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Optimization of Emergency Alternatives for Hydrogen Leakage and Explosion Accidents Based on Improved VIKOR

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Abstract: Hydrogen leakage and explosion accidents have obvious dangers, ambiguity of accident information, and urgency of decision-making time. These characteristics bring challenges to the optimization of emergency alternatives for such accidents. Effective emergency decision making is crucial to mitigating the consequences of accidents and minimizing losses and can provide a vital reference for emergency management in the field of hydrogen energy. An improved VIKOR emergency alternatives optimization method is proposed based on the combination of hesitant triangular fuzzy set (HTFS) and the cumulative prospect theory (CPT), termed the HTFS-CPT-VIKOR method. This method adopts the hesitant triangular fuzzy number to represent the decision information on the alternatives under the influence of multi-attributes, constructs alternatives evaluation indicators, and solves the indicator weights by using the deviation method. Based on CPT, positive and negative ideal points were used as reference points to construct the prospect matrix, which then utilized the VIKOR method to optimize the emergency alternatives for hydrogen leakage and explosion accidents. Taking an accident at a hydrogen refueling station as an example, the effectiveness and rationality of the HTFS-CPT-VIKOR method were verified by comparing with the existing three methods and conducting parameter sensitivity analysis. Research results show that the HTFS-CPT-VIKOR method effectively captures the limited psychological behavior characteristics of decision makers and enhances their ability to identify, filter, and judge ambiguous information, making the decision-making alternatives more in line with the actual environment, which provided strong support for the optimization of emergency alternatives for hydrogen leakage and explosion accidents.

Keywords: hydrogen leakage and explosion accident; emergency decision making; alternatives optimization; hesitant triangular fuzzy set; cumulative prospect theory; VIKOR

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1. Introduction

In the context of the global energy transition and carbon emission reduction, hydrogen, as a renewable and clean fuel, has garnered widespread attention and research [1,2]. However, with the rapid development of hydrogen technology and its application potential gradually emerging [3–5], the issue of hydrogen safety has garnered significant attention. In recent years, hydrogen accidents of varying degrees in South Korea [6], Norway [7], the United States [8], China, and other places have posed significant challenges to human safety and property safety [9]. A variety of different emergency alternatives can be used when a hydrogen accident occurs. The best one depends on the specific conditions and the intensity of the consequence. Therefore, it is particularly critical to select an emergency alternative with high comprehensive benefits and strong performance from multiple alternatives within a limited timeframe. In-depth research on the optimal method for emergency alternatives for hydrogen leakage and explosion accidents can provide vital support for the safety and sustainable development of hydrogen energy.

Compared with traditional energy sources, hydrogen has a broader flammable range (4–75%) [10], low minimum ignition energy (0.02 mJ) [11], and a higher calorific value (120–142 MJ/kg) [12], which exacerbate the risks during storage, transportation, and usage. It is worth noting that, in an (partly) enclosed environment with obstacles, a hydrogen deflagration may transition into a detonation [13–15]. Given that hydrogen is colorless, odorless, and burns with high concealment, obtaining and interpreting information during a hydrogen leakage and explosion accident becomes ambiguous, resulting in urgent decision-making time and increased psychological pressure on decision makers (DMs). In such emergencies, the psychological behavior of DMs is largely to avoid risks, and this behavioral pattern is crucial for selecting the optimal emergency alternative. While the existing research on optimal emergency alternatives provides significant contributions, it may not fully address the unique challenges posed by hydrogen leakage and explosion accidents. This decision-making process is constrained by various factors such as technology, experience, and environment, making it a multi-attribute decision-making problem [16]. Commonly used multi-attribute decision-making methods include TOPSIS, VIKOR, ELECTRE, and the Entropy Weight method [17]. Among them, the TOPSIS and VIKOR methods both consider the distance between the alternatives and the positive and negative ideal solutions. However, the advantage of the VIKOR method is that it simultaneously considers the maximum group utility value and the minimum individual regret value [18]. Particularly when facing decision-making problems characterized by high complexity and multiple attributes, such as hydrogen leakage and explosion accidents, the VIKOR method can better balance the benefits and risks of various alternatives, making the decision results more credible. The VIKOR method considers the maximum group utility value, the minimum individual regret value, and the proximity of each alternative to the positive and negative ideal solutions [18], making the decision results more credible. Currently, the VIKOR method is widely used in many fields. Wang et al. used the VIKOR method to assess construction project risks and prioritize risk factors [19]. However, the traditional VIKOR method has limitations when addressing emergency decision making for hydrogen accidents. In view of the ambiguous information at the scene of hydrogen leakage and explosion accidents and the subjective limitations of DMs, it is crucial to represent decision-making information using fuzzy sets. Scholars have proposed various fuzzy set theories, such as interval fuzzy sets [20], hesitant fuzzy sets [21], and type-II fuzzy sets [22]. Among them, HTFS is more suitable for handling the hesitancy uncertainty in the decision-making process [23]. The aforementioned studies are all based on complete rational psychology. However, when faced with unclear mechanisms of hydrogen leakage and explosion accidents and a lack of handling experience, DMs often experience significant psychological pressure, affecting the actual decision results [24]. With the emergence of behavioral decision theory, CPT can address the flaws of the complete rationality assumption [25,26]. Gao et al. proposed a method based on CPT and multi-attribute decision theory for travel behavior modeling [27]. Zhang et al. applied the SF-GRA method based on CPT to the selection of emergency material suppliers [28].

This paper proposes an improved VIKOR method based on HTFS and CPT to optimize the emergency decision-making process for hydrogen leakage and explosion accidents. The evaluation of alternative indicator information is integrated through the HTFS. On this basis, CPT is introduced to further optimize the VIKOR process and sort the alternatives according to the compromise results. For comparison, the characteristics of this method and existing research methods are shown in Table 1.

Table 1. Comparative analysis of method characteristics.

Methods	Handling Information Ambiguity	Capture Psychological Behavior of DMs	Rationality of Alternatives Ranking	Applicability of Hydrogen Accidents
IFS/IVFS-TOPSIS [29]	×	×	×	×
IFS/IVFS-CPT [30]	×	√	×	×
Fuzzy VIKOR [31]	√	×	√	×
AHP-VIKOR [32]	×	×	√	×
The proposed HTFS-CPT-VIKOR	√	√	√	√

2. Model Definition

2.1. Definition of Hesitant Triangular Fuzzy Set

The hesitant triangular fuzzy set [33,34] is a method based on fuzzy set theory. This method uses triangular fuzzy numbers to describe the membership degree of the fuzzy set, which can effectively address issues of ambiguity and providing scientific support for emergency decision making.

Definition 1. *Interpretation of Hesitant Triangular Fuzzy Set.*

Let X be a given domain of discussion, the hesitant triangular fuzzy set ($\widetilde{H}$, HTFS) on X is represented as:

$$\widetilde{H} = \left\{ \left\langle x, \widetilde{h}_H(x) \right\rangle \middle| x \in X \right\} \tag{1}$$

where x is an element in X and $\widetilde{h}_H(x)$ is a set of triangular fuzzy numbers on [0, 1], referred to as the hesitant triangular fuzzy element, representing the membership degree of element x in $\widetilde{H}$.

Definition 2. *Triangular Fuzzy Number Structure Element.*

For a given triangular fuzzy number $\tilde{A} = (a, b, c)$ and a fuzzy structure element E, there always exists a monotonic bounded function f on [−1, 1] such that $\tilde{A} = f(E)$. The monotonic bounded function is:

$$f(x) = \begin{cases} (b-a)x + b, -1 \le x < 0 \\ (c-b)x + b, 0 \le x < 1 \end{cases} \tag{2}$$

Definition 3. *Hesitant Triangular Fuzzy Element Structural Element.*

Let $\tilde{h} = \tilde{h}_H(x)$, the structural form of the hesitant triangular fuzzy element $\widetilde{h}$ is:

$$\widetilde{h} = \widetilde{h}_H(x) = \widetilde{H}\left\{ f^{\lambda}(E) \middle| \lambda = 1, 2, \ldots, l \right\} \tag{3}$$

where λ represents the length of $\widetilde{h}$.

Definition 4. *Hamming Distance between Hesitant Triangular Fuzzy Elements.*

Let $\widetilde{h}_1 = \widetilde{H}(f^{\lambda}(E)|\lambda = 1, 2, \ldots, l_1)$ and $\widetilde{h}_2 = \widetilde{H}(g^{\lambda}(E)|\lambda = 1, 2, \ldots, l_2)$ be two hesitant triangular fuzzy elements. The Hamming distance between $\widetilde{h}_1$ and $\widetilde{h}_2$ is:

$$d_H\left(\widetilde{h}_1, \widetilde{h}_2\right) = \frac{1}{l}\left(\sum_{\lambda=1}^{l} \left(\left| \widetilde{\gamma}_1^{\lambda} - \widetilde{\gamma}_2^{\lambda} \right| \right) \right) = \frac{1}{l}\left(\sum_{\lambda=1}^{l} \left(\int_{-1}^{1} \left| f^{\lambda}(x) - g^{\lambda}(x) \right| E(x) dx \right) \right) \tag{4}$$

where $l_1 = l_2 = l$, meaning the lengths of $\widetilde{h}_1$ and $\widetilde{h}_2$ are equal. The membership function $E(x)$ is defined as:

$$E(x) = \begin{cases} 1 + x, -1 \le x \le 0 \\ 1 - x, 0 < x < 1 \\ 0, \text{else} \end{cases} \quad (5)$$

2.2. The Foundation of Cumulative Prospect Theory

The cumulative prospect theory is an extended method of prospect theory proposed by Tversky and Kahneman [35]. The prospect theory posits that individuals have differing attitudes towards losses and gains, being cautious towards potential gains and more sensitive to impending losses [36]. The cumulative prospect theory converts the decision-making risk state into an uncertain state based on prospect theory. It can more comprehensively consider the risk attitude of the decision maker in emergency decision making for hydrogen leakage and explosion accidents, offering a more scientific and effective decision-making framework. The decision-making process is as follows [37]:

Composite Prospect Value:

$$V(x) = \sum_{i=1}^{n} v(x_i)\pi(p_i) \quad (6)$$

Value Function:

$$v(x_i) = \begin{cases} (x_i - b)^{\alpha}, x_i \ge b \\ -\theta(b - x_i)^{\beta}, x_i < b \end{cases} \quad (7)$$

Weight Function:

$$\pi(p_i) = \begin{cases} \pi^+(p_i) = \frac{p_i^{\chi}}{\left[p_i^{\chi} + (1-p_i)^{\chi}\right]^{1/\chi}}, x_i \ge b \\ \pi^-(p_i) = \frac{p_i^{\varepsilon}}{\left[p_i^{\varepsilon} + (1-p_i)^{\varepsilon}\right]^{1/\varepsilon}}, x_i < b \end{cases} \quad (8)$$

where b represents the reference point. α, $\beta \in (0,1)$ are the risk posture coefficients of value in the face of gains or losses. $\theta > 1$ is the loss aversion coefficient. χ, $\varepsilon \in (0,1)$ are the risk attitude coefficients for probability weight when facing gains or losses.

2.3. Introduction to the VIKOR Method

The VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) method is a multi-criteria decision-making approach proposed by Opricovic and Tzeng in 1994 [38], which is suitable for addressing multi-indicator issues in the emergency alternatives optimization for hydrogen leakage and explosion accidents. This method adheres to the principle of maximizing group interests and minimizing individual regrets, and the core idea is to rank the alternatives by calculating the maximum group utility value, the minimum individual regret value, and the alternatives compromise value based on determining the positive and negative ideal solution. The ranking process is as follows:

Step 1: Determine the positive ideal solution f_j^+ and negative ideal solution f_j^-.

$$f_j^+ = \max f_{ij}, f_j^- = \min f_{ij} \quad (9)$$

Step 2: Identify the maximum group utility value S_i and the minimum individual regret value R_i.

$$S_i = \sum_{j=1}^{m} \frac{w_j\left(f_j^+ - f_{ij}\right)}{f_j^+ - f_j^-} \quad (10)$$

$$R_i = \max_j \left\{ \frac{w_j \left(f_j^+ - f_{ij} \right)}{f_j^+ - f_j^-} \right\} \tag{11}$$

Step 3: Determine the compromise value Q_i of the alternatives.

$$Q_i = \nu \frac{S_i - S^-}{S^* - S^-} + (1 - \nu) \frac{R_i - R^-}{R^* - R^-} \tag{12}$$

where S^* is the maximum of S_i, S^- is the minimum of S_i, R^* is the maximum of R_i, and R^- is the minimum of R_i.

Step 4: Rank the alternatives in ascending order based on their compromise value Q_i.

3. Emergency Alternatives Optimization Model Based on HTFS-CPT-VIKOR

Considering the uncertainty and complexity of hydrogen leakage and explosion accidents, HTFS can more accurately depict the decision maker's attitude towards ambiguous information. While the VIKOR method can prioritize emergency decision-making options, it does not account for the limited psychological behavior of DMs. CPT can effectively avoid this shortcoming.

An improved VIKOR method based on HTFS and CPT was developed, aiming to optimize the emergency decision-making process for hydrogen leakage and explosion accidents. The HTFS-CPT-VIKOR process is shown in Figure 1.

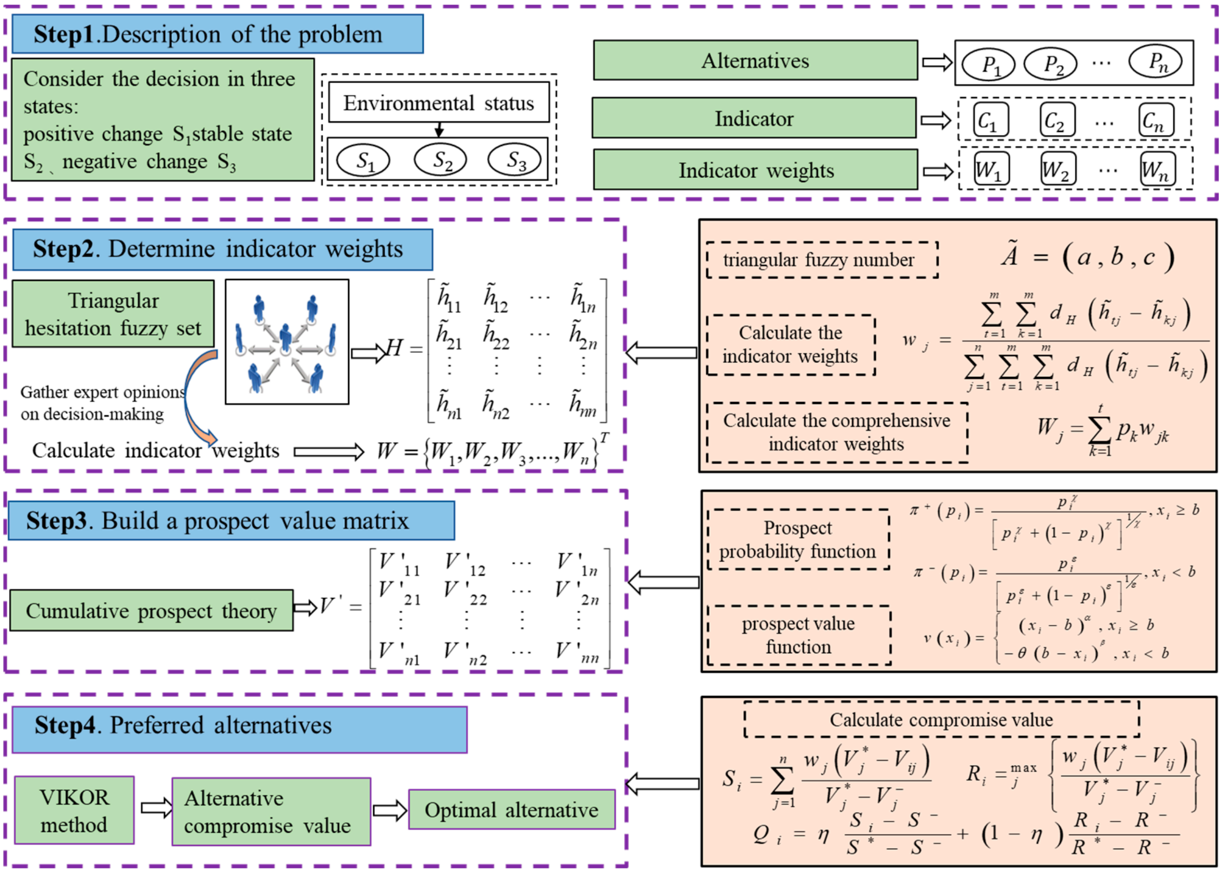

Figure 1. Flow chart of emergency decision making.

3.1. Description of Emergency Decision-Making Problem

Assume that there are m alternatives $P = \{P_1, P_2, P_3, \ldots, P_m\}$ in emergency decision making for hydrogen leakage and explosion accidents, and each alternative represents a set of emergency rescue measures. The emergency alternatives have n evaluation indicators $C = \{C_1, C_2, C_3, \ldots, C_n\}$ to measure its effect. For instance, C_1 stands for "safety" and C_2 denotes for "effectiveness". To quantify the evaluation indicators, assign the weights of the indicators $W = \{W_1, W_2, W_3, \ldots, W_n\}$ and satisfy $W_j \in [0, 1]$, $W_1 + W_2 + W_3 + \ldots + W_n = 1$, $j = 1, 2, 3, \ldots, n$. For example, if C_1 is the most crucial indicator, then W_1 is assigned the highest weight.

3.2. Construction of Evaluation Indicator for Emergency Alternatives

Evaluation indicators serve as the foundation for decision making and play a pivotal role in the emergency decision-making process, directly influencing the quality and efficiency of decisions. Here, the notable complexity, urgency, and uncertainty characteristics of hydrogen leakage and explosion accidents are considered. Safety, effectiveness, operability, and timeliness are established as the evaluation indicators for emergency alternatives, as shown in Figure 2.

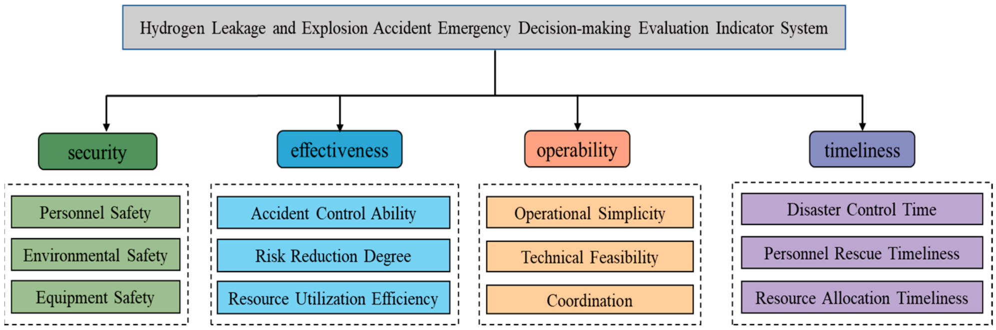

Figure 2. Evaluation indicators of emergency alternatives.

(1). Security: in hydrogen leakage and explosion accidents, ensuring the safety of personnel, the environment, and equipment is the primary task of emergency response. It is vital to evaluate whether the emergency alternatives provide clear guidance, ensuring that individuals can evacuate the accident scene quickly and orderly, and whether it provides measures to protect rescuers from harm.

(2). Effectiveness: effective emergency alternatives enable rapid response and resource allocation in emergencies. The alternatives should be assessed for its ability to quickly control the accident scene and avoid secondary accidents.

(3). Operability: the smooth execution of the alternatives depends on its feasibility. It is necessary to evaluate whether the implementation of the emergency alternatives is easy to operate and whether the allocation and use of resources are reasonable.

(4). Timeliness: given the rapid combustion speed of hydrogen, timeliness is a crucial indicator for evaluating emergency alternatives, ensuring prompt crisis control. Accident control time, personnel rescue time, and resource preparation time should be assessed.

3.3. Selection of an Emergency Alternative

Step 1: Establish the original evaluation value matrix $\left[h_{ij}\right]_{m\times n}$ of alternatives under n indicators.

In a real-world decision-making environment, on-site information often exhibits uncertainty and ambiguity. Linguistic variables are more appropriate for describing decision-maker preferences. For example, it could be expressed as low, slightly low, middle, slightly high, high, very high, and similar values [39]. DMs rate each indicator, and the corresponding hesitant triangular fuzzy numbers are shown in Table 2.

Table 2. The relationship between linguistic scale and triangular fuzzy number.

Serial Number	Linguistic Scale	Triangular Fuzzy Number
1	Very high (VH)	(0.7,0.8,0.9)
2	High (H)	(0.6,0.7,0.8)
3	Slightly High (SH)	(0.5,0.6,0.7)
4	Middle (M)	(0.4,0.5,0.6)
5	Slightly low (SL)	(0.2,0.3,0.4)
6	Low (L)	(0.1,0.2,0.3)

The hesitant triangular fuzzy element h_{ij} is chosen to represent the evaluation value of the alternative P_i concerning indicator C_j under state S_i. The specific form is:

$$H = \begin{array}{c} \\ P_1 \\ P_2 \\ \vdots \\ P_n \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \ldots & C_n \end{array} \\ \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1n} \\ h_{21} & h_{22} & \cdots & h_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ h_{m1} & h_{m2} & \cdots & h_{mn} \end{bmatrix} \end{array} \tag{13}$$

Step 2: Construct the standardized hesitant triangular fuzzy decision matrix $\left[\widetilde{h}_{ij}\right]_{m\times n}$.

Assume that the decision makers are more inclined to adopt a conservative strategy. For the same indicator, triangular fuzzy numbers with shorter lengths are added until the lengths of the hesitant triangular fuzzy elements under that indicator are equal. Since all indicators are income-based, there is no need for normalization.

Step 3: Select the positive and negative ideal points as decision reference points.

Typically, the reference points are mainly determined in the following ways: expected value reference point, median reference point, and positive/negative ideal point reference. Among them, the positive and negative ideal point reference points consider the relationship between the advantages and disadvantages of multiple objectives and focus on the proximity and distance of the alternatives to the objectives. This can assist DMs in making more comprehensive decisions [40].

Let $P^+ = \left\{P_1^+, P_2^+, P_3^+, \ldots, P_n^+\right\}$ and $P^- = \left\{P_1^-, P_2^-, P_3^-, \ldots, P_n^-\right\}$ represent the positive and negative ideal points containing hesitant triangular fuzzy information on the alternatives set P. The calculation formulas are:

$$P_j^+ = \widetilde{H}\left\{\left(\widetilde{\gamma}_j^1\right)^+, \left(\widetilde{\gamma}_j^2\right)^+, \ldots, \left(\widetilde{\gamma}_j^{l_j}\right)^+\right\} \tag{14}$$

$$P_j^- = \widetilde{H}\left\{\left(\widetilde{\gamma}_j^1\right)^-, \left(\widetilde{\gamma}_j^2\right)^-, \ldots, \left(\widetilde{\gamma}_j^{l_j}\right)^-\right\} \tag{15}$$

where l_j represents the length of the *j-th* indicator, $j = 1, 2, \ldots, n$, $\left(\widetilde{\gamma}_j^{l_j}\right)^+$ represents the maximum hesitant triangular fuzzy number of the *j-th* indicator, and $\left(\widetilde{\gamma}_j^{l_j}\right)^-$ represents the minimum hesitant triangular fuzzy number of the *j-th* indicator.

Step 4: Calculate the structural element form of the standardized indicator value $\widetilde{h}_{ij}$.

$$\widetilde{h}_{ij} = \widetilde{H}\left\{f_{ij}^{\lambda}(E)\middle|\lambda = 1, 2, \ldots, l_j\right\} \tag{16}$$

where l_j represents the length of the *j-th* indicator, $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n$.

Step 5: Determine the indicator weight using the deviation method.

Determining the indicator weight is crucial for multi-attribute decision making. Under the condition that the indicator weight information is completely unknown and the evaluation value is in the form of a linguistic variable, the deviation method [41] is used here to determine the indicator weight. This method is suitable for situations where the evaluation value is in the form of a linguistic variable. It determines indicator weight based on the inherent differences in the data, reducing the influence of subjective factors and making the weight more reflective of the actual situation. The calculation formula is:

$$w_{jk} = \frac{\sum\limits_{t=1}^{m}\sum\limits_{s=1}^{m} d_H\left(\widetilde{h}_{tj} - \widetilde{h}_{sj}\right)}{\sum\limits_{j=1}^{n}\sum\limits_{t=1}^{m}\sum\limits_{s=1}^{m} d_H\left(\widetilde{h}_{tj} - \widetilde{h}_{sj}\right)} \tag{17}$$

Step 6: Comprehensively determine the indicator weight $W = (W_1, W_2, \ldots, W_n)^T$ in each state. The calculation formula is:

$$W_j = \sum_{k=1}^{t} p_k w_{jk} \tag{18}$$

where $j = 1, 2, \ldots, n$.

Step 7: Calculate the distance from the standardized indicator value $\widetilde{h}_{ij}$ to the positive and negative ideal points.

Let $d_H\left(\widetilde{h}_{ij}, P_j^+\right)$ and $d_H\left(\widetilde{h}_{ij}, P_j^-\right)$ represent the Hamming distances from the alternatives to the positive and negative ideal points, respectively. The calculation formulas are:

$$D^+ = \left(d_{ij}^+\right)_{m\times n} = W_j d_H\left(\widetilde{h}_{ij}, P_j^+\right) = W_j\left(\frac{1}{l_j}\sum_{\lambda=1}^{l_j}\left(\int_{-1}^{1}\left|f_{ij}^{\lambda} - g_j^{\lambda}\right|E(x)dx\right)\right) \tag{19}$$

$$D^- = \left(d_{ij}^-\right)_{m\times n} = W_j d_H\left(\widetilde{h}_{ij}, P_j^-\right) = W_j\left(\frac{1}{l_j}\sum_{\lambda=1}^{l_j}\left(\int_{-1}^{1}\left|f_{ij}^{\lambda} - g_j^{\lambda}\right|E(x)dx\right)\right) \tag{20}$$

where l_i represents the length of the *j-th* indicator and $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n$, and f, g, g' are homotonic monotonic functions on $[-1, 1]$.

Step 8: Construct the matrix of prospect gains and prospects losses.

$$V^+ = \left(d_{ij}^+\right)_{m\times n} = \left(d_H\left(\widetilde{h}_{ij} - P_j^-\right)\right)^{\alpha} \tag{21}$$

$$V^- = \left(d_{ij}^-\right)_{m\times n} = -\theta\left(d_H\left(\widetilde{h}_{ij} - P_j^+\right)\right)^{\beta} \tag{22}$$

where α, β, and θ are known given parameters, respectively. According to Tversky's research [35], the parameter values can be taken as $\alpha = 0.88$, $\beta = 0.92$, and $\theta = 2.25$.

Step 9: Construct the prospect value matrix.

The decision gain and decision loss weight functions are represented as:

$$\pi(p_k)^+ = \frac{p_k^{\chi}}{\left[p_k^{\chi} + (1-p_k)^{\chi}\right]^{1/\chi}} \tag{23}$$

$$\pi(p_k)^- = \frac{p_k^{\varepsilon}}{\left[p_k^{\varepsilon} + (1-p_k)^{\varepsilon}\right]^{1/\varepsilon}} \tag{24}$$

where p_k is the given probability under various states and the parameter values χ and ε can be taken as 0.61 and 0.72, respectively [35].

The comprehensive prospect value of each alternative for each indicator is $V_{ij} = \sum_{j=1}^{m} v_{ij}^{+}\pi(p_k)^{+} + \sum_{j=1}^{m} v_{ij}^{-}\pi(p_k)^{-}$. From this, the prospect matrix can be derived as:

$$V' = \left[V'_{ij}\right]_{m\times n} \tag{25}$$

Step 10: Select the best alternative based on the compromise value.

Calculate the group utility value S_i of the alternatives, the minimum individual regret value R_i, and the alternatives compromise value:

$$S_i = \sum_{j=1}^{n} \frac{W_j\left(V_j^* - V_{ij}\right)}{V_j^* - V_j^-} \tag{26}$$

$$R_i = ^{\max}_{j} \left\{ \frac{W_j\left(V_j^* - V_{ij}\right)}{V_j^* - V_j^-} \right\} \tag{27}$$

$$Q_i = \eta \frac{S_i - S^-}{S^* - S^-} + (1-\eta)\frac{R_i - R^-}{R^* - R^-} \tag{28}$$

where the larger the value of Q_i, the closer the alternative P_i is to the positive ideal point and further from the negative ideal point, indicating a more optimal alternative. Typically, the parameter η is set to 0.5 [42].

In summary, the proposed emergency alternative selection model based on HTFS-CPT-VIKOR, which encompasses 10 core steps. The decision-making steps and task descriptions are shown in Table 3.

Table 3. Decision-making steps and task description.

Step	Task Description
1	Establish the original evaluation value matrix $\left[h_{ij}\right]_{m\times n}$ of alternatives under n indicators.
2	Construct the standardized hesitant triangular fuzzy decision matrix $\left[\widetilde{h}_{ij}\right]_{m\times n}$.
3	Select the positive and negative ideal points as decision reference points.
4	Calculate the structural element form of the standardized indicator value $\widetilde{h}_{ij}$.
5	Determine the indicator weight using the deviation method.
6	Comprehensively determine the indicator weight $W = (W_1, W_2, \ldots, W_n)^{\mathrm{T}}$ in each state.
7	Calculate the distance from the standardized indicator value $\widetilde{h}_{ij}$ to the positive and negative ideal points.
8	Construct the matrix of prospect gains and prospects losses.
9	Construct the prospect value matrix.
10	Select the best alternative based on the compromise value.

4. Case Analysis and Discuss

4.1. Case Description and Optimal Alternatives

The X Hydrogen Station in a certain city is located near a secondary urban road, surrounded by residential and commercial areas. Due to equipment malfunction, a primary connecting pipeline ruptured, resulting in a hydrogen leak. The formed cloud subsequently ignited by static electricity, causing a minor explosion. The residual fire posed a risk of a secondary incident. While the fire at the scene was not intense, the heat and shockwave produced injured several nearby individuals and caused panic among the surrounding residents. It is assumed that there were four emergency alternatives for this accident, denoted as $P = \{P_1, P_2, P_3, P_4\}$. Based on the emergency alternative indicators, the current accident severity and on-site conditions were judged from four aspects: safety (W_1), effectiveness (W_2), operability (W_3), and timeliness (W_4). The emergency alternatives are shown in Table 4.

Table 4. Overview of emergency alternatives.

Emergency Alternatives	Primary Actions	Detection and Sealing	Fire Control	Safety Measures	Medical and Notification
P_1	Shut off nearest hydrogen valve	Use hydrogen detector and regular sealant	Dry powder fire extinguishers	Isolation belts, inspect buildings, turn off power sources	First aid, notify medical institutions
P_2	Shut off all valves	Hydrogen detectors, acoustic equipment, high-density rubber, and metal clamps	Thermal imaging cameras, water mist extinguishers	Safety isolation zone, explosion-proof barriers, turn off power sources, inspect surroundings	Emergency medical treatment, evacuate, notify hospitals and emergency centers
P_3	Shut off all valves	Hydrogen detector, composite materials	ventilation equipment, thermal imaging/heat detection, CO_2 or foam suppressants	Safety isolation zone, explosion-proof barriers, water mist curtains [43,44], disconnect power sources, inspect major buildings	First aid, evacuate, notify hospitals and emergency centers
P_4	Shut off all valves	Infrared and ultrasonic equipment, advanced materials, ventilation systems	Thermal imaging cameras and sensors, gas fire extinguishing systems	Establish isolation zones, deploy barrier walls [45] and water mist curtains, inspect nearby buildings, turn off most power	First aid, notify medical institutions

Since the development of accidents is uncertain, consider the impact of environmental changes on emergency decision making within a certain time range, including the natural environment, working environment, etc. The environmental state is divided into three states: positive change (S_1), stable state (S_2), and negative change (S_3). Positive change refers to environmental shifts that contribute to accident control and, conversely, the environmental impact shows a negative trend. The probabilities of the accident scene given the three states are 0.3, 0.6, and 0.1, respectively.

Hesitant triangular fuzzy information is used to describe the uncertain decision-making information after the accident and the inconsistent opinions of decision-making experts. A hesitant triangular fuzzy decision matrix is constructed, as shown in Table 5.

Table 5. Hesitant triangular fuzzy decision matrix.

		W_1	W_2	W_3	W_4
S_1	P_1	{(0.4,0.5,0.6)(0.5,0.6,0.7)}	{(0.4,0.5,0.6)}	{(0.7,0.8,0.9)}	{(0.6,0.7,0.8)(0.7,0.8,0.9)}
	P_2	{(0.6,0.7,0.8)}	{(0.6,0.7,0.8)}	{(0.7,0.8,0.9)}	{(0.6,0.7,0.8)}
	P_3	{(0.6,0.7,0.8)(0.7,0.8,0.9)}	{(0.6,0.7,0.8)(0.7,0.8,0.9)}	{(0.5,0.6,0.7) (0.6,0.7,0.8)}	{(0.4,0.5,0.6)(0.5,0.6,0.7)}
	P_4	{(0.7,0.8,0.9)}	{(0.7,0.8,0.9)}	{(0.4,0.5,0.6)}	{(0.4,0.5,0.6)}
S_2	P_1	{(0.2,0.3,0.4)(0.4,0.5,0.6) }	{(0.2,0.3,0.4)}	{(0.7,0.8,0.9)}	{(0.6,0.7,0.8)}
	P_2	{(0.4,0.5,0.6)}	{(0.4,0.5,0.6)(0.5,0.6,0.7)}	{(0.6,0.7,0.8)(0.7,0.8,0.9)}	{(0.6,0.7,0.8)}
	P_3	{(0.6,0.7,0.8)}	{(0.5,0.6,0.7)(0.6,0.7,0.8)}	{(0.5,0.6,0.7)(0.6,0.7,0.8)}	{(0.4,0.5,0.6)}
	P_4	{(0.7,0.8,0.9)}	{(0.7,0.8,0.9)}	{(0.4,0.5,0.6)(0.4,0.5,0.6)}	{(0.2,0.3,0.4)(0.4,0.5,0.6)}
S_3	P_1	{(0.2,0.3,0.4)}	{(0.2,0.3,0.4)}	{(0.6,0.7,0.8)}	{(0.6,0.7,0.8)}
	P_2	{(0.4,0.5,0.6)}	{(0.4,0.5,0.6)(0.5,0.6,0.7)}	{(0.6,0.7,0.8)}	{(0.4,0.5,0.6)}
	P_3	{(0.5,0.6,0.7)}	{(0.4,0.5,0.6)}	{(0.4,0.5,0.6)}	{(0.2,0.3,0.4)(0.4,0.5,0.6)}
	P_4	{(0.5,0.6,0.7)(0.6,0.7,0.8)}	{(0.6,0.7,0.8)}	{(0.2,0.3,0.4)(0.4,0.5,0.6)}	{(0.2,0.3,0.4)(0.2,0.3,0.4)}

Step 1: Construct a standardized hesitant triangular fuzzy decision matrix, as shown in Table 6.

Step 2: According to Equations (14)–(18), calculate the indicator weights.

$$W = (0.2538, 0.2916, 0.2260, 0.2287)^T$$

Table 6. Standardized hesitant triangular fuzzy decision matrix.

		W_1	W_2	W_3	W_4
S_1	P_1	{(0.4,0.5,0.6)(0.5,0.6,0.7)}	{(0.4,0.5,0.6)(0.4,0.5,0.6)}	{(0.7,0.8,0.9)(0.7,0.8,0.9)}	{(0.6,0.7,0.8)(0.7,0.8,0.9)}
	P_2	{(0.6,0.7,0.8)(0.6,0.7,0.8)}	{(0.6,0.7,0.8)(0.6,0.7,0.8)}	{(0.7,0.8,0.9)(0.7,0.8,0.9)}	{(0.6,0.7,0.8)(0.6,0.7,0.8)}
	P_3	{(0.6,0.7,0.8)(0.7,0.8,0.9)}	{(0.6,0.7,0.8)(0.7,0.8,0.9)}	{(0.5,0.6,0.7) (0.6,0.7,0.8) }	{(0.4,0.5,0.6)(0.5,0.6,0.7)}
	P_4	{(0.7,0.8,0.9)(0.7,0.8,0.9)}	{(0.7,0.8,0.9)(0.7,0.8,0.9)}	{(0.4,0.5,0.6)(0.4,0.5,0.6)}	{(0.4,0.5,0.6)(0.4,0.5,0.6)}
S_2	P_1	{(0.2,0.3,0.4)(0.4,0.5,0.6) }	{(0.2,0.3,0.4)(0.2,0.3,0.4)}	{(0.7,0.8,0.9)(0.7,0.8,0.9)}	{(0.6,0.7,0.8)(0.6,0.7,0.8)}
	P_2	{(0.4,0.5,0.6)(0.4,0.5,0.6)}	{(0.4,0.5,0.6)(0.5,0.6,0.7)}	{(0.6,0.7,0.8)(0.7,0.8,0.9)}	{(0.6,0.7,0.8)(0.6,0.7,0.8)}
	P_3	{(0.6,0.7,0.8)(0.6,0.7,0.8)}	{(0.5,0.6,0.7)(0.6,0.7,0.8)}	{(0.5,0.6,0.7)(0.6,0.7,0.8)}	{(0.4,0.5,0.6)(0.4,0.5,0.6)}
	P_4	{(0.7,0.8,0.9)(0.7,0.8,0.9)}	{(0.7,0.8,0.9)(0.7,0.8,0.9)}	{(0.4,0.5,0.6)(0.4,0.5,0.6)}	{(0.2,0.3,0.4)(0.4,0.5,0.6)}
S_3	P_1	{(0.2,0.3,0.4)(0.2,0.3,0.4)}	{(0.2,0.3,0.4)(0.2,0.3,0.4)}	{(0.6,0.7,0.8)(0.6,0.7,0.8)}	{(0.6,0.7,0.8)(0.6,0.7,0.8)}
	P_2	{(0.4,0.5,0.6)(0.4,0.5,0.6)}	{(0.4,0.5,0.6)(0.5,0.6,0.7)}	{(0.6,0.7,0.8)(0.6,0.7,0.8)}	{(0.4,0.5,0.6)(0.4,0.5,0.6)}
	P_3	{(0.5,0.6,0.7)(0.5,0.6,0.7)}	{(0.4,0.5,0.6)(0.4,0.5,0.6)}	{(0.4,0.5,0.6)(0.4,0.5,0.6)}	{(0.2,0.3,0.4)(0.4,0.5,0.6)}
	P_4	{(0.5,0.6,0.7)(0.6,0.7,0.8)}	{(0.6,0.7,0.8)(0.6,0.7,0.8)}	{(0.2,0.3,0.4)(0.4,0.5,0.6)}	{(0.2,0.3,0.4)(0.2,0.3,0.4)}

Step 3: Taking S_1 as an example, construct the prospect gain and prospect loss matrix according to Equations (19)–(22).

$$V_{ij}^{+} = \begin{bmatrix} 0 & 0 & 0.0936 & 0.0806 \\ 0.0564 & 0.0820 & 0.0936 & 0.0662 \\ 0.0726 & 0.0636 & 0.0509 & 0.0195 \\ 0.0883 & 0.1172 & 0 & 0 \end{bmatrix}$$

$$V_{ij}^{-} = \begin{bmatrix} -0.1781 & -0.2392 & 0 & 0 \\ -0.0767 & -0.0872 & 0 & -0.0367 \\ -0.0405 & -0.0461 & -0.1000 & -0.1316 \\ 0 & 0 & -0.1892 & -0.1618 \end{bmatrix}$$

Step 4: According to Equations (23) and (24), calculate the weight coefficients of decision-making gains and decision-making losses.

Weight of risk gain: $\pi(p_k)^{+} = (0.3184, 0.4739, 0.1863)$.

Weight of risk loss: $\pi(p_k)^{-} = (0.3286, 0.5317, 0.1633)$.

Step 5: Construct the prospect value matrix according to Equation (25).

$$V\prime = \begin{bmatrix} -0.2439 & -0.3330 & 0.0794 & 0.0809 \\ -0.1117 & -0.0776 & 0.0482 & 0.0324 \\ 0.0178 & -0.0257 & -0.0684 & -0.1207 \\ 0.0983 & 0.1345 & -0.1937 & -0.1955 \end{bmatrix}$$

Step 6: Calculate the compromise values of the alternatives according to Equations (26)–(28), as shown in Table 7.

Table 7. Values of alternatives by S_i, R_i, and Q_i.

	P_1	P_2	P_3	P_4
S_i	0.5454	0.4337	0.4508	0.4547
R_i	0.2916	0.1558	0.1668	0.2287
Q_i	1.0000	0	0.1170	0.3624

Obviously, the order is $Q_2 < Q_3 < Q_4 < Q_1$. Based on the compromise values, the alternatives ranking is $P_2 > P_3 > P_4 > P_1$.

4.2. Comparative Analysis of Alternatives Optimization

1. Comparison of Decision-making Methods

To verify the effectiveness and feasibility of the HTFS-CPT-VIKOR method, a comparative analysis was conducted based on the above case. This analysis compared the HTFS-CPT-VIKOR method with the HTFS-CPT-TOPSIS method, HTFS-CPT method, and HTFS-VIKOR method. The ranking results of the four methods are shown in Figure 3.

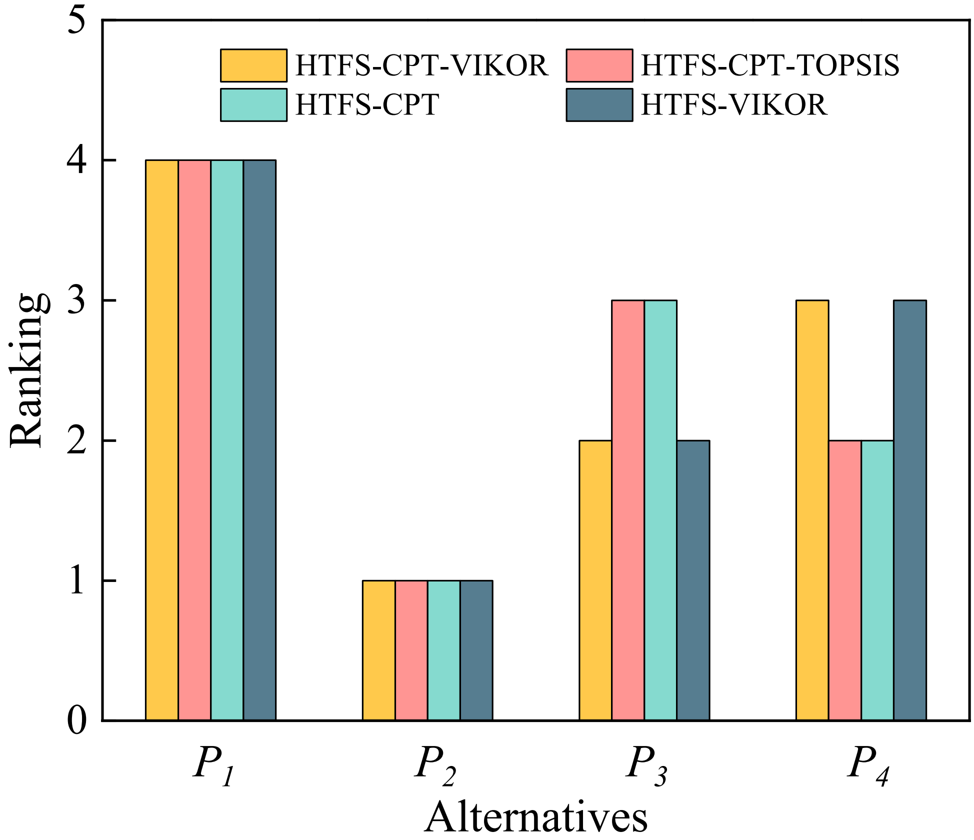

Figure 3. Ranking of alternatives based on different methods.

As can be seen from Figure 3, the overall priority trends of the four methods are consistent, with the optimal alternative being P_2, which verifies the effectiveness of the HTFS-CPT-VIKOR method. However, there are certain differences between the methods, which can be explained as follows:

(1). The ranking results of the HTFS-CPT-TOPSIS method slightly differ from those of the method proposed in this paper, which may be attributed to the difference in decision-making logic between the two methods. The core idea of the TOPSIS method is to determine the ranking based on the relative closeness of the alternatives to the ideal solution [46,47]. The VIKOR method integrates the balance degree of the alternatives based on the TOPSIS method. It not only considers the closeness of the alternatives to the ideal solution but also comprehensively evaluates the overall performance of the alternatives on various evaluation indicators, thereby producing a more reasonable ranking result.

(2). The ranking results of HTFS-CPT and the method in this paper are slightly different. This discrepancy may arise from differences in the theoretical basis and ranking mechanisms relied upon when addressing risk and uncertainty. This method is based on HTFS-CPT, comprehensively considers the overall performance and balance of the alternatives, and introduces additional variables and calculations of the VIKOR method.

(3). The ranking results of the HTFS-VIKOR method align with those of the method presented in this paper due to their core ideas and steps being similar. This article thoroughly accounts for the psychological behavior of decision makers facing gains and losses by incorporating risk preferences into the decision-making process and more comprehensive reflection of the decision maker's preferences and trade-offs, which has certain advantages.

2. Sensitivity analysis

Considering that parameter values may affect the decision-making results, it is essential to explore the impact of changing parameter values on the ranking of alternatives. Therefore, by altering the values of parameters ν, α, and β, the decision indicator Q_i value of each alternative is generated, including (1) changing the parameter ν value from 0.1 to 1.0; (2) changing the parameter α value from 0.1 to 1.0; and (3) changing the parameter β value from 0.1 to 1.0. For the above three scenarios, the Q_i values and changing trends of each alternative obtained through parameter sensitivity analysis are shown in Figures 4–6.

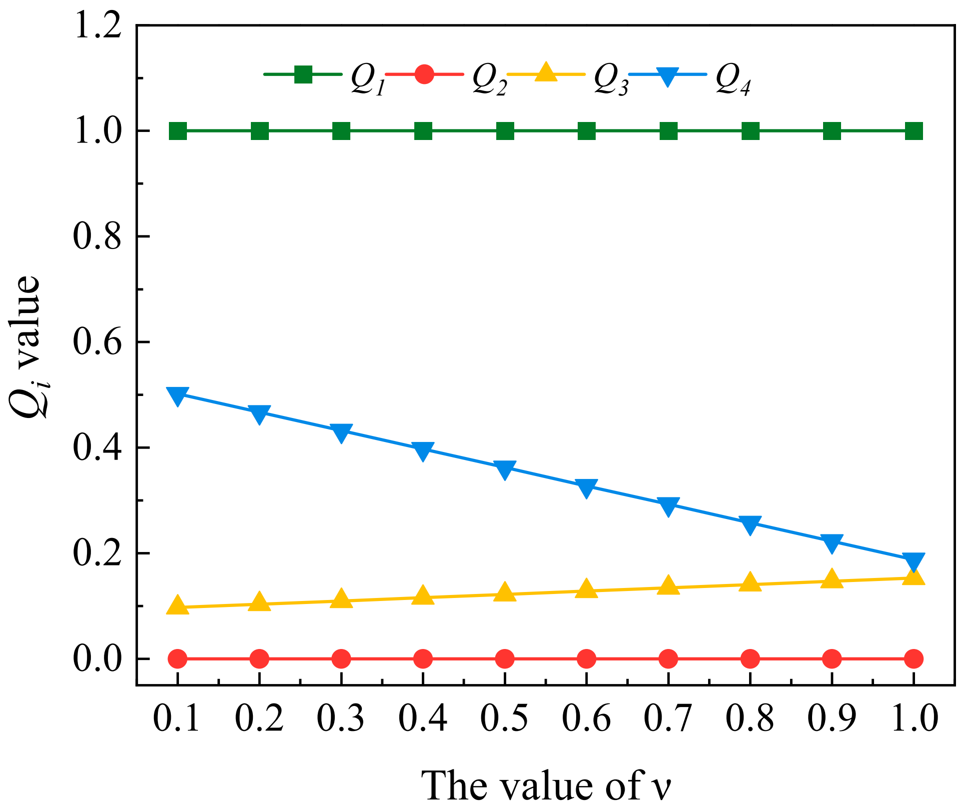

Figure 4. Sensitivity analysis in the case of the parameter ν changes.

From the figure, it can be observed that, as the parameters ν, α, and β change, the optimal alternative remains P_2. Specifically, as the parameters ν and β increase, the values of the four alternatives Q_i display consistent trends, consistently maintaining $Q_2 < Q_3 < Q_4 < Q_1$. However, when the parameter α ranges from 0.1 to 0.65, the Q_i value is $Q_2 < Q_4 < Q_3 < Q_1$ but the optimal alternative remains unchanged. The variations in parameter values do not affect the final decision-making result. Thus, the method proposed in this article has a certain stability in alternatives optimization.

The above results demonstrate that the THFS-CPT-VIKOR method has certain rationality and stability in addressing the problem of emergency alternatives optimization for hydrogen leakage and explosion accidents. It can offer systematic decision-making guidance for decision makers.

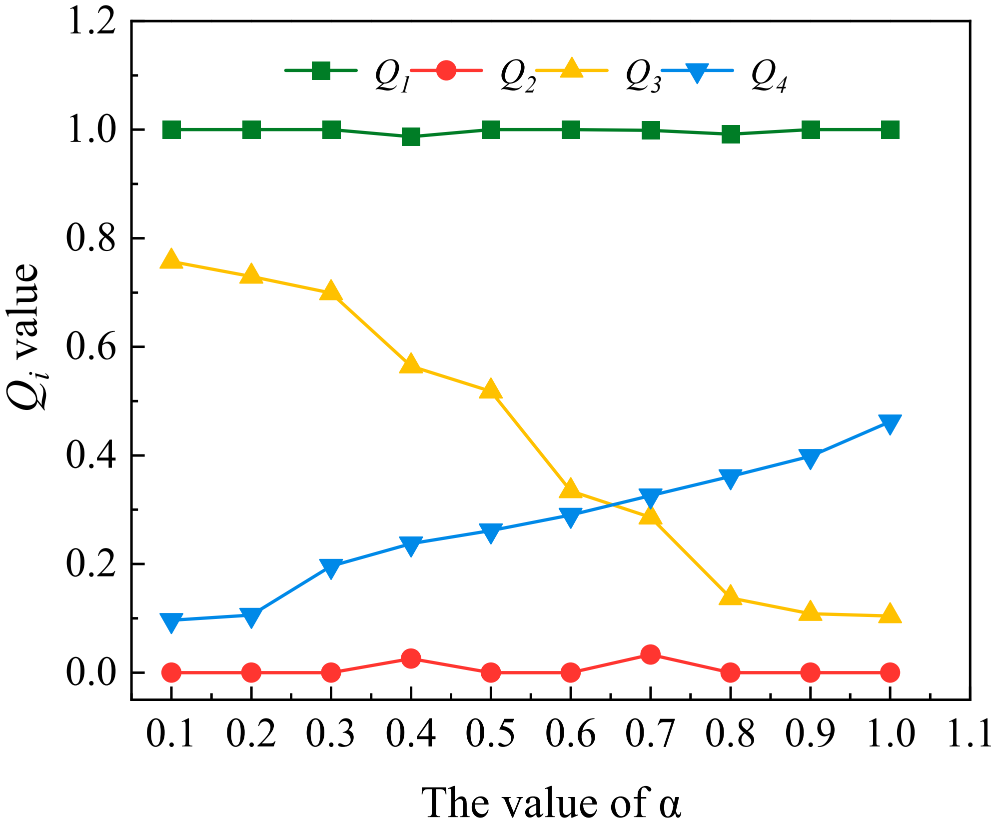

Figure 5. Sensitivity analysis in the case of the parameter α changes.

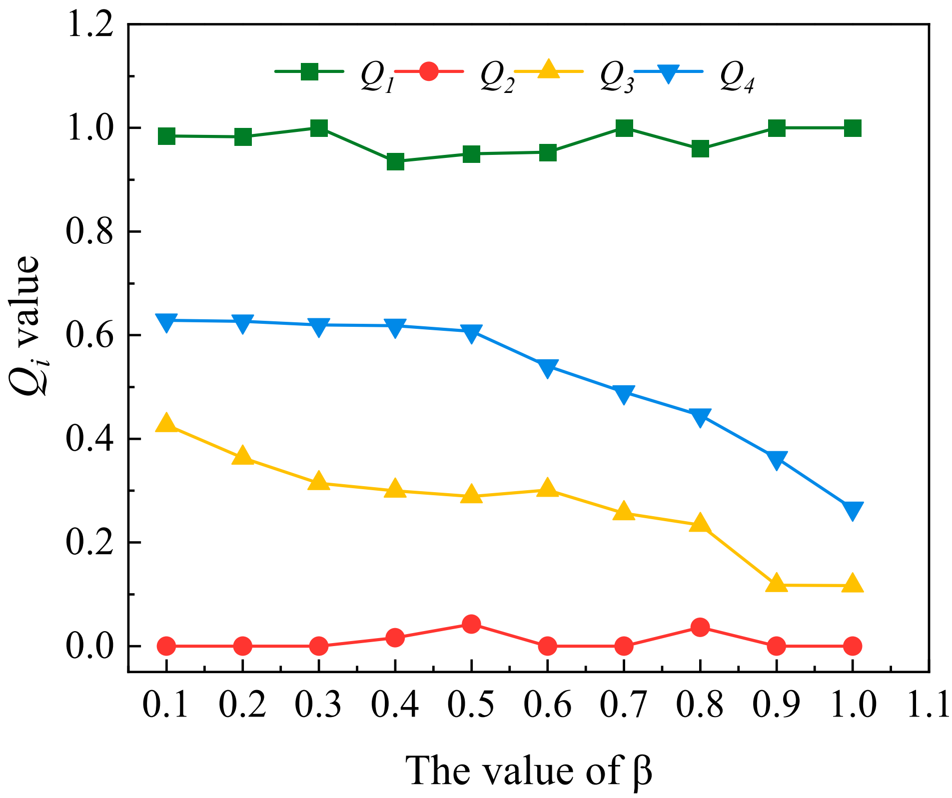

Figure 6. Sensitivity analysis in the case of the parameter β changes.

5. Conclusions

An improved VIKOR method based on hesitant triangular fuzzy set (HTFS) and cumulative prospect theory (CPT) is proposed to optimize emergency alternatives for hydrogen leakage and explosion accidents. This method has advantages in grasping ambiguous or uncertain information and fully takes into account the limited psychological behavior of decision makers. This study uses the deviation method to determine the indicator weights to make the results more objective. Finally, by examining a case analysis of a hydrogen refueling station accident, comparison with existing methods, and parameter sensitivity analysis, the effectiveness and stability of the method are validated.

In future research, the proposed HTFS-CPT-VIKOR method can be extended by adopting other fuzzy languages. Furthermore, combining more multi-attribute decision-making (MADM) methods with this method should be considered to provide more comprehensive and holistic decisions. Lastly, it is worth exploring the synergistic integration of the method with modern technologies, such as the digital economy or artificial intelligence, to enhance the speed and accuracy of decision making [48].

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