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A Hybrid Decision-Making Framework for Selecting the Emergency Alternatives

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Abstract The frequent occurrence of emergencies has created huge economic losses and numerous casualties and has seriously affected the sustainable development of many societies. The abruptness, destructiveness, unpredictability and complexity of emergency situations pose a great challenge in implementing appropriate responses. To effectively respond to emergencies, it is necessary to select the most suitable, or several, of the numerous emergency plan alternatives, especially when the evolutionary direction of the emergency is highly uncertain. Some progress has been made in the study of emergency alternative selection (EAS) but the capacity for emergency decision-making in real disasters is still quite limited. Therefore, more in-depth research is necessary. As a remedy to the EAS problems, such as unitary information expression, inflexible decision-making processes and insufficient attention to uncertainty, this study proposes a hybrid decision-making method that considers an intuitionistic fuzzy environment, linguistic environment and their hybrid environment, and implements the conversion and processing of decision-making information in different environments based on the Dempster–Shafer theory (DST). This model provides a more flexible evaluation method for decision-makers, and provides a complete decision-making process for EAS. A flood disaster case study from China is used to demonstrate and verify the effectiveness of the proposed model.

Keywords Intuitionistic fuzzy sets · Linguistic variables · Emergency alternative selection · Hybrid information · MADM

1 Introduction

The word "emergency" refers to sudden events that cause serious social harm and an emergency is generally divided into four categories, natural disasters, accident disasters, public health events and social security events [1]. In recent years, there have been frequent emergencies around the world, such as the "9. 11" terrorist attacks in the USA, the nuclear fuel leakage in Fukushima, the fire in the Amazon rainforest in Brazil and the global COVID-19 epidemic. These severe situations prompted governments and scholars to extensively evaluate emergency management procedures [2, 3].

To reduce the damage and casualties caused by emergencies, multiple corresponding emergency management alternatives are often needed, and the final alternative to be used needs to be determined by emergency managers after an evaluation [4]. In particular, the evolution of emergencies is highly uncertain; that is, the future trend may have a variety of natural conditions [5, 6]. In fact, there are many kinds of emergencies and different accident environments, so it is difficult to ensure the effectiveness of the emergency response alternatives [7]. Therefore, it is necessary to evaluate the effectiveness of the emergency response alternatives and select the most appropriate alternative.

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The selection of emergency alternatives has become a very important problem in the field of emergency management [8, 9], and it requires an algorithm to select the best choice from numerous alternative plans according to the relevant criteria, and the selection should consider the various evolvement states of the emergencies [10, 11]. Therefore, the problem of emergency alternative selection (EAS) essentially belongs to the multiattribute risk decision-making class of problems [12, 13]. The relevant previous studies are introduced below.

Ju and Wang [9] noted that in the evaluation and selection of emergency plans, incomplete and uncertain information usually exists, and it is not easy for decision-makers to express their choice of alternatives with accurate and clear values. Evidence theory is not usually suitable for dealing with such problems. They combined the DS/AHP (Dempster–Shafer/Analytic Hierarchy Process) method and extended TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method to solve the problem of EAS with incomplete information. Ju et al. [8] proposed a novel framework of emergency alternative evaluation combining network analysis, Decision-making Trial and Evaluation Laboratory (DEMATEL) and TOPSIS method for an urban fire emergency plan selection. Nassereddine et al. [14] pointed out that various emergency management agencies should cooperate to reduce casualties, that is, synergies between independent systems are crucial for an effective emergency response, so they proposed a multicriteria decision-making method to evaluate emergency response systems by examining synergies. Zhang et al. [15] proposed a fuzzy multicriteria group decision-making method based on interval-valued dual hesitant fuzzy (IVDHF)-TOPSIS and IVDHF-VIKOR (VlseKriterijuska Optimizacija I Komoromisno Resenje) to evaluate the emergency response alternatives considering the sustainable development of the community. Ding and Liu [16] proposed an emergency decision-making method based on linguistic information, and a new combination method was proposed to expand the zero-sum game by using the best and worst method and Pythagorean fuzzy uncertain linguistic variables. Chen et al. [17] proposed a new method combining entropy weight and DEMATEL technology to manage emergency alternative selection for group decision-making.

Choosing an appropriate emergency alternate is an urgent and complex process. The evaluation and selection of emergency alternate should take into account multiple factors and experts should balance these factors to arrive at the optimal solution. In addition, the criteria in decision-making are generally evaluated in a combination of qualitative and quantitative forms, i.e., there is ambiguity or imprecision. In this case, EAS is a classic fuzzy MCDM problem. Some achievements have been made in the study of EAS, but, after analysis, there are still some shortcomings. The existing methods mainly focus on the emergency plan construction process or the establishment of emergency plans for certain disasters, while the relevant research on how to select the appropriate emergency alternative after the occurrence of emergencies is not sufficient. In other words, the existing research focuses more on qualitative methods. In addition, the existing methods greatly restrict the information expression method and generally only study the EAS problem in a single decision-making environment; however, real-world complexities demand higher standards for emergency decision-making environments. Finally, there is a lack of modeling of EAS problems from the fuzzy and uncertain perspective, and more importantly, the uncertainty of the evolution of emergencies is ignored.

To overcome the above research limitations, this paper aims to answer the following research question: “How can a flexible, complete and comprehensive EAS model be established?”. Therefore, this study proposes an emergency alternative selection method in a hybrid decision-making environment, which considers the intuitionistic fuzzy environment, linguistic environment and their mixed environment. The model is friendly to decision-makers. It allows decision-makers to choose appropriate information representations according to their personal preferences, and is no longer restricted by a single data type. It makes the decision-making process more flexible, liberates decision-makers from the tedious information input tasks, and allows them to pay more attention to the decision itself. In addition, the effectiveness and consistency of the proposed model are demonstrated based on natural disaster case studies of EASs from China. In this paper, a multi-attribute EAS risk decision method including intuitionistic fuzzy and linguistic environments is proposed based on Dempster–Shafer theory (DST) to deal with various uncertain states that the evolution of emergency events may face.

The rest of this study is structured as follows. In Sect. 2, some basic knowledge is introduced, including the DST, intuitionistic fuzzy sets and linguistic variables. A hybrid decision-making framework for EAS is proposed in Sect. 3. In Sect. 4, a case study is constructed for the presented model. Analysis and discussion of the results are provided in Sect. 5. Finally, the findings of the study are summarized, and the future scope is prospected in Sect. 6.

2 Preliminaries

In this section, the theoretical basis of this study is mainly introduced, including DST, intuitionistic fuzzy sets and linguistic variables.

2.1 Dempster–Shafer Theory

As an inference method with uncertain characteristics, DST [18, 19] can better represent and process fuzzy and uncertain information, so it has been widely used in different fields, including information fusion [20–23], decision-making [24, 25] and knowledge reasoning [26, 27].

A subset of the sample space $\Theta = \{\phi, \theta_1, \theta_2, \ldots, \theta_n\}$ can describe all propositions in the domain. The function $m : 2^{\Theta} \to [0, 1]$ satisfies $m(\phi) = 0$, $\sum_{A \subseteq \Theta} m(A) = 1$, then m is defined as the basic probability assignment (BPA). The belief level of A can be described by $m(A)$. If m(A) is not less than 0, then it can be defined as a focal element, and the set of all components can be defined as a kernel.

DST is often used in information fusion, so the Dempster's fusion rule is mainly introduced. Let m_1 and m_2 be two BPAs, they can be combined as

$$m_1 \oplus m_2 = \frac{\sum_{B \cap C = A} m_1(B) m_2(C)}{1 - \sum_{B \cap C = \phi} m_1(B) m_2(C)}, \tag{1}$$

where $m(A)$ can reflect the common support level of A by different evidences corresponding to m_1 and m_2. The conflict factor $g = \sum_{B \cap C = \phi} m_1(B) m_2(C)$ can reflect the conflict level between different evidences.

For decision-making, the BPA is usually converted into probability distribution. Let a BPA be m, and it can be converted as follows [28]:

$$\mathrm{BetP}_m(w) = \sum_{A \subseteq \Theta, w \in A} \frac{m(A)}{A}. \tag{2}$$

2.2 Intuitionistic Fuzzy Sets

The membership degree of traditional fuzzy sets is only a single value, so its practical application is more and more restricted and challenged [29]. Atanassov [30] proposed an intuitionistic fuzzy set that can simultaneously consider membership degree, non-membership degree and hesitation degree. Compared with traditional fuzzy sets [31], intuitionistic fuzzy sets are more flexible and practical in dealing with uncertainty and fuzziness [32, 33].

Let X be a set, and $A = \{(x, \mu_A(x), v_A(x))\}$ is defined as an intuitionistic fuzzy set, where $\mu_A(x)$ and $v_A(x)$ are the membership degree and non-membership degree of element x belonging to set X and satisfy $\mu_A(x) + v_A(x) \in [0, 1]$, $\forall x \in X$. Furthermore, $1 - \mu_A(x) - v_A(x)$ represents the hesitancy of the element x belonging to set X.

Due to the complexity and uncertainty of objective things, it is often difficult to express the values of $\mu_A(x)$ and $v_A(x)$ with accurate values, but it is more practical to express them in the form of interval numbers. Therefore, Atanassov [34] extended the intuitionistic fuzzy set and defined $A = \{x, [\mu_A^-(x), \mu_A^+(x)], [v_A^-(x), v_A^+(x)]\}$ as an interval intuitionistic fuzzy set, where the interval numbers $[\mu_A^-(x), \mu_A^+(x)]$ and $[v_A^-(x), v_A^+(x)]$ satisfy $\mu_A^-(x), \mu_A^+(x) \in [0, 1]$, $v_A^-(x), v_A^+(x) \in [0, 1]$, and $\mu_A^+(x) + v_A^+(x) \in [0, 1]$, $\forall x \in X$. For two interval intuitionistic fuzzy sets A and B, their similarity measure [35] can be defined as $S(A, B) = \frac{1}{n} \sum_{i=1}^{n} \frac{2 - \min\{\mu_i^-, v_i^-\} - \min\{\mu_i^+, v_i^+\}}{2 + \max\{\mu_i^-, v_i^-\} + \max\{\mu_i^+, v_i^+\}}$.

2.3 Linguistic Variables

In the 1970s, Bellman and Zadeh [36] first proposed fuzzy decision-making, which attracted the attention of a large number of scholars. Based on linguistic information, decision information description tools in various complex environments were proposed [11, 37–39]. In the actual decision-making process, the linguistic term set (LTS) is widely used because it is more in line with the thinking habits of decision-makers.

Let $S = \{s_1, \ldots, s_\vartheta\}$ represent a finite and discrete set of ordered linguistic assessment scales, s_1 and s_ϑ represent the lower and upper limits of LTS, respectively. To express more uncertainty, the interval linguistic variable [40] was defined as $s = [s_a, s_b]$ where $s_a, s_b \in S$, s_a and s_b are the upper and lower limits of S, respectively. Consider two linguistic variables s_x and s_y, where s_x, s_y $\in S$ and $\lambda \in [0, 1]$, then the operations can be defined as [41]: (1) $\lambda s_x = s_{\lambda \times x}$, (2) $s_x \oplus s_y = s_{x+y}$, (3) $s_x \otimes s_y = s_{x \times y}$, (4) $(s_x)^{\lambda} = s_{x^{\lambda}}$.

3 A Hybrid Decision-Making Framework for Selecting the Emergency Alternative

This section presents a hybrid decision model for emergency alternative selection. The description of the decision problem is the basis, and the decision framework of the intuitionistic fuzzy environment, the linguistic environment and the mixed environment are given respectively. Finally, the prototype of the hybrid decision is described.

3.1 Problem Description of Emergency Alternative Selection

The following representations are employed to characterize an EAS problem. The set of q possible states faced by an emergency is $\mathcal{S} = \{\mathcal{S}_1, \mathcal{S}_2, \ldots, \mathcal{S}_q\}$, and $p^k = [p_a^k, p_b^k]$ is an interval probability used to represent the probability of $\mathcal{S}_k$ occurrence, such that $\sum_{k=1}^{q} p_b^k \leq 1$. All emergency alternatives are recorded in a set, which is expressed as $\mathrm{EA} = \{\mathrm{ea}_1, \mathrm{ea}_2, \ldots, \mathrm{ea}_m\}$. The criteria on which the emergency alternative is selected are expressed as set

$\mathbf{C} = \{c_1, c_2, \ldots, c_n\}$, and their weight is expressed as $W_c = \{w_{c_1}, w_{c_2}, \ldots, w_{c_n}\}$ ($w_{c_j} \geq 0$, and $\sum w_{c_j} = 1$). In this study, there are three ways to express the judgment of decision makers, namely intuitionistic fuzzy form and linguistic information form, which will be introduced respectively below.

- *Intuitionistic fuzzy representations* the evaluation information of emergency alternative ea_i against criterion c_j under state s_k is expressed using intuitionistic fuzzy as $I^k = (if_{ij}^k)_{m\times n}$, where $if_{ij}^k = (\mu_{if_{ij}^k}, v_{if_{ij}^k})$, and $\mu_{if_{ij}^k}$ and $v_{if_{ij}^k}$ represent the degree of support and opposition to emergency alternative ea_i.
- *Linguistic representations* when decision-makers use linguistic variables to express assessment information, the evaluation of emergency alternative ea_i against criterion c_j under state s_k is expressed as $L^k = (l_{ij}^k)_{m\times n}$, which is defined on the LTS $S = \{s_1, \ldots, s_\vartheta\}$. L^k comes in single and interval forms: $l_{ij}^k = s_a$ and $l_{ij}^k = [(l_{ij}^k)^-, (l_{ij}^k)^+] = [s_a, s_b], a < b$.
- *Hybrid information representations* under different evaluation criteria, decision-makers may have their own preferences. Therefore, this study does not force decision makers to apply only one way of information expression, but provides two choices, namely intuitionistic fuzzy sets and linguistic variables, which makes the decision-making process more flexible. For mixed information, the corresponding processing methods are proposed later.

3.2 Emergency Alternative Selection in an Intuitionistic Fuzzy Environment

The decision matrix under s_k state is denoted as $I^k = (if_{ij}^k)_{m\times n}$. Firstly, to obtain the comprehensive decision matrix, elements in the same position of q decision matrices will be aggregated, and the following definitions are proposed.

Definition 1 The intuitionistic fuzzy information of alternative ea_i against criterion c_j under state $\mathcal{S}_k$ is represented as if_{ij}^k, and the probability of $\mathcal{S}_k$ is $p^k = [p_a^k, p_b^k]$, then the aggregation result of $\{if_{ij}^1, if_{ij}^2, \ldots, if_{ij}^q\}$ can be calculated as

$$if_{ij} = if_{ij}^1 \oplus if_{ij}^2 \oplus \cdots \oplus if_{ij}^q = \left(\left[\mu_{if_{ij}}^-, \mu_{if_{ij}}^+\right], \left[v_{if_{ij}}^-, v_{if_{ij}}^+\right]\right), \quad (3)$$

where $\mu_{if_{ij}}^- = \sum_{k=1}^q \mu_{if_{ij}^k} p_a^k$, $\mu_{if_{ij}}^+ = \sum_{k=1}^q \mu_{if_{ij}^k} p_b^k$, $v_{if_{ij}}^- = \sum_{k=1}^q v_{if_{ij}^k} p_a^k$, and $v_{if_{ij}}^+ = \sum_{k=1}^q v_{if_{ij}^k} p_b^k$. It is worth noting that the aggregation result constitutes an interval-valued intuitionistic fuzzy set [42].

Further decision basis can be obtained by aggregating criteria information based on comprehensive decision matrix. First, entropy-based method is used to calculate criteria weight. The module of if_{ij} can be calculated as $|if_{ij}| = \sqrt{(\mu_{if_{ij}}^-)^2 + (\mu_{if_{ij}}^+)^2 + (v_{if_{ij}}^-)^2 + (v_{if_{ij}}^+)^2 + (\pi_{if_{ij}}^-)^2 + (\pi_{if_{ij}}^+)^2}$, where $\pi_{if_{ij}}^- = 1 - \mu_{if_{ij}}^- - v_{if_{ij}}^-$ and $\pi_{if_{ij}}^+ = 1 - \mu_{if_{ij}}^+ - v_{if_{ij}}^+$ [43].

Definition 2 The contribution degree of ea_i under the criteria c_j is denoted as $\mathrm{cd}_{ij} = \frac{|if_{ij}|}{\sum_{i=1}^m |if_{ij}|}$; then, the total contribution of all alternatives to criteria c_j can be calculated as $E_{c_j} = -\frac{1}{\ln(m)} \sum_{i=1}^m cd_{ij} \ln(\mathrm{cd}_{ij})$, so the consistency degree of contribution degree of each alternative under criteria c_j is defined as $d_{c_j} = 1 - E_{c_j}$. The weight of criterion c_j can be calculated as $w_{c_j} = d_{c_j} / \sum_{j=1}^n d_{c_j}$.

Then, the emergency alternative is selected based on TOPSIS. It should be noted that when the criteria is cost type, the corresponding interval-valued intuitionistic fuzzy value requires the complement operation.

Find out the positive-ideal solution M^+ and negative-ideal solution M^- in terms of each criterion:

$$M^+ = \left\langle \left[\mu_{if_{j+}}^-, \mu_{if_{j+}}^+\right], \left[v_{if_{j+}}^-, v_{if_{j+}}^+\right] \right\rangle = \left\langle \left[\max_i \mu_{if_{ij}}^-, \max_i \mu_{if_{ij}}^+\right], \left[\min_i v_{if_{ij}}^-, \min_i v_{if_{ij}}^+\right] \right\rangle,$$
$$M^- = \left\langle \left[\mu_{if_{j-}}^-, \mu_{if_{j-}}^+\right], \left[v_{if_{j-}}^-, v_{if_{j-}}^+\right] \right\rangle = \left\langle \left[\min_i \mu_{if_{ij}}^-, \min_i \mu_{if_{ij}}^+\right], \left[max_i v_{if_{ij}}^-, \max_i v_{if_{ij}}^+\right] \right\rangle. \quad (4)$$

Calculate the similarity measure between ea_i and the positive-ideal solution, and the similarity measure between ea_i and the negative-ideal solution by the following formulas [35], respectively:

$$S(\mathrm{ea}_i, M^+) = \sum_{j=1}^n w_{c_j} \frac{2 - \min\{\mu_{if_{ij}}^- - \mu_{if_{j+}}^-, v_{if_{ij}}^- - v_{if_{j+}}^-\} - \min\{\mu_{if_{ij}}^+ - \mu_{if_{j+}}^+, v_{if_{ij}}^+ - v_{if_{j+}}^+\}}{2 + \max\{\mu_{if_{ij}}^- - \mu_{if_{j+}}^-, v_{if_{ij}}^- - v_{if_{j+}}^-\} + \max\{\mu_{if_{ij}}^+ - \mu_{if_{j+}}^+, v_{if_{ij}}^+ - v_{if_{j+}}^+\}},$$
$$S(\mathrm{ea}_i, M^-) = \sum_{j=1}^n w_{c_j} \frac{2 - \min\{\mu_{if_{ij}}^- - \mu_{if_{j-}}^-, v_{if_{ij}}^- - v_{if_{j-}}^-\} - \min\{\mu_{if_{ij}}^+ - \mu_{if_{j-}}^+, v_{if_{ij}}^+ - v_{if_{j-}}^+\}}{2 + \max\{\mu_{if_{ij}}^- - \mu_{if_{j-}}^-, v_{if_{ij}}^- - v_{if_{j-}}^-\} + \max\{\mu_{if_{ij}}^+ - \mu_{if_{j-}}^+, v_{if_{ij}}^+ - v_{if_{j-}}^+\}}. \quad (5)$$

Calculate the closeness degree of ea_i as $\mathrm{clo}(\mathrm{ea}_i) = \frac{S(\mathrm{ea}_i, M^+)}{S(\mathrm{ea}_i, M^+) + S(\mathrm{ea}_i, M^-)}$, and the best emergency alternative is the one with the greatest closeness degree.

3.3 Emergency Alternative Selection in a Linguistic Environment

The decision matrix under $\mathcal{S}_k$ state is denoted as $L^k = (l^k_{ij})_{m\times n}$. To obtain the comprehensive decision matrix, elements in the same position of q decision matrices will be aggregated.

Definition 3 The linguistic information of alternative ea$_i$ against criterion c_j under state $\mathcal{S}_k$ is represented as l^k_{ij}, and the probability of $\mathcal{S}_k$ is $p^k = [p^k_a, p^k_b]$, then the aggregation result of $\{l^1_{ij}, l^2_{ij}, \ldots, l^q_{ij}\}$ can be calculated as

$$l_{ij} = l^1_{ij} \oplus l^2_{ij} \oplus \cdots \oplus l^q_{ij} = [(l_{ij})^-, (l^{ij})^+], \tag{6}$$

where $(l_{ij})^- = \sum_{k=1}^q l^k_{ij} p^k_a$, and $(l^{ij})^+ = \sum_{k=1}^q l^k_{ij} p^k_b$.

Further decision-making basis can be obtained by aggregating criteria information. The criteria weight is calculated using the method similar to that in Sect. 3.2. Here, only the expected value operator of interval linguistic variables is given as

$$E(l_{ij}) = (1-\zeta)(l_{ij})^- + \zeta(l_{ij})^+, \quad i = 1, \ldots, m, \\ j = 1, \ldots, n, \tag{7}$$

where presents risk attitude of decision makers and satisfies $0 \le \zeta \le 1$. For convenience, ζ is assumed equal to 0.5.

Next, a weighted aggregation method is proposed to obtain the corresponding linguistic expression of each emergency alternative

$$l_i = l_{i1} \oplus l_{i1} \oplus \cdots \oplus l_{in} = \sum_{j=1}^{n} w_{c_j} l_{ij}, \tag{8}$$

Then, the expected value of l_i can be calculated as $E(l_i)$, and the larger it is, the better the emergency alternative will be.

3.4 Emergency Alternative Selection in a Hybrid Environment

Considering the preferences of the decision-makers, this study provides an intuitionistic fuzzy-linguistic method for emergency alternative selection to flexibly express the choices. The general idea is to unify intuitionistic fuzzy expression and linguistic information into a BPA representation using DST, and then finalize the emergency decision under the DST framework.

In this study, linguistic item set $S = \{s_1, \ldots, s_\vartheta\}$ is regarded as the frame of discernment (FOD) in DST, so interval linguistic information $[s_a, s_b]$ can be translated into BPA expression as

$$[s_a, s_b] \longrightarrow m(\{s_a, \ldots, s_b\}) = 1, \tag{9}$$

where $a, b \in \{1, \ldots, \vartheta\}$ and $a \le b$.

For instance, the interval linguistic information $[s_1, s_3]$ can be converted to $m(\{s_1, s_2, s_3\}) = 1$.

For intuitionistic fuzzy expression (μ, v), the membership degree μ is regarded as support degree, corresponding to s_ϑ in the FOD, and non-membership degree v represents opposition degree, corresponding to s_1, because s_1 is defined as the worst and s_ϑ as the best in the linguistic item set S. In addition, the degree of hesitation in intuitionistic fuzzy sets corresponds to the complete set in DST, so there is the following conversion method

$$(\mu, v) \longrightarrow \begin{cases} m(\{s_\vartheta\}) = \mu, \\ m(\{s_1\}) = v, \\ m(\{S\}) = 1 - \mu - v. \end{cases} \tag{10}$$

To clearly demonstrate the information conversion process from intuitionistic fuzzy sets and linguistic variables to BPAs, two illustrative examples are provided below.

Example 1 Let the linguistic information be expressed as $\{s_1\}$, and it can be converted to the BPA as $m(\{s_1\}) = 1$ based on Eq. (9). For another linguistic information $[s_1, s_3]$, its BPA representation can be calculated as $m(\{s_1, s_2, s_3\}) = 1$.

Example 2 Let the intuitionistic fuzzy information be expressed as (0.6, 0.3), and it can be converted to the BPA as $m(\{s_1\}) = 0.3, m(\{s_5\}) = 0.6, m(\{S\}) = 0.1$ based on Eq. (10). For another intuitionistic fuzzy information (0.8, 0.2), its BPA representation can be calculated as $m(\{s_1\}) = 0.2, m(\{s_5\}) = 0.8$.

Thus, in the hybrid environment, the decision matrix under $\mathcal{S}_k$ state is denoted as $H^k = (m^k_{ij})_{m\times n}$. The first step is to combine the decision information in different states. First, convert the interval probability $p^k = [p^k_a, p^k_b]$ to a real number: $\widetilde{p}^k = (1-\beta)p^k_a + \beta p^k_b$, where the parameter β is used to express the attitude of the decision-maker, and the default value is 0.5.

Definition 4 The hybrid information of alternative ea$_i$ against criterion c_j under state $\mathcal{S}_k$ is represented as m^k_{ij}, and the probability of $\mathcal{S}_k$ is $\widetilde{p}^k$, then the aggregation result of $\{m^1_{ij}, m^2_{ij}, \ldots, m^q_{ij}\}$ can be calculated as

$$m_{ij} = \underbrace{\widehat{m}_{ij} \oplus \widehat{m}_{ij} \oplus \cdots \oplus \widehat{m}_{ij}}_{q}, \tag{11}$$

where $\oplus$ is the orthogonal sum defined in Eq. (1), and

$$\widehat{m}_{ij}(A) = \sum_{k=1}^{q} \widetilde{p}^k \cdot m^k_{ij}(A), \quad \forall A \subseteq S, \tag{12}$$

where S is the FOD denoted as $S = \{s_1, s_2, \ldots, s_\vartheta\}$.

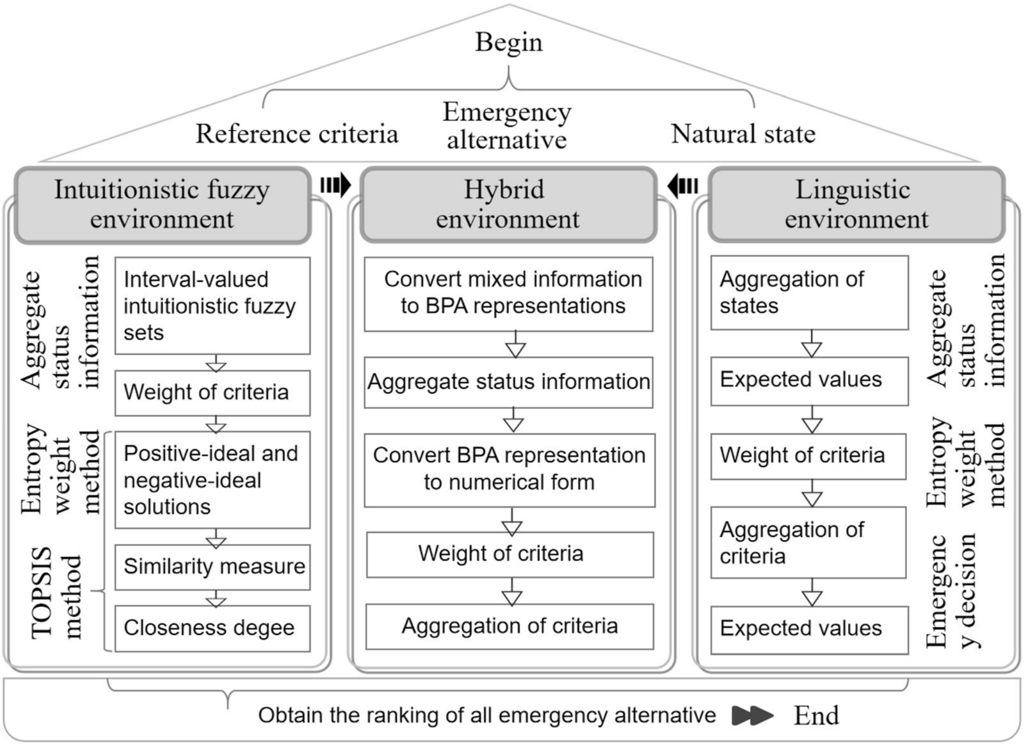

Fig. 1 Flowchart of the proposed emergency alternative selection method

The second step is to convert BPA expression into numerical expression. The transferable belief model is used:

$$\underline{m}_{ij}(s_\varphi)=\sum_{s_\varrho\subseteq S}\frac{s_\varphi\cap s_\varrho}{s_\varrho}\frac{\Im_{ij}(s_\varrho)}{1-\Im_{ij}(\phi)},\quad \forall s_\varphi\subseteq S, \tag{13}$$

where $|s_\varphi|$ is the cardinality of focal element s_φ, $\underline{m}_{ij}(s_\varphi)$ is the the belief of linguistic term s_φ. The numerical form of $\underline{m}_{ij}$ is defined as:

$$t_{ij}=\sum_{s_\varphi\in S}s_\varphi\underline{m}_{ij}(s_\varphi). \tag{14}$$

The third step is to calculate the weight of the criteria. The method is similar to that in Sect. 3.2. The fourth step is to aggregate the criteria values of each emergency alternative $h_i=\sum_{j=1}^{n}w_{c_j}t_{ij}$. Finally, the alternative are sorted according to h_i.

3.5 The Prototype of Emergency Alternative Selection

In the previous sections, the steps of EAS under different decision-making environments were given. To make the involved process more clearly understood, a prototype description and flowchart are provided below.

The main goal of this study is to provide a comprehensive method for EAS under various decision-making environments. Specifically, after determining the alternative emergency alternatives, decision criteria and natural states, the emergency decision methods in the intuitionistic fuzzy environment, linguistic environment and hybrid environment are given, which are described separately in the following sections, and the flowchart is shown in Fig. 1.

The EAS method processes in the three decision-making environments are similar but they have their own characteristics. In the intuitionistic fuzzy environment, the decision matrices under different states are aggregated first, the interval-valued intuitionistic fuzzy sets are obtained, the entropy weight method is used to determine the weight of the criteria and then TOPSIS is used to make decisions. The positive ideal solution and negative ideal solution are calculated, and then the closeness index of each alternative is determined based on the similarity measure, finalizing the EAS.

In the linguistic environment, the decision matrices in different states are also aggregated first, and the expected value of the interval-valued linguistic variable is calculated. Then, the weight of the criteria is calculated, the criteria information is aggregated, and finally, the expected value is calculated to complete the selection of the emergency alternatives. To express the decision-makers' subjective judgements flexibly, this paper considers a hybrid decision environment and proposes a method to unify intuitionistic fuzzy expression and linguistic information into a BPA expression using the DST. Then, BPA aggregation methods in different states are proposed. Finally, the best emergency alternative is determined by calculating the criteria weights and aggregating the criteria information.

4 A Case Study from China

To demonstrate the effectiveness of the emergency decision method constructed in this study, the process of emergency alternative selection in a mixed environment is presented with a case study of a heavy rainfall disaster in China.

In 2019, the middle and lower reaches of the Yangtze River in China were hit by sudden rainstorms and continuous rain in many places. Floods in Poyang Lake and other tributaries caused severe damage to parts of central and eastern China. In one of the villages, there was a serious flood under the action of heavy rainfall for several days, and most of the villagers were in extreme danger. In the face of a sudden major natural disaster, emergency management immediately began an emergency response. Based on careful investigation and detailed discussion, the following four emergency alternatives were presented.

Alternative 1 (ea_1): first use helicopters to rescue disaster areas, and then combine local blasting techniques to search for missing villagers. *Alternative* 2 (ea_2): first use ambulances and foot to rescue the disaster areas, and then combine local blasting technology to search for missing villagers. *Alternative* 3 (ea_3): first use ambulances and foot to rescue disaster areas, then use submersible pumps and other large tools to search for missing villagers. *Alternative* 4 (ea_4): first use helicopters to rescue disaster areas, then combine local blasting technology to search for missing villagers, and finally use large tools.

Three possible future weather conditions were reported, all in the form of interval probabilities. The probability of continuous expansion of precipitation scale ($\mathcal{S}_1$) is $p^1 = [0.4, 0.5]$, the probability of slightly smaller precipitation scale ($\mathcal{S}_2$) is $p^2 = [0.1, 0.3]$, and the probability of decreasing precipitation scale ($\mathcal{S}_3$) is $p^3 = [0.1, 0.2]$.

Based on the information provided by meteorological and geological departments, the following four criteria were determined as the basis of EAS by experts after repeated discussions: rescue effect (c_1), safety (c_2), economy (c_3), convenience (c_4). The methodology presented is used to analyze the alternatives to determine the most appropriate emergency response for the current flood.

To fully demonstrate the effectiveness of the proposed method in the hybrid decision environment, this section is divided into three scenarios for emergency decision-making.

Scenario 1 emergency decision-making in intuitionistic fuzzy environment.

Step 1 The decision information is given based on intuitionistic fuzzy sets as shown in Table 1.

Step 2 Definition 1 is used to aggregate different state information, and the aggregation results and weight of criteria are shown in Table 2. First, the decision matrices in different states are aggregated based on Eq. (3), and then the weight of the criteria is calculated based on the entropy weight method.

Step 3 The EAS process is then carried out using TOPSIS ideas, where the positive-ideal solution and the negative-ideal solution are calculated based on Eq. (4) as $M^+ = ([0.434, 0.693],$
$[0.044, 0.084]),([0.469, 0.748], [0.06, 0.1]),$

Table 1 Decision information based on intuitionistic fuzzy sets

States	Emergency Alternative	Criteria			
		c_1	c_2	c_3	c_4
$\mathcal{S}_1$	ea_1	(0.36, 0.5)	(0.84, 0.1)	(0.64, 0.2)	(0.6, 0.3)
	ea_2	(0.28, 0.3)	(0.5, 0.2)	(0.6, 0.1)	(0.8, 0.1)
	ea_3	(0.6, 0.2)	(0.55, 0.15)	(0.72, 0.1)	(0.65, 0.25)
	ea_4	(0.75, 0.15)	(0.85, 0.1)	(0.5, 0.2)	(0.4, 0.5)
$\mathcal{S}_2$	ea_1	(0.5, 0.4)	(0.65, 0.1)	(0.55, 0.25)	(0.45, 0.3)
	ea_2	(0.3, 0.6)	(0.62, 0.2)	(0.7, 0.1)	(0.65, 0.2)
	ea_3	(0.5, 0.1)	(0.62, 0.2)	(0.72, 0.2)	(0.55, 0.3)
	ea_4	(0.5, 0.3)	(0.65, 0.1)	(0.1, 0.9)	(0.4, 0.3)
$\mathcal{S}_3$	ea_1	(0.65, 0.2)	(0.64, 0.1)	(0.88, 0.1)	(0.76,0.15)
	ea_2	(0.25, 0.4)	(0.54, 0.3)	(0.92, 0)	(0.64, 0.1)
	ea_3	(0.72, 0.2)	(0.55, 0.15)	(0.65, 0.12)	(0.55, 0.2)
	ea_4	(0.84, 0.1)	(0.64, 0.2)	(0.36, 0.4)	(0.12, 0.6)

Table 2 Aggregation results of states in intuitionistic fuzzy environment

	c_1	c_2	c_3	c_4
ea$_1$	([0.144, 0.286], [0.044, 0.084])	([0.465, 0.743], [0.06, 0.1])	([0.4, 0.66], [0.115, 0.195])	([0.361, 0.587], [0.165, 0.27])
ea$_2$	([0.167, 0.28], [0.22, 0.41])	([0.316, 0.544], [0.13, 0.22])	([0.402, 0.694], [0.05, 0.08])	([0.449, 0.723], [0.07, 0.13])
ea$_3$	([0.362, 0.594], [0.11, 0.17])	([0.337, 0.571], [0.095, 0.165])	([0.425, 0.706], [0.072, 0.134])	([0.37, 0.6], [0.15, 0.255])
ea$_4$	([0.434, 0.693], [0.1, 0.185])	([0.469, 0.748], [0.07, 0.12])	([0.246, 0.352], [0.21, 0.45])	([0.212, 0.344], [0.29, 0.46])
Weight	0.7561	0.1250	0.0635	0.0553

([0.425, 0.706], [0.05, 0.08]), ([0.449, 0.723], [0.07, 0.13]) and $M^- = ([0.144, 0.28], [0.22, 0.41])$, ([0.316, 0.544], [0.13, 0.22]), ([0.246, 0.352], [0.21, 0.45]), ([0.212, 0.344], [0.29, 0.46]).

Step 4 The similarity between each alternative and the positive-ideal and the negative-ideal are calculated based on Eq. (5) as $S(\mathrm{ea}_1, M^+) = 0.7135$, $S(\mathrm{ea}_2, M^+) = 0.9547$, $S(\mathrm{ea}_3, M^+) = 0.8860$, $S(\mathrm{ea}_4, M^+) = 0.8121$ and $S(\mathrm{ea}_1, M^-) = 0.7899$, $S(\mathrm{ea}_2, M^-) = 0.8079$, $S(\mathrm{ea}_3, M^-) = 0.6895$, $S(\mathrm{ea}_4, M^-) = 0.7068$.

Step 5 The closeness index is obtained as $\mathrm{clo}(\mathrm{ea}_1) = 0.4746$, $\mathrm{clo}(\mathrm{ea}_2) = 0.5416$, $\mathrm{clo}(\mathrm{ea}_3) = 0.5624$, and $\mathrm{clo}(\mathrm{ea}_4) = 0.5347$.

Step 6 The order of the four emergency alternatives is $\mathrm{ei}_3 \succ \mathrm{ei}_2 \succ \mathrm{ei}_4 \succ \mathrm{ei}_1$. Therefore, the best emergency alternative for this flood is ei_3.

Scenario 2 emergency decision-making in linguistic environment.

Step 1 The decision information is given by linguistic variables as shown in Table 3.

Step 2 The decision matrices in different states are aggregated based on Eq. (6).

Step 3 The expected values of the comprehensive decision matrix are calculated based on Eq. (7) to further obtain the criteria weight.

Step 4 The different criteria are aggregated weighted using Eq. (8).

Step 5 The expected values of the aggregated criteria are calculated based on Eq. (7). The comprehensive decision matrix, the weight of criteria, aggregation results, and expected values are shown in Table 4. Therefore, the relationship of the four emergency alternatives is obtained as $\mathrm{ei}_3 \succ \mathrm{ei}_2 \succ \mathrm{ei}_4 \succ \mathrm{ei}_1$. So, the best one is ei_3.

Scenario 3 emergency decision-making in hybrid environment.

Step 1: To illustrate the hybrid environment, the data for this scenario is from Tables 1 and 3, with the corresponding data for criterion c_1 from Table 1 and the other data from Table 3.

Table 3 Decision information based on linguistic variables

States	Emergency Alternative	Criteria			
		c_1	c_2	c_3	c_4
$\mathcal{S}_1$	ea$_1$	$[s_1, s_2]$	$\{s_2\}$	$[s_2, s_3]$	$\{s_3\}$
	ea$_2$	$[s_1, s_2]$	$[s_2, s_3]$	$\{s_3\}$	$\{s_5\}$
	ea$_3$	$[s_1, s_5]$	$[s_2, s_3]$	$[s_3, s_4]$	$[s_3, s_4]$
	ea$_4$	$[s_3, s_5]$	$\{s_2\}$	$[s_2, s_3]$	$\{s_2\}$
$\mathcal{S}_2$	ea$_1$	$[s_2, s_3]$	$\{s_2\}$	$\{s_2\}$	$[s_2, s_3]$
	ea$_2$	$[s_1, s_2]$	$\{s_3\}$	$[s_3, s_4]$	$\{s_4\}$
	ea$_3$	$[s_2, s_3]$	$\{s_3\}$	$[s_3, s_4]$	$[s_2, s_3]$
	ea$_4$	$[s_2, s_3]$	$\{s_2\}$	$[s_1, s_2]$	$\{s_2\}$
$\mathcal{S}_3$	ea$_1$	$[s_2, s_4]$	$\{s_2\}$	$[s_2, s_3]$	$\{s_4\}$
	ea$_2$	$[s_1, s_2]$	$[s_2, s_3]$	$[s_4, s_5]$	$\{s_4\}$
	ea$_3$	$[s_3, s_4]$	$[s_2, s_3]$	$\{s_3\}$	$\{s_3\}$
	ea$_4$	$[s_3, s_5]$	$\{s_2\}$	$\{s_2\}$	$[s_1, s_2]$

Step 2: The hybrid information is then uniformly converted to BPA expression in DST by using Eqs. (9) and (10), as shown in Table 5.

Step 3: Based on Eqs. (11) and (12), the decision information of different states can be aggregated, and the results are shown in Table 6.

Step 4: The numerical form of BPAs can be calculated by using Eqs. (13) and (14), and the results are shown in Table 7, which also includes the weight of criteria.

Step 5: By aggregating criteria values, the representative values of each emergency alternative are $h_1 = 3.2183$, $h_2 = 3.2470$, $h_3 = 3.5956$, and $h_4 = 2.9984$. The order of the four emergency alternatives is $\mathrm{ei}_3 \succ \mathrm{ei}_2 \succ \mathrm{ei}_1 \succ \mathrm{ei}_4$. Therefore, the best emergency alternative for this flood is ei_3.

5 Results and Analysis

Table 8 further presents the results of the case study. On the whole, the ordering results in the intuitionistic fuzzy environment are consistent with those in the linguistic

Table 4 Aggregation results of states in intuitionistic fuzzy environment

	c_1	c_2	c_3	c_4	Aggregation results	The expected value
ea$_1$	$[s_{0.8}, s_{2.7}]$	$[s_{1.2}, s_2]$	$[s_{1.2}, s_{2.7}]$	$[s_{1.6}, s_{3.2}]$	$[s_{1.1770}, s_{2.8135}]$	$\{s_{1.9952}\}$
ea$_2$	$[s_{0.6}, s_2]$	$[s_{1.3}, s_3]$	$[s_{1.9}, s_{3.7}]$	$[s_{2.8}, s_{4.5}]$	$[s_{1.6339}, s_{3.2284}]$	$\{s_{2.4312}\}$
ea$_3$	$[s_{0.9}, s_{4.2}]$	$[s_{1.3}, s_3]$	$[s_{1.8}, s_{3.8}]$	$[s_{1.7}, s_{3.5}]$	$[s_{1.3570}, s_{3.7889}]$	$\{s_{2.5730}\}$
ea$_4$	$[s_{1.7}, s_{4.4}]$	$[s_{1.2}, s_2]$	$[s_{1.1}, s_{2.5}]$	$[s_{1.1}, s_2]$	$[s_{1.3521}, s_{3.0536}]$	$\{s_{2.2028}\}$
Weight	0.4056	0.0867	0.1600	0.3478	–	–

Table 5 Decision information based on hybrid form

States	Emergency Alternative	Criteria			
		c_1	c_2	c_3	c_4
$\mathcal{S}_1$	ea$_1$	$m(\{s_1, s_2\}) = 1$	$m(\{s_1\}) = 0.1$	$m(\{s_1\}) = 0.2$	$m(\{s_1\}) = 0.3$
			$m(\{s_5\}) = 0.84$	$m(\{s_5\}) = 0.64$	$m(\{s_5\}) = 0.6$
			$m(\{S\}) = 0.06$	$m(\{S\}) = 0.16$	$m(\{S\}) = 0.1$
	ea$_2$	$m(\{s_1, s_2\}) = 1$	$m(\{s_1\}) = 0.2$	$m(\{s_1\}) = 0.1$	$m(\{s_1\}) = 0.1$
			$m(\{s_5\}) = 0.5$	$m(\{s_5\}) = 0.6$	$m(\{s_5\}) = 0.8$
			$m(\{S\}) = 0.3$	$m(\{S\}) = 0.3$	$m(\{S\}) = 0.1$
	ea$_3$	$m(\{S\}) = 1$	$m(\{s_1\}) = 0.15$	$m(\{s_1\}) = 0.1$	$m(\{s_1\}) = 0.25$
			$m(\{s_5\}) = 0.55$	$m(\{s_5\}) = 0.72$	$m(\{s_5\}) = 0.65$
			$m(\{S\}) = 0.3$	$m(\{S\}) = 0.18$	$m(\{S\}) = 0.1$
	ea$_4$	$m(\{s_3, s_4, s_5\}) = 1$	$m(\{s_1\}) = 0.1$	$m(\{s_1\}) = 0.2$	$m(\{s_1\}) = 0.5$
			$m(\{s_5\}) = 0.85$	$m(\{s_5\}) = 0.5$	$m(\{s_5\}) = 0.4$
			$m(\{S\}) = 0.05$	$m(\{S\}) = 0.3$	$m(\{S\}) = 0.1$
$\mathcal{S}_2$	ea$_1$	$m(\{s_2, s_3\}) = 1$	$m(\{s_1\}) = 0.1$	$m(\{s_1\}) = 0.25$	$m(\{s_1\}) = 0.3$
			$m(\{s_5\}) = 0.64$	$m(\{s_5\}) = 0.55$	$m(\{s_5\}) = 0.45$
			$m(\{S\}) = 0.26$	$m(\{S\}) = 0.2$	$m(\{S\}) = 0.25$
	ea$_2$	$m(\{s_1, s_2\}) = 1$	$m(\{s_1\}) = 0.3$	$m(\{s_1\}) = 0.1$	$m(\{s_1\}) = 0.2$
			$m(\{s_5\}) = 0.54$	$m(\{s_5\}) = 0.7$	$m(\{s_5\}) = 0.65$
			$m(\{S\}) = 0.16$	$m(\{S\}) = 0.2$	$m(\{S\}) = 0.15$
	ea$_3$	$m(\{s_2, s_3\}) = 1$	$m(\{s_1\}) = 0.15$	$m(\{s_1\}) = 0.2$	$m(\{s_1\}) = 0.3$
			$m(\{s_5\}) = 0.55$	$m(\{s_5\}) = 0.72$	$m(\{s_5\}) = 0.55$
			$m(\{S\}) = 0.3$	$m(\{S\}) = 0.08$	$m(\{S\}) = 0.15$
	ea$_4$	$m(\{s_2, s_3\}) = 1$	$m(\{s_1\}) = 0.2$	$m(\{s_1\}) = 0.9$	$m(\{s_1\}) = 0.3$
			$m(\{s_5\}) = 0.64$	$m(\{s_5\}) = 0.1$	$m(\{s_5\}) = 0.4$
			$m(\{S\}) = 0.16$		$m(\{S\}) = 0.3$
$\mathcal{S}_3$	ea$_1$	$m(\{s_2, s_3, s_4\}) = 1$	$m(\{s_1\}) = 0.1$	$m(\{s_1\}) = 0.1$	$m(\{s_1\}) = 0.15$
			$m(\{s_5\}) = 0.76$	$m(\{s_5\}) = 0.88$	$m(\{s_5\}) = 0.76$
			$m(\{S\}) = 0.14$	$m(\{S\}) = 0.02$	$m(\{S\}) = 0.09$
	ea$_2$	$m(\{s_1, s_2\}) = 1$	$m(\{s_1\}) = 0.22$	$m(\{s_5\}) = 0.92$	$m(\{s_1\}) = 0.1$
			$m(\{s_5\}) = 0.54$	$m(\{S\}) = 0.08$	$m(\{s_5\}) = 0.64$
			$m(\{S\}) = 0.24$		$m(\{S\}) = 0.26$
	ea$_3$	$m(\{s_3, s_4\}) = 1$	$m(\{s_1\}) = 0.16$	$m(\{s_1\}) = 0.12$	$m(\{s_1\}) = 0.2$
			$m(\{s_5\}) = 0.57$	$m(\{s_5\}) = 0.65$	$m(\{s_5\}) = 0.55$
			$m(\{S\}) = 0.27$	$m(\{S\}) = 0.23$	$m(\{S\}) = 0.25$
	ea$_4$	$m(\{s_3, s_4, s_5\}) = 1$	$m(\{s_1\}) = 0.12$	$m(\{s_1\}) = 0.4$	$m(\{s_1\}) = 0.6$
			$m(\{s_5\}) = 0.76$	$m(\{s_5\}) = 0.36$	$m(\{s_5\}) = 0.12$
			$m(\{S\}) = 0.12$	$m(\{S\}) = 0.24$	$m(\{S\}) = 0.28$

Table 6 Aggregation results of states in the hybrid environment

	c_1	c_2	c_3	c_4
ea_1	$m(\{s_1, s_2\}) = 0.1780$ $m(\{s_2\}) = 0.7383$ $m(\{s_2, s_3\}) = 0.0771$ $m(\{s_2, s_3, s_4\}) = 0.0066$	$m(\{s_1\}) = 0.0157$ $m(\{s_5\}) = 0.9801$ $m(\{S\}) = 0.0041$	$m(\{s_1\}) = 0.0634$ $m(\{s_5\}) = 0.9313$ $m(\{S\}) = 0.0053$	$m(\{s_1\}) = 0.2248$ $m(\{s_5\}) = 0.7751$ $m(\{S\}) = 0.0001$
ea_2	$m(\{s_1, s_2\}) = 1$	$m(\{s_1\}) = 0.1505$ $m(\{s_5\}) = 0.8237$ $m(\{S\}) = 0.0258$	$m(\{s_1\}) = 0.0233$ $m(\{s_5\}) = 0.9606$ $m(\{S\}) = 0.0161$	$m(\{s_1\}) = 0.0237$ $m(\{s_5\}) = 0.9721$ $m(\{S\}) = 0.0042$
ea_3	$m(\{s_2, s_3\}) = 0.3584$ $m(\{s_3, s_4\}) = 0.2439$ $m(\{s_3\}) = 0.2197$ $m(\{S\}) = 0.1780$	$m(\{s_1\}) = 0.0944$ $m(\{s_5\}) = 0.8753$ $m(\{S\}) = 0.0303$	$m(\{s_1\}) = 0.0304$ $m(\{s_5\}) = 0.9631$ $m(\{S\}) = 0.0065$	$m(\{s_1\}) = 0.2531$ $m(\{s_5\}) = 0.6063$ $m(\{S\}) = 0.1406$
ea_4	$m(\{s_2, s_3\}) = 0.0156$ $m(\{s_3, s_4, s_5\}) = 0.4219$ $m(\{s_3\}) = 0.5625$	$m(\{s_1\}) = 0.0172$ $m(\{s_5\}) = 0.9803$ $m(\{S\}) = 0.0025$	$m(\{s_1\}) = 0.5376$ $m(\{s_5\}) = 0.4401$ $m(\{S\}) = 0.0223$	$m(\{s_1\}) = 0.6444$ $m(\{s_5\}) = 0.3409$ $m(\{S\}) = 0.0147$

Table 7 Numerical expression of BPAs and the weight of criteria

	c_1	c_2	c_3	c_4	c_1	c_2	c_3	c_4
ea_1	$\underline{m}(s_1) = 0.09$ $\underline{m}(s_2) = 0.86$ $\underline{m}(s_3) = 0.05$	$\underline{m}(s_1) = 0.02$ $\underline{m}(s_5) = 0.98$	$\underline{m}(s_1) = 0.07$ $\underline{m}(s_5) = 0.93$	$\underline{m}(s_1) = 0.23$ $\underline{m}(s_5) = 0.77$	1.96	4.92	4.72	4.10
ea_2	$\underline{m}(s_1) = 0.5$ $\underline{m}(s_2) = 0.5$	$\underline{m}(s_1) = 0.15$ $\underline{m}(s_5) = 0.85$	$\underline{m}(s_1) = 0.04$ $\underline{m}(s_5) = 0.96$	$\underline{m}(s_1) = 0.03$ $\underline{m}(s_5) = 0.97$	1.5	4.4	4.84	4.88
ea_3	$\underline{m}(s_1) = 0.04$ $\underline{m}(s_2) = 0.21$ $\underline{m}(s_3) = 0.55$ $\underline{m}(s_4) = 0.16$ $\underline{m}(s_5) = 0.04$	$\underline{m}(s_1) = 0.1$ $\underline{m}(s_5) = 0.9$	$\underline{m}(s_1) = 0.04$ $\underline{m}(s_5) = 0.96$	$\underline{m}(s_1) = 0.28$ $\underline{m}(s_2) = 0.03$ $\underline{m}(s_3) = 0.03$ $\underline{m}(s_4) = 0.03$ $\underline{m}(s_5) = 0.63$	2.94	4.6	4.84	3.71
ea_4	$\underline{m}(s_2) = 0.01$ $\underline{m}(s_3) = 0.71$ $\underline{m}(s_4) = 0.14$ $\underline{m}(s_5) = 0.14$	$\underline{m}(s_1) = 0.02$ $\underline{m}(s_5) = 0.98$	$\underline{m}(s_1) = 0.56$ $\underline{m}(s_5) = 0.44$	$\underline{m}(s_1) = 0.65$ $\underline{m}(s_5) = 0.35$	3.41	4.92	2.80	2.39
Weight					0.4790	0.0108	0.2165	0.2936

Table 8 Emergency alternative selection table under different decision environments

Decision environment	Emergency alternative (Score)				Ranking
	ei_1	ei_2	ei_3	ei_4	
Intuitionstic fuzzy environment	0.4746	0.5416	0.5624	0.5347	$\mathrm{ei}_3 \succ \mathrm{ei}_2 \succ \mathrm{ei}_4 \succ \mathrm{ei}_1$
Linguistic environment	$\{s_{1.9952}\}$	$\{s_{2.4312}\}$	$\{s_{2.5730}\}$	$\{s_{2.2028}\}$	$\mathrm{ei}_3 \succ \mathrm{ei}_2 \succ \mathrm{ei}_4 \succ \mathrm{ei}_1$
Hybrid environment	3.2183	3.2470	3.5956	2.9984	$\mathrm{ei}_3 \succ \mathrm{ei}_2 \succ \mathrm{ei}_1 \succ \mathrm{ei}_4$

environment, while the decision results in the hybrid environment are slightly different, which is mainly reflected in the order of ea_1 and ea_4. The reason for this difference may be the loss of information in the data type conversion. However, there is no overall impact on the selection of emergency alternatives because the top two are in the same order.

In the linguistic decision-making environment, a parameter ζ is involved to calculate the expected value of the linguistic interval. To study the influence of ζ on the decision-making results, the following sensitivity analysis

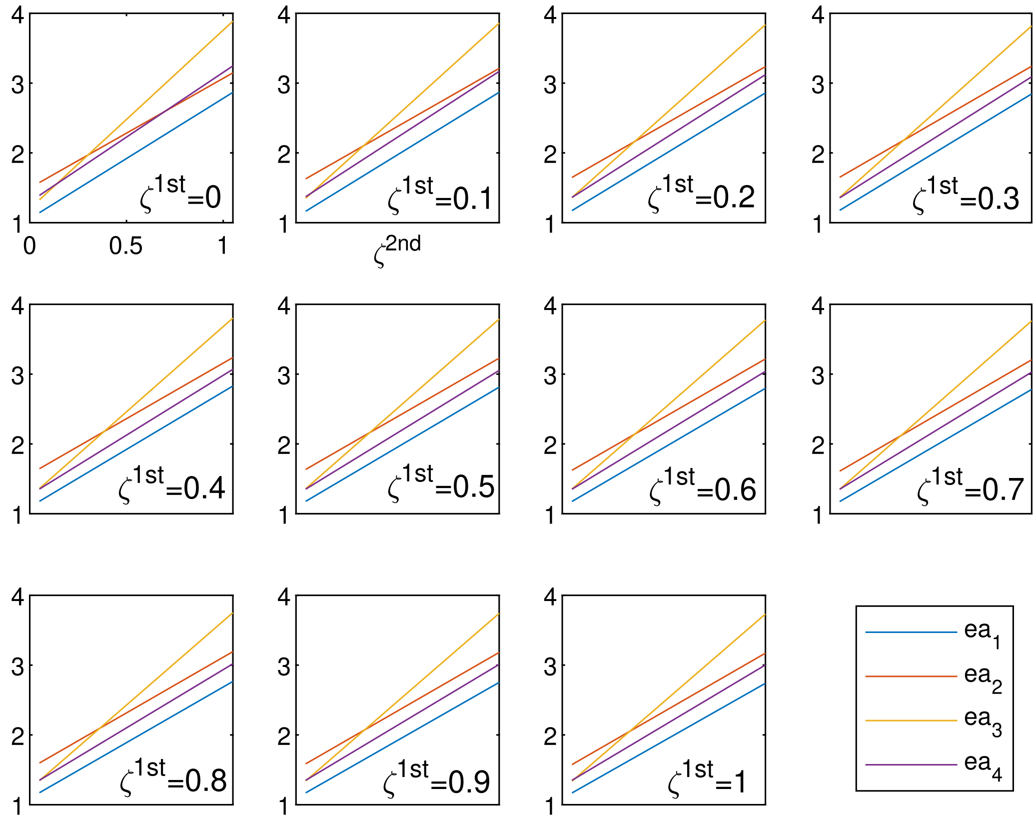

Fig. 2 Sensitivity analysis results of parameter ζ

is carried out. Because the decision-making process uses two expected value operators, in terms of calculating the weight and final ranking, in both processes, the value of ζ is set to increase from 0 to 1, with an interval of 0.1. The observation ranking results are shown in Fig. 2.

On the whole, ea_1 is always in the worst position, and ea_3 is the best one, and the result has not been greatly affected. Specifically, for the parameter in solving the weight, the change of ζ does not affect the overall trend, and the sorting result changes slightly, which is mainly reflected when $\zeta = 0$, and the order of ea_2 and ea_4 is different from that of other parameter values. When changing the second parameter ζ, it has an impact on the decision-making result, which is mainly reflected in the change of the order of ea_2 and ea_3. When the value of ζ is small, ea_2 is better than ea_3, and as ζ increases, the advantages of ea_3 begin to show, until a position less than 0.5, ea_3 begins to outperform ea_2 until the end.

In addition, in the hybrid decision-making environment, a parameter β is involved to quantify the probability interval corresponding to the natural states. To study the influence of β on the decision result, the following sensitivity experiment is carried out. Take different β values from 0 to 1 with an interval of 0.1, and observe the sorting results as shown in Fig. 3. It can be concluded from the

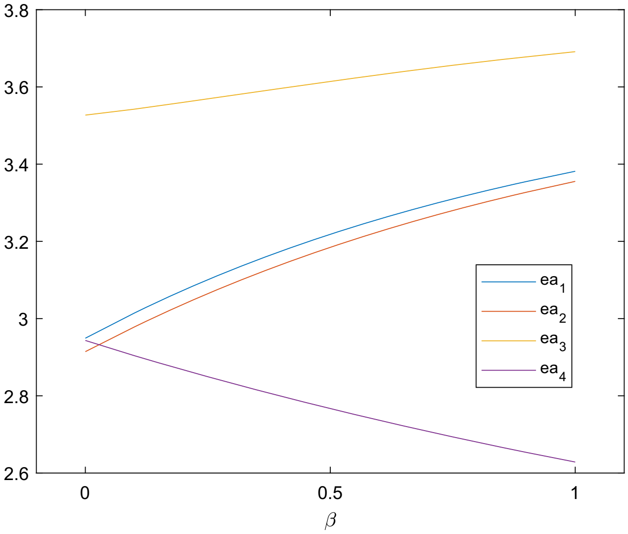

Fig. 3 Sensitivity analysis results of parameter β

figure that the parameter β hardly affects the decision-making result. The only change is that when $\beta = 0$, the order of ea_2 and ea_4 changes, but it does not affect the decision-making in general. It can be seen from the above two sensitivity analysis experiments that the parameter has a certain influence on the decision-making result, which is mainly reflected in the extreme values.

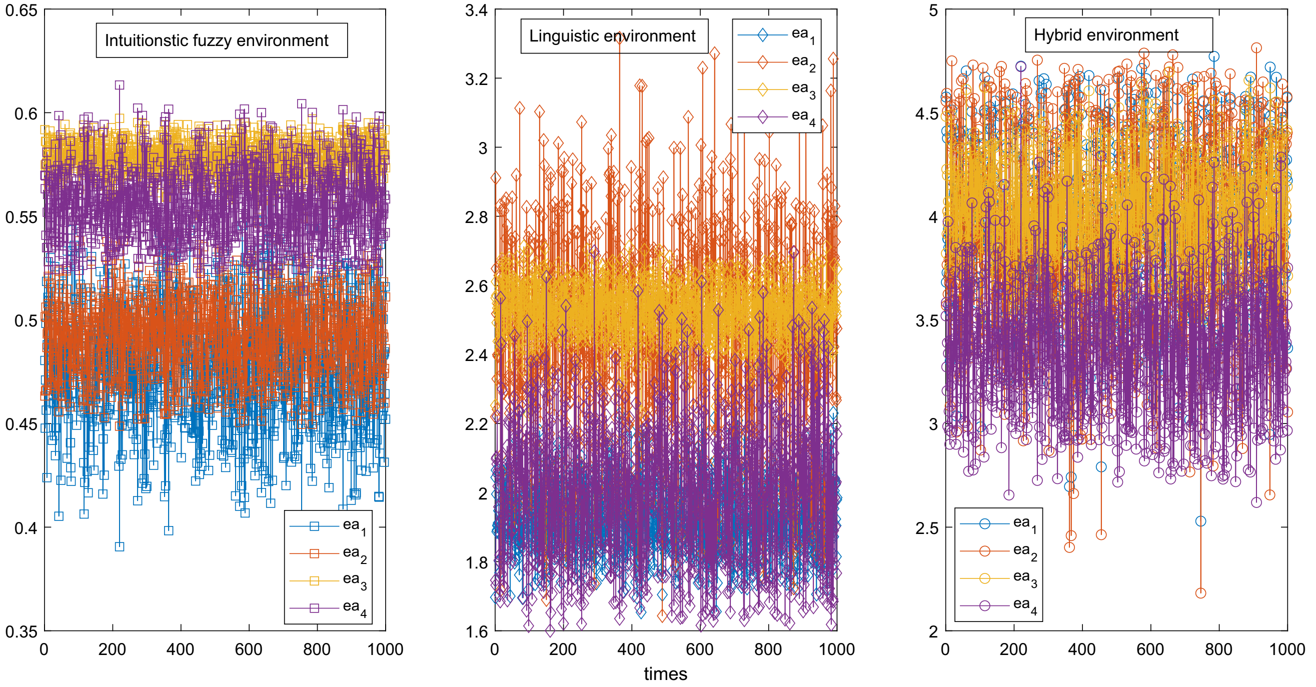

Fig. 4 Sensitivity analysis results of criteria weights

The criteria weight is a very key factor in different decision-making environments. To study the influence of criteria weight on decision-making results, sensitivity analysis is carried out in this part. In the three environments, the criteria weights are randomly generated and the decision results are obtained according to the decision process proposed in Sect. 3, as shown in Fig. 4.

In intuitionistic fuzzy environment, it is clearly observed that ea_3 and ea_4 are superior to ea_2 and ea_1, and in more detail, $ea_3 \succ ea_4$ and $ea_2 \succ ea_1$. A more accurate ranking can be obtained as $ea_3 \succ ea_4 \succ ea_2 \succ ea_1$ by calculating the average value of 1000 random results, which is consistent with the results obtained in *Scenario 1* in the best and worst alternates, while there are certain differences in the middle two.

In linguistic environment, it is clearly observed that ea_3 and ea_2 are superior to ea_4 and ea_1. A more accurate ranking can be obtained as $ea_3 \succ ea_2 \succ ea_4 \succ ea_1$ by calculating the average value of 1000 random results, which is consistent with the result obtained in *Scenario 2*, indicating that the decision result in the linguistic fuzzy environment is not sensitive to attribute weight.

In hybrid environment, it is clearly observed that ea_3 is superior to ea_4. A more accurate ranking can be obtained as $ea_3 \succ ea_1 \succ ea_2 \succ ea_4$ by calculating the average value of 1000 random results, which is different from the result $ea_3 \succ ea_2 \succ ea_4 \succ ea_1$ obtained in *Scenario 3*, but the optimal alternate is consistent.

Based on the above analysis, it can be concluded that the result of emergency decision has a certain sensitivity to criteria weight, but it does not affect the selection of optimal emergency alternate.

To further highlight the advantages of the constructed method, a qualitative comparative analysis is carried out first, including information expression, whether uncertainty and fuzziness are considered, and whether it can be used in a variety of decision-making environments. Table 9 shows the comparison results. In terms of information expression, only our method can realize emergency decision-making in a variety of environments, while other methods limit the way of information expression. In addition, our method considers both uncertainty and fuzziness, which is an advantage that other methods do not have.

For a further quantitative comparison, Table 10 shows the key technologies of each comparison method, and then an emergency plan selection experiment is conducted based on the data in this paper. Method [17] uses the intuitionistic fuzzy information in Table 1, while the other methods use the linguistic information in Table 3. From the decision-making results, all methods have obtained consistent results for the top two emergency alternatives, and the difference lies in the position of ei_1 and ei_4. In general, the usefulness of this study can be fully demonstrated for selecting the optimal emergency alternative.

Table 9 Qualitative comparison of emergency alternative selection methods

Method	Information expression	Consider uncertainty?	Consider fuzziness?	Alternative decision environments?
[8]	2-Tuple linguistic information	✓	×	×
[9]	Linguistic information	✓	×	×
[15]	Interval dual hesitant fuzzy set	×	✓	×
[16]	Linguistic information	✓	✓	×
[17]	Intuitionistic fuzzy sets	×	✓	×
Our method	Intuitionistic fuzzy sets and linguistic variables	✓	✓	✓

Table 10 Quantitative comparison of emergency alternative selection methods

Literature	Key technologies	Decision result
[8]	An emergency alternative selection method based on analytic network process (ANP), DEMATEL, and 2-tuple linguistic (TL)-TOPSIS	$ei_3 \succ ei_2 \succ ei_4 \succ ei_1$
[9]	A method of emergency alternative evaluation based on DS/AHP with extended TOPSIS	$ei_3 \succ ei_2 \succ ei_1 \succ ei_4$
[15]	A fuzzy multi-criteria decision-making approach for evaluating emergency response solutions	$ei_3 \succ ei_2 \succ ei_4 \succ ei_1$
[16]	An emergency decision method based on Pythagorean fuzzy uncertain linguistic variables	$ei_3 \succ ei_2 \succ ei_4 \succ ei_1$
[17]	An emergency alternative evaluation method based on entropy weight and DEMATEL	$ei_3 \succ ei_2 \succ ei_1 \succ ei_4$
Our method	A hybrid emergency alternative selection method is proposed	$ei_3 \succ ei_2 \succ ei_4 \succ ei_1$

6 Conclusion

In this study, a method of EAS in a hybrid decision-making environment is proposed. Theoretically, the research results show that the emergency decision method not only helps to express the subjective judgement of decision-makers in various forms, but also has a rigorous decision process and accurate decision results. The specific contributions of the hybrid approach in this paper are as follows.

First, the proposed EAS framework provides a new way of thinking about emergency decisions, which has the advantage of allowing emergency decision-makers to express evaluation information in a variety of decision-making environments, making the decision-making process more diverse and flexible, and reflecting the autonomy of the decision-makers in the implementation.

Second, an EAS method is proposed for intuitionistic fuzzy environments and linguistic environments. For a hybrid environment, an information conversion method is proposed, which can convert intuitionistic fuzzy sets and linguistic variables into BPA expressions using the DST, and the EAS method under the DST framework is given.

Finally, a flood disaster in China is taken as an example to verify the proposed model in three emergency decision-making environments. The effectiveness of the proposed method is verified by a sensitivity analysis and a comparative study.

In terms of practical significance, the EAS method developed in this study provides support for critical decisions in emergency situations. In particular, the convenience of decision-makers is fully considered so that they are no longer limited by information expression rigidity, and the wisdom of decision-makers is applied to the key points of emergency decision-making. In addition, the emergency decision method in this study supports intuitionistic fuzzy and linguistic information, which supports the decision-makers' preferences and helps decision-makers expand their sources of decision information and ensures the decision-making effectiveness.

The research limitations and future scope of this paper are as follows. First, the case analysis results in the three decision-making environments are different, indicating that there is information loss in the process of data type conversion. If the calculation method can be improved, and this loss can be reduced, the method proposed in this study will be more efficient.

Second, this study considers emergency decision-making in intuitionistic fuzzy and linguistic environments. In fact, there are many other ways of information expression in addition to these two. If more decision-making environments can be taken into account, the model will be more comprehensive.

Third, a methodology is only proposed at present. In the future, on the basis of more mature methods, procedures can be used to establish human–computer interaction with the emergency decision-making framework, and an automation of the input and a visualization of the output can be put in place.

Finally, the method in this paper is only applied to an abstract case study at present, and the framework in this paper should be used for more practical applications in the future to test its effectiveness in actual emergency decision-making.

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