A Multi-Criteria Decision Approach using Divergence Measures for Selection of the Best COVID-19 Vaccine

H. D. Arora, Anjali Naithani, and Aakanksha

Abstract COVID-19 is a worldwide health threat that has resulted in a significant number of deaths and complicated healthcare management issues. To prevent the COVID-19 pandemic, there is a need to choose a safe and most effective vaccine. Several Multi-criteria Decision-Making (MADM) techniques and approaches have been selected to choose the optimal probable options. The purpose of this article is to deliver divergence measures for fuzzy sets. To validate these measures, some of the properties were also proved. The Multi-criteria Decision-Making method is employed to rank and hence select the best vaccine out of available alternatives. The proposed research allows the ranking of different vaccines based on specified criteria in a fuzzy environment to aid in the selection process. The results suggest that the proposed model provides a realistic way to select the best vaccine from the vaccines available. A case study on the selection of the best COVID-19 vaccine and its experimental results using fuzzy sets are discussed.

Keywords TOPSIS · Multi-criteria decision-making · Triangular fuzzy sets

1 Introduction

The fuzzy set theory proposed by Zadeh in 1965 is a beneficial tool for solving problems in vague environments. Zadeh's fuzzy sets are intended to produce an analogue of crisp set theory in the field of uncertain conditions. Zadeh created a fuzzy set theory that may be used in incidents requiring ambiguity, vagueness, uncertainty

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and hazy judgements. Theoretically, fuzzy sets might be used as a foundation for an expansion of mathematical concepts such as probability, topology and so forth whose traditional counterparts are based on the subject of crisp set theory. A Fuzzy Set primarily defines the degree to which a particular element belongs to a given set.

Fuzzy numbers were employed to get better outcomes in situations involving decision-making and evaluations. Fuzzy numbers which are an extended version of real numbers have their own features that may be linked to number theory. To make a connection between number theory and fuzzy numbers, triangular fuzzy numbers were introduced which mirror Pythagorean triples. Triangular Fuzzy Numbers (TFN) have been used to describe ambiguous and partial data in assessing risk, partial calls and knowledge-based systems.

Multi-criteria Decision-Making (MCDM) is a data science field that assesses multiple competing factors in decision-making. In domains where selecting the optimal solution is exceedingly complicated, the multi-criteria decision-making delivers robust decision taking. During the previous several years, Multi-criteria Decision-Making has had a tremendous amount of applications. Its relevance has risen considerably in a number of application sectors, especially when new techniques arise and current ones adapt. Multi-criteria Decision-Making is often utilized in a variety of fields, such as earth science, power generation, sustainability management, numerical methods and others. This study proposes a supplement to the fuzzy MCDM technique, in which the ranking of alternatives versus characteristics, as well as the weights of all criteria, are evaluated in semantic results calculated by Fuzzy numbers. Several academics in the field of linguistic modeling [4, 5] and fuzzy linguistic modeling [6] have presented the MCDM model in a fuzzy environment. Triantaphyllou et al. [7] gave Multi-criteria Decision-Making an Operations research approach. Harrera et al. [8] used a fuzzy set technique to provide a linguistic methodology for group decision-making. Kacprzyk et al. [9] propose fuzzy logic with linguistic expressions for group decision-making. Liu et al. [10] proposed a strategy for resolving fuzzy MADM issues with triangular Fuzzy Numbers depending on the connection number. For tackling multi attribute decision-making issues with given criterion weights, Wang and Gong [11] proposed a Set Pair Analysis-Based decision-making approach. Zhao and Zhang [12] presented the Set Pair Analysis-Based Triangular Fuzzy number MADM approach to handle difficulties with Multi Attribute Decision-Making when both characteristic weight and value are Triangular Fuzzy Numbers. To analyze the ambiguous MADM issue, Huang and Luo [13] proposed an index weight measure based on TFN. Moreover, Seikh et al. [14] gave Generalized triangular fuzzy numbers in an Intuitionistic fuzzy environment, and Sudha and Jayalalitha [15] defined Fuzzy triangular numbers in Sierpinski Triangle and Right-Angle Triangle. Also, Gani [16] proposed a new operation on Triangular Fuzzy Numbers for solving the fuzzy LPP.

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is an MCDM approach established by Yoon and Hwang [17], which was updated by Yoon [18] and further by Hwang et al. [19]. The TOPSIS method is founded on the principle that the preferred choice should have the smallest Euclidean Distance from Positive Ideal Solution (PIS) and the greatest Euclidean Distance from Negative

Ideal Solution (NIS) [20]. The TOPSIS technique was used by several studies to investigate the MADM methodology [21]. TOPSIS method was employed for polar fuzzy linguistic [22, 24], environmental management [25, 26], supplier section [27] and several other realistic scenarios.

The COVID-19 pandemic is a worldwide health threat that has resulted in many deaths. In order to prevent further casualties, there is a need to choose the best vaccine when all the criteria are considered simultaneously. The criteria taken in this paper are taken from https://www.who.int/ [28]. India Today [29, 30] provided the data for the availability of different vaccines, and the data for the price of different vaccines [31, 32], their after-effects [33] and their efficacy [34] has been collected from Times of India [31, 34].

The following is how the entire article is structured: the second section discusses various fundamental definitions related to Fuzzy Sets, Triangular Fuzzy Numbers and Distance Measures. In the third section, a fuzzy TOPSIS algorithm is suggested as well as a case study to select the best COVID-19 vaccine is discussed and vaccines are ranked accordingly. Finally, Sect. 4 presents the paper's conclusion.

2 Preliminaries

The theoretical foundation of fuzzy sets suggested by Zadeh [35] and Zimmerman [36, 37] is covered in this section. The following is an overview of the fuzzy set concept.

Definition 2.1 [35]. The Fuzzy Set $\boldsymbol{A}$ in Υ is described by the membership function:

$$\boldsymbol{A} = \{\langle y, \mu_A(y)\rangle | y \in \Upsilon\} \tag{1}$$

where $\mu_A(y)$: $\Upsilon \to [0, 1]$ is the measure of the degree of belongingness of participation of an element $y \in \Upsilon$ in $\boldsymbol{A}$.

Definition 2.2 [38]. Let $A = [e, f, g, h]$ be any real Fuzzy Number, thus its membership function is as follows:

$$\mu_A(x) = \begin{cases} \mu_M^L(x) & e \le x \le f \\ 1 & f \le x \le g \\ \mu_M^U(x), & g \le x \le h \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where μ_M^L (x) and μ_M^U (x) are lower and the upper Membership Functions of the Fuzzy Number $\boldsymbol{A}$, respectively, and $p = -\infty$, or $p = q$, or $q = r$, or $r = s$, or $s = +\infty$.

Definition 2.3 [36, 37]. A Triangular Fuzzy Number (TFN) $\boldsymbol{A}$ is a Fuzzy Number with piece-wise linear membership function $\mu_A(x)$ described by

$$\mu_A(x) = \begin{cases} \frac{x-u}{v-u} & u \le x \le v \\ \frac{w-x}{w-v} & v \le x \le w \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

which is represented as (u, v, w).

Definition 2.4 [39]. Let $P = (u, v, w)$ and $Q = (x, y, z)$ be any two TFNs. Then the Distance Measure function $D(P, Q)$ can be defined as

$$D(P, Q) = \sqrt{\frac{1}{3}\left\{(x-u)^2 + (y-v)^2 + (z-w)^2\right\}}. \tag{4}$$

3 Suggested Fuzzy TOPSIS Algorithm

Due to its capacity to examine several attributes concurrently, Multi Attribute Decision-Making (MADM) has appeared to be a promising technique to solve problems with inadequate or vague data. This section discusses the MADM issue in the fuzzy domain. A feasible procedure is made available to deal with MADM issues in a fuzzy environment. We know that each decision matrix in the MADM method has four main components: (a) Criteria, (b) Alternative, (c) Weights and (d) assessment value of alternatives in relation to the criteria. The method of the proposed technique will then be applied to the selection of the best COVID-19 vaccine.

The procedure proposed to solve the MADM issue in a fuzzy environment is explained by the following steps:

Step 1: Gather the decision maker's subjective opinion on the relevance of the weights.

Step 2: Compute the Fuzzy significant coefficients or weights founded on the decision maker's subjective judgements utilizing the table of linguistic variables and their accompanying Triangular Fuzzy Weights.

Step 3: Structure the normalized Decision Matrix.

Step 4: Create the Fuzzy Weighted Decision Matrix by multiplying normalized decision matrix by their corresponding fuzzy weights.

Step 5: Calculate the Fuzzy Positive Ideal Solution and the Fuzzy Negative Ideal Solution.

Step 6: Calculate the Euclidean Distance of all alternatives from fuzzy positive and negative ideal solutions.

Step 7: Determine the fuzzy closeness coefficient.

Step 8: Sort the alternatives corresponding to their closeness coefficients and chose the foremost option.

3.1 Case Study

Coronavirus disease (COVID-19) is an infectious illness caused by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2). The symptoms of coronavirus range from none to life-threatening. COVID-19 can make anyone sick and cause them to become terminally sick or die at any time. To prevent these severe effects, vaccination is done in every country including India. The Oxford AstraZeneca vaccine, created by the Serum Institute of India (SII) under the title "Covishield" and BBV152 (Covaxin), a vaccine created by Bharat Biotech in conjunction with the National Institute of Virology and the Indian Council of Medical Research, was approved by the DCGI in January 2021. The DCGI authorized the Russian Sputnik V vaccine, which has been tested in India by Dr. Reddy's Laboratories, in April 2021. In late June 2021, DCGI authorized the Moderna vaccine for emergency use. The various criteria to choose the best COVID-19 vaccine are taken from https://www.who.int/publications/m/item/criteria-for-covid-19-vaccine-prioritization. The data for Covaxin, Covishield and Sputnik is taken for the Indian population, whereas the data for the Moderna vaccine is taken by considering the worldwide population as the jabs of the Moderna vaccine are given in India only in case of emergency. Data including various criteria Efficacy (C1), Availability (C2), Price (C3) and After Effect (C4) is given in the Table 1.

Based on the data given in the Table 1, the vaccines need to be ranked and the selection of the best COVID-19 vaccine needs to be done. The initial stage in MADM is to categorize the situation under consideration using benefit and cost criteria. Benefit criteria are those that are intended to have higher values, whereas cost criteria are those that are intended to have lower values. In the case study considered here, Efficacy (C1) and Availability (C2) are the criteria of benefit, and Price (C3) and After Effect (C4) are the criteria of cost. To proceed further, a 7-point scale of Triangular Fuzzy Numbers, as given in Table 2, must be chosen.

Step 1: Let there be four decision makers, DM1, DM2, DM3 and DM4 who will decide the best COVID-19 vaccine among the alternatives present. Table 3 given depicts the decision maker's choices in terms of linguistic factors as follows.

Step 2: Fuzzy weights are computed and given below, based on the subjective opinion of decision makers.

Table 1 Data set in the form of decision matrix

Alternative/criteria	Efficacy	Availability	Price	After Effect
Covaxin	81	55	1410	0.04
Covishield	90	75	780	0.03
Sputnik	91	15.6	1145	0.002
Moderna	95	0.75	800	0.00004

Table 2 Linguistic variables and their corresponding triangular fuzzy weights

Importance	Fuzzy weights
Very Low (VL)	(0, 0, 0.1)
Low (L)	(0, 0.1, 0.3)
Fairly Low (FL)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
Fairly High (FH)	(0.5, 0.7, 0.9)
High (H)	(0.7, 0.9, 1)
Very High (VH)	(0.9, 1, 1)

Table 3 Rating by decision makers on linguistic scale

Criteria/decision maker	DM1	DM2	DM3	DM4
Efficacy	H	FH	VH	VH
Availability	FH	H	M	FH
Price	M	FL	VL	FL
After effect	H	VH	FH	H

Step 3: Taking into account the highest, middle and lower values of the four ratings from Table 4, the aggregated fuzzy weights are generated as follows (Table 5).

Step 4: Multiply the Normalized Decision Matrix by its associated Fuzzy Weights to get the Fuzzy weighted Normalized Decision Matrix, as stated in the formula:

$$V = X \times W$$

Table 4 Conversion of linguistic rating of decision makers into fuzzy rating

Criteria/decision maker	DM1	DM2	DM3	DM4
C1	(0.7 0.9 1)	(0.5 0.7 0.9)	(0.9 1 1)	(0.9 1 1)
C2	(0.5 0.7 0.9)	(0.7 0.9 1)	(0.3 0.5 0.7)	(0.5 0.7 0.9)
C3	(0.3 0.5 0.7)	(0.1 0.3 0.5)	(0 0 0.1)	(0.1 0.3 0.5)
C4	(0.7 0.9 1)	(0.9 1 1)	(0.5 0.7 0.9)	(0.7 0.9 1)

Table 5 Aggregated fuzzy rating

Criteria/fuzzy weights	L fuzzy weight	M fuzzy weight	U fuzzy weight
Efficacy (C1)	0.75	0.90	0.98
Availability (C2)	0.50	0.70	0.88
Price (C3)	0.13	0.28	0.45
After effect (C4)	0.70	0.88	0.98

Table 6 Fuzzy weighted normalized decision matrix

	Efficacy			Availability		
Covaxin	0.3398	0.4077	0.4417	0.2916	0.4082	0.5103
Covishield	0.3775	0.4530	0.4908	0.3976	0.5567	0.6959
Sputnik	0.3817	0.4581	0.4962	0.0827	0.1158	0.1447
Moderna	0.3985	0.4782	0.5181	0.0040	0.0056	0.0070
	Price			After effect		
Covaxin	0.0826	0.1818	0.2975	0.5596	0.6994	0.7794
Covishield	0.0457	0.0457	0.1006	0.4197	0.5246	0.5845
Sputnik	0.0671	0.0671	0.1477	0.0280	0.0350	0.0390
Moderna	0.0469	0.0469	0.1032	0.0006	0.0007	0.0008

where V = v_{ij} (i = 1,…,4 and j = 1, 2, 3,…., 12) is normalized matrix, X = x_{ij} (i = 1,…,4 and j = 1,….., 4) is the decision matrix and W = w_{ij} (I = 1,….., 4, j = 1, 2, 3) are the aggregated fuzzy weights (Table 6).

Step 5: Using the following formulae, the fuzzy positive ideal solution (FPIS) A^{k+} and fuzzy negative ideal solution (NPIS) A^{k-} are calculated:

$$A^{k+} = \{r_1^{k+}, r_2^{k+}, \ldots, r_n^{k+}\} = \{(\max(r_{ij}^k)/j \in I), (\min(r_{ij}^k)/j \in J)\} \tag{5}$$

$$A^{k+} = \{r_1^{k-}, r_2^{k-}, \ldots, r_n^{k-}\} = \{(\min(r_{ij}^k)/j \in I), (\max(r_{ij}^k)/j \in J)\} \tag{6}$$

where I and J represent the criterion of benefit and criterion of cost, respectively.

Table 7 shows the results of the calculations.

Step 6: Separation measures $S_i{}^+, S_i{}^-$ and the Euclidean Distance [39] $D(A_i, A^+)$, $D(A_i, A^-)$ of each alternative from FPIS and FNIS have been determined using Formulae (7) and (8) and are provided in Tables 8 and 9.

$S_i^+ = \sum_{i=1}^n D(A_i, A^+)$, where

Table 7 Positive and negative ideal solution for each criterion

	Efficacy (C1)			Availability (C2)		
	Lower	Middle	Upper	Lower	Middle	Upper
A^+	0.3985	0.4782	0.5181	0.3976	0.5567	0.6959
A^-	0.3398	0.4077	0.4417	0.0040	0.0056	0.0070
	Price (C3)			After effect (C4)		
A^+	0.0457	0.1006	0.1646	0.0006	0.0007	0.0008
A^-	0.0826	0.1818	0.2975	0.5596	0.6994	0.7794

Table 8 Separation measures for FPIS for each criterion

		C1	C2	C3	C4	S_i^+
For FPIS	Covaxin	0.0689	0.1502	0.0924	0.6848	0.9964
	Covishield	0	0	0.5134	0.5134	0.5381
	Sputnik	0.4462	0.0536	0.0036	0.0336	0.5530
	Moderna	0.5578	0.0029	0.0029	0	0.5607

Table 9 Separation measures for FNIS for each criterion

		C1	C2	C3	C4	S_i^-
For FNIS	Covaxin	0	0.4075	0	0	0.4075
	Covishield	0.0443	0.5578	0.0924	0.1714	0.8659
	Sputnik	0.0492	0.1116	0.0389	0.6512	0.8509
	Moderna	0.0689	0	0.0895	0.6848	0.8432

$$D\left(A_i, A^+\right) = \sqrt{\frac{1}{3}\left\{(a_1 - b^+)^2 + \left(a_2 - b_2^+\right)^2 + \left(a_3 - b_3^+\right)^2\right\}} \quad \forall_i = 1, 2, 3, 4 \quad (7)$$

and

$S_i^- = \sum_{i=1}^{n} D\left(A_i, A^-\right)$, where

$$D\left(A_i, A^-\right) = \sqrt{\frac{1}{3}\left\{(a_1 - b^-)^2 + \left(a_2 - b_2^-\right)^2 + \left(a_3 - b_3^-\right)^2\right\}} \quad \forall_i = 1, 2, 3, 4 \quad (8)$$

Step 7: Equation (9) was used to get the closeness coefficient (R_i) for each evaluated alternative.

$$R_i = \frac{D\left(A_i, A^-\right)}{D(A_i, A^+) + D(A_i, A^-)} = \frac{S_i^-}{S_i^+ + S_i^-} \quad \text{where} \quad 0 \le R_i \le 1, \quad i = 1, 2, 3, 4 \quad (9)$$

As stated in Table 10, the rankings were done in decreasing order of magnitude.

Table 10 Ranking result obtained from TOPSIS approach

	S_i^+	S_i^-	R_i	Rank
Covaxin	0.9964	0.4075	0.2903	4
Covishield	0.5381	0.8659	0.6168	1
Sputnik	0.5530	0.8509	0.6061	2
Moderna	0.5607	0.8432	0.6006	3

3.2 Sensitivity Analysis

Originally, the decision makers were given equal importance while ranking the different alternatives. However, there are instances where the decision maker's opinions are prioritized differently. In this section, such scenarios have been examined.

Different priorities, $\beta_{i,}$ have been allotted to the four decision makers, where $\beta_i > 0, i = 1, 2, 3, 4$ and $\sum_{i=1}^{4} \beta_i = 1$. The distance measures $D_r{}^+, D_r{}^-$ and the closeness coefficient (R_i) have been calculated using Eqs. (10), (11) and (12) and are introduced in Table 11.

$$D_r^+ = \sum_{r=1}^{s} \beta_i S_r^+ \tag{10}$$

$$D_r^- = \sum_{r=1}^{s} \beta_i S_r^- \tag{11}$$

$$\text{Also,} \quad R_i = \frac{v_r^-}{v_r^+ + v_r^-} \quad \text{where } 0 \le R_i \le 1, \quad i = 1, 2, 3, 4 \tag{12}$$

The results of the suggested technique remained the same when different priorities were assigned to the judgements of decision makers and Covishield stood out to be the best vaccine against COVID-19 in all circumstances, hence proving the validity and dependability of the suggested technique.

4 Conclusion

In this paper, a novel technique to solve issues involving Multi-criteria Decision-Making was proposed and the same was applied in order to select the best COVID-19 vaccine. The selection was done by considering different criteria and a team of experts. Then we ranked various vaccines with the help of the TOPSIS approach, also the selection for the best vaccine was done by assigning priorities to different criteria. Eventually, it was found that Covishield is the best vaccine out of the available alternatives. Despite the Multi-Criteria domain, this approach supports decision makers in producing unbiased and systematic judgements. In the long term, this study can be used in various Multi-criteria Decision-Making procedures and could help in the analysis of various vague situations.

Table 11 Aggregated closeness coefficient and ranking of each alternative

Vaccines	Distance measure		R_i	Rank	Best vaccine
	D_r^+	D_r^-			
(a) Case 1: $\beta_1 = 0.4$, $\beta_2 = 0.3$, $\beta_3 = 0.2$ and $\beta_4 = 0.1$					
Covaxin	0.1596	0.1223	0.4337	3	Covishield
Covishield	0.0612	0.2207	0.7829	1	
Sputnik	0.1558	0.1261	0.4472	2	
Moderna	0.1679	0.1139	0.4043	4	
(b) Case 2: $\beta_1 = 0.35$, $\beta_2 = 0.25$, $\beta_3 = 0.23$ and $\beta_4 = 0.17$					
Covaxin	0.1994	0.1019	0.3382	4	Covishield
Covishield	0.0959	0.2053	0.6817	1	
Sputnik	0.1365	0.1648	0.5470	2	
Moderna	0.1401	0.1611	0.5349	3	
(c) Case 3: $\beta_1 = 0.3$, $\beta_2 = 0.28$, $\beta_3 = 0.27$ and $\beta_4 = 0.17$					
Covaxin	0.2041	0.1141	0.3586	4	Covishield
Covishield	0.0947	0.2236	0.7025	1	
Sputnik	0.1510	0.1672	0.5254	2	
Moderna	0.1570	0.1613	0.5067	3	
(d) Case 4: $\beta_1 = 0.33$, $\beta_2 = 0.29$, $\beta_3 = 0.2$ and $\beta_4 = 0.18$					
Covaxin	0.2081	0.1182	0.3622	4	Covishield
Covishield	0.1005	0.2257	0.6918	1	
Sputnik	0.1527	0.1736	0.5321	2	
Moderna	0.1623	0.1639	0.5024	3	

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