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Investigation of the pharmaceutical warehouse locations under COVID-19—A case study for Duzce, Turkey

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A B S T R A C T

Pharmaceutical warehouses are among the centers that play a critical role in the delivery of medicines from the producers to the consumers. Especially with the new drugs and vaccines added during the pandemic period to the supply chain, the importance of the regions they are located in has increased critically. Since the selection of pharmaceutical warehouse location is a strategic decision, it should be handled in detail and a comprehensive analysis should be made for the location selection process. Considering all these, in this study, a real-case application by taking the problem of selecting the best location for a pharmaceutical warehouse is carried out for a city that can be seen as critical in drug distribution in Turkey. For this aim, two effective multi-criteria decision-making (MCDM) methodologies, namely Analytic Hierarchy Process (AHP) and Evaluation based on Distance from Average Solution (EDAS), are integrated under spherical fuzzy environment to reflect fuzziness and indeterminacy better in the decision-making process and the pharmaceutical warehouse location selection problem is discussed by the proposed fuzzy integrated methodology for the first time. Finally, the best region is found for the pharmaceutical warehouse and the results are discussed under the determined criteria. A detailed robustness analysis is also conducted to measure the validity, sensibility and effectiveness of the proposed methodology. With this study, it can be claimed that literature has initiated to be revealed for the pharmaceutical warehouse location problem and a guide has been put forward for those who are willing to study this area.

1. Introduction and related studies

The warehouse location selection problem emerges as an area that has gained more importance for the medical sector during the pandemic period. In the pharmaceutical industry, drugs are handled differently from other physical goods supply chains because of the details in their storage, transportation and regulation (Kumar et al., 2018). It is crucial for pharmaceutical companies to decide on the storage area in order to regulate the costs during the pandemic period and to ensure that drugs and vaccines reach the citizens as soon as possible (Yaman and Akkartal, 2020). While the pharmaceutical market is already being heavily run in many countries due to the unique nature of demand and supply, it has become even more complex with the added uncertainty of the pandemic (Ghatari et al., 2013).

The facility location selection problem has a prevalent implementation in the healthcare industry, from hospitals to clinics, blood banks to pharmaceutical warehouses, and medical facilities. The first goal of the pharmaceutical industry is to make a profit, but the stakeholders of this industry must provide the necessary support for the health systems by providing the drugs at the right time and in the right place (Kumar et al., 2018). For this reason, it is critical that facilities in the pharmaceutical industry are located in the right place.

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selection requires simultaneous consideration of many different factors, such as investment cost, human resources, availability, traffic conditions, appropriate policy laws and regulations, zone functionality, effective accessibility, and lower rental costs (Li et al., 2020). In order to address this problem and find the most appropriate solutions, all these conflicting criteria must be evaluated simultaneously. One of the most effective approaches that can be applied to this problem is the MCDM methodology. Such real-life problems are often complex or inherently uncertain, resulting in the fact that the criterion weights and criterion scores of the alternatives are not determined exactly. In this case, criteria weights and criteria-alternative evaluations are determined using linguistic variables. At this point, the evaluations obtained should be converted to numerical values in order to use them in analytical methods. The fuzzy logic approach, which follows a similar path to human reasoning and imitates decision-making, can be used to obtain the numerical values of the evaluations in this step (Amirkhani et al., 2020b; Amirkhani and Barshoobi, 2021; Shukla et al., 2017).

Spherical fuzzy sets, proposed by Gündoğdu and Kahraman (Kutlu Gündoğdu and Kahraman, 2019a) as an extension of intuitionistic fuzzy sets, allow decision-makers to define a membership function on a spherical surface and can assign the parameters of this membership function to a wider area independently (Ayyıldız and Taskin Gumus, 2020; Erdoğan, 2022; Kutlu Gündoğdu and Kahraman, 2019a). It is frequently used especially in decision-making problems which is analyzed using linguistic variables and where uncertainty exists (Ayyıldız and Taskin Gumus, 2020; Erdoğan, 2022; Erdoğan et al., 2021; Gül and Ak, 2021; Menekse and Camgoz-Akdag, 2022). Spherical fuzzy numbers satisfy the condition that the sum of the degree of membership, degree of non-membership, and degree of hesitation is less than or equal to one (Erdoğan, 2022; Kutlu Gündoğdu and Kahraman, 2019b).

The AHP approach is an MCDM method that can be applied to rank more than one alternative, considering qualitative and quantitative criteria (Mathew et al., 2020; Saaty, 2008, 1990). In this method, a hierarchical structure is created among the decision elements and rankings of the alternatives are obtained by using the evaluations of the decision-makers (Kutlu Gündoğdu and Kahraman, 2020). Fuzzy set theory is usually integrated to reflect the uncertainty and vagueness in the decision-making problems using MCDM methods (Amirkhani et al., 2020a). In special, extended approaches of the ordinary fuzzy sets are frequently applied to deal with the uncertainty better. An extended fuzzy approach is used to reflect the ambiguity in the most possible way and to digitize the linguistic variables in the best way. Although spherical fuzzy sets are relatively newly developed compared to other fuzzy set extensions, they are frequently used in MCDM problems lately (Buyuk and Temur, 2021; Erdoğan, 2022; Hamal and Senvar, 2021; Kahraman et al., 2021; Omerali and Kaya, 2022; Sarucan et al., 2021; Toker and Görener, 2022; Unal and Temur, 2022). In this study, spherical fuzzy AHP (SF-AHP) is used to determine criteria weight.

EDAS, which is one of the widely used MCDM methods in recent years, is a method based on evaluating alternatives according to their mean solution distances (Ghorabaee et al., 2015). The evaluation of alternatives is carried out according to the higher values of the positive distance matrix from the mean and the lower values of the negative distance matrix from the mean (Stanujkic et al., 2017). Ghorabaee et al. firstly developed the fuzzy EDAS method for the supplier selection problem (Ghorabaee et al., 2016). In this study, the EDAS method has been expanded by using spherical fuzzy sets and the spherical fuzzy EDAS (SF-EDAS) method has been introduced to the literature as a group decision-making method based on uncertainty.

In recent years, artificial intelligence methods have been widely used in scientific research and businesses to minimize errors based on the decision-making mechanism. But sometimes, due to the nature of information, there are uncertain, complex and hesitant situations. With artificial intelligence applications that provide access to real-time information, the decision-maker can make quick and intuitive decisions when it comes to uncertainty, which is characterized as a lack of information about all alternatives or results. In the near future, rapid and effective solutions to problems can be obtained by using artificial intelligence applications with the proposed methodology in this study and similar methods. The proposed integrated fuzzy-based methodology can be applied to numerous problems in artificial intelligence, expert systems and more in today and the near future.

The problem of pharmaceutical warehouse location selection addressed in this paper is focused to ensure the most effective flow of the healthcare supply chain under the ongoing pandemic conditions. To cope with the increase in demand for drugs after the incremental coronavirus cases and to ensure that the vaccine supply chain operates systematically and effectively, the most suitable place for the pharmaceutical warehouse is determined among the alternative areas in a certain region determined for a city in the Black Sea Region of Turkey.

Apart from the locations selection papers using MCDM approach, an analytical and systematic way has been needed to determine the studies in which we can emphasize the differences and which will form the basis of this study. For this purpose, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach is used while researching the relevant literature. PRISMA approach is adopted as Systematic Literature Review Method (SLR) to minimize bias in the reviews and realize the reviews more systematic (Satiria et al., 2017). PRISMA is a systematic approach developed by David Moher to review the literature (Moher et al., 2009). The PRISMA approach has five steps in literature search: defining criteria, identifying sources, selecting literature, collecting data, and selecting data items (Santi and Putra, 2018).

Studies using the decision-making approaches for the warehouse location selection of pharmacies are investigated via PRISMA. Besides, the use of fuzzy logic with the adopted approach in decision-making studies is analyzed and examined in detail. Through studies that adopt the addressed approach in determining the location selection of pharmaceutical warehouses, criteria that can be used as evaluation criteria within the scope of this study have been revealed under pandemic conditions. The literature search was performed from 16th November 2021 to 25th December 2021 with the keywords used presented in Table 1.

A total of 96 papers are investigated as a result of the search in the Scopus database with the keywords shown in Table 1. By specifying both inclusion and exclusion criteria after the search, papers directly related to the study are presented. It is planned to reach similar studies that can form a background for the study and compare the inferences. Table 2 shows the inclusion and exclusion criteria for the papers encountered.

When the studies found as a result of the literature search are filtered with the criteria in Table 2, it can be observed that 19 studies could form the basis of this paper. To present the differences between these studies with our paper and to emphasize their contribution to the literature, Table 3 has been presented.

When the relevant literature is examined, the study of Arslan (Arslan, 2020) is found similar to this paper. In this study, a prioritization study is carried out for 3 different pharmaceutical warehouse locations in the Eastern and Southeastern Anatolia Region in Turkey. For this purpose, the AHP method, which is one of the most used MCDM approaches, is adopted. As the limitations of the study, it can be mentioned that implementation is conducted for a very large area, ignoring the uncertainties, using a relatively simple hierarchical structure, and presenting a superficial examination of the problem. In our study, the problem addressed is analyzed primarily by considering the pandemic conditions, a hierarchy of evaluation criteria is created for this special purpose, and a comparison of alternatives is carried out for a more specific area with handling the uncertainties.

The aforementioned literature review to solve different pharmaceutical warehouse location selection problems and its extensions reveal
that only a few studies focus to solve the problem under uncertain and fuzzy environments. Neither of these studies presents comprehensive and detailed criteria hierarchy to model the problem in a more realistic way. Therefore, this study proposes to construct a two-level criteria hierarchy that consists of thirty-three sub-criteria. With this hierarchy, a pharmaceutical warehouse location is modeled and solved under a fuzzy environment. The proposed hybrid decision-making model is applied to a real-world problem in Duzce for the post-COVID-19 era. Robustness analysis that includes sensitivity analysis and comparative analyses are also presented to show the applicability and validity of the model. In addition to all these, it is aimed to contribute to the literature by applying the AHP-EDAS MCDM combination under the extension of spherical fuzzy sets newly presented hybrid approach to the literature. The contribution of this research is to propose a spherical fuzzy-based MCDM model for the most appropriate pharmacy location in the hierarchical structure. Then, the proposed SF-EDAS methodology is employed to evaluate alternatives. The following sub-sections give information about the adopted methods in detail.

2. Spherical fuzzy based decision-making methodology

The proposed AHP integrated EDAS-based decision-making methodology under the spherical fuzzy environment includes two main stages. In the first stage, SF-AHP is used to determine the weight of each criterion in the hierarchical structure. Then, the proposed SF-EDAS methodology is employed to evaluate alternatives. The following sub-sections give information about the adopted methods in detail.

2.1. Preliminaries of spherical fuzzy sets

Kutlu Gundodug and Kahraman introduced to the literature spherical fuzzy sets (Kutlu Gundogdu and Kahraman, 2019b). Spherical fuzzy sets are developed on the basics pythagorean fuzzy (PF) sets and neutrosophic fuzzy sets (Dogan, 2021). Functions are identified on a spherical surface and parameters of the function are defined independently in a larger domain (Erdoğan et al., 2021). Three parameters are used to define spherical fuzzy numbers as the intuitionistic, pythagorean, and neutrosophic fuzzy sets (Ayyildiz and Taskin Gumus, 2020). The parameters are assigned on a spherical surface to generalize fuzzy sets. In this way, more freedom is provided to decision-makers to model ambiguity in information. The representation of the spherical and other extended fuzzy sets is shown in Fig. 1 (Kutlu Gundogdu and Kahraman, 2020).

The definitions of the spherical fuzzy sets are also explained in the following paragraphs.

**Definition 1.** Let \( X \) be a fixed set. A spherical fuzzy number \( \tilde{S} \) can be presented:

\[
\tilde{S} \equiv \{ x, \tilde{S}(\mu_{x}(x), \nu_{1}(x), \nu_{2}(x), \sigma_{x}(x)) : x \in X \}
\] (1)

where \( \mu_{x}(x) : X \rightarrow [0, 1], \nu_{1}(x) : X \rightarrow [0, 1] \) and \( \sigma_{x}(x) : X \rightarrow [0, 1] \) define the membership, non-membership, and hesitance function of the element \( x \in X \) to \( \tilde{S} \).

Table 1

| Database       | Details of the search                                                                 | Number of studies |
|----------------|---------------------------------------------------------------------------------------|-------------------|
| SCOPUS         | (TITLE-ABS-KEY (Pharmacy) AND TITLE-ABS-KEY (“Location selection”))                   | 2                 |
|                | (TITLE-ABS-KEY (Pharmacy) AND TITLE-ABS-KEY (“Site selection”))                      | 18                |
|                | (TITLE-ABS-KEY (“Pharmacy warehouse”))                                                | 24                |
|                | (TITLE-ABS-KEY (“Drug distribution”))                                                 | 1                 |
|                | AND TITLE-ABS-KEY (“Location selection”)                                              | 39                |
|                | (TITLE-ABS-KEY (“Pharmaceutical warehouse”))                                           |                   |
|                | (TITLE-ABS-KEY (“Medical warehouse”))                                                 | 12                |

Table 2

| Inclusion criteria                                                                 | Exclusion criteria                                       |
|-----------------------------------------------------------------------------------|----------------------------------------------------------|
| The studies include warehouse location selection implementation in MCDM analysis  | Studies whose full text could not be reached             |
| The studies include warehouse location selection in considering health centers    | Studies that do not explicitly mention the method used and the results |
| The studies include warehouse site selection in MCDM analysis                      | Studies that are written in languages other than English  |
| The studies include medical warehouse site selection implementations for healthcare supply chain |                                                           |
The main distinction between spherical fuzzy sets and other fuzzy sets is based on hesitancy. In spherical fuzzy sets, the hesitancy degree can be at most 1. Furthermore, the squared sum of three functions takes a value between 0 and 1, and all of the functions are defined independently in $[0,1]$ as aforementioned. Spherical fuzzy sets are defined via three parameters $\mathbf{Kieu}$ et al., 2021:

\begin{equation}
0 \leq \mu_{k}(x)^{2} + \nu_{k}(x)^{2} + \xi_{k}(x)^{2} \leq 1; \quad x \in U
\end{equation}

\begin{definition}
\begin{equation}
\vec{a} = S\left(\mu_{\vec{a}}, \nu_{\vec{a}}, \xi_{\vec{a}}\right) \quad \text{and} \quad \vec{b} = S\left(\mu_{\vec{b}}, \nu_{\vec{b}}, \xi_{\vec{b}}\right)
\end{equation}
\begin{equation}
\vec{a} \oplus \vec{b} = S\left(\sqrt{\mu_{\vec{a}}^{2} + \mu_{\vec{b}}^{2} - \mu_{\vec{a}}\mu_{\vec{b}}}, \nu_{\vec{a}}\nu_{\vec{b}}, \sqrt{(1 - \mu_{\vec{a}}^{2})\xi_{\vec{a}}^{2} + (1 - \mu_{\vec{b}}^{2})\xi_{\vec{b}}^{2} - \xi_{\vec{a}}\xi_{\vec{b}}^{2}}\right)
\end{equation}
\end{definition}

### Table 3

| # | Authors | Aim | Method | Published in Year |
|---|---------|-----|--------|-------------------|
| 1 | Yaman and Akkartal (2020) | Assessing the factors that influence the location of a warehouse for medical supplies and services | Pythagorean fuzzy set-based DEMATEL | Fourth World Conference on Smart Trends in Systems, Security and Sustainability 2020 |
| 2 | Zhang et al. (2019) | Employing an optimization method to allocate a certain amount of antiviral drug to selected distribution points | Willings-to-travel model | Journal of Ambient Intelligence and Humanized Computing 2019 |
| 3 | Arslan (2020) | Choosing the most suitable warehouse location for a pharmaceutical warehouse | AHP | J. Fac. Pharm. Ankara 2020 |
| 4 | Ceselli et al. (2014) | Presenting a model for the optimization of logistics operations in emergency health care systems. | Dynamic programming | Discrete Applied Mathematics 2014 |
| 5 | Chen et al. (2019) | Proposing a generalized multi-level optimization method for designing a common unit dose drug delivery network | Particle swarm optimization | Health Care Management Science 2019 |
| 6 | Rovers and Mages (2017) | Establishing a model for a drug supply, storage and distribution system in a remote area of Australia | Event Structure Analysis | BMC Health Services Research 2017 |
| 7 | Dodi et al. (2016) | Investigating the characteristics of direct distribution points of drugs and determining potentially error-prone aspects of the delivery process | Organizational ethnography methodology | Recenti Prog Med 2016 |
| 8 | Maheswari et al. (2021) | Developing a user-friendly smart MedDrone capable of delivering medication to and from the patient(s) location | Design study | Journal of Physics: Conference Series 2021 |
| 9 | Risanger et al. (2021) | To determine the geographic coverage that can be achieved through a pharmacy-based testing program in terms of the proportion of individuals willing to travel to the nearest pharmacy testing site to obtain a COVID-19 test | Facility location optimization model | Health Care Management Science 2021 |
| 10 | Volmer et al. (2015) | Assessing the current situation regarding medical technology in Estonian community pharmacies. | Descriptive cross-sectional questionnaire | Expert Review of Medical Devices 2015 |
| 11 | Alshehri and Alshammar (2016) | Determining the causes of drug supply shortage in KKESH pharmacy and seeking solutions to avoid this problem. | Descriptive questionnaire | International Business Management 2016 |
| 12 | Nakiboglu and Gunes (2019) | Identifying the distribution route from the main warehouse to the pharmacies with minimum cost by minimizing the total travel distance and the number of vehicles | Genetic Algorithms | 2018 International Conference on Artificial Intelligence and Data Processing (IDAP) 2018 |
| 13 | Özkam et al. (2017) | Minimizing risk factors in a pharmaceutical supply chain | Fuzzy-based goal programming | Journal of Multiple-Valued Logic and Soft Computing 2017 |
| 14 | Pappagourgiou et al. (2001) | Developing a mathematical model for pharmaceutical companies to develop their storage and distribution strategies | Mixed-integer linear programming | Industrial & Engineering Chemistry Research 2001 |
| 15 | Yu et al. (2010) | Examining the pharmaceutical products supply chain in China to identify its performance and weaknesses | Literature review | Health Policy 2010 |
| 16 | Nematollahi et al. (2017) | Presenting two-stage pharmaceutical product supply chains to maximize the occupancy rate in the supply chain | Mathematical modeling | Journal of Cleaner Production 2017 |
| 17 | Haial et al. (2020) | Identifying the most appropriate network structure in the pharmaceutical products supply chain | Multi-criteria decision-making methods | International Journal of Logistics Systems and Management 2020 |
| 18 | Ji (2019) | Modeling the problem of drug delivery from hospitals and pharmacies to patients as a vehicle routing problem with a time window | Mixed-integer programming | ACM International Conference Proceeding Series 2019 |
| 19 | Abdeen and Mohamad (2021) | Improving the performance of the Malaysian pharmaceutical warehouse supply chain | Value stream mapping | Journal of Modeling in Management 2021 |
To determine the best location for pharmaceutical warehouse

Stage 5: Describing the problem

- Literature Review
- Interviews with decision makers

Construction the decision hierarchy

Stage 2: Weighting of the criteria

Step 1. Construction of the pairwise comparison matrix
Step 2. Convert linguistic terms to spherical fuzzy numbers
Step 3. Check consistency of pairwise comparison matrices
Step 4. Apply the spherical weighted arithmetic mean operator
Step 5. Calculate the criteria weights

Stage 3: Comparison of the alternatives

Step 1. Gain opinions from each expert
Step 2. Consolidate expert opinion and construct decision matrix
Step 3. Create the average solution analogous to each criterion
Step 4. Calculate PDA and NDA matrices
Step 5. Determine the summation of PDA and NDA for alternatives
Step 6. Normalize the summations
Step 7. Calculate final appraisal values
Step 8. Rank the alternatives with the highest appraisal score
Step 9. Determine the best alternative with the highest score

Fig. 1. Flowchart for the proposed method.

\[ \tilde{a} \otimes \tilde{b} = \begin{cases} \langle \mu_{a} \mu_{b}, \sqrt{v_{a}^2 + v_{b}^2 - v_{a} v_{b}}, (1 - v_{a}^2) \pi_{a}^2 + (1 - v_{b}^2) \pi_{b}^2 - \pi_{a} \pi_{b} \rangle, & \text{if } 0 \leq \frac{\mu_{a}}{\mu_{b}} \frac{\pi_{a}}{\pi_{b}} \leq \frac{(1 - v_{a}^2)^{1/2}}{(1 - v_{b}^2)^{1/2}} \leq 1 \end{cases} \]

(0, 1, 0), Otherwise.

Definition 3. Spherical fuzzy number $\tilde{a} = S (\mu_{a}, v_{a}, \pi_{a})$ is multiplied by a positive scalar ($\lambda > 0$) (Ali, 2021):

\[ \lambda \tilde{a} = S \left( \sqrt{1 - (1 - \mu_{a}^2)^{1/2}}, \sqrt{1 - (1 - v_{a}^2)^{1/2}}, \sqrt{1 - (1 - \pi_{a}^2)^{1/2}} \right) \]

Definition 4. The positive power ($\lambda > 0$) of spherical fuzzy number $\tilde{a} = S (\mu_{a}, v_{a}, \pi_{a})$ is calculated:

\[ \tilde{a}^{\lambda} = S \left( \mu_{a}^{\lambda}, \sqrt{1 - (1 - v_{a}^2)^{1/2}}, \sqrt{1 - (1 - \pi_{a}^2)^{1/2}} \right) \]

Definition 5. Score function of spherical fuzzy number $\tilde{a} = S (\mu_{a}, v_{a}, \pi_{a})$ is given.

\[ S^{*} (\tilde{a}) = (2 \mu_{a} - \pi_{a})^2 - (v_{a} - \pi_{a})^2 \]

Definition 6. Spherical fuzzy number $\tilde{a} = S (\mu_{a}, v_{a}, \pi_{a})$ is defuzzified via Eq. (10).

\[ D (\tilde{a}) = \sqrt{100 \ast \left[ (3 \mu_{a} - \pi_{a})^2 - (v_{a} - \pi_{a})^2 \right]} \]

Definition 7. Euclidean distance between two spherical fuzzy numbers $\tilde{a} = S (\mu_{a}, v_{a}, \pi_{a})$ and $\tilde{b} = S (\mu_{b}, v_{b}, \pi_{b})$ is calculated:

\[ D (\tilde{a}, \tilde{b}) = \sqrt{(\mu_{a} - \mu_{b})^2 + (v_{a} - v_{b})^2 + (\pi_{a} - \pi_{b})^2} \]

Fig. 2. Geometric representations of the extended fuzzy sets (Kutlu Gündoğdu and Kahraman, 2020).
Definition 8. Spherical Weighted Arithmetic Mean (SWAM) operator is defined with respect to $w = (w_1, w_2, \ldots, w_n); w_i \in [0, 1]; \sum_{i=1}^{n} w_i = 1$ as below:

$$\text{SWAM}_w \left( \tilde{A}_1, \tilde{A}_2, \ldots, \tilde{A}_n \right) = w_1 \tilde{A}_1 + w_2 \tilde{A}_2 + \ldots + w_n \tilde{A}_n$$

$$= \left\{ \left[ \prod_{i=1}^{n} \left( 1 - \mu_{\tilde{a}_{ij}}^{2} - \nu_{\tilde{a}_{ij}}^{2} \right)^{1/n} \right]^{1/2} \right\}$$

$$- \left[ \prod_{i=1}^{n} \left( 1 - \mu_{\tilde{a}_{ij}}^{2} - \nu_{\tilde{a}_{ij}}^{2} \right)^{1/n} \right]^{1/2} \quad \left(12\right)$$

2.2. Spherical fuzzy AHP

AHP is used to determine the weight of importance of the criteria (Saaty, 2000). It enables complex decision-making problems to be solved in a simple hierarchical structure (Ayyildiz and Taskin Gumus, 2021). Both qualitative and quantitative criteria can be evaluated together in the AHP approach. The method allows the decision-maker to make a more consistent evaluation procedure. For these reasons, in this study, AHP is utilized to determine the weights of criteria under a spherical fuzzy environment. The steps of SF-AHP are given below (Ayyildiz and Taskin Gumus, 2020):

Step 1. The pairwise comparison matrix is constructed via linguistic terms given in Table 4 (Kutlu Gündoğdu and Kahraman, 2019b).

Step 2. The spherical fuzzy pairwise comparison matrix is constructed by converting linguistic terms to spherical fuzzy numbers.

$$M = \begin{bmatrix} 1 & \tilde{a}_{12} & \ldots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \ldots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \ldots & 1 \end{bmatrix} \quad \left(13\right)$$

Let $\tilde{a}_{ij}$ be the pairwise comparison value between criterion $i$ and criterion $j$.

Step 3. The consistency of the matrix is analyzed. For this purpose, first, the consistency ratio (CR) proposed by Saaty (1977) is calculated using SI. Then, the consistency index (CI) of the matrix is calculated.

$$CI = \frac{\lambda_{\text{max}} - n}{n-1} \quad \left(14\right)$$

$$CR = \frac{CI}{RI} \quad \left(15\right)$$

$\lambda_{\text{max}}$ is the largest eigenvalue of the pairwise comparison matrix. Random constant (RI) depends on matrix order $(n).$ RI is determined via the constant table suggested by Saaty (1977). The CR should be less than 0.1.

Step 4. Spherical weighted arithmetical mean (WM) operator is utilized to calculate the fuzzy weights of criteria.

$$\tilde{W}_j = \frac{S_j}{\sum_{j=1}^{n} S_j} \quad \left(17\right)$$

Step 5. Calculated weights of criteria in Step 4 are defuzzified via WM.

Step 6. The weights of the criteria are normalized.

$$w_j = \frac{S_j}{\sum_{j=1}^{n} S_j} \quad \left(17\right)$$

2.3. Spherical fuzzy EDAS

EDAS (Evaluation based on Distance from Average Solution) method, which was introduced to the literature by Ghorabaee et al. (2015) is a method that is evaluated by calculations according to the average solution distance in the process of determining the best among the decision alternatives. The underlying logic of the method is similar to the logic of the TOPSIS method. However, there is a fundamental difference, which distinguishes the EDAS method from the frequently used MCDM methods such as TOPSIS and VIKOR, which deal with the closeness of the optimal solution to the positive ideal and negative ideal solution. Accordingly, the evaluation process in the EDAS method is not done over the ideal solution set, but over the positive and negative distances to the mean solution. Therefore, it is rejected the idea of the distance from the ideal and negative ideal solution and considers the distance from the mean solution in the EDAS method. The desirability of alternatives depends on two different indicators and they guide the implementation in EDAS which are the positive distance to the mean solution and the negative distance to the mean solution. In the evaluation, it is required that the positive distance is the highest and the negative distance is the lowest for the optimal solution.
After determining criteria weights, spherical fuzzy EDAS (SF-EDAS) is operated to evaluate alternative locations. The steps of SF-EDAS are given below:

**Step 1.** The decision matrix is established to evaluate alternatives according to criteria using linguistic terms using Table 5 (Sharaf and Khalil, 2020). Then linguistic terms are converted to spherical fuzzy numbers.

Where \( \tilde{X}_{ij} \) be the spherical fuzzy evaluation value of alternative \( i \) with respect to criterion \( j \).

**Step 2.** The average solution analogous to each criterion is created.

\[
\tilde{A}_j = \frac{1}{m} \bigoplus_{i=1}^{m} \tilde{X}_{ij}, \forall i, j
\]  

(18)

Remember \( m \) is the number of alternatives.

**Step 3.** To determine the positive distance (PDA) and the negative distance (NDA) matrices from the average solutions, the score value of each average solution (\( \tilde{A}_j \)) is determined via Eq. (9). For each criterion, PDA and NDA matrices from the mean are determined. Each element of these matrices is calculated differently depending on the type of criterion.

\[
PDA = [a_{ij}]_{\text{mean}} \quad \text{and} \quad NDA = [\beta_{ij}]_{\text{mean}}
\]  

(19)

where \( a_{ij} \) and \( \beta_{ij} \) are the PDA and NDA of alternative \( i \).

The comparison function is defined to compare the difference with 0 and determine the maximum value, as below:

\[
z_{ij} = \begin{cases} 
S^*(\tilde{X}_{ij}) & \text{if } S^*(\tilde{X}_{ij}) > 0 \\
0 & \text{if } S^*(\tilde{X}_{ij}) \leq 0
\end{cases}
\]  

(20)

For benefit criteria:

\[
a_{ij} = \frac{\max\{0, (z_{ij} - S^*(\tilde{A}_j))\}}{S^*(\tilde{A}_j)}
\]  

(21)

\[
b_{ij} = \frac{\max\{0, (S^*(\tilde{A}_j) - z_{ij})\}}{S^*(\tilde{A}_j)}
\]  

(22)

For cost criteria:

\[
a_{ij} = \frac{\max\{0, (S^*(\tilde{A}_j) - z_{ij})\}}{S^*(\tilde{A}_j)}
\]  

(23)

\[
b_{ij} = \frac{\max\{0, (z_{ij} - S^*(\tilde{A}_j))\}}{S^*(\tilde{A}_j)}
\]  

(24)

**Step 4.** The weighted summation of PDA and NDA for alternatives is determined.

\[
P_{i}^{(+)} = \sum_{j=1}^{n} w_j a_{ij}
\]  

(25)

\[
N_{i}^{(-)} = \sum_{j=1}^{n} w_j b_{ij}
\]  

(26)

**Step 5.** The normalized values of \( P_{i}^{(+)} \) and \( N_{i}^{(-)} \) are calculated.

\[
nP_{i}^{(+)} = \frac{P_{i}^{(+)}}{\max_i \{P_{i}^{(+)}\}}
\]  

(27)

\[
nN_{i}^{(-)} = \frac{N_{i}^{(-)}}{\max_i \{N_{i}^{(-)}\}}
\]  

(28)

**Step 6.** The appraisal value of each alternative is computed.

\[
\phi_i = \frac{nP_{i}^{(+)} + nN_{i}^{(-)}}{2}
\]  

(29)

**Step 7.** Alternatives are ranked according to decreasing values of score values of appraisal scores and the alternative with the highest appraisal score is determined as the best choice among the alternatives.

### 3. Real case study

This section presents the real case analysis of the location selection problem for pharmaceutical warehouses. For this aim, data are collected for the city of Düüzce, where there is a lack in the number of pharmaceutical warehouses during the pandemic period and case analysis is carried out for this pilot city before. Six different regions are identified as potential alternatives by searching for suitable places for the new pharmaceutical warehouse planned to be opened. After the determination of the alternatives, the criteria to be used in evaluating and ranking these alternatives are investigated. As a result of the detailed literature research, the following criteria are revealed as given in Table 6 by examining the warehouse location problems and the location selection studies for health centers.

After the criteria hierarchy is clarified, the proposed fuzzy hybrid methodology is conducted to find the best location. Firstly, the criteria weights and criteria alternative scores are obtained. For this aim, three experts are consulted as decision-makers. The first expert is the pharmacist who is serving in the pilot region that we consider for 10 years. The second expert is the academician who is a researcher and studied location selection problems. The last expert is also the academician who is a researcher in the Faculty of Pharmaceutical Sciences. As a result of the surveys conducted by meeting with the experts, the weights of the criteria and the criteria-alternative scores are determined.

To calculate the weights, firstly, the evaluations of experts are taken to assess the main and sub-criteria. For this purpose, linguistic terms given in Table 4 are used to compare the determined criteria. Therefore, pairwise comparison matrices are structured for both main and sub-criteria by each expert. As an example, the pairwise comparison matrix for the main criteria by Expert-1 is presented in Table 7. The pairwise comparison matrix for the sub-criteria of C1. Economic main criterion is constructed according to the opinions from Expert-2 is presented in Table 8. In Table 9, the pairwise comparison matrix for the sub-criteria of C6. Resilience main criterion for Expert-3 is presented.

Then, all matrices are investigated to whether they are consistent or not. For this purpose, CR is calculated for each matrix. Table 10 presents the ratios for the main criteria and sub-criteria pairwise comparison matrices, constructed based on opinions from each expert.

After all the matrices are determined as consistent, the weight calculation process is initiated. Primarily, the weights of the main criteria are calculated by applying steps of SF-AHP and given in Table 11 for each expert.

According to the main criteria weights given in Table 11, C1. Economic main criterion is the most important main criterion to select the best location for a pharmaceutical warehouse according to Expert-1 and Expert-2. Expert-3 thinks C4. Infrastructure is the most important main criterion. C3. Opportunities criterion is determined as one of the two least important criteria for all experts.

After determining the main criteria weights, the same steps are repeated for sub-criteria and sub-criteria weights are determined for each expert as given in Table 12. The global weight of each sub-criterion is determined by multiplying the sub-criterion weight with the weight of the related main criterion for each expert. Then, the sub-criteria weights are aggregated considering the reputations (weights) of experts. During the interviews with the experts, their weights were determined by considering the years of work, experience, or level of expertise related to the subject. The weight of the first expert is determined as 0.45, the weight of the second expert is 0.20 and the weight of the third expert is 0.35. Table 12 also presents the final criteria weights.

When the results obtained for the criterion weights are examined, the most important criterion is determined as “energy” with an importance degree of 0.090. The following criterion is found as “investment cost” with an importance degree of 0.077. The cost of transportation appears as a criterion whose importance is calculated at higher ranks with an importance degree of 0.071. As can be seen, even during the
Table 6
Evaluation criteria for pharmaceutical warehouses.

| C1. Economic         | Demircan and Özcan (2021), Ehsanifar et al. (2021), He et al. (2017) |
|----------------------|---------------------------------------------------------------------|
| C11. Investment cost | Demircan and Özcan (2021), Ehsanifar et al. (2021), He et al. (2017) |
| C12. Operating cost  | Demircel et al. (2010), Kuo (2011), Ulutas et al. (2021)            |
| C13. Maintenance/ insurance cost | García et al. (2014)                                                |
| C14. Storage cost    | Demircan and Özcan (2021), Emeç and Akkaya (2018)                   |
| C15. Financial incentives | Demircan and Özcan (2021), Ehsanifar et al. (2021), Emeç and Akkaya (2018), García et al. (2014) |
| C16. Labor cost      | Demircan and Özcan (2021), Demircel et al. (2010), Ehsanifar et al. (2021), Emeç and Akkaya (2018), García et al. (2014) |
| C17. Transportation cost | Demircan and Özcan (2021), Demircel et al. (2010), Ehsanifar et al. (2021), Emeç and Akkaya (2018), García et al. (2014), Kuo (2011), Ocampo et al. (2020), Ulutas et al. (2021) |

Table 7
Pairwise comparison matrix for main criteria constructed by Expert-1.

| Main criteria | C1 | C2 | C3 | C4 | C5 | C6 |
|---------------|----|----|----|----|----|----|
| C1. Economic  | E  | VH | H  | SH | E  | SH |
| C2. Social    | L  | E  | SH | VL | L  | SL |
| C3. Opportunities | L  | SL | E  | SL | L  | E  |
| C4. Infrastructure | SL | VH | SH | E  | SL | SH |
| C5. Accessibility | E  | H  | H  | SH | E  | SH |
| C6. Resilience | SL | SH | E  | SL | SL | E  |

Table 8
Pairwise comparison matrix for sub-criteria of Economic constructed by Expert-2.

| Economic | C11 | C12 | C13 | C14 | C15 | C16 | C17 |
|----------|-----|-----|-----|-----|-----|-----|-----|
| C11. Investment cost | E   | SL  | SH | H  | H  | H  | H  |
| C12. Operating cost   | SH  | E   | SH | H  | H  | VH | H  |
| C13. Maintenance cost | SL  | SL  | E  | SH | SH | SH | SH |
| C14. Storage cost     | L   | L   | SL | E  | SH | SL | E  |
| C15. Financial incentives | L   | L   | SL | E  | SL | E  | SL |
| C16. Labor cost       | L   | VL  | SL | E  | E  | E  | E  |
| C17. Transportation cost | L   | L   | SL | SH | E  | E  | E  |

The pandemic period, cost-based criteria have emerged as more important factors in the selection of pharmaceutical warehouse best location with the total weight percent as 28.2%. The criteria under the “Social” class are calculated as the group of criteria with the least importance with the total weight percent as 9.6%. At this point, it can be interpreted that critical effects will not be encountered in the decision process regarding finding employees for the pharmaceutical warehouse to be established, the acceptance of this facility by the society, its environmental effects and its effects on traffic, and that there will be no issue.
in this sense for the regions considered as alternatives. Besides, when the four most important criteria are compared with the other criteria, it is seen that they have total importance of 30%. At this point, it can be interpreted that 12% of the criteria are the factors that affect the results the most in this decision-making problem.

After the importance of the criteria for the decision-making process is determined, the six different alternatives located in Duzce, Turkey are evaluated as candidate locations to place a pharmaceutical warehouse. Fig. 3 presents the alternative locations for the pharmaceutical warehouse location selection problem.

Experts’ evaluations are taken to assess the alternative locations by linguistic terms given in Table 5 with respect to each sub-criterion. For the criteria-alternative evaluations, consensus from the experts is sought. After experts have agreed on the assessments, evaluations are revealed as seen in Table 13.

Thereafter, evaluations of experts are converted to spherical fuzzy numbers to utilize in the proposed fuzzy decision-making methodology. The average solution analogous to each criterion is calculated by Eq. (18) and given in Table 14. The scores of average solutions are also presented in Table 14.

In MCDM problems, various analyses are often used to search for the robustness of the proposed methodology which are sensitivity analysis, validity analysis and comparative analysis (Alkan and Kahraman, 2022; İlbahar et al., 2022; Karasan et al., 2021). Through these analyses, the results are tried to be verified and the changes in the outputs can be observed. Based on these aims, it is revealed that especially since it is located at the connection point with other regions, that puts it at a critical point as a location and thus ensures lower transportation costs. It also appears as the farthest alternative location from the city center, which also provides comfort in terms of traffic complexity. This location, which is determined in the first place, is the alternative that can provide the lowest cost in terms of initial investment costs due to its distance from the city center. It is quite easy to reach the designated location, there is a two-way road and there is no traffic congestion as mentioned. This alternative is also located close to the villages and surrounding settlements, which has a positive effect in terms of finding workers and supporting employment. In terms of all the criteria considered in this paper, it seems quite reasonable to determine this location alternative in the first place.

4. Robustness analysis

In MCDM problems, various analyses are often used to search for the robustness of the proposed methodology which are sensitivity analysis, validity analysis and comparative analysis (Alkan and Kahraman, 2022; Celik and Gul, 2021; Gul and Ak, 2021; Haktanır and Kahraman, 2022; İlbahar et al., 2022; Karasan et al., 2022; Karaşan et al., 2021). Through these analyses, the results are tried to be verified and the changes in the outputs can be observed. Based on these aims, it is revealed that especially since it is located at the connection point with other regions, that puts it at a critical point as a location and thus ensures lower transportation costs. It also appears as the farthest alternative location from the city center, which also provides comfort in terms of traffic complexity. This location, which is determined in the first place, is the alternative that can provide the lowest cost in terms of initial investment costs due to its distance from the city center. It is quite easy to reach the designated location, there is a two-way road and there is no traffic congestion as mentioned. This alternative is also located close to the villages and surrounding settlements, which has a positive effect in terms of finding workers and supporting employment. In terms of all the criteria considered in this paper, it seems quite reasonable to determine this location alternative in the first place.

The positive and negative distance matrices are constructed based on Eqs. (19)–(25) considering the type of each criterion which can be beneficial or cost-oriented. Table 15 shows the PDA and NDA matrices for each criterion.

The weighted summation of PDA and NDA for alternatives is determined and normalized. By this way, the appraisal value of each alternative is calculated and given in Table 16.

After the application of the SF-EDAS approach, the rankings of the alternatives are obtained. The first-ranked alternative is the A-4 alternative with 0.800 appraisal score value. This alternative is followed by the alternatives of A-3 and A-5 with the appraisal score values of 0.728 and 0.666, respectively.

The A-4 alternative, which is found in the first place, is the closest alternative to the sea route and is also located on the strategic road connecting the Black Sea region, which is the northern region of the country, and the Marmara region, which is the heart of the country.
A validation analysis is performed to show and discuss the changes in the proposed novel integrated methodology results when some parameters are altered. For this purpose, the weights of experts are changed between two experts while the other ones remain the same. That is, the Expert-1 weight is replaced subsequently with the weights of Expert-2 and Expert-3, while the remaining one is constant. Then, the Expert-2 and Expert-3 weights are changed and go on. In the last scenario, all expert weights are assumed to be equal. Each scenario is detailed in Table 17.

The sub-criteria weights are aggregated and recalculated according to adjusted expert weights. Thus, the sensitivity of the proposed methodology against the changes in expert weights is analyzed. In this way, changes in the alternative rankings can be seen, and these results help decision-makers in determining priorities and alternative evaluations by making it easier to analyze the process. The results of sensitivity analysis can be seen in Fig. 4 with the final scores of each alternative.

As can be seen in Fig. 3, the best alternative is the same for all scenarios. So it can be said that A-3 is the best alternative for the evaluated problem for different expert weights and the stability of the proposed methodology is revealed.

4.2. Validation analysis

A validation analysis is performed for the proposed integrated SF sets based MCDM methodology used in the pharmaceutical warehouse location selection problem to evaluate its reliability and validity. The effect of the change for SF sets on the results is investigated in this validation analysis. The results are compared, and the validation of the proposed methodology is discussed. For this purpose, the problem is solved under pythagorean fuzzy (PF) environment with the same methods, namely AHP and EDAS. Firstly, PF-AHP is utilized to determine criteria weights, then alternative locations are evaluated by PF-EDAS. The steps of PF-AHP (Ayyildiz et al., 2021) integrated PF-EDAS (Göçer, 2022) methodology are presented below:

Step 1. The pairwise comparison matrix is constructed via linguistic terms (Ilbahar et al., 2018) given in Table 18.

Step 2. The differences matrix is constructed.

Step 3. The interval multiplicative matrix is determined.

Step 4. The indeterminacy value is calculated.

Step 5. Unnormalized weights are computed.

Step 6. The priority weights are determined.

4.1. Sensitivity analysis

Table 12

Weights of the sub-criteria.

| Sub-criteria                  | Sub-criteria weights for each expert | Final weights of criteria | Weight | Ranking |
|-------------------------------|-------------------------------------|---------------------------|--------|---------|
| Sub-criteria                  | Expert-1  | Expert-2  | Expert-3  | Priority |
| C11. Investment cost          | 0.236     | 0.278     | 0.330     | 0.077    | 2       |
| C12. Operating cost           | 0.112     | 0.336     | 0.050     | 0.042    | 7       |
| C13. Maintenance/insurance cost | 0.023     | 0.141     | 0.026     | 0.015    | 26      |
| C14. Storage cost             | 0.141     | 0.067     | 0.050     | 0.028    | 13      |
| C15. Financial incentives     | 0.043     | 0.044     | 0.213     | 0.025    | 16      |
| C16. Labor cost               | 0.087     | 0.044     | 0.117     | 0.024    | 17      |
| C17. Transportation cost      | 0.358     | 0.091     | 0.213     | 0.071    | 4       |
| C21. Available workforce      | 0.039     | 0.220     | 0.335     | 0.016    | 24      |
| C22. Local government support | 0.154     | 0.299     | 0.191     | 0.023    | 19      |
| C23. Environmental impact     | 0.184     | 0.247     | 0.066     | 0.020    | 20      |
| C24. Impact on traffic congestion | 0.242     | 0.033     | 0.018     | 0.010    | 31      |
| C25. Conformance to freight regulations | 0.106    | 0.120     | 0.066     | 0.010    | 30      |
| C26. Security                 | 0.207     | 0.050     | 0.191     | 0.012    | 28      |
| C27. Community acceptance     | 0.068     | 0.030     | 0.134     | 0.005    | 32      |
| C31. Development rate         | 0.351     | 0.550     | 0.053     | 0.016    | 25      |
| C32. Number of competitors in radius | 0.391    | 0.280     | 0.274     | 0.019    | 22      |
| C33. Parking area             | 0.089     | 0.046     | 0.112     | 0.005    | 33      |
| C34. Future expansion         | 0.168     | 0.124     | 0.562     | 0.019    | 21      |
| C41. Climate conditions       | 0.201     | 0.216     | 0.033     | 0.031    | 12      |
| C42. Energy                   | 0.391     | 0.437     | 0.368     | 0.090    | 1       |
| C43. Telecommunication systems | 0.308     | 0.130     | 0.368     | 0.072    | 3       |
| C44. Topographical features   | 0.101     | 0.216     | 0.230     | 0.039    | 9       |
| C51. Proximity to main roads  | 0.030     | 0.066     | 0.159     | 0.017    | 23      |
| C52. Proximity to producers   | 0.254     | 0.064     | 0.055     | 0.034    | 11      |
| C53. Proximity to multimodal transport | 0.097   | 0.174     | 0.159     | 0.026    | 14      |
| C54. Proximity to potential markets | 0.187   | 0.389     | 0.375     | 0.056    | 5       |
| C55. Proximity to suppliers   | 0.304     | 0.217     | 0.126     | 0.047    | 6       |
| C56. Proximity to opponents   | 0.129     | 0.091     | 0.126     | 0.026    | 15      |
| C61. Location resistance      | 0.057     | 0.392     | 0.176     | 0.024    | 18      |
| C62. Disaster free location   | 0.326     | 0.285     | 0.342     | 0.041    | 8       |
| C63. Stock holding capacity   | 0.110     | 0.070     | 0.071     | 0.010    | 29      |
| C64. Resource availability    | 0.349     | 0.172     | 0.342     | 0.039    | 10      |
| C65. Movement flexibility     | 0.157     | 0.081     | 0.071     | 0.013    | 27      |
### Table 13: Alternative evaluation matrix.

| Sub-criteria                  | Type of criteria | A-1 | A-2 | A-3 | A-4 | A-5 | A-6 |
|-------------------------------|------------------|-----|-----|-----|-----|-----|-----|
| C11. Investment cost          | Cost             | F   | F   | L   | VL  | VL  | EH  |
| C12. Operating cost           | Cost             | H   | F   | EL  | VL  | L   | EH  |
| C13. Maintenance/insurance cost | Cost            | L   | F   | VL  | F   | H   | VH  |
| C14. Storage cost             | Cost             | H   | VH  | VH  | L   | H   | VL  |
| C15. Financial incentives     | Benefit          | H   | F   | F   | H   | F   | VH  |
| C16. Labor cost               | Cost             | L   | L   | H   | L   | H   | VL  |
| C17. Transportation cost      | Cost             | H   | VH  | VL  | VH  | VL  | L   |
| C21. Available workforce      | Benefit          | L   | F   | VH  | F   | H   | F   |
| C22. Local government support | Benefit          | VH  | H   | F   | F   | F   | VH  |
| C23. Environmental impact     | Cost             | L   | L   | F   | L   | F   | L   |
| C24. Impact on traffic congestion | Cost           | VL  | VL  | H   | L   | H   | L   |
| C25. Conformance to freight regulations | Benefit     | F   | F   | L   | F   | L   | F   |
| C26. Security                 | Benefit          | L   | F   | H   | H   | H   | H   |
| C27. Community acceptance     | Benefit          | VH  | VH  | F   | VH  | H   | VH  |
| C31. Development rate         | Benefit          | L   | L   | F   | H   | F   | F   |
| C32. Number of competitors in radius | Cost         | VL  | EL  | H   | EL  | H   | EL  |
| C33. Parking area             | Benefit          | EH  | VH  | L   | EH  | VL  | EH  |
| C34. Future expansion         | Benefit          | VH  | H   | F   | H   | L   | VL  |
| C41. Climate conditions       | Benefit          | H   | F   | VH  | F   | VH  | F   |
| C42. Energy                   | Benefit          | F   | F   | H   | H   | H   | VH  |
| C43. Telecommunication systems | Benefit        | L   | L   | H   | F   | F   | VH  |
| C44. Topographical features   | Benefit          | F   | L   | F   | H   | F   | H   |
| C51. Distance to main roads   | Cost             | L   | H   | VL  | VL  | VL  | H   |
| C52. Distance to producers    | Cost             | H   | VL  | H   | VL  | H   | F   |
| C53. Distance to multimodal transport | Cost     | F   | F   | F   | F   | F   | F   |
| C54. Distance to potential markets | Cost         | F   | F   | L   | F   | F   | F   |
| C55. Distance to suppliers    | Cost             | F   | VL  | L   | VL  | F   | L   |
| C56. Distance to opponents    | Benefit          | VH  | EH  | EL  | VH  | VL  | VL  |
| C61. Location resistance      | Benefit          | L   | H   | F   | H   | F   | F   |
| C62. Disaster free location   | Benefit          | L   | H   | F   | F   | F   | L   |
| C63. Stock holding capacity   | Benefit          | F   | F   | EL  | VL  | L   | EH  |
| C64. Resource availability    | Benefit          | F   | L   | H   | F   | H   | F   |
| C65. Movement flexibility     | Benefit          | H   | L   | VL  | H   | VL  | H   |

Step 7. The alternative evaluation matrix is established to evaluate alternatives according to criteria using linguistic terms using Table 19 (Göçer, 2022).

Step 8. The average solution based on all criteria is calculated.

\[
\tilde{A}_{ij} = \frac{1}{m} \oplus \tilde{x}_{ij} = \left[ 1 - \left( \prod_{i=1}^{m} \left( 1 - \mu_{i} \tilde{x}_{ij} \right) \right)^{1/m} \prod_{i=1}^{m} \nu_{i}^{2} \tilde{x}_{ij} \right]^{1/m} \quad (37)
\]

Step 9. \( PDA = [a_{ij}]_{{max}} \) and \( NDA = [b_{ij}]_{{max}} \) are determined.

\[
a_{ij} = \max \left\{ e^{(A_{ij})}, e^{(L_{ij})} \right\} \quad (38)
\]

\[
b_{ij} = \max \left\{ e^{(L_{ij})}, e^{(A_{ij})}, e^{(L_{ij})} \right\} \quad (39)
\]

The score function \( s(\tilde{P}) \) of a PF number is defined (Zhang and Xu, 2014):

\[
S(\tilde{P}) = (\mu_{\tilde{P}})^{2} - (\nu_{\tilde{P}})^{2} \quad (40)
\]

The remaining steps are the same as SF-EDAS.

To determine criteria weights, linguistic terms are converted to PF numbers via Table 18. The PF-AHP methodology is applied to consistent pairwise comparison matrices and by this way both main and sub-criteria weights are calculated. Table 20 presents the aggregated sub-criteria weights as the result of PF-AHP. In the aggregation process, the same expert weights are used. The criteria weights determined by
and the robustness of the proposed hybrid methodology to determine the problems. An effective to solve complex location selection or different MCDM integrated EDAS methodology based on SF sets is determined as valid to six main and thirty-three sub-criteria. Therefore, the proposed AHP best candidate location to be a pharmaceutical warehouse with respect for the different fuzzy environments are almost the same, and A-4 is the ranking according to the integrated AHP-EDAS methodology under PF. In this table, \( W \) and \( R \) represent the final weight and final ranking, respectively.

As can be seen in Table 20, the most important criterion is determined as “C42. Energy” by both two methods. And the ten most important criteria are determined as the same in two methods with different orders. So, it can be said that the SF-AHP methodology produces robust criteria weights to evaluate alternative pharmaceutical warehouse location.

In the second stage of the validation analysis, PF-EDAS is applied to Table 13 and the most suitable location is analyzed. By applying the aforementioned steps of PF-EDAS, the following results given in Table 21 are obtained.

According to PF-EDAS results, the rankings of the candidate pharmaceutical warehouse locations with respect to the determined criteria are A-4 > A-3 > A-5 > A-6 > A-2 > A-1 which agrees with the SF-EDAS for the first three ranks. The rankings of remaining alternatives have changed among themselves. The comparison of the alternative locations ranking according to the integrated AHP-EDAS methodology under PF and SF environments is presented in Fig. 5.

As can be seen in Fig. 5, the results of the integrated methodology for the different fuzzy environments are almost the same, and A-4 is the best candidate location to be a pharmaceutical warehouse with respect to six main and thirty-three sub-criteria. Therefore, the proposed AHP integrated EDAS methodology based on SF sets is determined as valid and effective to solve complex location selection or different MCDM problems.

### 4.3. Comparative analysis

A comparative analysis is performed to validate the effectiveness and robustness of the proposed hybrid methodology to determine the best location for a pharmaceutical warehouse. The same criteria weight set which is determined by SF-AHP is used and alternatives are evaluated with the SF-VIKOR methodology to compare the results of SF-EDAS. The steps of the SF-VIKOR methodology are explained below (Ayyildiz and Taskin, 2022)

**Step 1.** The score value of each evaluation is calculated based on Definition 5.

**Step 2.** The positive ideal solution is determined for each criterion.

\[
\bar{X}^+ = \{C_i, \max_i < \text{Score}(X_{ij}) | i = 1, 2 \ldots m\}
\]

**Step 3.** The negative ideal solution is determined for each criterion.

\[
\bar{X}^- = \{C_i, \min_i < \text{Score}(X_{ij}) | i = 1, 2 \ldots m\}
\]

Let \( m \) be the number of alternatives.

**Step 4.** \( S_i \) (the weighted total regret) and \( R_i \) (the weighted maximum regret) values are calculated.

\[
S_i = \sum_{j=1}^{n} w_j \frac{d\left(\tilde{X}_{ij}, \tilde{X}_{ij}^+\right)}{d\left(\tilde{X}_{ij}, \tilde{X}_{ij}^+\right)}
\]

\[
R_i = \max_{j} \left\{ w_j \frac{d\left(\tilde{X}_{ij}, \tilde{X}_{ij}^-\right)}{d\left(\tilde{X}_{ij}, \tilde{X}_{ij}^-\right)} \right\}
\]

**Step 5.** \( Q \) values are computed for alternatives:

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

where \( R^+ = \min R_i, R^- = \max R_i, \) and \( S^+ = \min S_i, S^- = \max S_i. \) \( v \) represents the weight of strategy of maximum group utility and is generally determined as 0.5 (Kutlu Gündoğdu and Kahraman, 2019a).

**Step 6.** Alternatives are ranked by \( Q \), in ascending order.

After constructing the evaluation matrix for alternatives with experts, the positive and negative solutions are determined as given in Table 22. \( S_i, R_i \) and \( Q \) values are calculated with respect to criteria weights and the alternatives are ordered as given in Table 23.

According to the obtained result by SF-VIKOR, A3 has the lowest \( Q \) score with 0.015 and determined as the best option. It is followed by

| Sub-criteria | \( \mu \) | \( \gamma \) | \( \pi \) | \( S_i(\bar{A}) \) |
|-------------|------|------|------|--------|
| C11         | 0.642| 0.508| 0.356| 0.838  |
| C12         | 0.653| 0.532| 0.329| 0.913  |
| C13         | 0.631| 0.547| 0.365| 0.772  |
| C14         | 0.688| 0.345| 0.314| 1.129  |
| C15         | 0.679| 0.436| 0.332| 1.042  |
| C16         | 0.573| 0.468| 0.419| 0.525  |
| C17         | 0.681| 0.355| 0.293| 1.139  |
| C21         | 0.676| 0.444| 0.347| 1.003  |
| C22         | 0.679| 0.399| 0.332| 1.048  |
| C23         | 0.537| 0.497| 0.467| 0.368  |
| C24         | 0.561| 0.516| 0.403| 0.505  |
| C25         | 0.570| 0.461| 0.434| 0.499  |
| C26         | 0.660| 0.455| 0.350| 0.928  |
| C27         | 0.762| 0.349| 0.248| 1.615  |
| C31         | 0.612| 0.482| 0.400| 0.672  |
| C32         | 0.510| 0.514| 0.323| 0.448  |
| C33         | 0.812| 0.267| 0.217| 1.977  |
| C34         | 0.716| 0.366| 0.314| 1.247  |
| C41         | 0.701| 0.408| 0.314| 1.175  |
| C42         | 0.693| 0.448| 0.315| 1.131  |
| C43         | 0.612| 0.482| 0.400| 0.672  |
| C44         | 0.643| 0.477| 0.367| 0.833  |

Fig. 5. Results of the validation analysis.
The proposed hybrid methodology is consistent with SF-VIKOR which is not a considerable change, although the ranking methodology is altered. According to the comparative analysis, the result of the proposed hybrid methodology is consistent with SF-VIKOR which is also one of the most popular MCDM methodologies.

5. Conclusion and future directions

The choice of pharmaceutical warehouse location stands out as one of the issues that should be addressed as a priority. However, in addressing this problem, pandemic conditions should be taken into account, along with the details of the storage, transportation and distribution aspects.
M. Erdogan and E. Ayyildiz
Engineering Applications of Artificial Intelligence 116 (2022) 105389

Table 20
Sub-criteria weights comparison for PF-AHP and SF-AHP.

| Sub-criteria            | PF-AHP | SF-AHP |
|-------------------------|--------|--------|
|                         | W  | R  | W  | R |
| C11. Investment cost    | 0.078| 4   | 0.077| 2 |
| C12. Operating cost     | 0.041| 7   | 0.042| 7 |
| C13. Maintenance/insurance cost | 0.013| 26  | 0.015| 26 |
| C14. Storage cost       | 0.028| 12  | 0.028| 13 |
| C15. Financial incentives | 0.026| 13  | 0.025| 16 |
| C16. Labor cost         | 0.020| 19  | 0.024| 17 |
| C17. Transportation cost | 0.087| 3   | 0.071| 4 |
| C21. Available workforce | 0.015| 24  | 0.016| 24 |
| C22. Government support | 0.021| 18  | 0.023| 19 |
| C23. Environmental impact | 0.015| 25  | 0.020| 20 |
| C24. Impact on traffic cong. | 0.009| 30  | 0.010| 31 |
| C25. Conformance to freight reg. | 0.008| 31  | 0.010| 30 |
| C26. Security           | 0.009| 29  | 0.012| 28 |
| C27. Community acceptance | 0.004| 32  | 0.005| 22 |
| C31. Development rate   | 0.016| 23  | 0.016| 25 |
| C32. Number of competitors | 0.018| 20  | 0.019| 22 |
| C33. Parking area       | 0.003| 33  | 0.005| 33 |
| C34. Future expansion   | 0.016| 22  | 0.019| 21 |
| C41. Climate conditions | 0.030| 11  | 0.031| 12 |
| C42. Energy             | 0.098| 1   | 0.090| 1 |
| C43. Telecommunication systems | 0.095| 2   | 0.072| 3 |
| C44. Topographical features | 0.056| 9   | 0.039| 9 |
| C51. Prox. to main roads | 0.017| 21  | 0.017| 23 |
| C52. Prox. to producers  | 0.023| 17  | 0.034| 11 |
| C53. Prox. to multimodal transport | 0.024| 15  | 0.026| 14 |
| C54. Prox. to potential markets | 0.062| 5   | 0.056| 5 |
| C55. Proximity to suppliers | 0.051| 6   | 0.047| 6 |
| C56. Proximity to opponents | 0.025| 14  | 0.026| 15 |
| C61. Location resistance | 0.023| 16  | 0.024| 18 |
| C62. Disaster free location | 0.038| 8   | 0.041| 8 |
| C63. Stock holding capacity | 0.010| 28  | 0.010| 29 |
| C64. Resource availability | 0.030| 10  | 0.039| 10 |
| C65. Movement flexibility | 0.011| 27  | 0.013| 27 |

Fig. 6. The rankings of the alternatives for both SF-EDAS and SF-VIKOR.

Table 21
The results of PF-EDAS application.

| A1  | A2  | A3  | A4  | A5  | A6  |
|-----|-----|-----|-----|-----|-----|
| P<sup>+</sup> | 0.863| 0.957| 1.119| 1.122| 1.068| 0.919|
| N<sup>-</sup> | 0.968| 0.983| 0.910| 0.824| 0.894| 0.925|
| nP<sup>+</sup> | 0.769| 0.852| 0.997| 1.000| 0.952| 0.819|
| nN<sup>-</sup> | 0.014| 0.000| 0.074| 0.162| 0.090| 0.059|
| Score | 0.392| 0.426| 0.535| 0.581| 0.521| 0.439|
| Ranking | 6 | 5 | 2 | 1 | 3 | 4 |

arrangement of drugs. Since the warehouse location problem is a long-term strategic decision, it is a decision-making process that requires careful analysis and incorporation of as many factors as possible into the decision process. At this point, along with the criteria whose numerical values can be obtained for the warehouse location selection problem, it is necessary to take into account the effect of linguistically expressive criteria on the decision process. In addition, the fact that some criteria may be in conflict with each other forces the problem to be analyzed in detail with all the criteria expressed linguistically and numerous. The presence of multiple and conflicting criteria in a decision analysis makes it appropriate to use MCDM methodologies. The complexity of warehouse location selection problems involving real-life analysis is an important factor that should be included in the decision-making process. Uncertainty in the decision process and hesitations in the evaluations cause difficulties in determining the weights of the evaluation criteria and criterion-alternative scores, and it necessitates the use of linguistic variables in the decision-making process. Fuzzy logic enables the linguistically evaluated criteria and alternatives to be converted into numerical values so that they can be used in analytical methods.

Eventually, this study proposes a hybrid fuzzy decision-making methodology for the evaluation of alternative locations of pharmacy warehouses in order to ensure the most effective flow of the health supply chain in pandemic conditions. In this paper, the AHP method, which is one of the most frequently used approaches to determine criteria weights in MCDM problems, is applied under the SF environment to reflect the uncertainty in the best way for selection of appropriate pharmaceutical warehouse location. In order to rank the alternatives, EDAS, which is a method that has been used frequently in the MCDM literature has been applied in the SF framework. When the results obtained for the weights of criteria are examined, the most important criterion is determined as “energy” with an importance degree of 0.090. The following criterion is found as “investment cost” with an importance degree of 0.077. The cost of transportation appears as a criterion whose
be claimed that the proposed method is stable to changes in decision analysis results, it is determined that the best alternative remained the same for all scenarios for different weights of experts. Thus, it can be interpreted that the use of the first-ranked area as a pharmaceutical warehouse location is a reasonable result, due to its affordable cost, ease of transportation and supporting the region in terms of employment.

As future suggestions, different MCDM approaches can be applied to compare the results, or proposed fuzzy-based decision-making methodology can be conducted for different and/or larger regions.

### Table 22
The positive ideal and negative ideal solutions.

| Alternative | $S_i$ | $R_i$ | $Q_i$ | Rank |
|-------------|-------|-------|-------|------|
| 0.637       | 0.091 | 1.000 | 6     |
| 0.606       | 0.091 | 0.940 | 5     |
| 0.389       | 0.045 | 0.015 | 1     |
| 0.381       | 0.065 | 0.220 | 3     |
| 0.400       | 0.045 | 0.038 | 2     |
| 0.500       | 0.077 | 0.581 | 4     |

### Table 23
The values of $S_i$, $R_i$ and $Q_i$ rankings.

| Alternative | $S_i$ | $R_i$ | $Q_i$ | Rank |
|-------------|-------|-------|-------|------|
| 0.637       | 0.091 | 1.000 | 6     |
| 0.606       | 0.091 | 0.940 | 5     |
| 0.389       | 0.045 | 0.015 | 1     |
| 0.381       | 0.065 | 0.220 | 3     |
| 0.400       | 0.045 | 0.038 | 2     |
| 0.500       | 0.077 | 0.581 | 4     |

importance is calculated at higher ranks with an importance degree of 0.071. As can be seen, even during the pandemic period, cost-based criteria have emerged as more important factors in the selection of pharmaceutical warehouse best location with the total weight percent as %28.2. The criteria under the “Social” class are calculated as the group of criteria with the least importance. At this point, it can be interpreted that critical effects will not be encountered in the decision process regarding finding employees for the pharmaceutical warehouse to be established, the acceptance of this facility by the society, its environmental effects and its effects on traffic, and that there will be no issue in this sense for the regions considered as alternatives. Besides, when the four most important criteria are compared with other criteria, it is seen that they have total importance of 30%. At this point, it can be interpreted that 12% of the criteria are the factors that affect the results the most in this decision-making problem.

In the fuzzy multi-criteria analysis is carried out for the city of Düzce, which is located in the north of Turkey and is a bridge with other regions and the heart of the country, the Marmara Region, it is seen that the most suitable alternative is the region marked with A-4 on the map in Fig. 2 with 0.800 score value and this alternative is followed by the alternatives of A-3 and A-5 with the score values of 0.728 and 0.666, respectively. When a detailed examination is conducted in terms of the criteria considered and the results are discussed with the experts, it can be interpreted that the use of the first-ranked area as a pharmaceutical warehouse location is a reasonable result, due to its affordable cost, ease of transportation and supporting the region in terms of employment.

Determined robustness analysis is carried out to verify the stability and applicability of the proposed methodology. Firstly, a sensitivity analysis is also conducted in order to observe the effect of the parameters on the results in the proposed decision process. According to the sensitivity analysis results, it is determined that the best alternative remained the same for all scenarios for different weights of experts. Thus, it can be claimed that the proposed method is stable to changes in decision parameters. A validity analysis is also conducted to compare the results of the proposed methodology. Finally, a comparative analysis is carried out and it is revealed that there is no major change in the results, which indicates that the obtained ranking is consistent.

This paper proposes AHP-EDAS hybrid methodology under SF environment which is proved to be successful in handling fuzziness and indeterminacy in complex decision-making problems. The main contributions of this study to the current literature and application area can be summarized as follows: (1) The key factors to evaluate candidate pharmaceutical warehouse locations for the post-COVID-19 era are determined and classified under main titles; (2) AHP is integrated to EDAS methodology under SF environment to make more detailed and comprehensive multi-criteria analysis considering the indeterminacy and fuzziness in information; (3) The most important criteria are determined with respect to expert opinions via SF-AHP; (4) A real-life case for Düzce, Turkey is performed and the applicability and reliability of the proposed integrated MCDM methodology is shown with three-phase robustness analysis; (5) Six alternatives are analyzed with respect to thirty-three criteria and the most appropriate one is specified via SF-EDAS; (6) The proposed integrated methodology can be used a helpful guide for healthcare organizations to develop and improve their strategies considering the pharmaceutical supply chain. As future suggestions, different MCDM approaches can be applied to compare the results, or proposed fuzzy-based decision-making methodology can be conducted for different and/or larger regions.

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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