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# Evaluation of the Performance of Covid-19 Vaccines by F-DEMATEL and RAFSI Methods

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**ABSTRACT**

In this study, a new decision-making model based on Fuzzy The Decision Making Trial and Evaluation Laboratory (F-DEMATEL) technique, which evaluates many vaccines with Ranking of Alternatives through Functional mapping of criterion sub-intervals into a Single Interval (RAFSI) methods using multiple criteria to support decision making, is proposed. To demonstrate the usefulness of the suggested methodology, five COVID-19 vaccines (BioNTech, Moderna, Sputnik V, AstraZeneca, Sinovac) were chosen for a case study. Each vaccine was compared with others according to seven criteria (the effectiveness rate of vaccines, the storage time of vaccines, the cold chain of vaccines, the number of doses administered, the price of double doses, the protection of vaccines, side effects of vaccines) and all criteria were compared with both qualitative and quantitative data to calculate relative weights. Fuzzy Set Theory was applied to model the problem. The criteria were weighted with the F-DEMATEL approach. As a result of the application made with F-DEMATEL, the criteria used in the evaluation of COVID-19 vaccines showed that the protection feature of the vaccines was the most important criterion with a weight of 0,191, while the storage time of the vaccines was the least important criterion with a weight of 0,100. The BioNTech vaccine had the maximum performance, with a value of 0,6487, according to the criteria employed in the suggested model, while AstraZeneca had the lowest performance, with a value of 0,3752 as a consequence of the application with RAFSI.

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# Covıd-19 Aşılarının Performansının F-DEMATEL ve RAFSI Yöntemleri ile Değerlendirilmesi

**MAKALE BİLGİSİ**
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COVID-19 aşısı, MCDM, F-DEMATEL, RAFSI

**ÖZ**

Bu çalışmada, Bulanık Karar Verme Deneme ve Değerlendirme Laboratuvarı (F-DEMATEL) tekniğine dayalı, karar vermeyi desteklemek için çoklu kriterler kullanarak birçok aşıyı Kriter alt aralıklarının Tek Bir Aralığa İşlevsel Eşlenmesi Yoluyla Alternatiflerin Sıralanması (RAFSI) yöntemleri ile değerlendiren yeni bir karar verme modeli önerilmiştir. Önerilen metodolojinin yararlılığını göstermek için, bir vaka çalışması için beş COVID-19 aşısı (BioNTech, Moderna, Sputnik V, AstraZeneca, Sinovac) seçildi. Her aşı yedi kritere (aşıların etkililik oranı, aşıların saklanma süreleri, aşılara ait soğuk zincir, uygulanan doz sayısı, çift doz fiyatı, aşıların koruyuculuk özelliği, aşıların yan etkileri) göre diğerleriyle karşılaştırıldı ve nispi ağırlıkları hesaplamak için tüm kriterler hem nitel hem de nicel verilerle karşılaştırıldı. Kriterler F-DEMATEL yaklaşımı ile ağırlıklandırılmıştır. F-DEMATEL ile yapılan uygulama sonucunda COVID-19 aşılarının değerlendirilmesinde kullanılan kriterler, aşıların korunma özelliğinin 0,191 ağırlıkla en önemli kriter olduğunu, aşıların saklanma süresinin ise 0,100 ağırlıkla en az önemli kriter olduğunu göstermiştir. BioNTech aşısı, önerilen modelde kullanılan kriterlere göre 0,6487 değeri ile maksimum performansa sahipken, AstraZeneca RAFSI ile yapılan uygulama sonucunda 0,3752 değeri ile en düşük performansa sahip olmuştur.

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## 1. INTRODUCTİON

The COVID-19 virus was identified on January 13, 2020, following research on a population of people who had respiratory symptoms like fever, coughing, and shortness of breath. In China's Wuhan Province, it was first noted during the end of December. As is well known, the outbreak was first found among persons who worked in the local seafood and livestock markets. Later, it spreads from person to person to other Hubei provincial cities, particularly Wuhan, as well as to other People's Republic of China provinces and other nations throughout the world. The coronavirus is one of the principal viruses that mostly impact the human respiratory system. Animals and humans alike can become unwell from the huge virus family known as coronaviruses (Rothan & Byrareddy, 2020). Numerous coronaviruses are known to cause respiratory illnesses in people, including Middle East Respiratory Syndrome (MERS) and severe acute respiratory syndrome (SARS) (Hatmal et al., 2020). Coronavirus disease, which is seen in the world, especially in our country, is caused by the SAR-COV-2 virus. It's crucial to keep in mind that vaccination is the most effective therapy for COVID-19, even though basic habits like personal hygiene and cleanliness are recommended by specialists to reduce the overall risk of transmission of acute respiratory infections.

For COVID-19, several different vaccines have been created, and more research is still being done on each of them. The five vaccinations are created using three distinct processes and are now undergoing phase III research in the early stage. Inactivated vaccines, viral vector (adenovirus) vaccines, and messenger RNA (mRNA) vaccines are examples of these techniques. These vaccinations are all made to instruct the immune system of the body how to introduce and eradicate the COVID-19 virus in a safe manner. Vaccinations that include inactivated viruses that don't cause illness but do stimulate the immune system are known as inactivated vaccines. They are created using conventional techniques. Viruses in inactivated vaccines have had their genetic material altered by heat, chemicals, or radiation so they can no longer multiply in cells (Gao et al., 2020). Thus, the virus is broken down and neutralized, stimulating our immunity without harming our body. It is easier to use in the first stage because they contain killed viruses, it is considered to be cheaper and safer. The vaccine called Coronavac by Sinovac Biotech enters this group (Forni & Mantovani, 2021). In viral vector (adenovirus) vaccines, a virus (adenovirus) that makes flu-like disease is intended to be supported by coronavirus protein after genetic intervention and to create immunity in human beings. The production of these vaccines makes use of recombinant DNA technology. They are one of the new vaccine development technologies. The bacterium or viral vectors contain DNA that encodes a pathogen's antigen. The antigen is subsequently expressed in these cells by the bacteria or viral vectors. From the bacterium or viral vectors, the antigens are extracted and subsequently purified. Although the microorganisms in vaccines are alive, they can't cause disease in humans because they are weakened (Kashte et al., 2021). Gamaleya Research Institute/Sputnik-V and Oxford/AstraZeneca vaccines fall into this group (Forni & Mantovani, 2021). mRNA plays a role in protein synthesis that is naturally produced in our body. Artificially produced mRNAs in the laboratory work just like our own mRNAs to warn us against the virus. These molecules are then broken down like our own molecules and excreted from the body. The majority of mRNA-based vaccination initiatives use lipid microvesicles to transport the mRNA (liposomes). The Spike protein, as well as any of its variants or fragments, serves as the target antigen encoded by the anti-SARS-CoV-2 mRNA vaccines, if not fully. These types of vaccines are produced in a similar way to the technology that has been working with personalized immunotherapy methods for the treatment of many diseases, including cancer, for 25 years. These are considered safe and do not cause disease (Dai et al., 2019; Khuroo et al., 2020). BioNTech/Pfizer and Moderna/USA vaccines are included in this group. The biggest disadvantage of these vaccines is that they must be maintained at -20℃ (Moderna) and -70°C (BioNTech). For the other group of vaccines, -2 to -8°C degrees is sufficient (Forni & Mantovani, 2021).

These studies constitute a Multi Criteria Decision Making (MCDM) problem since a variety of criteria should be taken into account when determining how well COVID-19 vaccinations function, and MCDM approaches are typically applied in these investigations. First, seven criteria affecting the performance of vaccines were considered and data of the criteria were collected. Weighting was then performed with Fuzzy The Decision Making Trial and Evaluation Laboratory (F-DEMATEL). Then, Ranking of Alternatives through Functional mapping of criterion sub-intervals into a Single Interval (RAFSI) method was used to sort the performance of the five vaccine variants with the data of the criteria. The study is divided into three parts: the second part provides a brief overview of previous research on COVID-19 vaccines and the contribution this study makes to the field; the third part provides details on the suggested methodology for addressing the issue of determining the effectiveness of vaccines. The final part outlines the key findings of this investigation.

## 2. LİTERATURE REVİEW

There are many studies in the literature in which COVID-19 has been evaluated by MCDM methods from different angles. Some of these are included:

Alemdar et al. (2021) calculated the criterion weights using the Analytical Hierarchy Process (AHP) in the selection of the location of vaccination centers and spatial analysis of the criteria was performed using the Geographic Information System (GIS). A study vaccine selection decision-making model is proposed and created by Abdelwahab et al. (2021) based on the AHP approach, which assesses several alternatives (vaccines) using various criteria to promote decision-making. Hezam et al. (2021), in the study, it was determined that health personnel, people at high risk of health, the elderly, forced workers, pregnant and lactating mothers are the top priority people to receive the vaccine dose for the first time in ordering the COVID-19 vaccine alternatives using the neutrophisophilic TOPSIS method.

Forestal and Pi (2022) developed an integrated framework for selecting and sequencing the most appropriate potential vaccine against COVID-19, using a hybrid methodology based on the ELimination Et Choice Translating Reality III (ELECTRE III)-Genetic Algorithm (GA) and Technique of Order Preference by Similarity to the Ideal Solution (TOPSIS) approach. Garai and Garg (2022) suggested the interpreter technique under the neutrosophical environment, the only valuable bipolar with a new MCDM technique to select COVID-19 vaccines.

According to Yazıcı et al. (2022), factors influencing the vaccine selection process were identified, and the weights of these factors were estimated using the AHP approach. The Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) approaches were then used to order the alternatives in an integrated manner using the determined criteria weights. Comparative analysis of both approaches' outcomes was conducted.

Additionally, it is hoped that this study will contribute to the expanding body of information concerning the efficacy and security of COVID-19 vaccines.

## 3. METHODS

In order to assess options in relation to a set of specified criteria, which is the major topic of this article, the MCDM approaches have been picked since they comprise rigorous mathematical processes. While the fuzzy DEMATEL method was used to weighting the criteria affecting the performance of COVID-19 vaccine types, the RAFSI method was used to sort the performance of the vaccines with the determined criteria. The process steps of the study, which consists of 3 stages, are given in Figure 1.

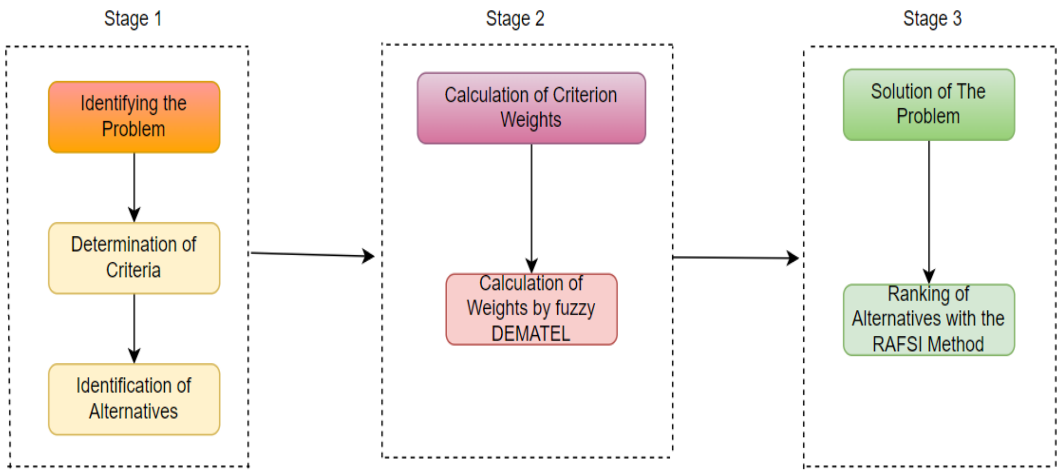


**Fig.1.** The flowchart of the proposed approach.

Source: Author

### 3.1. Fuzzy Theory

Fuzzy set its place in the literature with Zadeh's article called Fuzzy Sets published in the "Information and Control" journal in 1965. Fuzzy set theory is a method used to express uncertainty and enables decision-makers to make their evaluations using linguistic variables. Fuzzy sets can be thought of as a generalized form of the classical concept of sets. Membership function values that take {0,1} values in classical sets can take infinite values in the range of [0,1] in fuzzy sets. According to the properties of classical and fuzzy sets, the main difference between the two sets is that the membership functions are different. When evaluated theoretically, although the membership function of fuzzy sets is infinite, classical sets have only one membership function. Fuzzy numbers form special subsets of fuzzy sets. Fuzzy numbers can take place in a wide variety of ways in theory and practice. Fuzzy numbers are approximately 7, close to 8, around 9 etc. These are forms of expression developed to express uncertain quantities. However, the most common fuzzy numbers are triangular fuzzy numbers. In a fuzzy ($\tilde{N}$) set, triangular fuzzy numbers are expressed in the form of $(l, m, u)$. Looking at the expressed values;

$l$: Smallest possible value

$m$: Most expected value

$u$: Defined as the highest possible value.

A triangle fuzzy number is shown in Figure 2.

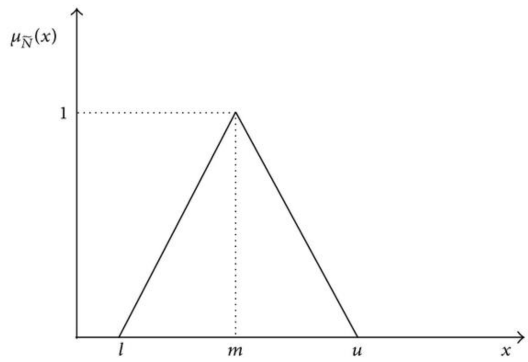


**Fig. 2.** A triangular fuzzy number $\tilde{N}$

Source: Chen (2000: 3).

Some basic definitions of fuzzy logic are given below:

**Definition 1:** In a fuzzy ($\tilde{N}$) set, the triangular fuzzy number $(l, m, u)$ is expressed with 3 values, and the membership function is expressed by equation (1).

$$\mu_{\tilde{N}}(x) = \begin{cases} 0 & x \leq l \\ \frac{x-l}{m-l} & l \leq x \leq m \\ \frac{u-x}{u-m} & m \leq x \leq u \\ 0 & x > u \end{cases} \quad (1)$$

Here $l, m$ and $u$ are real numbers and they must be $l \leq m \leq u$.

**Definition 2:** Let two fuzzy sets $\tilde{A}(a_1, a_2, a_3)$ and $\tilde{B}(b_1, b_2, b_3)$. Some operations belonging to these fuzzy sets are defined as follows.

1. $(a_1, a_2, a_3) \oplus (b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3)$
2. $(a_1, a_2, a_3) \otimes (b_1, b_2, b_3) = (a_1.b_1, a_2.b_2, a_3.b_3)$
3. $(a_1, a_2, a_3) \ominus (b_1, b_2, b_3) = (a_1 - b_3, a_2 - b_2, a_3 - b_1)$
4. $k \otimes (a_1, a_2, a_3) = (k.a_1, k.a_2, k.a_3)$, k>0

### 3.2. F-DEMATEL Method

DEMATEL method is a multi-criteria decision making method developed in 1973 by the Science and Human Relations program of the research center of Battelle Memorial Institute in Geneva. This method enables the structural model among complex factors to be revealed sağlar (Wu, 2008; Li & Tzeng, 2009). The technique that enables decision-makers to visually analyze becomes more relevant and simple to understand after identifying how the criteria interact (Li & Tzeng, 2009). In the method, the criteria are divided into two affecting (cause) and affected (result). The cause criterion is the criterion that has more influence over other criteria. The result criterion is the criterion that falls under the influence of other criteria.

The degree of interaction between criteria in cause and effect connections is extremely difficult to ascertain. Experts have a very difficult time quantifying the interplay between criteria, which is the cause of this. Due to this, Lin and Wu applied the DEMATEL approach to a fuzzy environment in 2008 and introduced the Fuzzy DEMATEL method to the literature. The following are the steps of the suggested fuzzy DEMATEL method (Seyed-Hosseini et al., 2006; Tseng & Lin, 2008; Demir, 2021a):

***Step1:*** Defining expert panel and evaluation criteria

In this process, the problem-related evaluation criteria are initially established. To make decisions on the issue at hand, a panel of subject-matter experts should be established.

***Step 2.*** Fuzzy pairwise comparison matrix

A scale is created so that decision-makers can compare the relationships between the criteria. In order to eliminate the difficulty in grading these relationships, the different degrees of 'influence', which consists of linguistic variables suggested by Li (1999) in group decisions, are expressed in five language terms such as {Very high, High, Low, Very low, No} and correspond to them. The positive triangle fuzzy numbers are given in Table 1.

**Table 1.** Linguistic terms and reciprocity of linguistic value

| Linguistic Terms | Triangular fuzzy numbers |
|---|---|
| Very high impact (VH) | (075 ; 1,00 ; 1,00) |
| High impact (H) | (0,50 ; 0,75 ; 1,00) |
| Low impact (L) | (0,25 ; 0,50 ; 0,75) |
| Very low impact (VL) | (0,00 ; 0,25 ; 0,50) |
| No effect (No) | (0,00 ; 0,00 ; 0,25) |

The triangular fuzzy numbers used for linguistic terms are given in Figure 3.

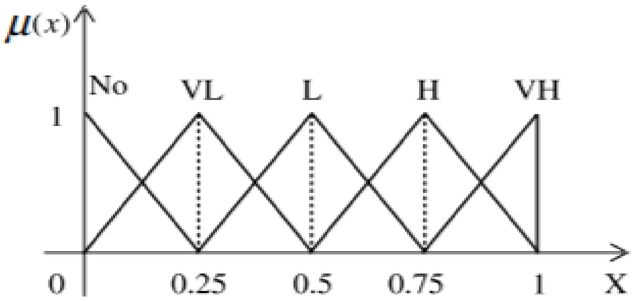


**Fig. 3.** Triangular fuzzy numbers for linguistic variables

***Step 3.*** Set-up fuzzy initial direct relation matrix

$C = \{C_i \mid i = 1,2,..,n\}$ to determine the relationships between criteria, decision makers, consisting of $p$ experts, make binary comparisons using linguistic terms. $p$ fuzzy matrices $\tilde{Z}^{(1)}$, $\tilde{Z}^{(2)}$,…, $\tilde{Z}^{(p)}$ each corresponding to an expert are obtained. Accordingly, the elements $i$. criterion $j$. direct relationship matrix of expert $k$ consisting of triangular fuzzy numbers $\tilde{z}_{ij}^{(k)} = (\tilde{l}_{ij}^{(k)}, \tilde{m}_{ij}^{(k)}, \tilde{u}_{ij}^{(k)})$. It is given in equation (2).

$$\tilde{Z}^{(k)} = \begin{bmatrix} 0 & \tilde{z}_{12}^{(k)} & \cdots & \tilde{z}_{1n}^{(k)} \\ \tilde{z}_{21}^{(k)} & 0 & \cdots & \tilde{z}_{2n}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{z}_{n1}^{(k)} & \tilde{z}_{n2}^{(k)} & \cdots & 0 \end{bmatrix} \quad k = 1,2,\dots,p \qquad (2)$$

***Step 4.*** Calculate normalised fuzzy direct relation matrix

Normalized fuzzy direct relation matrix shown as $\tilde{X}^k = [\tilde{x}_{ij}^k]_{nxn}$ is obtained by using equations (3) and (4).

$$\tilde{X}^k = \frac{\tilde{Z}^k}{r^k} \quad (3)$$

$$r^k = \max_{1 \le i \le n} \sum_{j=1}^{n} u_{ij}^k \quad (4)$$

***Step 5.*** Calculate fuzzy total relation matrix

The total fuzzy direct relationship matrix ($\widetilde{T}$ ) denoted by is calculated by equation (5) to show the identity matrix $I$.

$$\tilde{T} = \lim_{k \to \infty} (\tilde{X}^1 + \tilde{X}^2 + \cdots + \tilde{X}^k) = \tilde{X}(I - X)^{-1} \quad (5)$$

Here $\tilde{t}_{ij}$ = ($l_{ij}$ ′ , $m_{ij}$ ′ , $u_{ij}$ ′ ) is and ($\widetilde{T}$ ) matrix can be obtained by equation (6).

Matrix [$l_{ij}$ ′ ] = $X_l(I - X_l)^{-1}$, matrix [$m_{ij}$ ′ ] = $X_m(I - X_m)^{-1}$, matrix [$u_{ij}$ ′ ] = $X_u(I - X_u)^{-1}$ (6)

***Step 6.*** Determining cause and effect relationships

After the $\tilde{T}$ matrix is obtained, $\widetilde{D}_i + \tilde{R}_i$ and $\widetilde{D}_i - \tilde{R}_i$ values are calculated, with the sum of the row elements $\widetilde{D}_i$ and the sum of the column elements $\tilde{R}_i$. The following defuzzifying process is performed first to create the relationships. The term "def" in equations (7) and (8) is an abbreviation of the word "defuzzifying", which means clarification.

$$\widetilde{D}_i^{def} + \tilde{R}_i^{def} = 1/4\,(x_{ij,l} + 2x_{ij,m} + x_{ij,u}) \quad (7)$$

$$\widetilde{D}_i^{def} - \tilde{R}_i^{def} = 1/4\,(x_{ij,l} + 2x_{ij,m} + x_{ij,u}) \quad (8)$$

$\widetilde{D}_i^{def} + \tilde{R}_i^{def}$ value shows the importance and total effect of a criterion among other criteria, while the value of $\widetilde{D}_i^{def} - \tilde{R}_i^{def}$ allows the criteria to be divided into two groups as shipment or receiver. If the value is positive, it is understood that the relevant criterion is in the sending group and has a higher effect on other criteria. If it is negative, it is understood that the relevant criterion is included in the recipient group and has less effect on other criteria. Accordingly, a cause and effect diagram with $\widetilde{D}_i^{def} + \tilde{R}_i^{def}$ on the horizontal axis and $\widetilde{D}_i^{def} - \tilde{R}_i^{def}$ on the vertical axis can be obtained. Using $\widetilde{D}_i^{def} + \tilde{R}_i^{def}$ and $\widetilde{D}_i^{def} - \tilde{R}_i^{def}$ values, the level of influence and relationship between each criterion and other criteria is determined. Some criteria for the $\widetilde{D}_i^{def} - \tilde{R}_i^{def}$ value have a positive value. These criteria have a higher impact and priority over other criteria. This type of criteria is called an influencing criterion. Some criteria for the $\widetilde{D}_i^{def} - \tilde{R}_i^{def}$ value also have a negative value. These types of criteria have lower influence and priority over other criteria and are defined as affected criteria.

***Step 7.*** Calculation of weights

Criteria weights are calculated with the help of equations (9) and (10).

$$w_i = \sqrt{(\widetilde{D}_i^{def} + \tilde{R}_i^{def})^2 + (\widetilde{D}_i^{def} - \tilde{R}_i^{def})^2} \quad (9)$$

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad (10)$$

Since the obtained values are fuzzy numbers, the process of converting the fuzzy value to a normal value or converting it to a (crisp) value, called defuzzification, Vertex Method Equation (11) Method 1 Chen or COA (Center Of Area) method Cheng et al. Equation (12) can be achieved with the help of Method 2 (Chen, 2000; Cheng et al., 2008).

$$Y_1 = \frac{l+4m+u}{6} \quad (11)$$

$$Y_2 = [(u-l)+(m-l)]:3+1 \quad (12)$$

### 3.3. RAFSI Method

RAFSI is a new method used by Žižović et al. to sort the alternatives introduced into the literature in 2020. The RAFSI approach does not employ conventional methods for normalizing data. In its place, a novel standardization method is presented, enabling data translation from the basic decision matrix to any range and making this approach appropriate for making logical decisions. According to the properties of the criterion, a special range of criteria is developed using mathematical and harmonic techniques. The method's most crucial characteristic that sets it apart from other alternative sequencing approaches is the fact that it enables a forecast of the decision-subjectivity maker's to be included in the model when establishing ideal and anti-ideal values.

Suppose that decision-makers should sort on the basis of the $m$ alternatives (line) $n$ on the basis of the criterion (column).

To satisfy the condition of the criterion weights $(w_j, j = 1,2,\ldots,n)$ and $\sum_{j=1}^{n} w_j = 1$, the criteria are given in the utility (max) or cost (min) properties and the initial decision matrix ($N$) Equation (13).

$$N = [n_{ij}]_{mxn} = \begin{bmatrix} n_{11} & \cdots & n_{1n} \\ \cdots & \cdots & \cdots \\ n_{m1} & \cdots & n_{mn} \end{bmatrix} \; i = 1,2,\ldots,m \; and \; j = 1,2,\ldots,n \quad (13)$$

The application steps for the method are as follows (Žižović et al., 2020; Demir, 2021b):

***Step 1.*** Determination of ideal and anti-ideal values

For each $C_j$ $(j = 1,2,\ldots,n)$ criterion, two values, $a_{I_j}$ and $a_{N_j}$, are determined by the decision maker.

$a_{I_j}$: The ideal value of criterion $C_j$

$a_{N_j}$: It shows the anti-ideal value of criterion $C_j$.

For the benefit criteria $a_{I_j} > a_{N_j}$

For cost criteria, there is a relationship between ideal and anti-ideal values in the form of $a_{I_j} < a_{N_j}$

***Step 2.*** Matching the elements of the starting decision matrix to the criterion intervals

If $C_j$ is the benefit criterion, $C_j \in [a_{N_j}, a_{I_j}]$ then $C_j$ is the cost criterion $C_j \in [a_{I_j}, a_{N_j}]$

To transfer all the criteria of the initial decision matrix to the $[n_1, n_{2k}]$ criterion range, a sequence of numbers is created from the $k$ range by adding the points $k-1$ between the largest and smallest values of the criterion range.

$$n_1 < n_2 \leq n_3 < n_4 \leq n_5 < n_6 \leq \cdots \leq n_{2k-1} < n_{2k} \tag{14}$$

The criterion range is constant for all criteria and has fixed points such as $n_1$ and $n_{2k}$.

The minimum value is $a_{N_j}$ (for the benefit-featured criterion) and $a_{I_j}$ (for the cost criterion) is $n_1$.

The maximum value is $a_{I_j}$ (for the benefit criterion) and $a_{N_j}$ (for the cost-specificated criterion) is $n_{2k}$.

It is recommended that the ideal value be at least 6 times better than the anti-ideal value or $n_1$ be at least 6 times better than $n_{2k}$ ($n_1 = 1$ and $n_{2k} = 6$).

However, it has been suggested that it can be used at preferred values in the form of a decision maker ($n_1 = 1$ and $n_{2k} = 9$). However, it has been suggested that it can be used at preferred values in the form of a decision maker.

Equation (15) defines a function $f_s(x)$ that maps subranges to the criterion range $[n_1, n_{2k}]$.

$$f_s(x) = \frac{n_{2k} - n_1}{a_{I_j} - a_{N_j}}.x + \frac{a_{I_j}.n_1 - a_{N_j}.n_{2k}}{a_{I_j} - a_{N_j}} \tag{15}$$

Here, $n_{2k}$ and $n_1$ represent the relationship that indicates the degree to which the ideal value is preferred over the anti-ideal value.

Equation (15) is part of a function that maps part of the range $\left[a_{N_j}, a_{I_j}\right]$ to the interval $[n_1, n_{2k}]$.

Determination of numbers $a_{I_j}$and $a_{N_j}$;

- Values in the criteria range
- Extremes of the criterion range

are determined by application. The second case is used in this article. In this way, the standardized decision matrix $S = \left[s_{ij}\right]_{mxn}( i = 1,2, \dots, m \; and \; j = 1,2, \dots, n)$ is obtained, in which all the elements of the matrix are mapped to the range $[n_1, n_{2k}]$. After the initial decision matrix $N$ elements are functionally mapped to the criterion range $[n_1, n_{2k}]$, $n_1 < s_{ij} < n_{2k}$ is obtained for each $i$ and $j$.

$$S = \left[s_{ij}\right]_{mxn} = \begin{bmatrix} s_{11} & \cdots & s_{1n} \\ \cdots & \cdots & \cdots \\ s_{m1} & \cdots & s_{mn} \end{bmatrix} \; i = 1,2, \dots, m \; and \; j = 1,2, \dots, n \tag{16}$$

Pay attention to the following:

- For benefit criteria, if there is an $a_{xj}$ that will be $a_{xj} > a_{Ij}$, there is $f\left(a_{xj}\right) = f(a_{Ij})$.
- For cost criteria, if there is an $a_{xj}$ that will be $a_{xj} < a_{Ij}$, there is $f\left(a_{xj}\right) = f(a_{Ij})$.

***Step 3.*** Calculation of arithmetic and harmonic averages

Using equation (17-18), arithmetic and harmonic means are calculated for the minimum and maximum sequence of elements $n_1$ and $n_{2k}$.

$$A = \frac{n_1 + n_{2k}}{2} \tag{17}$$

$$H = \frac{2. n_1. n_{2k}}{n_1 + n_{2k}} \tag{18}$$

***Step 4.*** Obtaining the normalized decision matrix $(\hat{S})$

$\hat{S} = [\hat{s}_{ij}]_{mxn} = \begin{bmatrix} \hat{s}_{11} & \cdots & \hat{s}_{1n} \\ \cdots & \cdots & \cdots \\ \hat{s}_{m1} & \cdots & \hat{s}_{mn} \end{bmatrix}, (i = 1,2, \dots, m \; and \; j = 1,2, \dots, n)$ using Equation (19-20) for the normalized matrix, the elements of the $S$ matrix are normalized and transferred to the interval [0,1].

For benefit criteria;

$$\hat{s}_{ij} = \frac{s_{ij}}{2A} \tag{19}$$

For cost criteria;

$$\hat{s}_{ij} = \frac{H}{2s_{ij}} \tag{20}$$

The following conditions apply to the elements of the normalized decision matrix $\hat{S} = [\hat{s}_{ij}]_{mxn}$ matrix obtained using equality (19-20).

- For benefit criteria; $0 < \frac{n_1}{2A} \leq \hat{s}_{ij} \leq \frac{n_{2k}}{2A} < 1$
- For cost criteria; $0 < \frac{H}{2n_{2k}} \leq \hat{s}_{ij} \leq \frac{H}{2n_1} < 1$

are valid.

***Step 5.*** Determination of the criterion functions of alternatives

Using equation (21), the criterion functions of the alternatives $(V(A_i))$ are calculated.

$$V(A_i) = w_1. \hat{s}_{i1} + w_2. \hat{s}_{i2} + \cdots + w_n. \hat{s}_{in} \tag{21}$$

Then the values found are sorted according to the decreasing order.

## 4. APPLİCATİON

### 4.1. Description of the Problem

The study is based on quantitative assessment of the performance of COVID-19 vaccines, characteristics that describe the status of each vaccine and the use of multi-criteria evaluation methods. All data used in the analysis were obtained from the vaccine website. The criteria used are given in Table 2 with the codes to be used in the study and the features they have.

**Table 2.** Evaluation Criteria

| | |
|---|---|
| CR1 | Effectiveness rate of vaccines (%) (max) |
| CR2 | Storage periods of vaccines (day) (max) |
| CR3 | Cold chain of vaccines (°C) (max) |
| CR4 | Number of doses applied (min) |
| CR5 | Double dose price ($) (min) |
| CR6 | Protective properties of vaccines (max) |
| CR7 | Side effects of vaccines (min) |

Given that vaccines are produced by different methods, CR6 special fuzzy linguistic identifiers have been used to evaluate this criterion. These are; very low (1;1;2), low (1,5; 2;2,5), small (2;3;4), medium (3,5;4;4,5), high (4;5;6), very high (5,5;6;6). This criterion has been determined in line with the opinions of the decision-making group consisting of 10 academicians who have scientific studies in the field of health and follow these studies. Likewise, special fuzzy linguistic identifiers were used to evaluate the CR7 criterion. These are; very small (1;1;2), small (1,5;3;4,5), medium (3,5;5;6,5), high (6;7;7For this criterion, it was determined by taking the opinions of the decision-making group consisting of doctors/nurses working in the health sector. The COVID-19 vaccines whose performance was examined in the study are given in Table 3.

**Table 3.** COVID-19 vaccines

| Alternatives | CR1 | CR2 | CR3 | CR4 | CR5 | CR6 | CR7 |
|---|---|---|---|---|---|---|---|
| BioNTech (V1) | 95 | 14 | -70 | 2 | 50 | (5,5;6;6) | (1;1;2) |
| Moderna (V2) | 92 | 30 | -20 | 2 | 39 | (4;5;6) | (6;6;7) |
| Sputnik V (V3) | 92 | 180 | 4 | 2 | 20 | (3,5;4;4,5) | (1,5;3;4,5) |
| AstraZeneca (V4) | 79 | 180 | 4 | 2 | 6 | (2;3;4) | (1,5;3;4,5) |
| Sinovac (V5) | 97 | 150 | -20 | 3 | 60 | (5,5;6;6) | (6;7;7) |

### 4.2. The Application of F-DEMATEL Method

***Step1:*** Defining expert panel and evaluation criteria

The criteria created with expert opinions and given in Table 2 were used.

***Step 2.*** Fuzzy pairwise comparison matrix

The fuzzy triangular numbers in Table 1 are used for binary comparison.

***Step 3.*** Set-up fuzzy initial direct relation matrix

The fuzzy direct relationship matrix obtained is given in Table 4.

**Table 4.** Direct Relationship Matrix with Fuzzy Numbers

| Criteria | CR1 | CR2 | CR3 | CR4 | CR5 | CR6 | CR7 |
|---|---|---|---|---|---|---|---|
| **CR1** | (0;0;0) | (0;0,25;0,5) | (0;0;0,25) | (0;0;0,25) | (0;0;0,25) | (0,75;1;1) | (0;0,25;0,5) |
| **CR2** | (0,75;1;1) | (0;0;0) | (0;0;0,25) | (0;0;0,25) | (0,25;0,5;0,75) | (0,5;0,75;1) | (0;0,25;0,5) |
| **CR3** | (0,75;1;1) | (0,75;1;1) | (0;0;0) | (0;0,25;0,50) | (0,5;0,75;1) | (0,25;0,5;0,75) | (0,25;0,5;0,75) |
| **CR4** | (0,5;0,75;1) | (0;0;0,25) | (0,25;0,5;0,75) | (0;0;0) | (0,75;1;1) | (0,75;1;1) | (0,5;0,75;1) |
| **CR5** | (0;0;0,25) | (0;0;0,25) | (0;0;0,25) | (0,5;0,75;1) | (0;0;0) | (0,5;0,75;1) | (0,5;0,75;1) |
| **CR6** | (0,75;1;1) | (0;0,25;0,50) | (0,75;1;1) | (0,75;1;1) | (0;0;0,25) | (0;0;0) | (0,5;0,75;1) |
| **CR7** | (0,25;0,5;0,75) | (0;0;0,25) | (0,25;0,50;0,75) | (0;0,25;0,5) | (0,5;0,75;1) | (0,5;0,75;1) | (0;0;0) |

***Step 4.*** Calculate normalised fuzzy direct relation matrix

Matrix is normalized by Equation (3-4). Decision makers' normalized matrix is given in the Table 5.

**Table 5.** Normalized Direct Relation Matrix

| Criteria | CR1 | CR2 | CR3 | CR4 | CR5 | CR6 | CR7 |
|---|---|---|---|---|---|---|---|
| **CR1** | (0;0;0) | (0;0,043;0,087) | (0;0;0,043) | (0;0;0,043) | (0;0;0,043) | (0,130;0,174;0,174) | (0;0,043;0,087) |
| **CR2** | (0,130;0,174;0,174) | (0;0;0) | (0;0;0,043) | (0;0;0,043) | (0,043;0,087;0,130) | (0,087;0,130;0,174) | (0;0,043;0,087) |
| **CR3** | (0,130;0,174;0,174) | (0,130;0,174;0,174) | (0;0;0) | (0;0,043;0,087) | (0,087;0,130;0,174) | (0,043;0,087;0,130) | (0,043;0,087;0,130) |
| **CR4** | (0,087;0,130;0,174) | (0;0;0,0625) | (0,043;0,087;0,130) | (0;0;0) | (0,130;0,174;0,174) | (0,130;0,174;0,174) | (0,087;0,130;0,174) |
| **CR5** | (0;0;0,043) | (0,0625;0,125;0,1875) | (0;0;0,043) | (0,087;0,130;0,174) | (0;0;0) | (0,087;0,130;0,174) | (0,087;0,130;0,174) |
| **CR6** | (0,130;0,174;0,174) | (0;0,043;0,087) | (0,130;0,174;0,174) | (0,130;0,174;0,174) | (0;0;0,043) | (0;0;0) | (0,087;0,130;0,174) |
| **CR7** | (0,043;0,087;0,130) | (0;0;0,043) | (0,043;0,087;0,130) | (0;0,043;0,087) | (0,087;0,130;0,174) | (0,087;0,130;0,174) | (0;0;0) |

***Step 5.*** Calculate fuzzy total relation matrix

Equation is used to generate the total relation matrix after getting the normalized relation matrix (5-6). The whole relation matrix that was obtained is presented in Table 6.

**Table 6.** Total Relation Matrix

| Criteria | CR1 | CR2 | CR3 | CR4 | CR5 | CR6 | CR7 |
|---|---|---|---|---|---|---|---|
| **CR1** | (0,023;0,074;0,230) | (0,003;0,065;0,210) | (0,019;0,052;0,209) | (0,018;0,050;0,216) | (0,005;0,033;0,224) | (0,138;0,225;0,406) | (0,015;0,093;0,300) |
| **CR2** | (0,150;0,245;0,437) | (0,002;0,029;0,164) | (0,017;0,054;0,248) | (0,019;0,062;0,265) | (0,048;0,122;0,343) | (0,116;0,222;0,479) | (0,017;0,112;0,361) |
| **CR3** | (0,166;0,298;0,525) | (0,132;0,209;0,369) | (0,016;0,070;0,264) | (0,021;0,123;0,366) | (0,102;0,203;0,461) | (0,094;0,244;0,548) | (0,063;0,189;0,481) |
| **CR4** | (0,130;0,262;0,533) | (0,010;0,056;0,265) | (0,073;0,175;0,395) | (0,037;0,108;0,300) | (0,152;0,253;0,470) | (0,179;0,326;0,591) | (0,122;0,248;0,532) |
| **CR5** | (0,033;0,100;0,357) | (0,003;0,027;0,214) | (0,025;0,074;0,278) | (0,105;0,191;0,397) | (0,025;0,072;0,263) | (0,118;0,226;0,505) | (0,110;0,205;0,462) |
| **CR6** | (0,177;0,319;0,529) | (0,019;0,107;0,297) | (0,149;0,247;0,421) | (0,142;0,241;0,427) | (0,042;0,114;0,359) | (0,063;0,179;0,424) | (0,115;0,239;0,511) |
| **CR7** | (0,069;0,185;0,447) | (0,008;0,044;0,237) | (0,060;0,147;0,358) | (0,023;0,119;0,343) | (0,098;0,186;0,427) | (0,113;0,238;0,532) | (0,023;0,093;0,333) |

***Step 6.*** Determining cause and effect relationships

The sum of row and columns are shown with the vectors $\widetilde{D}_i$ and $\tilde{R}_i$ seperately. Later, $\widetilde{D}_i + \tilde{R}_i$ and $\widetilde{D}_i - \tilde{R}_i$ values are calculated and given in Table 7.

**Table 7**. Affecting and Affected Criteria

| Criteria | $\widetilde{D}_i$ | $\widetilde{R}_i$ | $\widetilde{D}_i + \widetilde{R}_i$ | $\widetilde{D}_i - \widetilde{R}_i$ |
|---|---|---|---|---|
| **CR1** | (0,221;0,592;1,795) | (0,748;1,483;3,058) | (0,969;2,075;4,853) | (-0,527;-0,891;-1,263) |
| **CR2** | (0,369;0,846;2,297) | (0,177;0,537;1,756) | (0,546;1,383;4,053) | (0,192;0,309;0,541) |
| **CR3** | (0,594;1,336;3,014) | (0,359;0,819;2,173) | (0,953;2,153;5,187) | (0,235;0,519;0,841) |
| **CR4** | (0,703;1,428;3,086) | (0,365;0,894;2,314) | (1,068;2,322;5,400) | (0,338;0,534;0,772) |
| **CR5** | (0,419;0,895;2,476) | (0,472;0,983;2,547) | (0,891;1,878;5,023) | (-0,053;-0,071; -0,088) |
| **CR6** | (0,707;1,446;2,968) | (0,821;1,660;3,485) | (1,528;3,106;6,453) | (-0,114;-0,214;-0,517) |
| **CR7** | (0,394;1,012;2,677) | (0,465;1,179;2,980) | (0,859;2,191;5,657) | (-0,071;-0,167;-0,303) |

Equation (7-8)'s vertex technique is used to defuzzify triangular fuzzy integers, returning them to a single value. Defuzzified values are provided in Table 8.

**Table 8.** Defuzzified Values

| Criteria | $\widetilde{D}_i^{def} + \widetilde{R}_i^{def}$ | $\widetilde{D}_i^{def} - \widetilde{R}_i^{def}$ |
|---|---|---|
| **CR1** | 2,493 | -0,893 |
| **CR2** | 1,841 | 0,338 |
| **CR3** | 2,612 | 0,529 |
| **CR4** | 2,778 | 0,545 |
| **CR5** | 2,418 | -0,075 |
| **CR6** | 3,548 | -0,265 |
| **CR7** | 2,725 | -0,177 |

Then, using defuzzifying fuzzy triangular numbers, a cause-effect diagram is drawn and given in Figure 4.

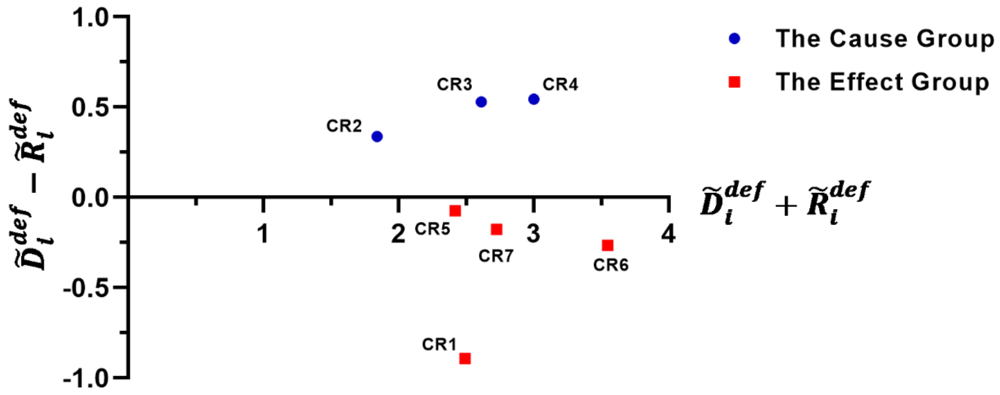


**Fig. 4.** Cause-Effect Relation Diagram

According to figure, CR2, CR3 and CR4 criteria show the reasons affecting the performance of COVID-19 vaccines, while CR1, CR5, CR6 and CR7 criteria are the result criteria of this performance. In other words, it can be said that CR2, CR3 and CR4 criteria affect the performance of COVID-19 vaccines and CR4 criterion is the criterion that affects this performance the most. It can be said that CR1, CR5, CR6 and CR7 criteria are also affected by this performance.

***Step 7.*** Calculation of weights

Equation (9) is used to determine the importance weights for the criterion, and Equation (10) is used to normalize the results (10). The Table 9 displays these values.

**Table 9.** Weights of Criteria

| **Criteria** | ***w*** | ***W*** |
|---|---|---|
| **CR1** | 2,648 | 0,141 |
| **CR2** | 1,872 | 0,100 |
| **CR3** | 2,665 | 0,142 |
| **CR4** | 2,831 | 0,151 |
| **CR5** | 2,419 | 0,129 |
| **CR6** | 3,558 | 0,191 |
| **CR7** | 2,731 | 0,146 |
| **Total** | 18,724 | 1 |

Protective properties of vaccines (CR6) is the best critera.

### 4.3. The Application of RAFSI Method

***Step 1.*** Determination of ideal and anti-ideal values

Using Table 3, ideal and anti-ideal values were determined for all criteria.

$$\tilde{\Sigma}_{I_j} = \{100; 360; 4; 1; 5; 6; 1\}$$

$$\tilde{\Sigma}_{N_j} = \{90; 7; -70; 3; 60; 2; 7\}$$

***Step 2.*** Matching the elements of the initial decision matrix to the criterion intervals
$CR1 \in [75,100]$ $CR2 \in [7,360]$ $CR3 \in [-70,4]$ $CR4 \in [1,3]$ $CR5 \in$
$[5,60]$ $CR6\ [2,6]$

$CR7 \in [1,7].\ n_1 = 1\ ve\ n_6 = 6.$

***Step 3.*** Calculation of arithmetic and harmonic means

Using equation (17-18), $A = 3{,}5$ and $H = 1{,}71$ were calculated.

***Step 4.*** Obtaining the normalized decision matrix

The decision matrix normalized using equation (19-20) is given in Table 10.

**Tablo 10.** Normalized decision matrix

| Alternatives | CR1 | CR2 | CR3 | CR4 | CR5 | CR6 | CR7 |
|---|---|---|---|---|---|---|---|
| V1 | 0,714 | 0,157 | 0,143 | 0,244 | 0,448 | (0,768;0,857;0,857) | (0,467;0,855;0,855) |
| V2 | 0,629 | 0,189 | 0,625 | 0,244 | 0,303 | (0,5;0,679;0,857) | (0,143;0,143;0,165) |
| V3 | 0,629 | 0,493 | 0,857 | 0,244 | 0,184 | (0,411;0,5;0,589) | (0,218;0,320;0,602) |
| V4 | 0,257 | 0,493 | 0,857 | 0,244 | 0,145 | (0,143;0,321;0,5) | (0,218;0,320;0,602) |
| V5 | 0,771 | 0,432 | 0,625 | 0,143 | 0,855 | (0,768;0,857;0,857) | (0,143;0,143;0,165) |

***Step 5.*** Determination of the criterion functions of alternatives

First, Equation (11) was used to clarify the CR6 and CR7 criteria. Then, using Equation (21), the criterion functions of the alternatives were calculated. All these obtained values are given in Table 11.

**Table 11.** Defuzzied Values and Criterion Function Values of Alternatives

| Alternatives | $\widetilde{CR}6^{def}$ | $\widetilde{CR}7^{def}$ | $Q(A_i)$ | Ranking |
|---|---|---|---|---|
| V1 | 0,842 | 0,790 | 0,6487 | 1. |
| V2 | 0,679 | 0,147 | 0,4234 | 3. |
| V3 | 0,500 | 0,350 | 0,4669 | 2. |
| V4 | 0,321 | 0,350 | 0,3752 | 5. |
| V5 | 0,842 | 0,147 | 0,4136 | 4. |

As a result of the evaluation made for the performance of COVID-19 vaccines with the determined criteria, it was seen that the performance of the BioNTech vaccine was the highest and the performance of the AstraZeneca vaccine was the lowest.

## RESULT

The COVID-19 virus is still spreading over the world. The need for safe and efficient vaccinations has skyrocketed as a result of this global dissemination. The purpose of this essay is to compare the many vaccination choices and select the best choice. Seven criteria, encompassing quantitative and qualitative assessments and requiring many complicated aspects, were employed in the decision-making and evaluation procedures. MCDM techniques may be used to accurately choose the best COVID-19 vaccination in such procedures.

Abdelwahab et al. (2021), while they preferred AstraZeneca (22.38%) and then Janssen (21.56%) with the first participant they benefited from in their study, they preferred the NIH-Moderna vaccine and then the Pfizer-BioNTech vaccine (30.15% and 30.11%, respectively) with the other participant. Yazıcı et al. (2022) found that AstraZeneca vaccines were the first alternative for all countries according to the TOPSIS method and BioNTech vaccines were preferred for all countries in the PROMETHEE method. The vaccines that took the first place in these studies using the names of the vaccines differ from the vaccine that took place in the first place of this study. It is similar to the result of the PROMETHEE method only.

After conducting a detailed research, a model was developed that evaluates the protection of the vaccines and the side effects of the vaccines together by taking into account the effectiveness rate of the vaccines, the storage times of the vaccines, the cold chain of the vaccines, the number of doses administered, the double dose price and expert opinions. F-DEMATEL method was used to weight these criteria. The protective property of vaccines (CR6) has been the most important criterion. The best pandemic vaccine was chosen using a hybrid MCDM strategy based on the RAFSI technique. The outcomes demonstrated that, in accordance with the suggested paradigm, BioNTech was the best vaccination.

This study adds to the body of knowledge by extending the useful uses of RAFSI and F-DEMATEL. The F-DEMATEL method is a simple and understandable analysis used in criterion weighting. RAFSI, which does not use traditional normalization methods, is the model used to enumerate the alternatives that allow a prediction of the subjectivity of the decision maker to be in the model in determining ideal and anti-ideal values. According to the results of the F-DEMATEL method, the criteria used in the evaluation of COVID-19 vaccines showed that the protection feature of the vaccines was the most important criterion with a weight of 0,191, while the storage period of the vaccines was the least important criterion with a weight of 0,100. According to the RAFSI method, BioNTech vaccine had the maximum performance with a value of 0.6487 according to the criteria used in the proposed model, while AstraZeneca had the lowest performance with a value of 0.3752. Thus, for these reasons, the combination of F-DEMATEL and RAFSI methods ensures successful results in reaching strategic decisions.

Although a significant addition to the literature has been made, it is necessary to mention several limitations that future study may take into account. First of all, the criteria are dependent on individual assessment. As a result, this framework may be improved by include in the research certain important factors like supply chain and environment. Sensitivity analysis constitutes a second drawback. By adjusting the weights and thresholds and analyzing the outcomes, a sensitivity analysis is necessary to determine whether the decision model's conclusions are resilient. A robustness test may be included in later work to verify the model's general validity.

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