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# Vaccine selection for COVID-19 by AHP and novel VIKOR hybrid approach with interval type-2 fuzzy sets

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## ABSTRACT

Decisions in the health industry have a significant impact on human lives. With the COVID-19 pandemic, a global war is being waged. Vaccination is a critical component in this fight. The governments are attempting to offer their citizens the best vaccine for the public based on limitations. However, due to the unique characterizations of countries and the people who live in the country, the definition of "the ideal vaccination" is indefinite. Fuzzy set theory has been an ideal tool to cope with problems involving imprecise information such as the meaning of "ideal" in this case. In this study Interval Type-2 Fuzzy Sets (IT2FSs) will be used to describe uncertainty. This IT2FS structure will be the framework of the AHP (Analytic Hierarchy Process), to determine the criteria weights, and the VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje), to generate a set of optimal choices. The main objective of this study is to sustain the necessary effect of uncertainty of fuzzy sets via the Interval Type-2 Fuzzy (IT2F) metric to the VIKOR method and thus propose an extended VIKOR. The presented new approach will be applied to the problem of vaccine selection for COVID-19. Hence, for the first time in the literature, an application with a multilevel hierarchy will be used in IT2FAHP-VIKOR. Also, obtained optimal solution set with this hybrid framework will be compared with fuzzy AHP-VIKOR and the rankings evaluated with the IT2FTOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and sensitivity analysis will be performed.

## 1. Introduction

The earth encounters extensive epidemics from time to time. The most serious epidemic ever encountered is the COVID-19 pandemic. This pandemic has changed the world and created the concept of new normal. In previous outbreaks, coronaviruses have induced Middle East Respiratory Syndrome (MERS), Severe Acute Respiratory Syndrome (SARS), and a simple common cold in humans. However, the COVID-19 virus has provided a basis for people having permanent respiratory disorders and living in intensive care units. Due to this situation, states have experienced serious disruptions in health services. Vaccine studies have been carried on rapidly to lessen the health problems experienced by people. Politicians, scientists, and business people all across the globe have been operating under a cloud of ambiguous and changeable information concerning the effectiveness of the COVID-19 pandemic response measures. Only broad and universal immunity, it seemed clear, could return social life to normal. The creation of a vaccine was a watershed moment in pandemic preparedness in this scenario. The coronavirus disease pandemic of 2019 creates terrible consequences in terms of death, economic activity, social life, education, and debt accumulation. COVID-19 vaccinations, which were recently produced, have sparked optimism for a comeback. A country's capacity to reach the herd immunity threshold is critical to its ability to return to some semblance of order or the "new normal" (Becchetti et al., 2021). In healthcare, decision-making entails a complicated series of pragmatic interactions involving a large number of stakeholders (Oztürk et al., 2017).

Currently, only a few mathematical models or methodologies are employed to aid in the preference for a good vaccine to overcome epidemics. For example, researchers benefited from the time series for the analysis of different data (Xing et al., 2022a,b). The time series are also used for COVID-19 and vaccine related studies (Zeitouny et al., 2021; Hsieh et al., 2022; Kim and Lee, 2022). The contribution of these analyzes are important but the "selection" part in decision science has no place in these analyzes. According to the best of the authors' knowledge, there is limited research in the literature on the decision-making approaches for the factors that may influence the admissibility of vaccination among vaccine alternatives for COVID-19 (Abdelwahab et al., 2021; Ecer, 2022; Forestal and Pi, 2022). Fan et al. (2022) investigated the effectiveness of the vaccines against the new variants of COVID-19. Garai and Garg (2022) made an multi-criteria decision-making application for vaccine selection in India under the single

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valued bipolar neutrosophic fuzzy environment. Ilieva and Yankova (2022) made a ranking for COVID-19 vaccines with interval valued Fermatean fuzzy TOPSIS approach. Valizadeh et al. (2023) proposed a mathematical supply chain model for vaccines. Yet, none of them involves comprehensive techniques such as the AHP-VIKOR hybrid approach or IT2FSs to describe the natural uncertainty and detailed data types to evaluate a currently existing problem type. However, the COVID-19 pandemic, in particular, has been a compelling subject with no prior data and still ongoing findings. For this reason, it has great importance to consider sophisticated tools to work with.

In this study, the authors preferred the AHP technique, a basic and effective algorithm, to evaluate the priority of the importance weights for the criteria, since it is a critical part of the decision process. Then, the authors selected and proposed an extended VIKOR methodology that produces the optimal solution set for the alternatives rather than sorting and with only one solution providing techniques such as TOPSIS to be able to obtain more than one ideal alternative. Furthermore, the authors aimed to prevent the unwanted consequence, i.e lack of thoroughness in defuzzified data, of the early defuzzification process with the proposed VIKOR approach. Please see Meniz (2021) for more detail about the decay of meaningful data with defuzzification unless the algorithm is completed. Another advantage of employing IT2F metrics in the VIKOR technique is that it eliminates the complexity that appears from consecutive subtraction and division operations for Interval Type-2 Fuzzy Numbers (IT2FNs) in the VIKOR method's final phase. Because of the fact that the IT2FNs obtained as an outcome of the subtraction process might well have negative signed components with a high probability, exhaustive precautions are to be required during the division to assure the closeness between the IT2FNs. The IT2F metric, on the other hand, may simply substitute the difference operation in VIKOR, and since its components cannot be negative owing to the function's nature, it facilitates the division operation without any trouble. It should be noted that the AHP can also be used for the final rankings of the optimal solutions yet the obtained results may not be clear about the optimality of the second-ranked or next-ranked alternatives. Similarly, VIKOR can be used as a single approach however the weights are not evaluated via an algorithm but in this case, they are assigned by the decision-makers. Thus the use of a single method is inadequate for this kind of real-life problem. Furthermore, due to its detailed framework and ability to process any multi-structured hierarchy, the given combined algorithm can be applied to any real-life problem without any defections or data loss.

The novelty of this paper to the literature is summarized as follows:

- VIKOR method with IT2FN structure has been enhanced. This novel VIKOR has no problems such as negative results (i.e. failure) at the final step of the procedure unlike fuzzy VIKOR or IT2F VIKOR mostly used in the literature. Thus, it is guaranteed to reach a solution without any compulsory intervention.
- The proposed VIKOR has been unified with a multilevel AHP approach. Hence problems with detailed structures have been possible to be solved with AHP-VIKOR. This is an important result since AHP has its own methodology to evaluate the criteria weights and VIKOR has the ability to construct a set of acceptable alternatives.
- The given hybrid method has been applied to a current and valuable problem of vaccine selection for COVID-19. There are some studies for vaccine selection yet it is easy to see that these studies cannot handle detailed data such as those given in this paper. The reason is that our procedures benefit the IT2TFNs to be able to use comprehensive data. The algorithm is relatively simple and compatible with any size of hierarchy, and for this algorithm, the IT2FN input has no defect that may lead to a meaningless result.

The rest of the paper is organized as follows. In Section 2, a comprehensive literature review is presented. In Section 3, preliminary information is provided. In Section 4, the IT2F AHP (Analytic Hierarchy Process) method, the proposed IT2F VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje) approach, and methodology for the hybrid of these two methods are presented. Then, in Section 5, this hybrid technique is implemented for the vaccine selection case for the COVID-19 pandemic. Also, a comparison is made with type-1 fuzzy AHP-VIKOR and another comparison is made with the results in which the weights were obtained by AHP again, but the optimality is ranked with TOPSIS. In addition, a sensitivity analysis is performed for this application. Lastly, in Section 6, the attained results are summarized.

## 2. Literature review

AHP, a fundamentally quantitative and qualitative technique established by Saaty (1980), assists decision-makers with multi-attribute decision-making situations under uncertainty by adding their experience, knowledge, and intuition to the choice. AHP, in essence, simplifies difficult situations. The decision-maker gains knowledge of the problem's description and aspects. In the decision-making process, AHP allows for the incorporation of both personal and impersonal viewpoints on the topic. Furthermore, it is better suited for collective choices than other techniques. AHP is a mathematical approach that considers the group or individual's preferences in decision-making and may examine qualitative and quantitative aspects concurrently (Lin et al., 2008). There are numerous many applications with the AHP approach that rely on type-1 fuzzy sets in the literature. The fuzzy AHP methodology is an enhanced evaluation technique that evolved from conventional AHP. Regardless of the practicality with which AHP's algorithm for optimum choice evaluations in multi-criteria decision-making problems is implemented, the fuzziness and uncertainty inherent in many decision-making problems can give rise to imprecise judgments of decision-makers in typical AHP frameworks (Chen and Hwang, 1992). Some fuzzy multi-criteria techniques have recently been improved by the use of type-2 fuzzy sets. Among them, AHP has been a popular multi-criteria technique that may consider many, often contradictory criteria at the same time. Fuzzy AHP based on IT2FSs has been first introduced by Kahraman et al. (2014), and linguistic scales have been also improved to be used in this method. Thus, by providing a flexible definition opportunity to the decision-makers, Buckley's fuzzy AHP approach (Buckley, 1985) has been expanded with the IT2FSs. For the first time, a group decision technique based on AHP and IT2FSs has been implemented by Oztaysi (2015) to a real-world enterprise resource planning selection problem. A model for the determination of wind farm locations with the principles of the IT2F AHP has been presented and applied in Nigeria to discover potential wind farm locations with the use of a geographic information system by Ayodele et al. (2018). The approach has focused on using fuzzy set theory to reflect the linguistic judgment of an expert, for the purpose of eliminating ambiguity, uncertainty, and discrepancy within the optimal wind farm site choice. An expanded synthesis process in the IT2FS-based AHP that uses linguistic quantifier-guided ordered weighted average variations of Bonferroni mean operators has been developed by Chiao (2020). To better deal with ambiguity and uncertainty, an amplification for the AHP with the IT2F framework to analyze the supplier selection problem by including green principles has been applied by Ecer (2020). IT2FS gathering models have been created with multiple-criteria decision-making factors in mind. When considering the uncertainty regarding the nature of humanity, the AHP solution technique has been addressed by applying IT2FNs to generate more reasonable outcomes, according to Meniz et al. (2021). The AHP approach employing the type-2 fuzzy sets has been applied to portfolio optimization which is an important subject of financial theory for the first time in the literature with this study. The AHP technique has been employed as a single approach by Yildiz et al. (2021) to define and determination for the importance weights of public anticipations from water treatment plants. The modified Delphi technique has been used to consolidate their evaluations, and the trapezoidal type-2 fuzzy AHP has been emphasized in the calculation of weights of criteria based on the conclusions. A method has been provided by Azadi et al. (2021) for discriminating Parkinson's patients from healthy people by analyzing sound waves that simultaneously consider the influence of five factors utilizing IT2F AHP. A variety of major phonic disturbance metrics, comprising 339 features with varying audio signal properties have been observed as a result. A comparative study of T1FS and IT2FS with fuzzy AHP presented by Milošević et al. (2021). It has been shown that membership functions are related to uncertainty within type-1 fuzzy sets; thus, type-2 fuzzy sets provide a chance to incorporate membership value uncertainty in fuzzy set theory even at the price of an increased number of extra computing processes. IT2F AHP has been employed by Atıcı et al. (2022) to examine the major success aspects of e-learning systems. A performance assessment for the supply chain has been conducted by Ayyildiz and Taskin (2022) with interval type-2 trapezoidal fuzzy numbers. The ability for weight evaluation of AHP and IT2F framework has been benefitted by Gupta and Lee (2022) for an industrial selection problem. IT2F AHP has been used by Torğul and Paksoy (2022) effectively for a supplier selection problem in the automotive industry.

Rather than ordering alternatives, decision-makers may desire to see a set of optimal alternatives in decision analysis. VIKOR is a multi-featured decision-making system that gives a solution that has the property of compromise with the greatest group benefit and least remorse for experts with immeasurable and contradictory qualities. A VIKOR approach that also includes a fuzzy ranking method has been developed for IT2FSs by Yazici and Kahraman (2015). In the proposed method, a sensitivity analysis has been used to examine the consequences of decisions in response to altering weights of the maximum group benefit tactics by employing IT2F weights for the decision-makers' strategies. Based on the probability theory, the VIKOR approach to accepting IT2F conditions has been presented by Qin et al. (2015). A decision model that merges the VIKOR approach and expectation theory by presenting a new distance measurement for IT2FS has been created. The multi-criteria project selection problem has been solved by using an enhanced VIKOR approach with an IT2FS by Ghorabaee et al. (2015). It has been demonstrated by Wang et al. (2017) how the VIKOR approach may be extended to cope with multi-featured decision-making issues in the context of IT2FSs. A numerical example has been used to show the consistency of the suggested technique. An integrated methodology to produce an optimal solution to multiple-criteria group decision-making problems using the best-worst approach and the VIKOR technique with an IT2F environment, by the use of the IT2FSs' advantage in representing complexity and uncertainty has been suggested by Wu et al. (2019). Using the IT2FSs' ranking score value, an extended VIKOR approach has been provided that can interact effectively with decision-making features offered by Wang et al. (2019) using IT2FSs. A decision-making approach has been conducted by Wan et al. (2021) for the hospital selection problem under IT2FN-based VIKOR. An evaluation with IT2F VIKOR has been made for the supply chain model for the automotive industry by Aleksić et al. (2022). A supply chain problem from the literature has been resolved by Haghighi et al. (2022) with VIKOR based on the IT2FN structure.

Researchers have combined decision-making strategies in some cases to benefit their most noticeable aspects. In the literature, the AHP approach, which is successful in weight calculation for criteria, and the VIKOR method, which is successful in establishing the compromise solution set, have been employed together. The AHP and VIKOR techniques in an IT2F structure have been used by Soner et al. (2017) to choose a hatch cover type for container vessels. In the study, researchers used a hierarchy only involving the main criteria level but without any sub-criteria. Risk factors and hazard probabilities have been examined with the AHP-VIKOR hybrid approach with a simple and undetailed hierarchical structure based on the IT2FS structure for chemical laboratories by Ozdemir et al. (2017). A study with IT2F AHP and crisp VIKOR methods which evaluates the credibility of the reviewers is conducted by Abbasimehr et al. (2020). It has been observed that there is no application of the AHP-VIKOR hybrid approach with IT2FSs in the literature that contains sub-criteria levels inside the hierarchical structure for a better reflection of real life. To the authors' knowledge, there are no more recent studies of the AHP-VIKOR hybrid approach within the IT2FN framework.

## 3. Preliminaries

In this section, preliminary information to be used for the methodology is given.

**Definition 1.** Let $\tilde{\tilde{A}}$ be an Interval Type-2 Trapezoidal Fuzzy Number (IT2TrFN). The IT2TrFN is described as (Chen and Lee, 2010),

$$\begin{aligned}\tilde{\tilde{A}} = \big(&\left(a_1^U, a_2^U, a_3^U, a_4^U; H_1\left(\tilde{A}^U\right), H_2\left(\tilde{A}^U\right)\right),\\ &\left(a_1^L, a_2^L, a_3^L, a_4^L; H_1\left(\tilde{A}^L\right), H_2\left(\tilde{A}^L\right)\right)\big)\end{aligned} \tag{1}$$

where $\tilde{A}^U$ is the upper membership function and $\tilde{A}^L$ is the lower membership function which are both type-1 trapezoidal fuzzy numbers. A representation of an IT2TrFN is shown in Fig. 1. These IT2TrFNs can represent the expert evaluations not by only one number but as an "interval" of values with an "interval" of membership degrees. By this, an evaluation can be stated in both mathematical and natural ways rather than the unrealistic "crisp or sharp" value.

**Definition 2.** Let $\tilde{\tilde{A}} = \left(\left(a_1^U, a_2^U, a_3^U, a_4^U; H_1\left(\tilde{A}^U\right), H_2\left(\tilde{A}^U\right)\right), \left(a_1^L, a_2^L, a_3^L, a_4^L; H_1\left(\tilde{A}^L\right), H_2\left(\tilde{A}^L\right)\right)\right)$ be an IT2TrFN. This IT2TrFN can be denoted by $\tilde{\tilde{A}} = \left(\tilde{A}^U, \tilde{A}^L\right)$ shortly.

**Definition 3.** Let $\tilde{\tilde{A}}$ and $\tilde{\tilde{B}}$ be two IT2TrFNs. The sum of $\tilde{\tilde{A}}$ and $\tilde{\tilde{B}}$ is defined by Meniz (2021),

$$\begin{aligned}\tilde{\tilde{A}} \oplus \tilde{\tilde{B}} &= \left(\tilde{A}^U, \tilde{A}^L\right) \oplus \left(\tilde{B}^U, \tilde{B}^L\right)\\ &= \big(a_1^U + b_1^U, a_2^U + b_2^U, a_3^U + b_3^U, a_4^U + b_4^U;\\ &\quad \max\left(H_1\left(\tilde{A}^U\right), H_1\left(\tilde{B}^U\right)\right), \max\left(H_2\left(\tilde{A}^U\right), H_2\left(\tilde{B}^U\right)\right)\big),\\ &\quad \big(a_1^L + b_1^L, a_2^L + b_2^L, a_3^L + b_3^L, a_4^L + b_4^L;\\ &\quad \max\left(H_1\left(\tilde{A}^L\right), H_1\left(\tilde{B}^L\right)\right), \max\left(H_2\left(\tilde{A}^L\right), H_2\left(\tilde{B}^L\right)\right)\big).\end{aligned} \tag{2}$$

**Definition 4.** Let $\tilde{\tilde{A}}$ and $\tilde{\tilde{B}}$ be two IT2TrFNs. The difference of $\tilde{\tilde{A}}$ from $\tilde{\tilde{B}}$ is defined by Meniz (2021),

$$\begin{aligned}\tilde{\tilde{A}} \ominus \tilde{\tilde{B}} &= \left(\tilde{A}^U, \tilde{A}^L\right) \ominus \left(\tilde{B}^U, \tilde{B}^L\right)\\ &= \big(a_1^U - b_4^U, a_2^U - b_3^U, a_3^U - b_2^U, a_4^U - b_1^U;\\ &\quad \max\left(H_1\left(\tilde{A}^U\right), H_1\left(\tilde{B}^U\right)\right), \max\left(H_2\left(\tilde{A}^U\right), H_2\left(\tilde{B}^U\right)\right)\big),\\ &\quad \big(a_1^L - b_4^L, a_2^L - b_3^L, a_3^U - b_2^L, a_4^L - b_1^L;\\ &\quad \max\left(H_1\left(\tilde{A}^L\right), H_1\left(\tilde{B}^L\right)\right), \max\left(H_2\left(\tilde{A}^L\right), H_2\left(\tilde{B}^L\right)\right)\big).\end{aligned} \tag{3}$$

**Remark 1.** Here, the maximum operator has been included in the addition and subtraction operations out of the usual. The reason for this is to mathematically satisfy the basic condition $\tilde{\tilde{0}} \oplus \tilde{\tilde{A}} = \tilde{\tilde{A}}$, as stated by Meniz (2021).

**Definition 5.** Let $\tilde{\tilde{A}}$ be an IT2TrFN and $t$ be a positive, real scalar. Multiplication of the scalar $t$ and $\tilde{\tilde{A}}$ is defined by Chen and Lee (2010),

$$\begin{aligned}t \odot \tilde{\tilde{A}} = \big(&\left(t \times a_1^U, t \times a_2^U, t \times a_3^U, t \times a_4^U; H_1\left(\tilde{A}^U\right), H_2\left(\tilde{A}^U\right)\right),\\ &\left(t \times a_1^L, t \times a_2^L, t \times a_3^L, t \times a_4^L; H_1\left(\tilde{A}^L\right), H_2\left(\tilde{A}^L\right)\right)\big).\end{aligned} \tag{4}$$

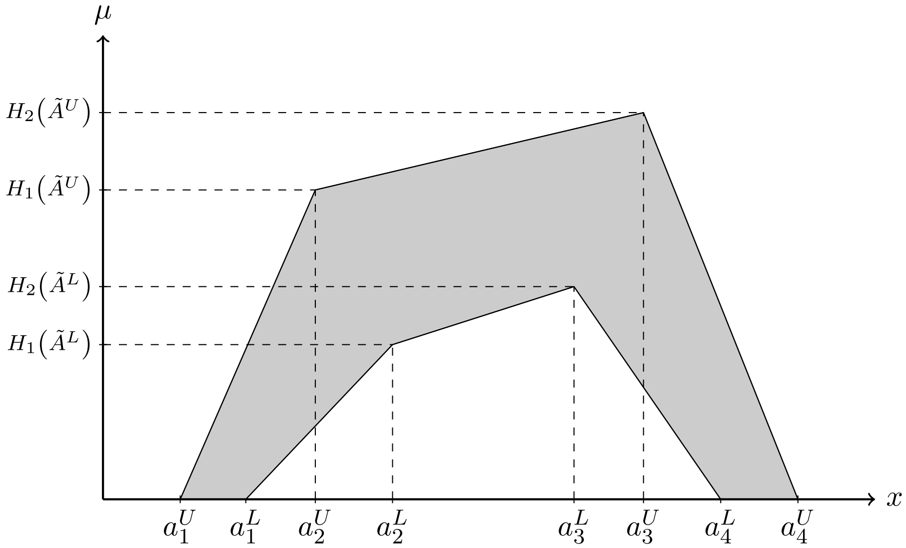

**Fig. 1.** Interval type-2 (trapezoidal) fuzzy number.

**Definition 6.** Let $\tilde{\tilde{A}}$ and $\tilde{\tilde{B}}$ be two IT2TrFNs. The multiplication operation between $\tilde{\tilde{A}}$ and $\tilde{\tilde{B}}$ is given by Chen and Lee (2010),

$$\begin{aligned}\tilde{\tilde{A}} \otimes \tilde{\tilde{B}} &= \left(\tilde{A}^U, \tilde{A}^L\right) \otimes \left(\tilde{B}^U, \tilde{B}^L\right)\\ &= \left(a_1^U \times b_1^U, a_2^U \times b_2^U, a_3^U \times b_3^U, a_4^U \times b_4^U;\right.\\ &\quad \min\left(H_1\left(\tilde{A}^U\right), H_1\left(\tilde{B}^U\right)\right), \min\left(H_2\left(\tilde{A}^U\right), H_2\left(\tilde{B}^U\right)\right)),\\ &\quad \left(a_1^L \times b_1^L, a_2^L \times b_2^L, a_3^L \times b_3^L, a_4^L \times b_4^L;\right.\\ &\quad \min\left(H_1\left(\tilde{A}^L\right), H_1\left(\tilde{B}^L\right)\right), \min\left(H_2\left(\tilde{A}^L\right), H_2\left(\tilde{B}^L\right)\right)).\end{aligned} \tag{5}$$

**Definition 7.** Let $\tilde{\tilde{A}}$ be an IT2TrFN. The inverse of $\tilde{\tilde{A}}$ with respect to multiplication is given by Kahraman et al. (2014),

$$\begin{aligned}\frac{\tilde{\tilde{1}}}{\tilde{\tilde{A}}} = &\left(\left(\frac{1}{a_4^U}, \frac{1}{a_3^U}, \frac{1}{a_2^U}, \frac{1}{a_1^U}; H_1\left(\tilde{A}^U\right), H_2\left(\tilde{A}^U\right)\right),\right.\\ &\left.\left(\frac{1}{a_4^L}, \frac{1}{a_3^L}, \frac{1}{a_2^L}, \frac{1}{a_1^L}; H_1\left(\tilde{A}^L\right), H_2\left(\tilde{A}^L\right)\right)\right).\end{aligned} \tag{6}$$

**Definition 8.** Let $\tilde{\tilde{A}}$ be an IT2TrFN. The $n$th degree root of $\tilde{\tilde{A}}$ is defined by Kahraman et al. (2014),

$$\begin{aligned}\tilde{\tilde{A}}^{1/n} = &\left(\left(\sqrt[n]{a_1^U}, \sqrt[n]{a_2^U}, \sqrt[n]{a_3^U}, \sqrt[n]{a_4^U}; H_1\left(\tilde{A}^U\right), H_2\left(\tilde{A}^U\right)\right)\right.\\ &\left.\left(\sqrt[n]{a_1^L}, \sqrt[n]{a_2^L}, \sqrt[n]{a_3^L}, \sqrt[n]{a_4^L}; H_1\left(\tilde{A}^L\right), H_2\left(\tilde{A}^L\right)\right)\right).\end{aligned} \tag{7}$$

**Definition 9.** Let $\tilde{\tilde{A}}$ be an IT2TrFN. The defuzzified value of $\tilde{\tilde{A}}$ can be evaluated with the equation (Kahraman et al., 2014),

$$\begin{aligned}Df\left(\tilde{\tilde{A}}\right) = \frac{1}{8}&\left(a_1^U + \left(H_1\left(\tilde{A}^U\right) \times a_2^U\right) + \left(H_2\left(\tilde{A}^U\right) \times a_3^U\right) + a_4^U\right.\\ &\left. + a_1^L + \left(H_1\left(\tilde{A}^L\right) \times a_2^L\right) + \left(H_2\left(\tilde{A}^L\right) \times a_3^L\right) + a_4^L\right).\end{aligned} \tag{8}$$

**Definition 10.** Let $\tilde{\tilde{A}}$ and $\tilde{\tilde{B}}$ be two IT2TrFNs. The IT2TrFN metric $\tilde{\tilde{d}}\left(\tilde{\tilde{A}}, \tilde{\tilde{B}}\right)$ is given with the formula (Meniz, 2021),

$$\begin{aligned}\tilde{\tilde{d}}\left(\tilde{\tilde{A}}, \tilde{\tilde{B}}\right) = &((c_1^U, c_1^U + c_1^L + c_2^U, c_1^U + c_1^L + c_2^U + c_2^L + c_3^U\\ &\quad + c_3^L, c_1^U + c_1^L + c_2^U + c_2^L + c_3^U + c_3^L + c_4^U + c_4^L;\\ &\min\left\{\left[c_1^U + c_2^U + c_3^U + c_4^U + \left|H_1\left(\tilde{A}^U\right) - H_1\left(\tilde{B}^U\right)\right|\right], \max\left\{H_1\left(\tilde{A}^U\right), H_1\left(\tilde{B}^U\right)\right\}\right\},\\ &\min\left\{\left[c_1^U + c_2^U + c_3^U + c_4^U + \left|H_2\left(\tilde{A}^U\right) - H_2\left(\tilde{B}^U\right)\right|\right], \max\left\{H_2\left(\tilde{A}^U\right), H_2\left(\tilde{B}^U\right)\right\}\right\}),\\ &(c_1^U + c_1^L, c_1^U + c_1^L + c_2^U + c_2^L, c_1^U + c_1^L + c_2^U + c_2^L + c_3^L, c_1^U\\ &\quad + c_1^L + c_2^U + c_2^L + c_3^U + c_3^L + c_4^L;\\ &\min\left\{\left[c_1^L + c_2^L + c_3^L + c_4^L + \left|H_1\left(\tilde{A}^L\right) - H_1\left(\tilde{B}^L\right)\right|\right], \min\left\{H_1\left(\tilde{A}^L\right), H_1\left(\tilde{B}^L\right)\right\}\right\},\\ &\min\left\{\left[c_1^L + c_2^L + c_3^L + c_4^L + \left|H_2\left(\tilde{A}^L\right) - H_2\left(\tilde{B}^L\right)\right|\right], \min\left\{H_2\left(\tilde{A}^L\right), H_2\left(\tilde{B}^L\right)\right\}\right\})).\end{aligned} \tag{9}$$

**Table 1**
Fuzzy scales for the linguistic variables.

| Linguistic variable | Interval type-2 trapezoidal fuzzy number |
|---|---|
| Absolutely Strong (AS) | (7,8,9,9;1,1),(7.2,8.2,8.8,9;0.8,0.8) |
| Very Strong (VS) | (5,6,8,9;1,1),(5.2,6.2,7.8,8.8;0.8,0.8) |
| Fairly Strong (FS) | (3,4,6,7;1,1),(3.2,4.2,5.8,6.8;0.8,0.8) |
| Slightly Strong (SS) | (1,2,4,5;1,1),(1.2,2.2,3.8,4.8;0.8,0.8) |
| Exactly Equal (E) | (1,1,1,1;1,1),(1,1,1,1;1,1) |

Here, $c_r^\omega = \left|a_r^\omega - b_r^\omega\right|$, $r = 1,4$; $\omega \in \{U, L\}$ and $c_s^\omega = \left|H_{s-1}\left(\tilde{A}^\omega\right) \times a_s^\omega - H_{s-1}\left(\tilde{B}^\omega\right) \times b_s^\omega\right|$, $s = 2,3$; $\omega \in \{U, L\}$.

## 4. Methodology

In this section, a solution methodology for the decision-making problems using the AHP-VIKOR hybrid approach with IT2FNs will be given.

### 4.1. Interval type-2 AHP

First, the algorithm of the AHP technique will be described. This part will be used to obtain the IT2F weight vector for the next steps.

**Step 1:** IT2F Pairwise Comparison Matrices (PCMs) are created for all of the criteria at every level of the hierarchy with the expertise of all decision-makers. The matrices are established separately per decision-maker. The reciprocal components of the matrices are evaluated with the help of Eq. (6) as follows (Meniz et al., 2021):

$$\tilde{\tilde{A}}^p = \begin{bmatrix} \tilde{\tilde{1}} & \tilde{\tilde{a}}_{12}^p & \dots & \tilde{\tilde{a}}_{1n}^p \\ \tilde{\tilde{a}}_{21}^p & \tilde{\tilde{1}} & \dots & \tilde{\tilde{a}}_{2n}^p \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{\tilde{a}}_{n1}^p & \tilde{\tilde{a}}_{n2}^p & \dots & \tilde{\tilde{1}} \end{bmatrix} = \begin{bmatrix} \tilde{\tilde{1}} & \tilde{\tilde{a}}_{12}^p & \dots & \tilde{\tilde{a}}_{1n}^p \\ \tilde{\tilde{1}}/\tilde{\tilde{a}}_{12}^p & \tilde{\tilde{1}} & \dots & \tilde{\tilde{a}}_{2n}^p \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{\tilde{1}}/\tilde{\tilde{a}}_{1n}^p & \tilde{\tilde{1}}/\tilde{\tilde{a}}_{2n}^p & \dots & \tilde{\tilde{1}} \end{bmatrix} \tag{10}$$

where $p$ describes the number of decision-makers. The elements of these matrices are linguistic variables with equivalent IT2TrFNs. Table 1 shows the fuzzy scales that will be utilized for linguistic variables (Kahraman et al., 2014).

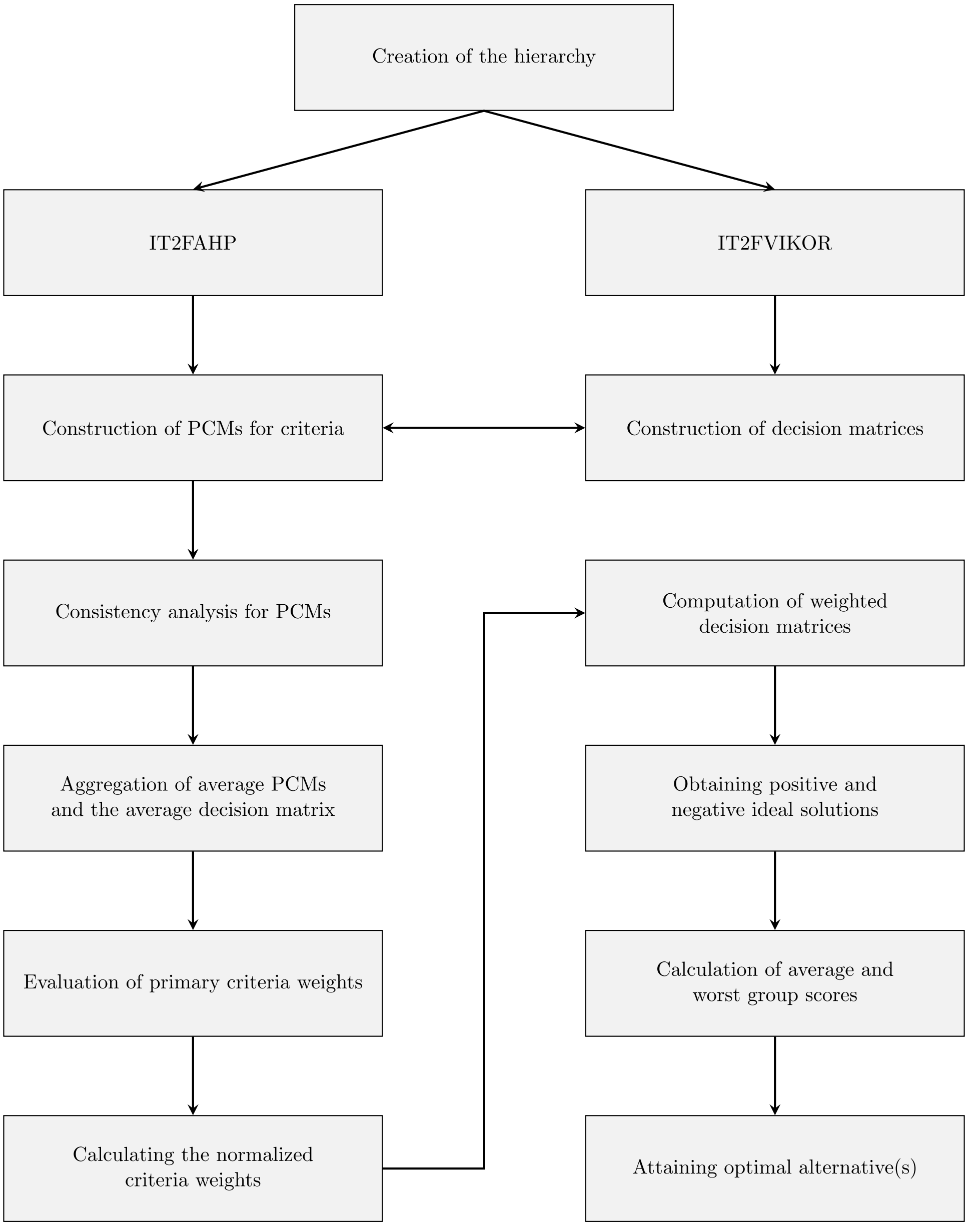

**Fig. 2.** Description of the methodology.

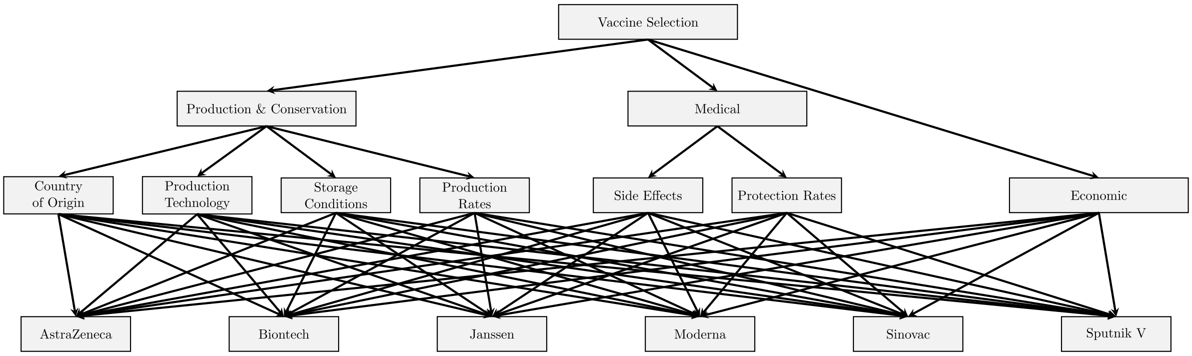

**Fig. 3.** The hierarchical structure of the problem.

**Table 2**
Fuzzy scales for the linguistic variables.

| Linguistic variable | Interval type-2 trapezoidal fuzzy number |
|---|---|
| Very Poor (VP) | $((0, 0, 0, 1; 1, 1), (0, 0, 0, 0.5; 0.9, 0.9))$ |
| Poor (P) | $((0, 1, 1.5, 3; 1, 1), (0.5, 1, 1.5, 2; 0.9, 0.9))$ |
| Medium Poor (MP) | $((1, 3, 3.5, 5; 1, 1), (2, 3, 3.5, 4; 0.9, 0.9))$ |
| Fair (F) | $((3, 5, 5.5, 7; 1, 1), (4, 5, 5.5, 6; 0.9, 0.9))$ |
| Medium Good (MG) | $((5, 7, 7.5, 9; 1, 1), (6, 7, 7.5, 8; 0.9, 0.9))$ |
| Good (G) | $((7, 8.5, 9, 10; 1, 1), (8, 8.5, 9, 9.5; 0.9, 0.9))$ |
| Very Good (VG) | $((9, 10, 10, 10; 1, 1), (9.5, 10, 10, 10; 0.9, 0.9))$ |

**Table 3**
PCM for main criteria.

| | Production & Conservation | Medical | Economic |
|---|---|---|---|
| Production & Conservation | E, E, E | 1/VS, 1/RSS, SS | 1/SS, 1/FS, VS |
| Medical | VS, SS, 1/SS | E, E, E | AS, AS, SS |
| Economic | SS, 1/FS, 1/VS | 1/AS, 1/AS, 1/SS | E, E, E |

**Step 2:** All IT2F PCMs are subjected to consistency verification. To make this analysis, defuzzified correspondences of these matrices are taken into account. If the crisp matrix equivalent of the IT2F PCM is consistent, then the original matrix is as well (Kahraman et al., 2014).

**Step 3:** To aggregate and construct the average IT2F PCMs of all decision-makers, Eqs. (4) and (5) are used.

**Step 4a:** The geometric means $\tilde{\tilde{r}}_i$ of each of the IT2F PCMs are evaluated by using Eqs. (5) and (7) (Meniz et al., 2021). The obtained IT2F vector is the non-normalized weight of all of the criteria.

**Step 4b:** The hierarchical composition of priorities principle is performed by using Eq. (5) to evaluate the normalized IT2F weights of the criteria at the lowest level of the hierarchy (Meniz et al., 2021).

With this step, IT2F weights which are normalized for the criteria at the lowest level are calculated. Thus, the necessary parts of the AHP method are concluded.

### *4.2. Enhanced interval type-2 VIKOR*

Now, by benefitting from the IT2F weight vector gathered by IT2F AHP, phases of the IT2F VIKOR procedure will be given for the optimal solution(s) of the decision-making problems.

**Step 5:** The IT2F performance matrices of each alternative regarding the criteria at the lowest level are constructed for each decision-maker,

$$\tilde{\tilde{E}}^p = \left(\tilde{\tilde{e}}^p_{ji}\right)_{n\times m} = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{array} \begin{array}{c} \begin{array}{cccc} A_1 & A_2 & \cdots & A_m \end{array} \\ \begin{bmatrix} \tilde{\tilde{e}}^p_{11} & \tilde{\tilde{e}}^p_{12} & \cdots & \tilde{\tilde{e}}^p_{1m} \\ \tilde{\tilde{e}}^p_{21} & \tilde{\tilde{e}}^p_{22} & \cdots & \tilde{\tilde{e}}^p_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{\tilde{e}}^p_{n1} & \tilde{\tilde{e}}^p_{n2} & \cdots & \tilde{\tilde{e}}^p_{nm} \end{bmatrix} \end{array} \tag{11}$$

where $m$ is the number of presented alternatives and $n$ is the number of criteria at the lowest level of the hierarchy. Linguistic variables to construct these matrices are given in Table 2 (Ghorabaee et al., 2017).

**Step 6:** To aggregate and construct the average IT2F performance matrix of all decision-makers, Eqs. (4) and (5) are used.

**Step 7:** The weighted fuzzy decision matrix is found by multiplying the weight vector with the performance matrix by Eq. (5),

$$\tilde{\tilde{V}} = \left[\tilde{\tilde{\upsilon}}_{ji}\right]_{n\times m} \tag{12}$$

where

$$\begin{aligned} \tilde{\tilde{\upsilon}}_{ji} &= \tilde{\tilde{w}}_j \otimes \tilde{\tilde{e}}_{ji} \\ &= \left(\left(f^U_{i1}, f^U_{i2}, f^U_{i3}, f^U_{i4}; H_1\left(\tilde{F}^U_i\right), H_2\left(\tilde{F}^U_i\right)\right),\right. \\ &\quad \left.\left(f^L_{i1}, f^L_{i2}, f^L_{i3}, f^L_{i4}; H_1\left(\tilde{F}^L_i\right), H_2\left(\tilde{F}^L_i\right)\right)\right). \end{aligned} \tag{13}$$

**Table 4**
PCM for sub-criteria of Production & Conservation.

| | Country of origin | Production technology | Storage conditions | Production rates |
|---|---|---|---|---|
| Country of origin | E, E, E | 1/SS, 1/RFS, SS | 1/SS, FS, VS | 1/VS, 1/SS, AS |
| Production technology | SS, FS, 1/SS | E, E, E | E, AS, FS | 1/FS, SS, FS |
| Storage conditions | SS, 1/FS, 1/VS | E, 1/AS, 1/FS | E, E, E | 1/FS, 1/VS, E |
| Production rates | VS, SS, 1/AS | FS, 1/SS, 1/FS | FS, VS, E | E, E, E |

**Table 5**
PCM for sub-criteria of Medical.

| | Side effects | Protection Rates |
|---|---|---|
| Side effects | E, E, E | 1/FS, E, SS |
| Protection rates | FS, E, 1/SS | E, E, E |

**Step 8:** Upper and lower basis points for Positive Ideal Solution (PIS) $(P^{e*}, P^{\upsilon*})$ and Negative Ideal Solution (NIS) $(N^{e-})$ are evaluated,

$$P^{e*}_j = \left\{\tilde{\tilde{e}}^*_{ji}, \tilde{\tilde{e}}^*_{ji}, \ldots, \tilde{\tilde{e}}^*_{ji}\right\} = \begin{cases} \max_i \tilde{\tilde{e}}^*_{ji}, & j \in J_1 \\ \min_i \tilde{\tilde{e}}^*_{ji}, & j \in J_2 \end{cases} \tag{14}$$

$$P^{\upsilon*}_j = \left\{\tilde{\tilde{\upsilon}}^*_{ji}, \tilde{\tilde{\upsilon}}^*_{ji}, \ldots, \tilde{\tilde{\upsilon}}^*_{ji}\right\} = \begin{cases} \max_i \tilde{\tilde{\upsilon}}^*_{ji}, & j \in J_1 \\ \min_i \tilde{\tilde{\upsilon}}^*_{ji}, & j \in J_2 \end{cases} \tag{15}$$

$$N^{e-}_j = \left\{\tilde{\tilde{e}}^-_{ji}, \tilde{\tilde{e}}^-_{ji}, \ldots, \tilde{\tilde{e}}^-_{ji}\right\} = \begin{cases} \min_i \tilde{\tilde{e}}^-_{ji}, & j \in J_1 \\ \max_i \tilde{\tilde{e}}^-_{ji}, & j \in J_2 \end{cases} \tag{16}$$

where $J_1$ describes the set of benefit criteria and $J_2$ describes the set of cost criteria.

**Step 9:** Thus, the IT2F average group score $\left(\tilde{\tilde{S}}_i\right)$ and worst group score $\left(\tilde{\tilde{R}}_i\right)$ are found with Eqs. (2), (5), (6), and (9),

$$\begin{aligned} \tilde{\tilde{T}}_{ji} &= \tilde{\tilde{d}}\left(P^{\upsilon*}_j, \tilde{\tilde{\upsilon}}_{ji}\right) \otimes \frac{\tilde{\tilde{1}}}{\tilde{\tilde{d}}\left(P^{e*}_j, N^{e-}_j\right)} \\ &= \left(\left(t^U_{ji1}, t^U_{ji2}, t^U_{ji3}, t^U_{ji4}; H_1\left(\tilde{T}^U_{ji}\right), H_2\left(\tilde{T}^U_{ji}\right)\right),\right. \\ &\quad \left.\left(t^L_{ji1}, t^L_{ji2}, t^L_{ji3}, t^L_{ji4}; H_1\left(\tilde{T}^L_{ji}\right), H_2\left(\tilde{T}^L_{ji}\right)\right)\right). \end{aligned} \tag{17}$$

$$\tilde{\tilde{S}}_i = \sum_{j=1}^{n} \tilde{\tilde{T}}_{ji} \tag{18}$$

and

$$\begin{aligned} \tilde{\tilde{R}}_i = &\left(\left(\max_j t^U_{ji1}, \max_j t^U_{ji2}, \max_j t^U_{ji3}, \max_j t^U_{ji4}; \max_j H_1\left(\tilde{T}^U_{ji}\right), \max_j H_2\left(\tilde{T}^U_{ji}\right)\right),\right. \\ &\left.\left(\max_j t^L_{ji1}, \max_j t^L_{ji2}U, \max_j t^L_{ji3}, \max_j t^L_{ji4}; \max_j H_1\left(\tilde{T}^L_{ji}\right), \max_j H_2\left(\tilde{T}^L_{ji}\right)\right)\right). \end{aligned} \tag{19}$$

**Step 10:** By using the $\tilde{\tilde{S}}_i$ and $\tilde{\tilde{R}}_i$ values, $\tilde{\tilde{Q}}_i$ values are evaluated with Eqs. (2), (4), (5), (6), and (9)

$$\tilde{\tilde{Q}}_i = \nu \odot \frac{\tilde{\tilde{d}}\left(\tilde{\tilde{S}}^*, \tilde{\tilde{S}}_i\right)}{\tilde{\tilde{d}}\left(\tilde{\tilde{S}}^*, \tilde{\tilde{S}}^-\right)} \oplus (1-\nu) \odot \frac{\tilde{\tilde{d}}\left(\tilde{\tilde{R}}_i, \tilde{\tilde{R}}^*\right)}{\tilde{\tilde{d}}\left(\tilde{\tilde{R}}^-, \tilde{\tilde{R}}^*\right)} \tag{20}$$

where $\tilde{\tilde{S}}^* = \min_i \tilde{\tilde{S}}_i$, $\tilde{\tilde{S}}^- = \max_i \tilde{\tilde{S}}_i$, $\tilde{\tilde{R}}^* = \min_i \tilde{\tilde{R}}_i$, $\tilde{\tilde{R}}^- = \max_i \tilde{\tilde{R}}_i$, and $\nu$ show the decision strategy weight for maximization of group utility. Then, by using Eq. (8), $\tilde{\tilde{S}}_i$, $\tilde{\tilde{R}}_i$, and $\tilde{\tilde{Q}}_i$ values are defuzzified. Crisp equivalents of $S_i$, $R_i$, and $Q_i$ values are sorted in increasing order. Hence, the lowest $Q_i$ value which satisfies the two conditions below is the alternative which is called the compromise solution.

**Table 6**
PCM for main criteria.

| | Production & Conservation | Medical | Economic |
|---|---|---|---|
| Production & Conservation | ((1.000, 1.000, 1.000, 1.000; 1, 1),<br>(1.000, 1.000, 1.000, 1.000; 1, 1)) | ((0.281, 0.397, 0.693, 1.000; 1, 1),<br>(0.305, 0.420, 0.653, 0.916; 0.8, 0.8)) | ((1.442, 1.817, 2.884, 3.979; 1, 1),<br>(1.513, 1.899, 2.739, 3.681; 0.8, 0.8)) |
| Medical | (( 1.000, 1.442, 2.520, 3.557; 1, 1),<br>(1.091, 1.531, 2.379, 3.277; 0.8, 0.8)) | ((1.000, 1.000, 1.000, 1.000; 1, 1),<br>(1.000, 1.000, 1.000, 1.000; 1, 1)) | ((3.659, 5.039, 6.868, 7.398; 1, 1),<br>(3.962, 5.288, 6.651, 7.298; 0.8, 0.8)) |
| Economic | ((0.251, 0.346, 0.550, 0.693; 1, 1),<br>(0.271, 0.365, 0.526, 0.660; 0.8, 0.8)) | ((0.135, 0.145, 0.198, 0.273; 1, 1),<br>(0.137, 0.150, 0.189, 0.252; 0.8, 0.8)) | ((1.000, 1.000, 1.000, 1.000; 1, 1),<br>(1.000, 1.000, 1.000, 1.000; 1, 1)) |

**Table 7**
PCM for sub-criteria of Production & Conservation.

| | Country of origin | Production technology | Storage conditions | Production rates |
|---|---|---|---|---|
| Country of origin | ((1.000, 1.000, 1.000, 1.000; 1, 1),<br>(1.000, 1.000, 1.000, 1.000; 1, 1)) | ((0.305, 0.437, 0.793, 1.185; 1, 1),<br>(0.332, 0.464, 0.743, 1.077; 0.8, 0.8)) | ((1.442, 1.817, 2.884, 3.979; 1, 1),<br>(1.513, 1.899, 2.739, 3.681; 0.8, 0.8)) | ((0.538, 0.630, 0.908, 1.216; 1, 1),<br>(0.554, 0.651, 0.864, 1.130; 0.8, 0.8)) |
| Production technology | ((0.843, 1.260, 2.289, 3.271; 1, 1),<br>(0.928, 1.344, 2.155, 3.007; 0.8, 0.8)) | ((1.000, 1.000, 1.000, 1.000; 1, 1),<br>(1.000, 1.000, 1.000, 1.000; 1, 1)) | ((2.759, 3.175, 3.780, 3.979; 1, 1),<br>(2.845, 3.253, 3.709, 3.941; 0.8, 0.8)) | ((0.754, 1.100, 1.817, 2.268; 1, 1),<br>(0.826, 1.168, 1.738, 2.168; 0.8, 0.8)) |
| Storage conditions | ((0.251, 0.346, 0.550, 0.693; 1, 1),<br>(0.271, 0.365, 0.526, 0.660; 0.8, 0.8)) | ((0.251, 0.264, 0.315, 0.362; 1, 1),<br>(0.254, 0.269, 0.307, 0.351; 0.8, 0.8)) | ((1.000, 1.000, 1.000, 1.000; 1, 1),<br>(1.000, 1.000, 1.000, 1.000; 1, 1)) | ((0.251, 0.275, 0.346, 0.405; 1, 1),<br>(0.255, 0.280, 0.337, 0.391; 0.8, 0.8)) |
| Production rates | ((0.822, 1.100, 1.587, 1.859; 1, 1),<br>(0.885, 1.157, 1.534, 1.803; 0.8, 0.8)) | ((0.441, 0.550, 0.908, 1.326; 1, 1),<br>(0.461, 0.575, 0.856, 1.210; 0.8, 0.8)) | ((2.466, 2.884, 3.634, 3.979; 1, 1),<br>(2.553, 2.964, 3.563, 3.911; 0.8, 0.8)) | ((1.000, 1.000, 1.000, 1.000; 1, 1),<br>(1.000, 1.000, 1.000, 1.000; 1, 1)) |

**Table 8**
PCM for sub-criteria of Medical.

| | Side effects | Protection Rates |
|---|---|---|
| Side Effects | ((1.000, 1.000, 1.000, 1.000; 1, 1),<br>(1.000, 1.000, 1.000, 1.000; 1, 1)) | ((0.523, 0.693, 1.000, 1.185; 1, 1),<br>(0.561, 0.724, 0.967, 1.144; 0.8, 0.8)) |
| Protection Rates | ((0.843, 1.000, 1.442, 1.913; 1, 1),<br>(0.873, 1.034, 1.381, 1.783; 0.8, 0.8)) | ((1.000, 1.000, 1.000, 1.000; 1, 1),<br>(1.000, 1.000, 1.000, 1.000; 1, 1)) |

**Table 9**
Geometric means of each row for main criteria.

| | |
|---|---|
| Production & Conservation | ((0.740, 0.896, 1.260, 1.584; 1, 1),(0.773, 0.927, 1.214, 1.499; 0.8, 0.8)) |
| Medical | ((1.541, 1.937, 2.586, 2.974; 1, 1),(1.629, 2.008, 2.510, 2.881; 0.8, 0.8)) |
| Economic | ((0.324, 0.369, 0.478, 0.574; 1, 1),(0.334, 0.380, 0.463, 0.550; 0.8, 0.8)) |

**Table 10**
Geometric means for the rows of Production & Conservation sub-criterion.

| | |
|---|---|
| Country of origin | ((0.698, 0.841, 1.201, 1.548; 1, 1),(0.727, 0.870, 1.152, 1.455; 0.8, 0.8)) |
| Production technology | ((1.151, 1.448, 1.991, 2.331; 1, 1),(1.215, 1.503, 1.930, 2.251; 0.8, 0.8)) |
| Storage conditions | ((0.355, 0.398, 0.495, 0.565; 1, 1),(0.364, 0.407, 0.483, 0.549; 0.8, 0.8)) |
| Production rates | ((0.972, 1.149, 1.513, 1.770; 1, 1),(1.010, 1.185, 1.471, 1.709; 0.8, 0.8)) |

**Table 11**
Geometric means for the rows of Medical sub-criterion.

| | |
|---|---|
| Side effects | ((0.723, 0.832, 1.000, 1.089; 1, 1),(0.749, 0.850, 0.983, 1.070; 0.8, 0.8)) |
| Protection rates | ((0.918, 1.000, 1.201, 1.383; 1, 1),(0.934, 1.017, 1.175, 1.335; 0.8, 0.8)) |

**Condition 1:** The acceptable advantage:

Where, $DQ = 1/(m-1)$,

$$Q_{A_1} - Q_{A_2} \geq DQ \tag{21}$$

**Condition 2:** Acceptable stability:

In the ordering of $S$ and/or $R$ the alternative $Q_{A_1}$ is in the first place.

If the case two conditions are dissatisfied at the same time, then a compromise solution set is selected as the optimal alternative.

The methodology to be applied is given in Fig. 2.

## 5. Vaccine selection

In this section, the AHP approach and enhanced VIKOR method based on IT2TrFNs given in Section 4 will be implemented in the vaccine selection problem for COVID-19. The hierarchical structure for this decision-making problem is given in Fig. 3. In this model "Production & Conservation", "Medical", and "Economic" criteria are the main criteria. In the first main criterion, there are "Country of Origin", "Production Technology", "Storage Condition", and "Production Rates" as sub-criteria. The second main criterion is divided into two sub-criteria which are "Side Effects", and "Protection Rates". There are no sub-criteria under the "Economic" criterion. The criteria "Country of Origin", "Production Technology", "Storage Condition", "Production Rates", and "Protection Rates" are qualified as the benefit criteria while "Side Effects" and "Economic" criteria are the cost criteria. The vaccines considered for this application are "AstraZeneca", "Biontech", "Janssen", "Moderna", "Sinovac", and "Sputnik V" which are alphabetically ordered.

First, weight vectors for criteria at each level will be evaluated with pairwise comparisons from experts. Then, using the assessments of the experts' decision matrices will be constructed for each vaccination regarding the criteria at the lowest level. To get the PCMs for the AHP method and decision matrices for the proposed enhanced VIKOR approach, three competent decision-makers serve as experts. As a result, six candidates will be ranked using the hybrid methodology described

**Table 12**
Weights of criteria at the lowest level.

| | |
|---|---|
| Country of origin | ((0.016, 0.033, 0.123, 0.296; 1, 1),(0.019, 0.038, 0.106, 0.240; 0.8, 0.8)) |
| Production technology | ((0.026, 0.058, 0.204, 0.446; 1, 1),(0.032, 0.066, 0.178, 0.372; 0.8, 0.8)) |
| Storage conditions | ((0.008, 0.016, 0.050, 0.108; 1, 1),(0.009, 0.018, 0.044, 0.090; 0.8, 0.8)) |
| Production rates | ((0.022, 0.046, 0.155, 0.339; 1, 1),(0.026, 0.052, 0.136, 0.282; 0.8, 0.8)) |
| Side effects | ((0.088, 0.169, 0.440, 0.757; 1, 1),(0.103, 0.189, 0.398, 0.669; 0.8, 0.8)) |
| Protection rates | ((0.111, 0.203, 0.529, 0.962; 1, 1),(0.128, 0.226, 0.476, 0.835; 0.8, 0.8)) |
| Economic | ((0.063, 0.085, 0.149, 0.220; 1, 1),(0.067, 0.090, 0.140, 0.201; 0.8, 0.8)) |

**Table 13**
Decision matrices for alternatives.

| Criteria | Alternatives | $DM_1$ | $DM_2$ | $DM_3$ | Average of the rating |
|---|---|---|---|---|---|
| Country of Origin | AstraZeneca | F | G | MG | ((5.000, 6.833, 7.333, 8.667; 1, 1),(6.000, 6.833, 7.333, 7.833; 0.9, 0.9)) |
| | Biontech | G | VG | VG | ((8.333, 9.500, 9.667, 10.000; 1, 1),(9.000, 9.500, 9.667, 9.833; 0.9, 0.9)) |
| | Janssen | F | G | F | ((4.333, 6.167, 6.667, 8.000; 1, 1),(5.333, 6.167, 6.667, 7.167; 0.9, 0.9)) |
| | Moderna | F | G | F | ((4.333, 6.167, 6.667, 8.000; 1, 1),(5.333, 6.167, 6.667, 7.167; 0.9, 0.9)) |
| | Sinovac | P | P | P | ((0.000, 1.000, 1.500, 3.000; 1, 1),(0.500, 1.000, 1.500, 2.000; 0.9, 0.9)) |
| | Sputnik V | MP | MG | VG | ((3.667, 5.333, 5.667, 6.667; 1, 1),(4.500, 5.333, 5.667, 6.000; 0.9, 0.9)) |
| Production Technology | AstraZeneca | MP | F | MP | ((1.667, 3.667, 4.167, 5.667; 1, 1),(2.667, 3.667, 4.167, 4.667; 0.9, 0.9)) |
| | Biontech | MG | G | MG | ((5.667, 7.500, 8.000, 9.333; 1, 1),(6.667, 7.500, 8.000, 8.500; 0.9, 0.9)) |
| | Janssen | MP | F | MP | ((1.667, 3.667, 4.167, 5.667; 1, 1),(2.667, 3.667, 4.167, 4.667; 0.9, 0.9)) |
| | Moderna | MG | G | MG | ((5.667, 7.500, 8.000, 9.333; 1, 1),(6.667, 7.500, 8.000, 8.500; 0.9, 0.9)) |
| | Sinovac | F | MP | F | ((2.333, 4.333, 4.833, 6.333; 1, 1),(3.333, 4.333, 4.833, 5.333; 0.9, 0.9)) |
| | Sputnik V | MP | F | MP | ((1.667, 3.667, 4.167, 5.667; 1, 1),(2.667, 3.667, 4.167, 4.667; 0.9, 0.9)) |
| Storage Conditions | AstraZeneca | MG | MG | F | ((4.333, 6.333, 6.833, 8.333; 1, 1),(5.333, 6.333, 6.833, 7.333; 0.9, 0.9)) |
| | Biontech | VP | P | VP | ((0.000, 0.333, 0.500, 1.667; 1, 1),(0.167, 0.333, 0.500, 1.000; 0.9, 0.9)) |
| | Janssen | MG | MP | F | ((4.333, 6.333, 6.833, 8.333; 1, 1),(5.333, 6.333, 6.833, 7.333; 0.9, 0.9)) |
| | Moderna | MP | MP | VG | ((3.667, 5.333, 5.667, 6.667; 1, 1),(4.500, 5.333, 5.667, 6.000; 0.9, 0.9)) |
| | Sinovac | VG | VG | VG | ((9.000, 10.000, 10.000, 10.000; 1, 1),(9.500, 10.000, 10.000, 10.000; 0.9, 0.9)) |
| | Sputnik V | MP | F | VP | ((1.333, 2.667, 3.000, 4.333; 1, 1),(2.000, 2.667, 3.000, 3.500; 0.9, 0.9)) |
| Production Rates | AstraZeneca | VG | VG | MG | ((7.667, 9.000, 9.167, 9.667; 1, 1),(8.333, 9.000, 9.167, 9.333; 0.9, 0.9)) |
| | Biontech | MG | VG | F | ((5.667, 7.333, 7.667, 8.667; 1, 1),(6.500, 7.333, 7.667, 8.000; 0.9, 0.9)) |
| | Janssen | MP | G | F | ((3.667, 5.500, 6.000, 7.333; 1, 1),(4.667, 5.500, 6.000, 6.500; 0.9, 0.9)) |
| | Moderna | MP | G | MP | ((3.000, 4.833, 5.333, 6.667; 1, 1),(4.000, 4.833, 5.333, 5.833; 0.9, 0.9)) |
| | Sinovac | MP | G | MP | ((3.000, 4.833, 5.333, 6.667; 1, 1),(4.000, 4.833, 5.333, 5.833; 0.9, 0.9)) |
| | Sputnik V | MP | G | F | ((3.667, 5.500, 6.000, 7.333; 1, 1),(4.667, 5.500, 6.000, 6.500; 0.9, 0.9)) |
| Side Effects | AstraZeneca | VG | VG | VG | ((9.000, 10.000, 10.000, 10.000; 1, 1),(9.500, 10.000, 10.000, 10.000; 0.9, 0.9)) |
| | Biontech | MG | G | MG | ((5.667, 7.500, 8.000, 9.333; 1, 1),(6.667, 7.500, 8.000, 8.500; 0.9, 0.9)) |
| | Janssen | MP | F | MG | ((3.000, 5.000, 5.500, 7.000; 1, 1),(4.000, 5.000, 5.500, 6.000; 0.9, 0.9)) |
| | Moderna | MG | G | MG | ((5.667, 7.500, 8.000, 9.333; 1, 1),(6.667, 7.500, 8.000, 8.500; 0.9, 0.9)) |
| | Sinovac | P | P | VP | ((0.000, 0.667, 1.000, 2.333; 1, 1),(0.333, 0.667, 1.000, 1.500; 0.9, 0.9)) |
| | Sputnik V | F | MG | P | ((1.000, 2.333, 2.833, 4.333; 1, 1),(1.667, 2.333, 2.833, 3.333; 0.9, 0.9)) |
| Protection Rates | AstraZeneca | F | MP | F | ((2.333, 4.333, 4.833, 6.333; 1, 1),(3.333, 4.333, 4.833, 5.333; 0.9, 0.9)) |
| | Biontech | VG | VG | VG | ((9.000, 10.000, 10.000, 10.000; 1, 1),(9.500, 10.000, 10.000, 10.000; 0.9, 0.9)) |
| | Janssen | F | MP | F | ((2.333, 4.333, 4.833, 6.333; 1, 1),(3.333, 4.333, 4.833, 5.333; 0.9, 0.9)) |
| | Moderna | VG | VG | VG | ((9.000, 10.000, 10.000, 10.000; 1, 1),(9.500, 10.000, 10.000, 10.000; 0.9, 0.9)) |
| | Sinovac | F | P | P | ((1.000, 2.333, 2.833, 4.333; 1, 1),(1.667, 2.333, 2.833, 3.333; 0.9, 0.9)) |
| | Sputnik V | VG | VG | G | ((8.333, 9.500, 9.667, 10.000; 1, 1),(9.000, 9.500, 9.667, 9.833; 0.9, 0.9)) |
| Economic | AstraZeneca | P | P | F | ((1.000, 2.333, 2.833, 4.333; 1, 1),(1.667, 2.333, 2.833, 3.333; 0.9, 0.9)) |
| | Biontech | F | F | MG | ((3.667, 5.667, 6.167, 7.667; 1, 1),(4.667, 5.667, 6.167, 6.667; 0.9, 0.9)) |
| | Janssen | MP | MP | F | ((1.667, 3.667, 4.167, 5.667; 1, 1),(2.667, 3.667, 4.167, 4.667; 0.9, 0.9)) |
| | Moderna | VG | VG | VG | ((9.000, 10.000, 10.000, 10.000; 1, 1),(9.500, 10.000, 10.000, 10.000; 0.9, 0.9)) |
| | Sinovac | MG | G | VG | ((7.000, 8.500, 8.833, 9.667; 1, 1),(7.833, 8.500, 8.833, 9.167; 0.9, 0.9)) |
| | Sputnik V | P | P | F | ((1.000, 2.333, 2.833, 4.333; 1, 1),(1.667, 2.333, 2.833, 3.333; 0.9, 0.9)) |

in Section 4. MATLAB software is used to perform the mathematical computations for the two approaches.

**Step 1:** The PCMs are established by using the linguistic variables given in Table 1 by the importance ratings of experts. In the PCMs created for the criterion weights, the evaluations of all three decision-makers were collected and given in Tables 3, 4, and 5:

**Step 2:** The PCMs constituted in the previous step are defuzzified. The consistency assessment is carried out on the IT2TrFN matrices' crisp counterparts. All of the matrices' consistency ratios for each expert are found under 0.1.

**Step 3:** The aggregated average PCMs are constructed. Evaluated average matrices are given in Tables 6, 7, and 8.

**Step 4a:** Geometric means for each row of the alternative matrices are calculated. Obtained results are given in Tables 9, 10, and 11.

**Step 4b:** Normalized IT2TrFN weights are calculated. The normalized weight vector for the criteria at the lowest level of the hierarchy is given in Table 12.

**Step 5:** The decision matrices are generated by expert evaluations of the linguistic elements listed in Table 2. The assessments of all three decision-makers were collected and shown in Table 13 in the decision matrices constructed for the alternatives in terms of criteria.

**Step 6:** The aggregated average decision matrices are constructed. Evaluated average matrices are given in Table 13.

**Step 7:** The weighted decision matrix is calculated. Obtained IT2TrFNs are presented in Table 14.

**Step 8:** Upper and lower reference points for PIS and NIS are evaluated. Calculated IT2TrFNs are given in Tables 15, 16, and 17.

**Step 9:** The average group score and worst group score are evaluated. Obtained results are given in Tables 18 and 19.

**Table 14**
Weighted decision matrix.

| Criteria | Alternatives | | | | | |
|---|---|---|---|---|---|---|
| | AstraZeneca | Biontech | Janssen | Moderna | Sinovac | Sputnik V |
| Country of origin | ((0.081, 0.229, 0.902, 2.569; 1, 1), (0.114, 0.261, 0.779, 1.883; 1, 1)) | ((0.135, 0.318, 1.190, 2.964; 1, 1), (0.172, 0.363, 1.027, 2.364; 0.8, 0.8)) | ((0.070, 0.207, 0.820, 2.371; 1, 1), (0.102, 0.236, 0.709, 1.723; 0.8, 0.8)) | ((0.070, 0.207, 0.820, 2.371; 1, 1), (0.102, 0.236, 0.709, 1.723; 0.8, 0.8)) | ((0.000, 0.033, 0.184, 0.889; 1, 1), (0.009, 0.038, 0.159, 0.481; 0.8, 0.8)) | ((0.059, 0.179, 0.697, 1.976; 1, 1), (0.086, 0.204, 0.602, 1.442; 0.8, 0.8)) |
| Production technology | ((0.044, 0.212, 0.850, 2.530; 1, 1), (0.085, 0.242, 0.742, 1.736; 0.8, 0.8)) | ((0.151, 0.433, 1.632, 4.167; 1, 1), (0.213, 0.496, 1.425, 3.162; 1, 1)) | ((0.044, 0.212, 0.850, 2.530; 1, 1), (0.085, 0.242, 0.742, 1.736; 0.8, 0.8)) | ((0.151, 0.433, 1.632, 4.167; 1, 1), (0.213, 0.496, 1.425, 3.162; 0.8, 0.8)) | ((0.062, 0.250, 0.986, 2.827; 1, 1), (0.106, 0.286, 0.861, 1.984; 0.8, 0.8)) | ((0.044, 0.212, 0.850, 2.530; 1, 1), (0.085, 0.242, 0.742, 1.736; 0.8, 0.8)) |
| Storage conditions | ((0.035, 0.100, 0.346, 0.902; 1, 1), (0.051, 0.113, 0.305, 0.665; 0.8, 0.8)) | ((0.000, 0.005, 0.025, 0.180; 1, 1), (0.001, 0.006, 0.022, 0.090; 0.8, 0.8)) | ((0.035, 0.100, 0.346, 0.902; 1, 1), (0.051, 0.113, 0.305, 0.665; 1, 1)) | ((0.030, 0.085, 0.287, 0.721; 1, 1), (0.043, 0.095, 0.253, 0.544; 0.8, 0.8)) | ((0.074, 0.159, 0.507, 1.082; 1, 1), (0.091, 0.179, 0.446, 0.907; 0.8, 0.8)) | ((0.011, 0.042, 0.152, 0.469; 1, 1), (0.019, 0.048, 0.134, 0.3176; 0.8, 0.8)) |
| Production rates | ((0.173, 0.412, 1.421, 3.277; 1, 1), (0.221, 0.469, 1.244, 2.636; 0.8, 0.8)) | ((0.128, 0.336, 1.189, 2.938; 1, 1), (0.172, 0.382, 1.041, 2.259; 0.8, 0.8)) | ((0.082, 0.252, 0.930, 2.486; 1, 1), (0.124, 0.286, 0.814, 1.836; 0.8, 0.8)) | ((0.067, 0.221, 0.827, 2.260; 1, 1), (0.106, 0.252, 0.724, 1.647; 1, 1)) | ((0.067, 0.221, 0.827, 2.260; 1, 1), (0.106, 0.252, 0.724, 1.647; 0.8, 0.8)) | ((0.082, 0.252, 0.930, 2.486; 1, 1), (0.124, 0.286, 0.814, 1.836; 0.8, 0.8)) |
| Side Effects | ((0.790, 1.694, 4.406, 7.574; 1, 1), (0.977, 1.889, 3.987, 6.692; 1, 1)) | ((0.497, 1.271, 3.525, 7.069; 1, 1), (0.686, 1.417, 3.190, 5.688; 0.8, 0.8)) | ((0.263, 0.847, 2.423, 5.302; 1, 1), (0.411, 0.945, 2.193, 4.015; 0.8, 0.8)) | ((0.497, 1.271, 3.525, 7.069; 1, 1), (0.686, 1.417, 3.190, 5.688; 0.8, 0.8)) | ((0.000, 0.113, 0.440, 1.767; 1, 1), (0.034, 0.126, 0.398, 1.004; 0.8, 0.8)) | ((0.088, 0.395, 1.248, 3.282; 1, 1), (0.171, 0.441, 1.129, 2.231; 0.8, 0.8)) |
| Protection Rates | ((0.260, 0.882, 2.557, 6.093; 1, 1), (0.428, 0.978, 2.303, 4.454; 0.8, 0.8)) | ((1.003, 2.035, 5.291, 9.621; 1, 1), (1.219, 2.258, 4.765, 8.352; 1, 1)) | ((0.260, 0.882, 2.557, 6.093; 1, 1), (0.428, 0.978, 2.303, 4.454; 0.8, 0.8)) | ((1.003, 2.035, 5.291, 9.621; 1, 1), (1.219, 2.258, 4.765, 8.352; 0.8, 0.8)) | ((0.111, 0.475, 1.499, 4.169; 1, 1), (0.214, 0.527, 1.350, 2.784; 0.8, 0.8)) | ((0.929, 1.933, 5.115, 9.621; 1, 1), (1.155, 2.145, 4.606, 8.212; 0.8, 0.8)) |
| Economic | ((0.063, 0.199, 0.423, 0.955; 1, 1), (0.113, 0.211, 0.396, 0.670; 0.8, 0.8)) | ((0.231, 0.484, 0.920, 1.690; 1, 1), (0.316, 0.514, 0.862, 1.341; 0.8, 0.8)) | ((0.105, 0.313, 0.621, 1.249; 1, 1), (0.180, 0.332, 0.582, 0.939; 0.8, 0.8)) | ((0.568, 0.854, 1.492, 2.205; 1, 1), (0.643, 0.907, 1.397, 2.011; 0.8, 0.8)) | ((0.441, 0.726, 1.318, 2.131; 1, 1), (0.530, 0.771, 1.234, 1.844; 0.8, 0.8)) | ((0.063, 0.199, 0.423, 0.955; 1, 1), (0.113, 0.211, 0.396, 0.670; 0.8, 0.8)) |

**Table 15**
Upper reference point for positive ideal solutions ($P^{e*}$).

| | |
|---|---|
| Country of origin | ((8.333, 9.500, 9.667, 10.000; 1, 1),(9.000, 9.500, 9.667, 9.833; 0.9, 0.9)) |
| Production technology | ((5.667, 7.500, 8.000, 9. 333; 1, 1),(6.667, 7.500, 8.000, 8.500; 0.9, 0.9)) |
| Storage conditions | ((9.000, 10.000, 10.000, 10.000; 1, 1),(9.500, 10.000, 10.000, 10.000; 0.9, 0.9)) |
| Production rates | ((7.667, 9.000, 9.167, 9.667; 1, 1),(8.333, 9.000, 9.167, 9.333; 0.9, 0.9)) |
| Side effects | ((0.000, 0.667, 1.000, 2.333; 1, 1),(0.333, 0.667, 1.000, 1.500; 0.9, 0.9)) |
| Protection rates | ((9.000, 10.000, 10.000, 10.000; 1, 1),(9.500, 10.000, 10.000, 10.000; 0.9, 0.9)) |
| Economic | ((1.000, 2.333, 2.833, 4.333; 1, 1),(1.667, 2.333, 2.833, 3.333; 0.9, 0.9)) |

**Table 16**
Lower reference point for positive ideal solutions ($P^{v*}$).

| | |
|---|---|
| Country of origin | ((0.135, 0.318, 1.190, 2.964; 1, 1),(0.172, 0.363, 1.027, 2.364; 0.8, 0.8)) |
| Production technology | ((0.151, 0.433, 1.632, 4.167; 1, 1),(0.213, 0.496, 1.425, 3.162; 0.8, 0.8)) |
| Storage conditions | ((0.074, 0.159, 0.507, 1.082; 1, 1),(0.091, 0.179, 0.446, 0.907; 0.8, 0.8)) |
| Production rates | ((0.173, 0.412, 1.421, 3.277; 1, 1),(0.221, 0.469, 1.244, 2.636; 0.8, 0.8)) |
| Side effects | ((0.000, 0.113, 0.440, 1.767; 1, 1),(0.034, 0.126, 0.398, 1.004; 0.8, 0.8)) |
| Protection rates | ((1.003, 2.035, 5.291, 9.621; 1, 1),(1.219, 2.258, 4.765, 8.352; 0.8, 0.8)) |
| Economic | ((0.063, 0.199, 0.423, 0.955; 1, 1),(0.113, 0.211, 0.396, 0.670; 0.8, 0.8)) |

**Table 17**
Negative ideal solutions ($N^{e-}$).

| | |
|---|---|
| Country of origin | ((0.000, 0.033, 0.184, 0.889; 1, 1),(0.009, 0.038, 0.159, 0.481; 0.8, 0.8)) |
| Production technology | ((0.044, 0.212, 0.850, 2.530; 1, 1),(0.085, 0.242, 0.742, 1.736; 0.8, 0.8)) |
| Storage conditions | ((0.000, 0.005, 0.025, 0.180; 1, 1),(0.001, 0.006, 0.022, 0.090; 0.8, 0.8)) |
| Production rates | ((0.067, 0.221, 0.827, 2.260; 1, 1),(0.106, 0.252, 0.724, 1.647; 0.8, 0.8)) |
| Side effects | ((0.790, 1.694, 4.406, 7.574; 1, 1),(0.977, 1.889, 3.987, 6.692; 0.8, 0.8)) |
| Protection rates | ((0.111, 0.475, 1.499, 4.169; 1, 1),(0.214, 0.527, 1.350, 2.784; 0.8, 0.8)) |
| Economic | ((0.568, 0.854, 1.492, 2.205; 1, 1),(0.643, 0.907, 1.397, 2.011; 0.8, 0.8)) |

**Table 18**
Average group score.

| | |
|---|---|
| AstraZeneca | ((0.055, 0.434, 5.146, 32.155; 1, 1),(0.155, 0.949, 2.476, 13.095; 0.8, 0.8)) |
| Biontech | ((0.043, 0.356, 4.189, 31.447; 1, 1),(0.129, 0.762, 1.980, 11.155; 0.8, 0.8)) |
| Janssen | ((0.033, 0.260, 2.953, 21.454; 1, 1),(0.095, 0.542, 1.390, 7.765; 0.8, 0.8)) |
| Moderna | ((0.076, 0.509, 5.041, 40.000; 1, 1),(0.211, 1.008, 2.417, 13.361; 0.8, 0.8)) |
| Sinovac | ((0.054, 0.281, 1.791, 17.669; 1, 1),(0.139, 0.468, 0.888, 4.680; 0.8, 0.8)) |
| Sputnik V | ((0.011, 0.089, 1.133, 8.183; 1, 1),(0.031, 0.191, 0.521, 3.022; 0.8, 0.8)) |

**Table 19**
Worst group score.

| | |
|---|---|
| AstraZeneca | ((0.040, 0.365, 4.696, 29.179; 1, 1),(0.121, 0.834, 2.251, 12.028; 0.8, 0.8)) |
| Biontech | ((0.025, 0.254, 3.516, 23.593; 1, 1),(0.080, 0.589, 1.652, 9.302; 0.8, 0.8)) |
| Janssen | ((0.013, 0.151, 2.212, 15.179; 1, 1),(0.045, 0.358, 1.027, 5.898; 0.8, 0.8)) |
| Moderna | ((0.048, 0.254, 3.516, 23.593; 1, 1),(0.123, 0.589, 1.652, 9.302; 0.8, 0.8)) |
| Sinovac | ((0.036, 0.187, 1.137, 13.156; 1, 1),(0.094, 0.308, 0.566, 3.098; 0.8, 0.8)) |
| Sputnik V | ((0.0045, 0.0559, 0.8740, 6.1930; 1, 1),(0.0158, 0.1341, 0.3984, 2.3559; 0.8, 0.8)) |

**Table 20**
$\tilde{\tilde{Q}}_i$ values.

| | |
|---|---|
| AstraZeneca | ((0.0009, 0.0729, 11.8898, 759.1667; 1, 1),(0.0093, 0.3961, 2.2388, 87.1183; 0.8, 0.8)) |
| Biontech | ((0.0006, 0.0513, 8.4764, 607.6617; 1, 1),(0.0065, 0.2776, 1.5749, 64.1359; 0.8, 0.8)) |
| Janssen | ((0.0003, 0.0293, 4.6338, 329.5700; 1, 1),(0.0037, 0.1560, 0.8674, 34.7480; 0.8, 0.8)) |
| Moderna | ((0.0012, 0.0759, 9.8001, 703.0868; 1, 1),(0.0118, 0.3714, 1.9159, 72.2340; 0.8, 0.8)) |
| Sinovac | ((0.0008, 0.0440, 1.9854, 194.1514; 1, 1),(0.0079, 0.1742, 0.5782, 11.5025; 0.8, 0.8)) |
| Sputnik V | ((0.0000, 0.0000, 0.0000, 0.0000; 0, 0),(0.0000, 0.0000, 0.0000, 0.0000; 0, 0)) |

**Step 10:** Finally, $\tilde{\tilde{Q}}_i$ values are calculated with $v = 0.5$ decision strategy weight. Obtained scores are given in Table 20.

Now, to obtain the optimum alternative(s), $S$, $R$, and $Q$ values are given in Table 21.

The methodology shows that the vaccine "Sputnik V" is the optimum vaccine regarding expert opinions. Also, there is an important advantage of the usage of VIKOR as a decision tool. If one would like to choose an optimum alternative set rather than only one optimum solution, looking at Table 21, it is possible to say that the optimum solution set would include "Sputnik V", "Sinovac", and "Janssen" vaccines.

It is clear that the fuzzy AHP-VIKOR methodology has failed to handle this application with a multilevel hierarchy. The values for $S$, $R$, and $Q$ are consistent with the proposed IT2FAHP-IT2FVIKOR as it needs to be. Yet, the values that type-1 fuzzy AHP-VIKOR produces are unbalanced and almost irrelevant. Even though the defuzzified values of $S$ and $R$ are positive, some of the defuzzified values of $Q$ are negative. The main reason for the type-1 fuzzy AHP-VIKOR to fail is the negativity in the fuzzy numbers. The authors observed from

**Table 21**
Results and optimum alternative (s).

| Alternative | IT2FAHP-IT2FVIKOR | | | | | | Fuzzy AHP-VIKOR | | | | IT2FAHP-IT2FTOPSIS | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $S_i$ | $R_i$ | $Q_i$ | Ranking | Condition 1 | Condition 2 | $S_i$ | $R_i$ | $Q_i$ | Ranking | Crisp score | Normalized score | Ranking |
| AstraZeneca | 6.722 | 6.112 | 107.545 | 6 | – | No | 2.739 | 1.310 | 0.076 | 3 | 1.756 | 0.109 | 6 |
| Biontech | 6.189 | 4.820 | 85.227 | 4 | No | Yes | 1.883 | 0.740 | −0.131 | 2 | 3.311 | 0.206 | 2 |
| Janssen | 4.263 | 3.076 | 46.225 | 3 | Yes | Yes | 4.048 | 1.310 | 0.104 | 5 | 2.263 | 0.14 | 4 |
| Moderna | 7.742 | 4.829 | 98.380 | 5 | Yes | No | 2.155 | 1.217 | −0.172 | 1 | 2.816 | 0.175 | 3 |
| Sinovac | 3.212 | 2.301 | 26.036 | 2 | Yes | Yes | 4.498 | 1.561 | 0.217 | 6 | 2.089 | 0.13 | 5 |
| Sputnik V | 1.630 | 1.240 | 0 | 1 | Yes | Yes | 3.310 | 1.175 | 0.086 | 4 | 3.862 | 0.24 | 1 |

**Table 22**
Sensitivity analysis results depending on the decision strategy weight.

| $v$ | $Q$ Values | | | | | | Ranking | Optimal alternative set |
|---|---|---|---|---|---|---|---|---|
| | AstraZeneca ($A_1$) | Biontech ($A_2$) | Janssen ($A_3$) | Moderna ($A_4$) | Sinovac ($A_5$) | Sputnik V ($A_6$) | | |
| $v = 0$ | 127.460 | 93.127 | 47.673 | 93.367 | 25.970 | 0 | $A_6 \succ A_5 \succ A_3 \succ A_2 \succ A_4 \succ A_1$ | Sputnik V |
| $v = 0.1$ | 123.477 | 91.547 | 47.384 | 94.393 | 25.982 | 0 | $A_6 \succ A_5 \succ A_3 \succ A_2 \succ A_4 \succ A_1$ | Sputnik V |
| $v = 0.2$ | 119.494 | 89.967 | 47.094 | 95.390 | 25.996 | 0 | $A_6 \succ A_5 \succ A_3 \succ A_2 \succ A_4 \succ A_1$ | Sputnik V |
| $v = 0.3$ | 115.511 | 88.387 | 46.805 | 96.386 | 26.009 | 0 | $A_6 \succ A_5 \succ A_3 \succ A_2 \succ A_4 \succ A_1$ | Sputnik V |
| $v = 0.4$ | 111.528 | 86.807 | 46.515 | 97.383 | 26.023 | 0 | $A_6 \succ A_5 \succ A_3 \succ A_2 \succ A_4 \succ A_1$ | Sputnik V |
| $v = 0.5^*$ | 107.545 | 85.227 | 46.225 | 98.380 | 26.036 | 0 | $A_6 \succ A_5 \succ A_3 \succ A_2 \succ A_4 \succ A_1$ | Sputnik V |
| $v = 0.6$ | 103.563 | 83.646 | 45.936 | 99.376 | 26.050 | 0 | $A_6 \succ A_5 \succ A_3 \succ A_2 \succ A_4 \succ A_1$ | Sputnik V |
| $v = 0.7$ | 99.580 | 82.066 | 45.646 | 100.373 | 26.064 | 0 | $A_6 \succ A_5 \succ A_3 \succ A_2 \succ A_1 \succ A_4$ | Sputnik V |
| $v = 0.8$ | 95.597 | 80.486 | 45.356 | 101.370 | 26.077 | 0 | $A_6 \succ A_5 \succ A_3 \succ A_2 \succ A_1 \succ A_4$ | Sputnik V |
| $v = 0.9$ | 91.614 | 78.906 | 45.067 | 102.366 | 26.091 | 0 | $A_6 \succ A_5 \succ A_3 \succ A_2 \succ A_1 \succ A_4$ | Sputnik V |
| $v = 1$ | 87.631 | 77.326 | 44.777 | 103.363 | 26.104 | 0 | $A_6 \succ A_5 \succ A_3 \succ A_2 \succ A_1 \succ A_4$ | Sputnik V |

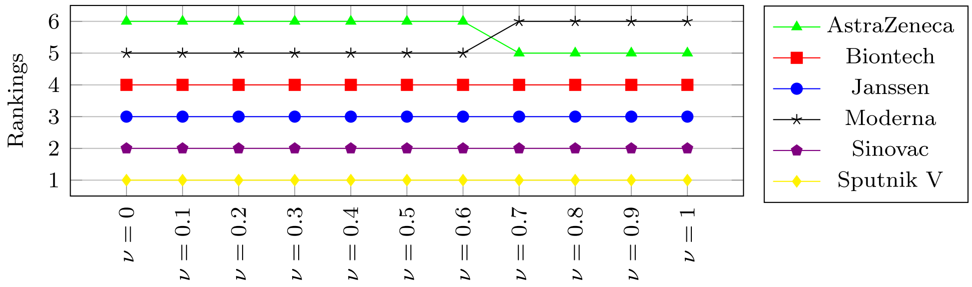

**Fig. 4.** Ranking of alternatives with different decision strategy weights.

the MATLAB package program that, after the steps of the procedure with negative numbers, the results start to deviate. Nevertheless, the IT2FAHP-IT2FVIKOR approach does not lead to this kind of unstable outcome through the IT2F metric.

When the ranking obtained by the TOPSIS method in Meniz (2021) is compared with the results obtained with the proposed enhanced VIKOR, it is seen that the first and last alternatives do not change. But, there are some variations between the four alternatives in-between. However, in the TOPSIS method, the alternative that is at the top of the ranking is optimal, and the other alternatives are not in the optimality set. On the other hand, the VIKOR method can test all alternatives with some conditions in order to form an optimal alternative set.

**Remark 2.** It should be noted that the 6th alternative (ranked as 1) which is "Sputnik V" has the $\tilde{\tilde{0}}$ as $\tilde{\tilde{Q}}$ value independent from the value of $v$. However, by looking at the crisp values instead of the use of IT2TrFN operators, it may not be possible to obtain the value 0.

### *5.1. Sensitivity analysis*

In the last step of the study, the methodology will be subjected to sensitivity analysis. The weight of the decision strategy, which was set to 0.5 during the implementation phase, will fluctuate between 0 and 1 at intervals of 0.1 in this study. Table 22 displays the $Q$ values and the alternative(s) based on these values to highlight the score difference between the alternatives for each decision strategy weight studied. Fig. 4 also shows the ranking of the options based on the change in the decision strategy weight.

Table 22 shows that, while the first four alternatives in the ranking of alternatives stay consistent, the final two alternatives changes. While the set of optimum alternatives remains constant, due to the VIKOR technique's result assessment mechanism, possible choices other than the best can be added to the set of optimum solutions. An assessment with $S$ and $R$ values must be included in the table for this.

## 6. Conclusions

The problem setup for mathematical issues with real-world applications should incorporate probable unknown conditions. IT2FSs were employed to account for the vagueness. Two of the most commonly utilized decision-making strategies in the literature have been combined to solve a real-world problem. The first is the AHP technique, which serves as a useful tool used to find out the weights of the criteria. The second one is the VIKOR approach, which is notable for its ability to provide a set of optimal selections rather than a single best option. Several improvements to the existing VIKOR technique in the literature have been made through the use of the IT2F metric. This ensures that the process continues for a longer period with IT2FNs and prevents negative numbers that cause deterioration. As a corollary, rather than continuing with crisp numbers after a threshold, the presence of IT2FNs has been maintained until the end. It has been aimed to maintain reality in computations while maintaining the continuation of uncertainty in the problem's solution stages.

The COVID-19 outbreak has been on the global agenda since the end of 2019. To neutralize the pandemic, the health authorities suggest that the majority of the population should be vaccinated. There are many vaccines that have been manufactured in 2021–2022 with various technologies. Having more than one choice necessitates a decision between vaccines that will be administered individually and vaccines that will be purchased by a country. In this study, six different vaccines, which have been the subject of many academic and medical studies, have been discussed. The IT2FAHP and the extended IT2FVIKOR hybrid approach have been used to choose the best vaccination. The Sputnik V vaccine has been identified as the most optimal vaccination among these vaccines, according to expert evaluations. However, if a set of ideal vaccinations rather than a single vaccine is requested, it has been observed that Sinovac and Janssen vaccines could be included in the set in accordance with the VIKOR method's notion of optimality. In addition, it has been seen that the same alternative with the proposed approaches is in the first place in the results obtained in the TOPSIS technique. But it has been observed that the type-1 fuzzy AHP-VIKOR has been unsuccessful to solve this decision-making problem. Furthermore, sensitivity evaluation has been carried out on the collection of ideal selections. The choice strategy weight has been shown to have no effect on the top four vaccines. It has also been discovered that the methodology produces consistent results when the decision weights are modified.

## 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.

## Data availability

Data will be made available on request.

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