights of the criteria. This method has been selected due to its ability to handle uncertainty and its efficiency in determining the weights of decision

criteria in a hierarchical structure (Salehi et al., 2022). Our study uses SWARA to deal with subjectivity and bias associated with the evaluation of decision criteria (Appendix). In order to implement the SWARA method, a group of highly experienced experts in the logistics industry was surveyed. These experts were asked to fill in SWARA forms, expressing their opinions on the importance of different criteria for the selection of resilience locations. The experts' opinions, captured through SWARA, formed the basis for the weighting of the decision criteria. Table 3 presents the outcomes of the SWARA method.

Table 3
The ranks of the factors

Factors	Comparative importance of average value (SC_j)	Coefficient ($KC_j = SC_j + 1$)	Recalculated ($QC_j = (QC_{j-1}) / KC_j$)	Weight (WC_j)	Rank
C_1	0	1.00	1.00	0.22	1
C_2	0.09	1.09	0.92	0.20	2
C_3	0.1625	1.16	0.79	0.18	3
C_6	0.23125	1.23	0.64	0.14	4
C_4	0.275	1.28	0.50	0.11	5
C_7	0.35	1.35	0.37	0.08	6
C_5	0.34375	1.34	0.28	0.06	7

3.1.3 EDAS Method

The EDAS method is utilized in the second phase of the process, ranking the zones based on the weighted criteria derived from the SWARA method. In order to mitigate the high complexity inherent in the continuous form of the hub location problem, a clustering strategy has been devised to partition Tehran (the region of our case study) into distinct zones. This approach facilitates the transformation of the problem into a discrete hub location, whereby a finite set of potential hub locations can be identified. Unlike typical discrete hub location problems where candidate locations are predetermined, in this particular case, the list of potential locations is unknown. Consequently, a set of notable criteria, as detailed in Table 2, have been established to evaluate potential hub locations. To that end, the EDAS method has been selected due to its ability to provide an objective and precise ranking of alternative locations based on multiple criteria. This method calculates the distances of each alternative from the average solutions, considering both the best and worst performance of each criterion. It uses these distances to calculate a relative closeness coefficient for each alternative, which in turn forms the basis for the final ranking of locations. The outcomes are shown in Table 4.

Table 4
The outcomes of the EDAS method

Area	SP_i[8]	SN_i[9]	NSP_i[10]	NSN_i[11]	AS_i[12]
A_1	0.094	0.194	0.108	0.687	0.398
A_2	0.137	0.167	0.159	0.731	0.445
A_3	0.442	0.147	0.512	0.763	0.638
A_4	0.562	0.097	0.651	0.844	0.747
A_5	0.779	0.031	0.902	0.950	0.926
A_6	0.846	0.031	0.980	0.950	0.965
A_7	0.863	0.028	1.000	0.955	0.978
A_8	0.139	0.380	0.161	0.388	0.275
A_9	0.061	0.414	0.071	0.333	0.202
A_{10}	0.413	0.042	0.478	0.933	0.706
A_{11}	0.308	0.042	0.357	0.933	0.645
A_{12}	0.116	0.143	0.134	0.770	0.452
A_{13}	0.102	0.142	0.118	0.772	0.445
A_{14}	0.061	0.379	0.071	0.389	0.230
A_{15}	0.061	0.379	0.071	0.389	0.230
A_{16}	0.149	0.386	0.173	0.378	0.276
A_{17}	0.014	0.621	0.016	0.000	0.008
A_{18}	0.014	0.621	0.016	0.000	0.008
A_{19}	0.015	0.551	0.018	0.112	0.065
A_{20}	0.160	0.354	0.186	0.430	0.308
A_{21}	0.160	0.354	0.186	0.430	0.308
A_{22}	0.144	0.138	0.167	0.778	0.472

The column header of Table 4 is described in the following (Keshavarz Ghorabaee et al., 2015).

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[8] The sum of positive distances for location i
[9] The sum of negative distances for location i
[10] Normalized sum of positive distances for location i
[11] Normalized sum of negative distances for location i
[12] Appraisal score for location i

SP: This metric calculates the aggregate positive deviation of each alternative from the average solution for all criteria. A higher SP value indicates that an alternative performs significantly better than the average across multiple criteria, highlighting its strengths.

For each alternative i, SPi is calculated as:

$$SP_i = \sum_{j=1}^{m} w_j \frac{\max(0,(AV_j - X_{ij}))}{AV_j}, \qquad \text{where } AV_j = \frac{\sum_{i=1}^{n} x_{ij}}{n} \qquad (1)$$

where x_{ij} embodies the performance score of alternative A_i with respect to criterion C_j, w_j is the weight of criterion j, and n is the total number of locations.

SN: Conversely, SN measures the total negative deviation of each alternative from the average solution. A lower SN value is preferable, indicating fewer or less significant weaknesses relative to the average performance.

$$SN_i = \sum_{j=1}^{m} w_j \frac{\max\left(0,(X_{ij} - AV_j)\right)}{AV_j} \qquad (2)$$

NSP: Normalization of SP is crucial for ensuring comparability between alternatives. NSP is obtained by dividing the SP of each alternative by the sum of all SPs. This step adjusts for scale differences and provides a relative measure of each alternative's positive aspects.

NSN: This involves normalizing the SN values. It is calculated by dividing the SN of each alternative by the sum of all SNs.
AS: The AS is a comprehensive metric that combines the positive and negative aspects of each alternative.

$$NSP_i = \frac{SP_i}{max_i(SP_i)} \qquad (3)$$

$$NSN_i = 1 - \frac{SN_i}{max_i(SN_i)} \qquad (4)$$

$$AS_i = \frac{(NSP_i + NSN_i)}{2} \qquad (5)$$

Upon generating scores for each location using the EDAS method, these scores were subsequently normalized to facilitate further analysis and comparison among the locations. This normalization process involved dividing each EDAS score (A7=0.863) by the maximum score obtained among all locations, effectively translating the raw scores into a range of 0 to 1 (Table 5).

Table 5
Normalizing scores and selecting the most appropriate areas

Area	Normalized Score	Area	Normalized Score
A_1	0.407	A_{12}	0.463
A_2	0.455	A_{13}	0.455
A_3	0.652	A_{14}	0.235
A_4	0.765	A_{15}	0.235
A_5	0.947	A_{16}	0.282
A_6	0.987	A_{17}	0.008
A_7	1.000	A_{18}	0.008
A_8	0.281	A_{19}	0.067
A_9	0.207	A_{20}	0.315
A_{10}	0.722	A_{21}	0.315
A_{11}	0.660	A_{22}	0.483

Following this, the locations with normalized scores exceeding the middle score (0.5) were identified as potential candidates. The locations that met this criterion were A_3, A_4, A_5, A_6, A_7, A_{10}, and A_{11}. These locations emerged as suitable candidates owing to their superior scoring under the hybrid SWARA-EDAS methodology. It is important to note that this selection represents a relative superiority in disaster resilience hub characteristics, as defined by the multi-criteria decision framework of our study. These candidate locations were earmarked for further examination and subsequently underwent a mathematical model.

The proposed hybrid methodology integrates the strengths of both the SWARA and EDAS methods. The scores derived from the SWARA method are used as input for the EDAS method, ensuring that the final ranking of locations incorporates the expert opinion on the importance of different decision criteria. This two-phase process provides a robust and

comprehensive approach to the selection of disaster resilience hub location centers. In the following, we present our mathematical modeling for the resilient hub location.

3.2 Phase Two: Mathematical Formulation

In this section, we present a discrete hub location approach by taking into account the resilient potential hub location identified in the previous stage.

Parameters:

K: Set of all potential resilient locations

C_{ij}: The distance cost between non hub cluster i and hub cluster j.

h_{ij}: The flow from cluster i to cluster j.

Decision variables:

y_{ij}: Binary variable; takes value 1 if cluster t is allocated to candidate location k.

y_{jj}: Binary variable; takes value 1 if the hub is established in location k.

Considering the above definitions, the hub location problem is stated as follows.

$$min \sum_i \sum_j \sum_k h_{ij}\left(C_{ik} + C_{jk}\right)y_{ij} \times y_{kj} \tag{6}$$

subject to

$$\sum_j y_{jj} = 1 \tag{7}$$

$$y_{ij} \leq y_{jj} \qquad \forall i, j \tag{8}$$

$$\sum_j y_{ij} = 1 \qquad \forall i \tag{9}$$

$$y_{ij} = (0,1) \tag{10}$$

Objective function (6) minimizes the overall transfer cost through the hub. Eq. (7) specifies the existence of a single hub. Additionally, Eq. (8) mandates that node i is exclusively connected to an established hub at a cluster j. Constraint (9) ensures that each cluster is assigned to the hub. Constraint (10) shows the domains of decision variables.

4. Region Clustering

As mentioned before, to ascertain the prospective locations for the hub and mobile distribution centers, we employ a clustering analysis on 122 regions within Tehran city. This analysis considers four key features: population, economic index, internet accessibility, and number of business units. Drawing from our expertise in the chosen company, we believe these features serve as reliable indicators of customer demands within a given region.

The objective of this clustering analysis is to identify regions that exhibit similarities in terms of the aforementioned features. Each cluster can be regarded as a demand point, which is then assigned to either the main hub or a mobile DC within that cluster.

The primary consideration in clustering is that only regions in close proximity can be grouped together. In other words, clustered regions should share similar boundaries. To address this, we utilized RapidMiner, a renowned data mining tool, to perform clustering on the 122 regions of Tehran. To account for proximity constraints, we introduced a new feature called "relative distance", which captures the C2C[13] distance between each region and a predetermined reference region (such as region 1). Notably, neighboring regions to region 1 exhibit lesser distances compared to more remote regions. Thus, the geographic location of each region was taken into account during the clustering process. The resulting clustered regions, obtained through the K-means algorithm in RapidMiner, are illustrated in Fig. 1.
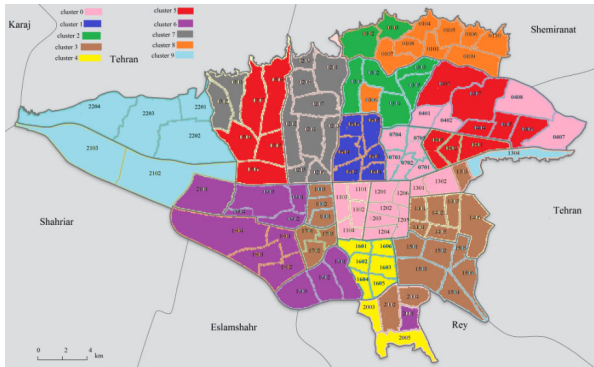
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[13] Center to Center

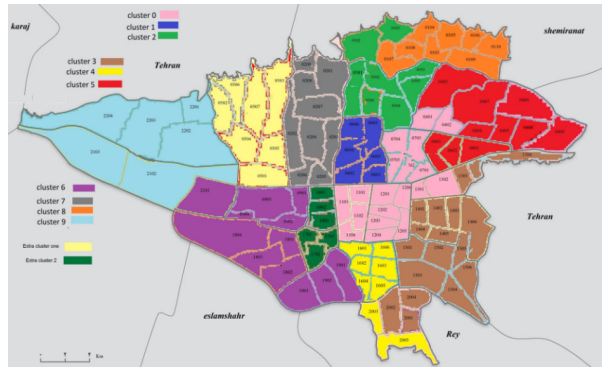**Fig. 1.** Clustering the regions of Tehran by K-means algorithm (K=10)

Fig. 2. The amended clustering of Tehran

As depicted in Fig. 1, although the relative distance was defined, certain non-adjacent regions were grouped together in the clustering process. In order to address this issue and account for the proximity constraint of each region, we introduced the Euclidean distance between every pair of cluster centers. To mitigate scale-dependent challenges in clustering, we normalized each feature using the following formulation.

$$Normalized\ observation = \frac{u_j - \mu_j}{\sigma_j} \tag{11}$$

In which μ_j and σ_j are the mean and standard deviation of observation u_j, respectively. Thus, by incorporating the distance between each pair of clusters, we refine the clustering depicted in Fig. 1. In this updated clustering, each heterogeneous region[14] is assigned to the cluster with the minimum distance from its current location. The resultant revision of the clustering is illustrated in Fig. 2. By this clustering, there are already 12 potential candidate locations for DCs.

5. Case Study

Due to the scarcity of reliable shipping demand data for our specific case study, we rely on demographic and economic indicators of the diverse regions in Tehran to estimate customer demands. Population and economic status are identified as the key determinants of demand in our chosen 3PL company. Consequently, we employ Eq. (12) to predict the demand for each cluster based on these factors. It is important to highlight that the population and economic status of each region in Tehran have been derived from experimental studies conducted by the local government.

$$demand\ of\ each\ region = population\ of\ the\ region \times economic\ status\ of\ the\ region \tag{12}$$

Considering the economic situation within a range of 0 to 1, a higher index value indicates a more favorable economic condition in the respective area. For instance, if a region has a population of 1000 and an economic index of 0.1, it implies that the potential demand for that region is estimated to be 100. To determine the most suitable resilient locations for our case study, we implemented the two-phase methodology outlined in section 3. In the first phase, we assessed and ranked the candidate locations based on their resilience criteria using the SWARA-EDAS method. Subsequently, we utilized CPLEX 12.6 to solve the proposed model and identify the optimal hub location. The optimal hub location is denoted by a star symbol in Fig. 3.
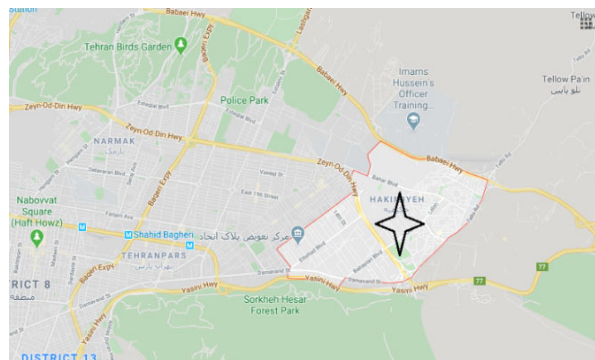

Fig. 3. The optimal location for establishing hub logistics in the eastern part of Tehran

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[14] The regions that are not in the neighborhood of others.

While the optimization model designates the star location as the optimal hub site, concerns arise regarding the restriction on truck traffic. In accordance with the regulations in Tehran, the main highways on star location permits trucks weighing more than 6.2 tonnes to operate only between the hours of 10:00 p.m. and 6:00 a.m. Consequently, this limitation not only hampers the efficiency of hub capacity utilization but also leads to shipment delays. To address this issue, we identify an alternative location by excluding the star location from the list of candidate sites. By solving the mathematical model, we determine the following optimal location, which is depicted in Fig. 4.
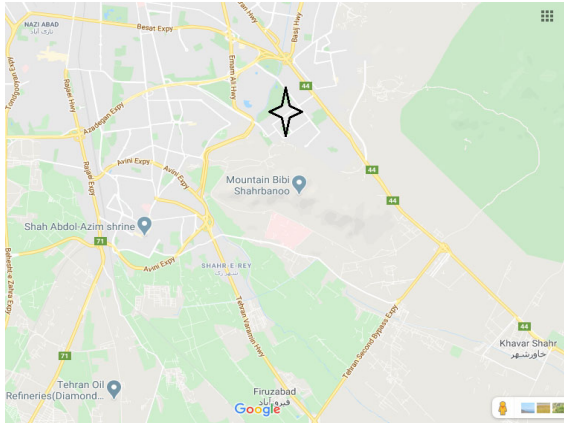

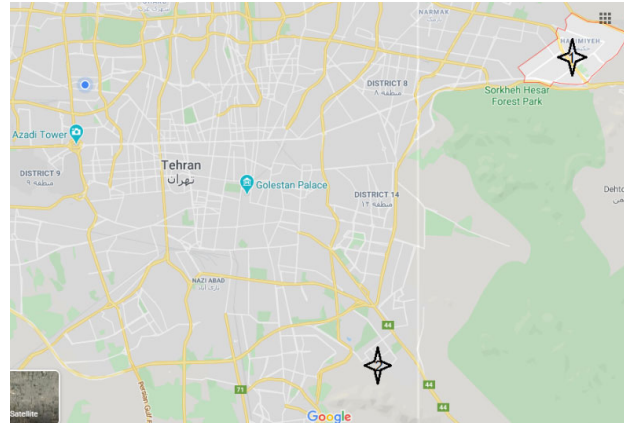**Fig. 4.** The second optimal location for establishing hub logistics in the eastern part of Tehran

Fig. 5. The optimal location and its second alternative for establishing the hub in the eastern part of Tehran

Fig. 5 displays both alternate locations for the hub on a single map.

5.1 Hub and DC Relationship

The selected company currently operates a hub in the western part of Tehran, functioning as both a sorting center and a distribution center. Under the existing structure, collected goods from all areas of the city are consolidated at this hub for sorting and subsequent dispatch according to their respective delivery points. However, due to the continuous growth in shipment demand, the current capacity of this single hub is insufficient. Moreover, the current practice of routing all goods (from various geographical zones) through this central facility before distributing them across Tehran results in significant inefficiencies in the pickup and distribution of shipments throughout the city. Therefore, we have identified the need for an additional hub located on the eastern side of the city (see Fig.). Furthermore, for the purpose of enhancing network resilience, we consider deploying mobile DCs in designated clusters. In the subsequent analysis, we ascertain the optimal number and placements of mobile DCs within the cluster. The clusters' assignment, whether to a mobile DC or a fixed hub, is determined with the objective of reducing the total cost. The assumptions, parameters, and decision variables of the model are presented as follows.

Assumption:

- When a mobile DC is deployed in a cluster j, it is positioned at the central area of that cluster.
- When a mobile DC is located in a cluster j, all customers within the regions of a cluster j are assigned to that particular mobile DC.
- Each cluster is assigned exactly to one main hub or one mobile DC.

Parameters:

d_i: demand of cluster i

c_l: the average distance cost of all regions in cluster l from its centroid.

b_{ik}: the distance cost between cluster i and main hub k.

f: the fixed cost of buying or renting mobile DC

Q_k: the capacity of main hub k.

Decision variables:

x_{ik}: a binary variable; takes the value 1 if cluster i is assigned to main hub k (k$\in$ {1,2}).

y_j: a binary variable; takes the value 1 if a mobile DC is deployed at location j.

z_{jk}: a binary variable; takes the value 1 if mobile DC j transferred the parcel to main hub k ($k\in$ {1,2}).

In view of the above formulation, the mathematical formulation is described as follows:

$$min \sum_i \sum_k d_i \times b_{ik} \times x_{ik} + \sum_l d_l \times c_l \times y_l + \sum_j \sum_k b_{jk} \times z_{jk} + \sum_j f \times y_j \tag{13}$$

s.t:

$$\sum_k x_{ik} + y_i = 1\forall i \qquad\qquad \forall i \tag{14}$$

$$\sum_k z_{jk} = y_j \qquad\qquad \forall j \tag{15}$$

$$\sum_k x_{ik} \times d_i \leq Q_k \qquad\qquad \forall k \tag{16}$$

$$x_{ik}, y_j, z_{jk} \in \{0,1\} \qquad\qquad \forall i, j, k \tag{17}$$

Objective function (13) represents the total cost, which is composed of four components. The first component represents the transportation cost of the clusters that are assigned to the main hubs. Components two and three indicate the average transportation cost from the customers within a cluster to a mobile DC within that cluster, and the cost of shipping from that cluster to a main hub, respectively. The final component of objective function (13) represents the fixed cost associated with acquiring or renting a mobile DC. Constraint (14) dictates that each cluster must be assigned to either a main hub or a mobile DC located within that cluster. Constraint (15) specifies that each mobile DC must be assigned to one of the main hubs for the purpose of (de)consolidating parcels from customers. Constraint (16) ensures that the total assigned demands to each hub do not surpass the capacity of that hub. Constraint (17) defines the domain of all decision variables involved in the problem. Upon solving the aforementioned mathematical model (equations 13 to 17), the deployment of three mobile distribution centers (DCs) was determined for clusters 4, 7, and 8. Subsequently, based on the positioning of the primary hubs and mobile DCs, the relationship between the hubs and mobile DCs was analyzed under two scenarios: one where the eastern hub is situated at the star location in Fig. 4, and the other where it is located at the star position in Fig. 5.

Case 1: Hub establishment based on Fig. 4: In this case, after optimally solving the problem with CPLEX 12.9, the total weighted transportation cost is 84589325.7.
Case 2: Hub establishment based on Fig. 5: By locating the hub in the second optimal place (shown in Fig. 5), the total weighted cost is 85041011.2.

Upon comparing these two cases, it can be concluded that the difference is not significant, with a variation of less than 1%. Consequently, if the truck traffic regulations impose limitations on establishing the hub at the most optimal location, the second proposed location could be considered as an alternative for the eastern hub placement.

6. Conclusions

Due to the considerable advance in the e-commerce market, the demand for parcel delivery services has been increasing. We selected one of the foremost delivery service providers in Tehran, and we proposed a resilient framework especially in dealing with disruption and unforeseen events. The proposed framework utilizes a two-phase decision-making methodology, incorporating a novel MCDM approach called hybrid SWARA- EDAS and a mathematical model for hub location. In the first phase (SWARA- EDAS), the identified criteria for the resilient hub location are weighted based on their significance using the SWARA method. This facilitates a systematic assessment of their relative importance. Subsequently, the EDAS method is employed to score and rank potential hub locations according to the weighted criteria. However, given the lack of demand and flow data in our selected case study, we used Tehran's data to predict demand and shipment flow in various regions of the city. We conducted a clustering analysis on the 122 regions of Tehran, considering population, economic status, internet accessibility, and the number of business units in each region. In order to enhance network resilience, the deployment of mobile DCs in designated clusters is being considered. Then each cluster can be assigned to the main hub or the mobile DC within that cluster. Our proposed structure does have certain limitations. Due to the unavailability of precise demand data for our case study, we relied on estimations derived from the population and economic status of each region. However, in the event of a disaster the city-wide demand pattern might change and become random, it is more realistic to treat demand as an uncertain parameter. Furthermore, for the purpose of simplicity, we have chosen to focus solely on a static model that encompasses only one time period. Although, including different time periods during which a mobile DC can relocate within various clusters, in response to prevailing conditions or fluctuations in demand, makes the proposed structure more realistic. It's worth noting that comparing our methodology with other MCDM methods to select resilient hub locations seems to be beneficial as well.

Funding

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available upon request.

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Appendix

The SWARA method is an expert-driven approach used for decision-making, comprising the ensuing steps:

Step 1: Ranking of Criteria

This initial step involves experts ranking the criteria based on their relevance to the issue at hand. The most critical criterion is assigned the highest rank, with subsequent criteria ranked in descending order of importance. This ranking process is

reliant on the expertise and insights of the experts into the problem being addressed.

Step 2: Calculation of Weighted Average Value (SCⱼ)

Here, the focus is on determining each criterion's relative weight by comparing it with the criterion that follows it in the ranking. Experts choose a significance rate, ranging from 0 to 1, for each criterion, indicative of its importance over the next. This value is determined through the weighted average value (SC_j) of the subsequent criterion, calculated using the formula:

$$SC_j = \frac{\sum_{j=1}^{N} W_j R_{ij}}{\sum_{j=1}^{N} W_j},$$

where W_j represents the weight of criterion C_j, R_{kj} its rank as determined by expert i, and n represents the total number of experts involved.

Step 3: Calculation of the KCⱼ Coefficient

Once the SC_j values for all criteria are established, the next step is to compute the KC_j coefficient. This coefficient, representing each criterion's relative significance, is derived using the SC_j value of the criterion immediately below in the ranking.

Step 4: Computation of Initial Criterion Weight

In this phase, the primary weight for each criterion is calculated. The criterion deemed most important is given a weight of 1. Subsequent criteria are assigned weights using the formula:

$$QC_1 = 1 \text{ and } \frac{QC_{j-1}}{KC_j} \qquad j > 1.$$

Step 5: Normalization of Criterion Weights

The concluding step consists of modifying the weights of the criteria to guarantee their collective sum equals one. This normalization is executed using the formula:

$$WC_j = \frac{QC_j}{\sum_{j=1}^{N} QC_j}$$

where WC_j represents the normalized weight assigned to criterion C_j, and N denotes the overall number of criteria.