Environmental impact assessment using D-VIKOR approach

Liguo Fei and Yong Deng

Abstract—**Environmental impact assessment (EIA) is an open and important issue depends on factors such as social, ecological, economic, etc. Due to human judgment, a variety of uncertainties are brought into the EIA process. With regard to uncertainty, many existing methods seem powerless to represent and deal with it effectively. A new theory called D numbers, because of its advantage to handle uncertain information, is widely used to uncertainty modeling and decision making. VIKOR method has its unique advantages in dealing with multiple criteria decision making problems (MCDM), especially when the criteria are non-commensurable and even conflicting, it can also obtain the compromised optimal solution. In order to solve EIA problems more effectively, in this paper, a D-VIKOR approach is proposed, which expends the VIKOR method by D numbers theory. In the proposed approach, assessment information of environmental factors is expressed and modeled by D numbers. And a new combination rule for multiple D numbers is defined. Subjective weights and objective weights are considered in VIKOR process for more reasonable ranking results. A numerical example is conducted to analyze and demonstrate the practicality and effectiveness of the proposed D-VIKOR approach.**

Index Terms—**Environmental Impact Assessment, D numbers, VIKOR, Uncertainty Modelling, Subjective and objective weights.**

I. Introduction

The environmental impact assessment is to analyse, predict and assess for environmental impact results from planning and implementation of construction projects. It requires to put forward measures to prevent or mitigate adverse environmental impact. All the influences of human activities on the environment are the critical factors to evaluate plans and projects.

EIA problems have attracted more and more researchers, a number of EIA frameworks have been developed such as Life cycle assessment (LCA) [1], [2], [3] provides a classical and generic environmental evaluation framework for EIA, and as a result it has been widely applied to various kinds of EIA problems in many fields [4], [5], [6]. Soft computing method [7], [8], [9], data envelopment analysis (DEA) [10], [11], input-output analysis [12], [13] and rapid impact assessment matrix (RIAM) [14] have also been used for EIA problems. Uncertainty methods [15], [16], [17], especially Dempster-Shafer evidence theory, have been applied to the EIA problem in [18], [19], [20] to express and deal with uncertain information from expert's inaccurate judgements.

Under real world, because the potential environmental impact of a project or program cannot be quantified accurately, the assessment information obtained is usually subjective, ambiguous, or incomplete. How to express and deal with uncertain information is a key issue in EIA problem. There are many theories for uncertainty representation such as fuzzy set [21], [22], [23], [24], neural methods [25], [26], and Dempster-Shafer evidence theory [27], [28], [29], [30], [31]. Due to the advantage to handle uncertain information, Dempster-Shafer theory is applied widely in decision making analysis [32], [33], [34], data fusion [35], [36], and risk assessment [37], [38]. In spite of all its good points, there are bound to be shortcomings such as completeness constraint and exclusiveness hypothesis. So in this paper, a new expression of uncertain information called D numbers [39], [40], [41] is introduced. And it has also been applied widely to solve multiple criteria decision making problem [42], [43], [44], [45]. It is the extension of Dempster-Shafer theory but more effective. Human judgment has a great influence on the environmental impact assessment, and this may involve uncertainty. So in this paper, assessment information from domain experts will be represented by D numbers.

Recently, advantages of VIKOR method [46], [47], [48] are more and more obvious in dealing with the problems of multi-criteria optimization in complex systems. In [49], the VIKOR method is combined by DEMATEL-based ANP to explore smart phone improvements. A multi-criteria assessment model of technologies is proposed based on VIKOR method in [50], [51], [52], [53]. A group multi-criteria supplier selection method using an extended VIKOR method with interval 2-tuple linguistic information is introduced in [54], [55], [56]. And many others method applied VIKOR are developed in [57], [58], [59]. In this paper, the VIKOR method is extended by D numbers theory that has more prominent performance in dealing with uncertain problems.

A D-VIKOR method has been proposed in [60] for medicine provider selection. However, its theory is not perfect, the method is not specific and there are many shortcomings with it. For example, weights in VIKOR process are determined by medical experts directly, which will bring a great uncertainties and could lead to

L. Fei and Y. Deng is with the Institute of Fundamental and Frontier Science, University of Electronic Science and Technology of China, Chengdu, 610054, China, and also with the School of Computer and Information Science, Southwest University, Chongqing, 400715, China. e-mail: (dengentropy@uestc.edu.cn, prof.deng@hotmail.com.)

inaccurate results. In addition, as mentioned in Section III-C1, it does not deal well with the order of combination for multiple D numbers. In order to solve above problems, in this paper, subjective and objective weights are considered and a new combination rule for multiple D numbers is defined in Section III-C1.

The rest of the paper is organized as follows. Section II gives a brief introduction about D numbers theory and VIKOR method. In Section III, the proposed approach for EIA using D numbers and VIKOR method is developed. An illustrative example is given to show the effectiveness of the proposed method in Section IV, and conclusions are given in Section V.

II. Preliminaries

A. D numbers Theory

D numbers theory is the expansion of Dempster-Shafer theory [27], [28]. It has more advantages to represent and handle uncertain information because the elements do not require mutually exclusive in D numbers and the completeness constraint is released in D numbers. As a generalization of evidence theory, D numbers theory has a wide application especially in linguistic assessment [42], [43], [44], [40]. It is also applied in other fields, such as failure mode and effects analysis [61], [62], bridge condition assessment [63], supplier selection [64], [65] and curtain grouting efficiency assessment [66]. In addition, some basic properties and operators are studied in [67] and [68]. It is defined as follows.

Definition II.1. *Let Ω be a finite nonempty set, D numbers is a mapping formulated by*

$$D : \Omega \rightarrow [0,1] \tag{1}$$

with

$$\sum_{B \subseteq \Omega} D(B) \leq 1 \quad and \quad D(\emptyset) = 0 \tag{2}$$

where $\emptyset$ is an empty set and B is a subset of Ω.

An illustrative example is given to show the D numbers as below.

Example II.1. *Suppose a project is assessed, and the assessment score is represented by an interval $[0,100]$. If an expert gives his assessment result by D numbers, it could be:*

$$\begin{array}{l} D(\{b_1\}) = 0.2 \\ D(\{b_3\}) = 0.6 \\ D(\{b_1, b_2, b_3\}) = 0.1 \end{array}$$

where $b_1 = [0,45]$, $b_2 = [38,73]$, $b_3 = [61,100]$. Note that the set of $\{b_1, b_2, b_3\}$ isn't a frame of discernment actually, because the elements in the set of $\{b_1, b_2, b_3\}$ are not mutually exclusive. Due to $D(\{b_1\}) + D(\{b_3\}) + D(\{b_1, b_2, b_3\}) = 0.9$, the information is incomplete.

For a discrete set $\Omega = \{b_1, b_2, \cdots, b_i, \cdots, b_n\}$, where $b_i \in R$ and $b_i \neq b_j$ if $i \neq j$, a special form of D numbers can be expressed by

$$\begin{array}{l} D(\{b_1\}) = v_1 \\ D(\{b_2\}) = v_2 \\ \cdots \quad \cdots \\ D(\{b_i\}) = v_i \\ \cdots \quad \cdots \\ D(\{b_n\}) = v_n \end{array} \tag{3}$$

or simply denoted as $D = \{(b_1, v_1), (b_2, v_2), \cdots, (b_i, v_i), \cdots, (b_n, v_n)\}$, where $v_i > 0$ and $\sum_{i=1}^{n} v_i \leq 1$.

Some properties of D numbers are introduced as follows.

Definition II.2. *Permutation invariability. If there are two D numbers that*

$$D_1 = \{(b_1, v_1), \cdots, (b_i, v_i), \cdots, (b_n, v_n)\}$$

and

$$D_2 = \{(b_n, v_n), \cdots, (b_i, v_i), \cdots, (b_1, v_1)\},$$

then $D_1 \Leftrightarrow D_2$.

Example II.2. *If there are two D numbers:*

$$D_1 = \{(0, 0.7), (1, 0.3)\} \quad and \quad D_2 = \{(1, 0.3), (0, 0.7)\}$$

Then

$$D_1 \Leftrightarrow D_2$$

Definition II.3. *For $D = \{(b_1, v_1), (b_2, v_2), \cdots, (b_i, v_i), \cdots, (b_n, v_n)\}$, the integration representation of D is defined as*

$$I(D) = \sum_{i=1}^{n} b_i v_i \tag{4}$$

where $b_i \in R$, $v_i > 0$ and $\sum_{i=1}^{n} v_i \leq 1$.

Example II.3. *Let $D = \{(1, 0.2), (2, 0.1), (3, 0.3), (4, 0.3), (5, 0.1)\}$, then*

$$I(D) = 1 \times 0.2 + 2 \times 0.1 + 3 \times 0.3 + 4 \times 0.3 + 5 \times 0.1 = 3.0$$

Next, a combination rule is proposed to combine two D numbers as below.

Definition II.4. *Let D_1 and D_2 be two D numbers, that:*

$$D_1 = \{(b_1^1, v_1^1), \cdots, (b_i^1, v_i^1), \cdots, (b_n^1, v_n^1)\}$$

$$D_2 = \{(b_1^2, v_1^2), \cdots, (b_j^2, v_j^2), \cdots, (b_m^2, v_m^2)\}$$

The combination of D_1 and D_2, indicated by $D = D_1 \oplus D_2$, is defined as

$$D(b) = v \tag{5}$$

with

$$b = \frac{b_i^1 + b_j^2}{2} \tag{6}$$

$$C = \begin{cases} \sum_{j=1}^{m}\sum_{i=1}^{n}(\frac{v_i^1+v_j^2}{2}), & \sum_{i=1}^{n} v_i^1 = 1 \quad and \quad \sum_{j=1}^{m} v_j^2 = 1\,; \\ \sum_{j=1}^{m}\sum_{i=1}^{n}(\frac{v_i^1+v_j^2}{2}) + \sum_{j=1}^{m}(\frac{v_c^1+v_j^2}{2}), & \sum_{i=1}^{n} v_i^1 < 1 \quad and \quad \sum_{j=1}^{m} v_j^2 = 1\,; \\ \sum_{j=1}^{m}\sum_{i=1}^{n}(\frac{v_i^1+v_j^2}{2}) + \sum_{i=1}^{n}(\frac{v_i^1+v_c^2}{2}), & \sum_{i=1}^{n} v_i^1 = 1 \quad and \quad \sum_{j=1}^{m} v_j^2 < 1\,; \\ \sum_{j=1}^{m}\sum_{i=1}^{n}(\frac{v_i^1+v_j^2}{2}) + \sum_{j=1}^{m}(\frac{v_c^1+v_j^2}{2}) & \\ \quad + \sum_{i=1}^{n}(\frac{v_i^1+v_c^2}{2}) + \frac{v_c^1+v_c^2}{2}, & \sum_{i=1}^{n} v_i^1 < 1 \quad and \quad \sum_{j=1}^{m} v_j^2 < 1\,. \end{cases} \tag{8}$$

$$v = \frac{v_i^1 + v_j^2}{2} \Big/ C \tag{7}$$

where $v_c^1 = 1 - \sum_{i=1}^{n} v_i^1$ *and* $v_c^2 = 1 - \sum_{j=1}^{m} v_j^2$. *Note that superscript in above equations is not exponent.*

Example II.4. *If two D numbers:*

$$D_1 = \{(0, 0.7), (1, 0.3)\} \quad and \quad D_2 = \{(0, 0.6), (1, 0.4)\}$$

the combination of D_1 *and* D_2 *using Eqs. (5 - 8) is*

$$D = \{(0.0, 0.325), (0.5, 0.500), (1.0, 0.175)\}$$

B. VIKOR method

Vlsekriterijumska Optimizacija I Kompromisno Resenje (i.e. VIKOR) method was developed by Opricovic in 1998 for multi-criteria optimization of complex systems [46], [47]. This is a kind of compromise sorting method, which compromises ranking of a finite decision scheme by maximizing group utility and minimizing individual regret. This method is a powerful tool for multi-criteria decision making problems, and it can solve the following problems effectively [48], [69]: (1) Decision makers cannot or do not determine how to express their preferences accurately; (2) There are conflicts and incommensurability between evaluation criteria (different measure units); (3) Decision makers cannot deal with the conflict but can accept the compromise solution.

The key idea of the VIKOR method is to determine the positive ideal solution (PIS) and negative ideal solution (NIS) firstly. Then selecting the optimal solution according to the closeness degree between the evaluation value of each solution and PIS under the conditions that acceptable advantages and decision process stability. The solution obtained by the VIKOR method is usually a compromise solution, which is the feasible solution of the most close to the optimal solution in all solutions. The VIKOR algorithm obtains the compromise solution which can be accepted by decision makers by maximizing the group benefit and minimizing the individual losses. The VIKOR and TOPSIS both are the compromise methods which are most close to the ideal solution. But the VIKOR algorithm does not need to consider the problem that the closest solution should also be the closest to the ideal solution and the most distant from the negative ideal point. It is an excellent multi-criteria decision making method, and it can sort the solutions directly. The optimal solution obtained by VIKOR is closer to the ideal scheme, but the TOPSIS method is not [70].

For the synthesis method, VIKOR uses an aggregate function developed by $L_p - metric$ [71], [72]. The $L_{p,j}$ measures the distance between the best ideal solution and the alternative A_j that was proposed by Duckstein and Opricovic in 1980. The value obtained from jth alternative under ith criterion is denoted by f_{ij}.

The VIKOR method is derived from the following form of $L_p - metric$:

$$L_{p,j} = \{\sum_{i=1}^{n}[w_i(f_i^* - f_{ij})/(f_i^* - f_i^-)]^p\}^{1/p} \tag{9}$$

where $1 \le p \le \propto, j = 1, 2, ...J$.

F^c is the compromise solution which is the "closest" feasible solution to the ideal solution F^*. It established on the premise that mutual concessions, which is shown in Figure 1 with $\Delta f_1 = f_1^* - f_1^c$ and $\Delta f_2 = f_2^* - f_2^c$.

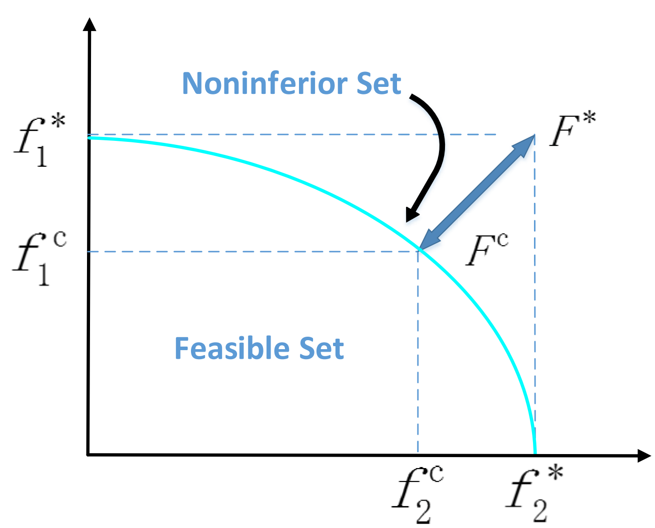

Fig. 1. Ideal and compromise solutions

III. THE D-VIKOR APPROACH FOR EIA

In this paper, a new approach for EIA problem based on VIKOR method extended by D numbers theory is proposed, which considers subjective and objective weights of the identified environmental factors. Generally, it contains four parts: 1) Identifying environmental factors for EIA. 2) Constructing D numbers framework for the identified environmental factors. 3) Determining the final decision matrix and weights of environmental factors. 4) Ranking all project options. The flow chart of the proposed approach is shown in Figure 2.

A. Identifying environmental factors for EIA

In order to start the study of EIA problems, it is necessary to identify as much as possible environmental impact factors. In general, the environment includes the natural environment and the social environment. The former is the basis of the latter, and the latter is the development of the former. The natural environment is the sum of all kinds of natural factors around mankind, consisting mainly of physical-chemical and biological factors. The social environment is the result of human long-term conscious social labor, processing and transformation, consisting mainly of cultural resources and socioeconomic concerns. Typical environmental factors for each class have been concluded as follows [73]. Natural environment: Air, water, plants, animals, soil, rocks, minerals, solar radiation, etc. Social environment: buildings, roads, factories; domesticated, domesticated plants and animals; human behavior, customs, law and language, etc.

Our main purpose is to identify the most valuable environmental factors, while to ignore those factors that have little impact on the environment, so as to reduce unnecessary computation. In order to determine the potential impact of a project, behavior analysis is necessary of the background. The relevant impact factors can also be identified through extensive literature reviews. The potential list of environmental factors related to a certain project can then be determined through field trips, interdisciplinary panel discussions, expert assessment, and so on.

There are many ways to determine the environmental impact factors. However, this is not the focus of this paper. In the following case study, the factors will be used identified in literature [14].

B. Constructing D numbers framework for the identified environmental factor

In order to analyze EIA problem, the impacts of the environmental factors need to be further represented, operate and assessed. The assessment standard for the impact level can be described by the grades in Table I, which are from [14] to assess the total environmental impact. The difference is that we use the numerical rating to represent the impact level, while the scoring range is used in [14]. The different assessment grades can be used in the specific application. The numerical assessment is chosen to adapt to D-VIKOR approach.

Suppose there are M alternatives or options $o_l(l = 1, ..., M)$, one total environmental factor and L sub-factor $e_i(i = 1, ..., L)$ in a two-level EIA problem. Note that the proposed D-VIKOR approach in the paper can be applied in multi-level problems. Suppose under an environmental factor e_i, an option o_l is assessed as a grade B_n with the belief degree $v_{n,i}(o_l)$. This can be described by D numbers as $D(e_i(a_l)) = \{B_n, v_{n,i}(o_l)\}$, where B_n denotes the nth element (assessment grade). For example, there are 10 domain experts to assess the environmental impact of a plastic processing plant. If 4 experts give "Significant positive impact", 5 experts consider "Slightly positive impact" and 1 expert has "No impact", then the assessment result could be represented by D numbers as $D(e_i(a_l)) = \{(9, 40\%), (6, 50\%), (5, 10\%)\}$.

The distributed modelling framework is a prominent advantage of D numbers method, which is applicable to various types of information, including complete and incomplete information. In a distributed assessment problem, it needs to meet that $v_{n,i}(o_l) \geq 0$ and $\sum_{n=1}^{N} v_{n,i}(o_l) \leq 1$. When $\sum_{n=1}^{N} v_{n,i}(o_l) = 1$, the assessment information is seen as complete, otherwise it is not complete. Take the above assessment about plastic processing plant for example, because the 10 experts have given the assessment, such an assessment is called information complete, while if 6 experts are "Major positive impact" and 2 experts are "Significant positive impact", the assessment could be expressed as $D(e_i(a_l)) = \{(10, 60\%), (9, 20\%)\}$, the other 20% is the uncertainty with information incomplete because there are two experts cannot give any assessment. Consider a special case that all the 10 experts have no idea about the impact of the project, that is, the assessment is completely ignorant. The D-VIKOR approach can effectively deal with the above situations.

The assessment results of each option with each environmental factor can be expressed as the following D numbers decision matrix:

$$D_g = \{(B_n, v_{n,i}(o_l))\}_{L \times M} \tag{10}$$

A new D numbers combination rule will be defined to aggregate all the D numbers of the decision matrix in the next section. And the finial decision matrix for the overall environmental impact and weight for each environmental factor will be determined for ranking all the options using the VIKOR approach in the next section.

C. The final decision matrix and weights of environmental factors

In order to obtain the final decision matrix, a new D numbers combination rule will be defined to aggregate all the D numbers of the decision matrix constructed in the last section. A method to determine objective weights of all the environmental factors will be put forward

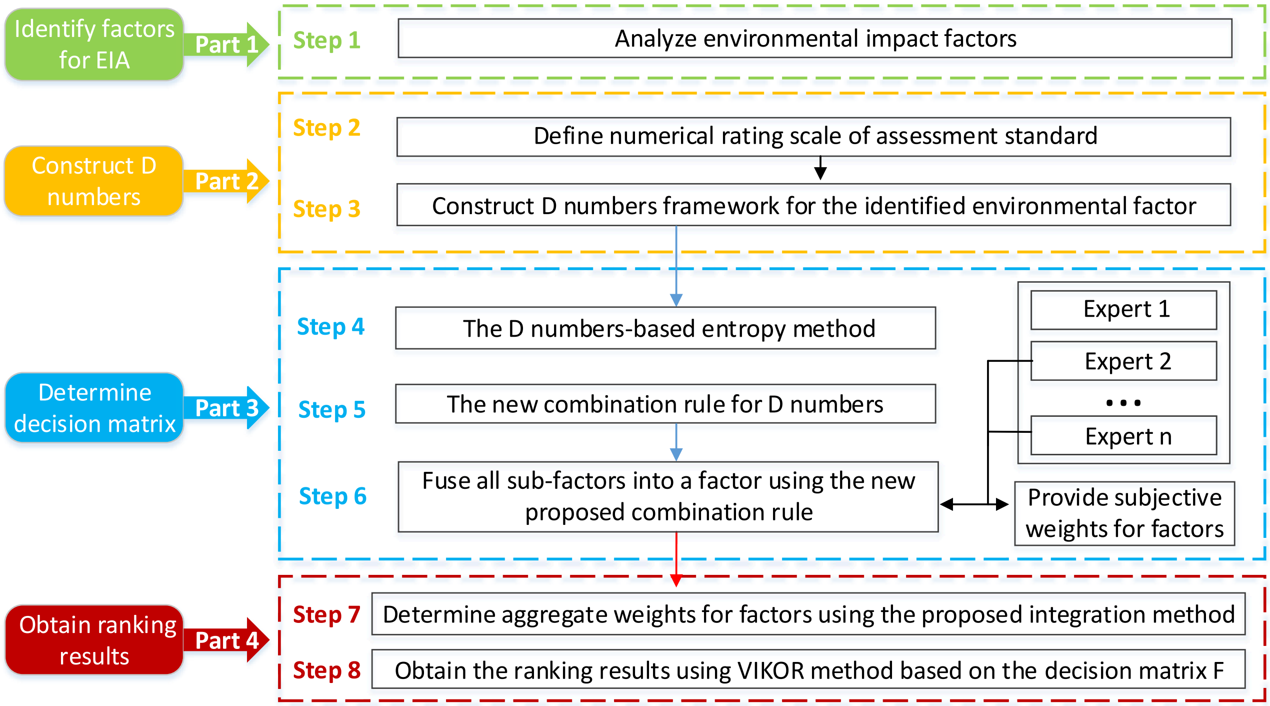

Fig. 2. The flow chart for the proposed method for EIA

TABLE I
AN ASSESSMENT STANDARD FOR EIA BASED ON PASTAKIA ET AL. AND WANG ET AL.

Assessment grade	Numerical rating	Description
+E	+5	Major positive impact
+D	+4	Significant positive impact
+C	+3	Moderately positive impact
+B	+2	Positive impact
+A	+1	Slightly positive impact
N	0	No impact
-A	-1	Slightly negative impact
-B	-2	Negative impact
-C	-3	Moderately negative impact
-D	-4	Significant negative impact
-E	-5	Major negative impact

based on the proposed combination rule and entropy method. The details of the above methods are as follows.

1) The new combination rule for D numbers: In Definition II.4, the combination rule for two D numbers is given, but it must be pointed out that the combination operation defined in Definition II.4 does not preserve the associative property. It is clear that $(D_1 \oplus D_2) \oplus D_3 \neq D_1 \oplus (D_2 \oplus D_3) \neq (D_1 \oplus D_3) \oplus D_2$. To determine the order of combination, μ_j is used as the order variable for each D_j in [74], but how to obtain μ_j has not been mentioned. In order that multiple D numbers can be combined correctly and efficiently, in this paper, a combination operation for multiple D numbers is developed as follows.

Definition III.1. *Let D_1, D_2, $\cdots$,D_C are c D numbers, which are shown as follows:*

$$D_1 = \{(b_1^1, v_1^1), \cdots, (b_i^1, v_i^1), \cdots, (b_n^1, v_n^1)\}$$

$$D_2 = \{(b_1^2, v_1^2), \cdots, (b_j^2, v_j^2), \cdots, (b_m^2, v_m^2)\}$$

$$\vdots$$

$$D_C = \{(b_1^C, v_1^C), \cdots, (b_k^C, v_k^C), \cdots, (b_p^C, v_p^C)\}$$

The first step is to obtain a D numbers by averaging all the subset B of the finite nonempty set Ω.

$$D_{AVG} = \{(b_1^{AVG}, v_1^{AVG}), \cdots, (b_t^{AVG}, v_t^{AVG}), \cdots, (b_q^{AVG}, v_q^{AVG})\} \tag{11}$$

where $b_t^{AVG} = \underbrace{b_i^1 = b_j^2 = \cdots = b_k^C}_{if\ they\ are\ the\ same}$, $v_t^{AVG} = \frac{v_i^1+v_j^2+\cdots+v_k^C}{C}$.

The second step is to combine the averages of c D numbers c − 1 times using Definition II.4.

$$D_1 \oplus D_2 \oplus \cdots \oplus D_C = \underbrace{D_{AVG} \oplus D_{AVG} \oplus, \cdots, \oplus D_{AVG}}_{c-1} \tag{12}$$

Example III.1. *Let D_1, D_2, D_3 be three D numbers that:*

$$D_1 = \{(0, 0.6), (1, 0.4)\},$$
$$D_2 = \{(0, 0.5), (1, 0.5)\},$$
$$D_3 = \{(0, 0.1), (1, 0.9)\}.$$

The average D numbers of D_1, D_2 and D_3 can be obtained by Eq. (11)

$$D_{AVG} = \{(0, \frac{0.6 + 0.5 + 0.1}{3}), (1, \frac{0.4 + 0.5 + 0.9}{3})\} = \{(0, 0.4), (1, 0.6)\}$$

Then, the combination of D_1, D_2 and D_3 can be calculated by Eq. (12) as follows.

$$\begin{aligned} & D_1 \oplus D_2 \oplus D_3 = D_{AVG} \oplus D_{AVG} \oplus D_{AVG} \\ & = \{(0, 0.4), (1, 0.6)\} \oplus \{(0, 0.4), (1, 0.6)\} \oplus \{(0, 0.4), (1, 0.6)\} \\ & = \{(0, 0.12), (0.25, 0.18), (0.50, 0.30), (0.75, 0.22), (1, 0.18)\} \end{aligned}$$

It is clear that the new combination rule has no limit to the number of D numbers and it satisfies the associative property.

2) The D numbers-based entropy method: The entropy method is defined based on Shannon entropy [75], which can be applied to determine the weight of multi-criteria decision-making problems. To improve this method, we proposed a new method to determine weights based on D numbers, which is defined as follows.

Definition III.2. *Suppose the decision matrix of multi-criteria is defined based on D numbers as follows*

$$\begin{array}{c c} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{m1} & d_{m2} & \cdots & d_{mn} \end{bmatrix} \end{array} \tag{13}$$

where d_{ij} is the D numbers representation of alternative A_i for the criterion C_j.

Definition III.3. *For each criterion C_j, we combine all the D numbers representations of alternatives using the new proposed combination rule defined in Section III-C1.*

$$D_j = d_{1j} \oplus d_{2j} \oplus \cdots \oplus d_{mj} \tag{14}$$

where D_j is the combination result of all the alternatives for criterion C_j, and $D_j = \{(b_1^j, v_1^j), \cdots, (b_i^j, v_i^j), \cdots, (b_n^j, v_n^j)\}$.

Based on Section II-A, we know b_i^j represents element and v_i^j is its reliability. So, for each criterion C_j, we could have a corresponding one-dimensional reliability matrix $[v_1^j, v_2^j, ..., v_m^j]$.

Definition III.4. *Then, the contribution degree of ith alternative for jth criterion can be represented by the following form*

$$P_{ij} = \frac{x_i^j}{\sum_{i=1}^m x_i^j} \tag{15}$$

Definition III.5. *The amount of contribution degree of all the alternatives for criterion C_j can be defined as E_j as follows*

$$E_j = -K \sum_{i=1}^m P_{ij} ln(P_{ij}) \tag{16}$$

where $K = 1/ln(m)$, note that it can satisfy $0 \le E_j \le 1$. It is obvious that E_j will reach 1 when the contribution degree of each alternative tends to be uniform for certain criterion, especially when they have the same value, the criterion will fare the worst, that is, the weight of the criterion is 0. So, the weight of the criterion is determined by the otherness of all the alternatives.

Definition III.6. *Therefore, the D_j can be defined as the consistency of each alternative for jth criterion.*

$$D_j = 1 - E_j \tag{17}$$

Definition III.7. *Based on the analysis above, the weight of each criterion W_j can be described as*

$$W_j = \frac{D_j}{\sum_{j=1}^n D_j} \tag{18}$$

note that the weight of jth criterion is 0 if $D_j = 0$.

Normalize the obtained weights to determine the final results. The new entropy method provides a methodology to calculate weights based on D numbers decision matrix, which effectively avoids the subjective judgement of decision-makers.

3) Obtaining the final decision matrix: In order to illuminate how to obtain the final decision matrix more clearly, we give a schematic diagram of the environmental factor with a three-layer structure based on the introduction in Section III-A. The diagram is shown as Figure 3.

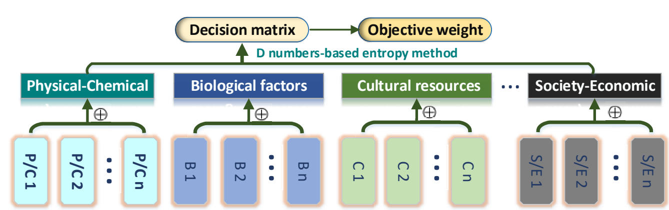

Fig. 3. The calculation of overall environmental impacts for each proposal

Note that, all the environmental factors in Figure 3 has been represented by the constructed D numbers framework in Section III-B. The new proposed combination rule will be used to combine all sub-factors into a factor for determining the decision matrix. Take the first factor "physical-chemical" for an example, the n sub-factors will be combined into a factor $physical-chemical$, and the other factors as well. When the fusion results are obtained, the aggregation values of factors under each option will be calculated using integration function of D numbers. So far, the decision matrix could be obtained composed by these aggregation values. Then objective weights of factors could be calculated using the D numbers-based entropy method introduced in Section III-C2. In order to clearly illuminate the process to obtain decision matrix $F = (f_{ij})_{m\times n}$, the flow chart is given and shown in Figure 3.

D. The weight aggregation method and D-VIKOR approach

1) A subjective and objective aggregation approach to determine option weights: In the above parts, the subjective and objective weights have been obtained, now the aggregation weights will be determined for factors using the proposed aggregation approach based on D-S theory, which is the prototype of D numbers.

Dempster-Shafer evidence theory [27], [28] is also called D-S theory, which supposes the definition of a set of elementary hypotheses called the frame of discernment, defined as: $\theta = \{H_1, H_2, ..., H_N\}$, where θ is a set of mutually exclusive and collectively exhaustive events. Let us denote 2^θ as the power sets of θ. A mass function m is defined as $m : 2^\theta \to [0, 1]$, which satisfies the conditions: $m(\phi) = 0$ and $\sum_{A\in 2^\theta} m(A) = 1$. Suppose m_1 and m_2 are two mass functions. The Dempster's rule of combination denoted by $m = m_1 \oplus m_2$ is defined as follows:

$$m(A) = \frac{\sum_{B\bigcap C=A} m_1(B)m_2(C)}{1-K} \tag{19}$$

with

$$K = \sum_{B\bigcap C=\phi} m_1(B)m_2(C) \tag{20}$$

For integrating the subjective and objective weights into the final factor weights, all the weights will be represented by the mass function of D-S evidence theory, and the final factor weights will be obtained using the combination rule.

According to the above description, suppose there are L sub-factors $e_i(i = 1, 2, ..., L)$ under the total environmental factor. The relative weights of the L environmental factors are represented by $W = (w_1, ..., w_L)$, which is constructed by subjective weight $W^s = (w^s_1, ..., w^s_L)$ and objective weight $W^o = (w^o_1, ..., w^o_L)$. They are normalised to satisfy the following conditions:

$$\sum_{i=1}^{L} w_i = \sum_{i=1}^{L} w^s_i = \sum_{i=1}^{L} w^o_i = 1, \quad w_i, w^s_i, w^o_i \geq 0, \quad i = 1, ..., L \tag{21}$$

Without loss of generality, L environmental factors construct the elements of the frame of discernment in D-S evidence theory. So, the subjective and objective weights can be considered as two mass functions $m_s = \{(e_1, w^s_1), (e_2, w^s_2), ..., (e_n, w^s_L)\}$ and $m_o = \{(e_1, w^o_1), (e_2, w^o_2), ..., (e_n, w^o_L)\}$. The total weight can be aggregated by the Dempster's combination rule as follows.

$$w_i = \frac{w^s_i w^o_i}{1 - \sum_{j=1}^{L}(w^s_j \sum_{k=1,k\neq j}^{L} w^o_k)}, \quad i = 1, ..., L \tag{22}$$

Obviously, w satisfies the constraint Eq. (21).

To aggregate subjective and objective weights using D-S theory can make the objective weight and subjective weight get a better trade-off from the perspective of information fusion. It reflects both subjective information and objective information, and makes the following sorting process more scientific.

2) Ranking all the options using VIKOR method: In the last few steps, the final decision matrix and aggregation weights have been obtained, then VIKOR method will be applied to rank all options based on the decision matrix and aggregation weights.

At first, determine the best f^*_i and worst f^-_i values in all the criteria.

$$\begin{cases} f^*_i = max_j(f_{ij}), \quad f^-_i = min_j(f_{ij}) & i\text{th function denotes a benefit} \\ f^*_i = min_j(f_{ij}), \quad f^-_i = max_j(f_{ij}) & i\text{th function denotes a cost} \end{cases}$$

Then, calculate the values S_j and R_j as follows:

$$S_j = \sum_{i=1}^{n} w_i \frac{(f^*_i - f_{ij})}{(f^*_i - f^-_i)} \tag{23}$$

$$R_j = max[w_i \frac{(f^*_i - f_{ij})}{(f^*_i - f^-_i)}] \tag{24}$$

where w_i represents the weight of ith criterion.

Next, compute Q_j values according to S_j and R_j as follows:

$$Q_j = v\frac{(S_j - S^*)}{(S^- - S*)} + (1-v)\frac{(R_j - R^*)}{(R^- - R*)} \tag{25}$$

where $S^* = min_j S_j$, $S^- = max_j S_j$,$R^* = min_j R_j$ and $R^- = max_j R_j$. v is the weight of the strategy of the majority of criteria, and $1 - v$ is the weight of the individual regret. In this paper, the value of v is set to 0.5.

Finally, rank the options by sorting the values of S, R and Q with decreasing order. The compromise solution is determined to be $O^{(1)}$, which obtains the minimum value by Q when the following two conditions are satisfied:

Condition 1. $Q(O^{(2)}) - Q(O^{(1)}) \geq DQ$, where $O^{(2)}$ is the alternative with second position in the ranking list by Q, and $DQ = 1/(n - 1)$.

Condition 2. If alternative $O^{(1)}$ is also the best one ranked by S and R, then it is the most stable optimal selection in the process of decision-making.

If one of the conditions is not satisfied, then the compromise solutions will be divided into two cases:

- Alternatives $O^{(1)}$ and $O^{(2)}$ can be considered as the compromise solution if only Condition 2 is not satisfied, or

- The compromise solution is alternatives $O^{(1)}$, $O^{(2)}$,...,$O^{(N)}$ if Condition 1 is not satisfied, and $O^{(N)}$ is determined by the relation $Q(O^{(N)}) - Q(O^{(1)}) < DQ$ for maximum N.

IV. Case study

The first environmental impact assessment study was conducted to conserve Rupa Tal Lake as the initial environmental evaluation (IEE) based on the Rapid Impact Assessment Matrix (RIAM) method [14]. In the case study section, in order to analyze the strengths and weaknesses of RIAM method and detail the process of the proposed D-VIKOR approach, the assessment information from the literature [14] will be reused and further modified. We also try to use D numbers method only to solve the EIA problem, but there are still some shortcomings, which will be made up by combining VIKOR method.

A. The description of problem

Rupa Tal is called 'The Lake of Beauty', and is also a big tourist area. There is a lot of rice growing on its uphill. But the lake is facing a serious problem that its surface is falling down. In the most recent period, the lake has shrunk to less than half its original size and continues to shrink. In addition, it is also home to a large number of organisms because of its rich nutrition. The presence of weed peat may accelerate the deposition of Lake.

The local authorities are eager to figure out if the lake is still likely to be preserved. It is obvious that if the lake continues to deposit, it will be very detrimental to the lake's preservation. So, some measures need to be taken to protect the lake area, tourism, and agriculture. There are four options need to be evaluated for conservation of the lake area to prevent its continue sedimentation: Option 1:

1) No change is needed. Until the lake disappeared because of sedimentation, a small gorge could be built to take the inflow/outflow streams.
2) By blocking the dam to raise the overall level. But the in-lake areas formed by sedimentation over the last few decades could be submerged due to the rise of the water level.
3) A smaller and higher dam would be built between two bluffs. It would be about one third of the way up from the southern shore. This dam is smaller than Option 2 but has similar upstream effects.
4) A sedimentation cascade will be built based on a large sedimentation reservoir in the upstream area or a series of smaller retaining walls. The water area may be remain intact using this way.

B. Rapid Impact Assessment Matrix (RIAM)

The initial environmental evaluation (IEE) is proposed by Pastakia and Bay based on RIAM through a few days of field trips to Rupa Tal. The assessment information in this example is IEE information rather than complete EIA information, but this has no effect on illustrating the effectiveness of the proposed D-VIKOR approach. For a complete EAI problem, it can be implemented in the same way using D-VIKOR approach.

In order to obtain the environmental factors, the lake environment was investigated, and the possible reasons for lake deposition are analyzed. Finally, the possible environmental factors were identified and a hierarchical structure model for EIA was established and shown in Figure 4. The detailed meanings of these factors are described in Table II.

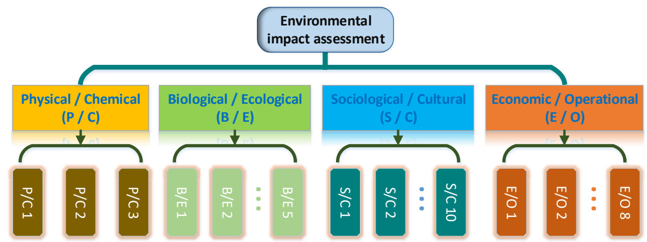

Fig. 4. A hierarchical structure model for EIA

The RIAM method is used to evaluate the environmental factors for finishing IEE, and the results of all the factors under each option are shown in Table III. And the overall assessment results for all the options are shown in Figure 5. From the RIAM results, we can draw the conclusion that option 1 will lead to a complete collapse of the lake, because it has a great negative impact on the lake. In addition, option 4 and 2 can be considered as the reference schemes for the sustainable development of this lake. If the government or local management is determined to invest heavily, then the implementation of the plan will not be affected by funding, thus, option 2 would be recommended, while if it is for economic frugality, then option 4 will be the best choice.

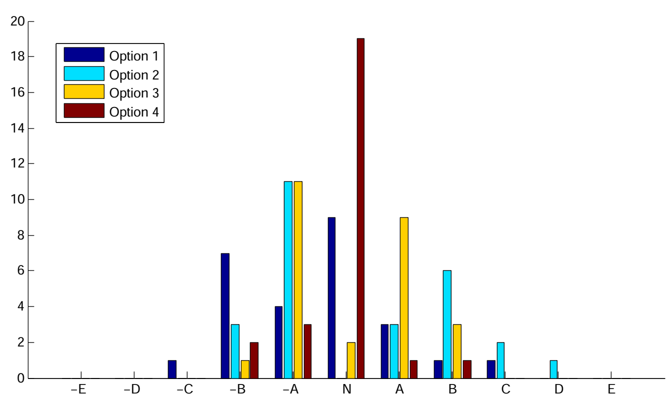

Fig. 5. The overall assessment results for the four options by RIAM.

C. The advantages and disadvantages of the RIAM method

There are many superiorities of RIAM method to solve EIA problems. This method can draw the conclusion

TABLE II
THE MEANINGS OF FACTORS AND SUB-FACTORS IN EIA PROBLEM

Environmental factors	Sub-factors
Physical / Chemical (P/C)	
P/C 1	P/C 1. The impacts of lake water volume
P/C 2	P/C 2. The impacts of the lake sedimentation
P/C 3	P/C 3. The impacts of crop and grazing areas
Biological / Ecological (B/E)	
B/E 1	B/E 1: The impacts of lake fisheries
B/E 2	B/E 2. The impacts of biodiversity
B/E 3	B/E 3. The impacts of primary production
B/E 4	B/E 4. The impacts of aquatic macrophytes
B/E 5	B/E 5. The impacts of disease vector populations
Sociological / Cultural (S/C)	
S/C 1	S/C 1. The loss of housing
S/C 2	S/C 2. The loss of shops/public buildings
S/C 3	S/C 3. The impacts of accessing routes
S/C 4	S/C 4. The impacts induced by changes of tourism patterns
S/C 5	S/C 5. The impacts of water supplies
S/C 6	S/C 6. The impacts of diet/nutrition
S/C 7	S/C 7. The impacts of aesthetic landscapes
S/C 8	S/C 8. The impacts of water/vector borne disease
S/C 9	S/C 9. The impacts of upstream quality of life
S/C 10	S/C 10. The impacts of downstream quality of life
Economical / Operational (E/O)	
E/O 1	E/O 1. The impacts of crop-generated incomes
E/O 2	E/O 2. The impacts of fishery generated incomes
E/O 3	E/O 3. The convenience of operation and Maintenance of option
E/O 4	E/O 4. The cost of operation and Maintenance of option
E/O 5	E/O 5. The cost of resettlement/compensation for land loss
E/O 6	E/O 6. The cost of rehabilitation/restoration of shops/public buildings
E/O 7	E/O 7. The cost of restoration of accessing routes
E/O 8	E/O 8. The impacts of tourism-generated incomes

TABLE III
THE ASSESSMENT RESULTS ON THE IDENTIFIED ENVIRONMENTAL FACTORS BY RIAM

Environmental factors	Option 1	Option 2	Option 3	Option 4
Physical / Chemical				
P/C 1	- C	B	B	N
P/C 2	- B	B	- A	B
P/C 3	C	-B	N	N
Biological / Ecological				
B/E 1	- B	D	A	N
B/E 2	- B	-A	- B	N
B/E 3	- B	- B	- A	N
B/E 4	- B	- B	- A	N
B/E 5	A	A	A	- A
Sociological / Cultural				
S/C 1	N	- A	- A	N
S/C 2	N	- A	- A	N
S/C 3	A	- A	- A	N
S/C 4	- A	B	A	N
S/C 5	- A	C	A	A
S/C 6	N	A	A	N
S/C 7	- B	B	A	N
S/C 8	A	- A	A	- A
S/C 9	N	A	A	- A
S/C 10	- A	B	B	N
Economical / Operational				
E/O 1	B	- A	B	N
E/O 2	- B	B	N	N
E/O 3	N	- A	- A	- B
E/O 4	N	- A	- A	- B
E/O 5	N	- A	- A	N
E/O 6	N	- A	- A	N
E/O 7	N	- A	- A	N
E/O 8	- A	C	A	N

without a lot of complex calculations, so it is simple and rapid. But compared to the shortcomings of RIAM, its advantages are not so valuable. Some shortcomings of RIAM method are listed below. First, the weights of environmental factors are ignored in RIAM method, and the significance of all the factors is considered to be the same. For general EIA problem, this is not tenable, because the impact of different factors on the environment is different. In general, the more important factors should be assigned more weights. Second, there is a mandatory requirement that the full belief degree must be assigned to assessment information when using the RIAM method. However, there may be cases where information is incomplete or distribution assessments in practical EIA problems, but the RIAM method cannot handle this situation. In this type of multi-criteria decision-making problem, there is usually uncertain information, which requires a better model to deal with it. Third, assessment information in RIAM method is aggregated by simple additive method, which is not appropriate in most cases. In addition, this method does not provide a scientific, complete sorting method for all the options. The results obtained using only linear additive method are not easy to draw the clear conclusion. Finally, if the assessment information obtained in EIA problem is fuzzy or vague, the RIAM method will not be applicable to handle it. RIAM, as a method to deal with EIA problem, is also a good way due to its simplicity and rapidity. However, because of its disadvantages, new approaches are necessary to deal with EIA problems for uncertain environment.

D. D numbers approach

In order to overcome the shortcomings mentioned above, at first, we use the D numbers approach, which can combine assessment information based on the rule proposed in Section III-C1. D numbers framework will be constructed from the original assessment information in Table III based on Section III-B. And then a full IEE analysis is given using the D numbers approach based on the D numbers representation of the assessment information.

The assessment information given in Table III will be expressed by the D numbers framework in Table IV for using D numbers approach. Hierarchical relationship between all the environmental factors for this EIA problem is shown in Figure 4. The sub-factors P/C $1-3$, B/E $1-5$, S/C $1-10$, and E/O $1-8$ will be aggregated to upper factors P/C, B/E, S/C and E/O based on the new combination rule of D numbers. Thus, there is a D numbers representation for all the environmental factors of each option. Due to the characteristics of D numbers combination rule, the numerical representation of assessment grade will be split with the combination process. So in order to aggregate belief degree of each assessment grade, the method is defined as follows.

$$D(\widetilde{b},\widetilde{v}) = \begin{cases} (\lfloor b \rfloor, \sum\limits_{b\subseteq(\lfloor b \rfloor, \lceil b \rceil]} v), b < 0 \\ (0, v_{b=0}), b = 0 \\ (\lceil b \rceil, \sum\limits_{b\subseteq(\lfloor b \rfloor, \lceil b \rceil]} v), b > 0 \end{cases}$$

where b represents assessment grade, and v is its belief degree. The results of each assessment grade under each option are shown in Table V and Figure 6.

It is obvious from Table V and Figure 6 that option 2 has the least negative impacts on the total environment. Its positive impacts on the environment are the most. Option 1 has the largest negative impacts on the total environment among the four options. Option 3 has more positive impact and less negative impact than option 4.

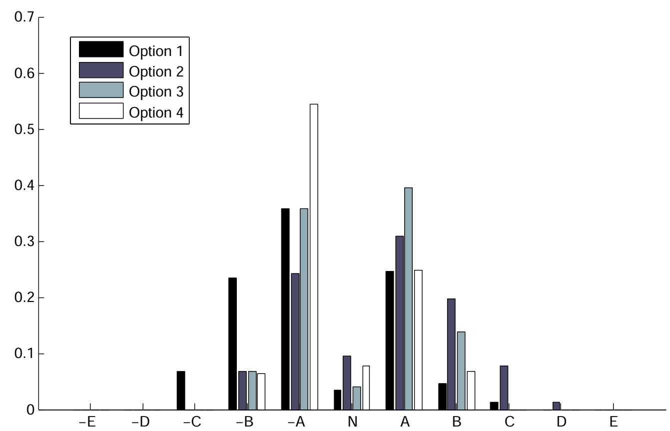

Fig. 6. The overall assessment results for the four options using the D numbers approach.

The information used in the above D numbers assessment method is from RIAM. In practical EIA problem, there will be multiple experts involved with different views or opinions. For the same factor, they are likely to give different assessment information. Information from RIAM may fail to express this fact. The original assessment information will be modified in order to demonstrate the proposed D-VIKOR approach and adapt to the real environment.

E. The modified belief matrix and D-VIKOR method

In order to construct the assessment information closer to the real problem, the original information is modified to the new belief matrix and shown in Table VI, which includes incomplete and ignored information. The subjective weights are given to environmental factors by decision makers. All the information will be aggregated based on D numbers approach firstly, and the results are shown in Table VII and Figure 7, where H represents the ignorant part from lack of information or incomplete information.

In Table VII and Figure 7, intuitively, option 3 has a high negative impact, but its impact is mainly at

TABLE IV
ASSESSMENT INFORMATION OF D NUMBERS REPRESENTATION BASED ON TABLE III

Environmental factors	Option 1	Option 2	Option 3	Option 4
Physical / Chemical				
P/C 1	{(-3, 1.0)}	{(2, 1.0)}	{(2, 1.0)}	{(0, 1.0)}
P/C 2	{(-2, 1.0)}	{(2, 1.0)}	{(-1, 1.0)}	{(2, 1.0)}
P/C 3	{(3, 1.0)}	{(-2, 1.0)}	{(0, 1.0)}	{(0, 1.0)}
Biological / Ecological				
B/E 1	{(-2, 1.0)}	{(4, 1.0)}	{(1, 1.0)}	{(0, 1.0)}
B/E 2	{(-2, 1.0)}	{(-1, 1.0)}	{(-2, 1.0)}	{(0, 1.0)}
B/E 3	{(-2, 1.0)}	{(-2, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
B/E 4	{(-2, 1.0)}	{(-2, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
B/E 5	{(1, 1.0)}	{(1, 1.0)}	{(1, 1.0)}	{(-1, 1.0)}
Sociological / Cultural				
S/C 1	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
S/C 2	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
S/C 3	{(1, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
S/C 4	{(-1, 1.0)}	{(2, 1.0)}	{(1, 1.0)}	{(0, 1.0)}
S/C 5	{(-1, 1.0)}	{(3, 1.0)}	{(1, 1.0)}	{(1, 1.0)}
S/C 6	{(0, 1.0)}	{(1, 1.0)}	{(1, 1.0)}	{(0, 1.0)}
S/C 7	{(-2, 1.0)}	{(2, 1.0)}	{(1, 1.0)}	{(0, 1.0)}
S/C 8	{(1, 1.0)}	{(-1, 1.0)}	{(1, 1.0)}	{(-1, 1.0)}
S/C 9	{(0, 1.0)}	{(1, 1.0)}	{(1, 1.0)}	{(-1, 1.0)}
S/C 10	{(-1, 1.0)}	{(2, 1.0)}	{(2, 1.0)}	{(0, 1.0)}
Economical / Operational				
E/O 1	{(2, 1.0)}	{(-1, 1.0)}	{(2, 1.0)}	{(0, 1.0)}
E/O 2	{(-2, 1.0)}	{(2, 1.0)}	{(0, 1.0)}	{(0, 1.0)}
E/O 3	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(-2, 1.0)}
E/O 4	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(-2, 1.0)}
E/O 5	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
E/O 6	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
E/O 7	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
E/O 8	{(-1, 1.0)}	{(3, 1.0)}	{(1, 1.0)}	{(0, 1.0)}

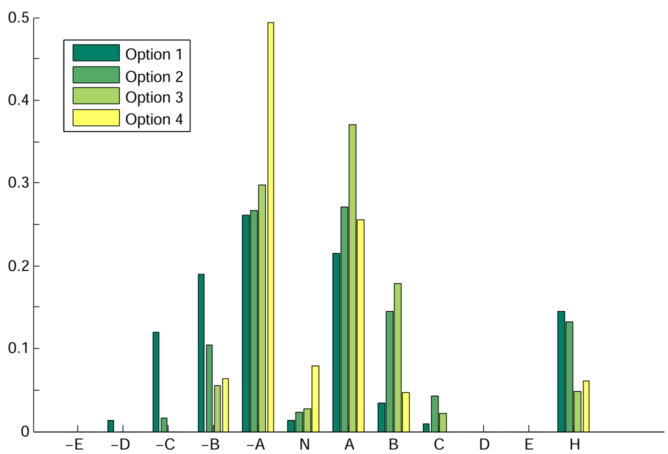

Fig. 7. The overall reassessment results for the four options using the D numbers approach

the low assessment grades. In fact, the largest negative impact should be option 1, and its positive impact on the environment is small, while the uncertainty is large, so it is obviously the worst selection. Option 3 has the most positive impact and the least negative impact among all the four options. Option 2 has more positive impact than option 4, but the comparison of the negative impact is not obvious in the figure.

From the above analysis we can see that only D numbers method is not effective enough. In order to assess these four options further, the D-VIKOR approach is used for more precise decision making. Above, the belief decision matrix has been obtained and expressed with D numbers representation. The next step is to determine the final decision matrix $F = (f_{ij})_{m\times n}$. At first, fusing all sub-factors into a factor using the new proposed combination rule defined in Section III-C1. Next, calculating the aggregate values of factors under each option using integration function of D numbers based on Eq. (4). So the decision matrix is composed by the aggregate values, and the results are shown in Table VIII. Then, determining the objective weights for factors using the D numbers-based entropy method, and the relative results are shown in Table IX. The aggregation weights will be determined based on the D-S theory introduced in Section III-D1. The mass functions of subjective and objective weights have been represented as:

$$m(w^o) = \{('P/C', 0.2731), ('B/E', 0.2262), ('S/C', 0.2499)$$
$$, ('E/O', 0.2508)\}$$
$$m(w^s) = \{('P/C', 0.35), ('B/E', 0.25), ('S/C', 0.25)$$
$$, ('E/O', 0.15)\}$$

The aggregation result is $m(w) = \{('P/C', 0.3790), ('B/E', 0.2242), ('S/C', 0.2477)$ $, ('E/O', 0.1491)\}$, and the relative results are shown in Table IX.

After obtaining the final decision matrix $F = (f_{ij})_{m\times n}$ and the aggregation weights, we can apply VIKOR

TABLE V
THE BELIEF DEGREE OF ALL THE ASSESSMENT GRADES UNDER EACH OPTION USING D NUMBERS METHOD

Option	Factors	Belief degree of each assessment grade										
		-E	-D	-C	-B	-A	N	A	B	C	D	E
Option 1	P/C	0	0	0.2716	0.1728	0.1234	0.0988	0.1606	0.1234	0.0494	0	0
	B/E	0	0	0	0.5129	0.3285	0	0.1586	0	0	0	0
	S/C	0	0	0	0.1506	0.5426	0.0096	0.2972	0	0	0	0
	E/O	0	0	0	0.1014	0.4349	0.0311	0.3695	0.0631	0	0	0
Option 2	P/C	0	0	0	0.1000	0.1667	0.3000	0.2333	0.2000	0	0	0
	B/E	0	0	0	0.1696	0.2408	0.0561	0.2410	0.1563	0.0866	0.0496	0
	S/C	0	0	0	0	0.2020	0.0006	0.3623	0.3071	0.1280	0	0
	E/O	0	0	0	0	0.3567	0.0201	0.4022	0.1205	0.0960	0	0
Option 3	P/C	0	0	0	0	0.3334	0.1111	0.3827	0.1728	0	0	0
	B/E	0	0	0	0.2733	0.4466	0.0328	0.2473	0	0	0	0
	S/C	0	0	0	0	0.2044	0.0028	0.5368	0.2560	0	0	0
	E/O	0	0	0	0	0.4481	0.0168	0.4135	0.1216	0	0	0
Option 4	P/C	0	0	0	0	0	0.2000	0.5333	0.2667	0	0	0
	B/E	0	0	0	0	0.9138	0.0862	0	0	0	0	0
	S/C	0	0	0	0	0.5377	0.0015	0.4608	0	0	0	0
	E/O	0	0	0	0.2588	0.7214	0.0198	0	0	0	0	0

method to sort all the options. The ranking results are shown in Table X. Therefore, a conclusion could be drawn that option 3 is the best one and the first option is the worst.

TABLE VIII
AGGREGATION VALUES OF FACTORS UNDER EACH OPTION (DECISION MATRIX)

Environmental factors	Option 1	Option 2	Option 3	Option 4
Physical/Chemical	-0.7227	-0.0495	0.8426	0.8240
Biological/Ecological	-1.3753	-0.5661	-0.4018	-0.2399
Sociological/Cultural	-0.1941	0.8835	0.5607	-0.0596
Economical/Operational	-0.0918	0.3812	0.1121	-0.7320

In summary, no matter which method is used to solve this EIA problem, option 1 is considered to be the worst one. The key issue lies in the sorting of other options. The RIAM method recommends option 2 and 4 are as the alternative, while the option 2 and 4 cannot be compared easily using D numbers only, but option 3 is identified as the optimal. Option 3 is also considered the best way with the proposed D-VIKOR approach, and option 2 is determined to be better than option 4. Comparing the results between D-VIKOR method and that of previous study in [18], both of them consider option 1 is the worst choice. The difference is the final recommended option. The best choices are option 2 and option 4 in [18]. By the proposed D-VIKOR method, the best choices is option 3. However, it is still an open issue due to the complexity in real world. As for which option to adopt in the end need to be further considered from the real financial situation. This goes beyond the category of this study and will not be discussed in the paper. In addition, subjective weight and assessment information from decision makers have certain influence on the final ranking results.

From the comparison of the RIAM and D-VIKOR approach, it is obvious that the D-VIKOR approach provides a general and pragmatic way for EIA problem. And it can handle various kinds of uncertainties factors involved in EIA problem.

V. CONCLUSIONS

In this paper, a new methodology called D-VIKOR is proposed to handle EIA problem using D numbers theory to extend the traditional VIKOR method. In our proposed approach, the assessment information of environmental factors is represented by D numbers that can handle uncertain information effectively. A new combination rule for multiple D numbers is defined with associative property. What's more, with the advantage that providing a maximum group utility of the majority and a minimum of the individual regret of the opponent, VIKOR method can give the compromise solution in many decision problems. The combination between D numbers theory and VIKOR method ont only can deal with uncertain information effectively, but also can obtain the compromise solution reasonably in EIA problem. In addition, subjective and objective weights are considered in VIKOR process in order to avoid inaccurate results from human being's subjective judgment. And a D numbers-based entropy method is improved for determining the objective weights of environmental factors. An illustrative example for EIA is conducted to demonstrate the effectiveness of the proposed D-VIKOR approach. The RIAM method, as a contrast, is introduced and its assessment information is reused and modified to adapt to the D numbers representation. In the future research, the theoretical framework of D-VIKOR approach needs to be increasingly perfected. And the proposed method should be applied to more fields such as disaster management, decision analysis, and risk assessment to further verity its feasibility.

ACKNOWLEDGMENT

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TABLE VI
Assessment matrix and subjective weights of environmental impact factors for options

Environmental factors	Option 1	Option 2	Option 3	Option 4
Physical / Chemical (0.35)				
P/C 1	{(-4, 0.3), (-3, 0.7)}	{(1, 0.1),(2 0.9)}	{(2, 0.8), (3, 0.2)}	{(0, 1.0)}
P/C 2	{(-2, 0.8), (-1, 0.2)}	{(1, 0.1), (2, 0.85)}	{(-1, 0.85), (0, 0.15)}	{(1, 0.3), (2, 0.7)}
P/C 3	{(2, 0.45), (3, 0.35)}	{(-3, 0.2), (-2, 0.8)}	{(0, 0.5), (1, 0.5)}	{(0, 1.0)} }
Biological / Ecological (0.25)				
B/E 1	{(-3, 0.5), (-2, 0.4)}		{(0, 0.2), (1, 0.8)}	{(0, 1.0)}
B/E 2	{(-2, 0.5), (-1, 0.5)}	{(-1, 1.0)}	{(-2, 0.8), (-1, 0.1)}	{(0, 1.0)}
B/E 3	{(-2, 1.0)}	{(-2, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
B/E 4	{(-2, 1.0)}	{(-2, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
B/E 5		{(1, 1.0)}	{(0, 1.0)}	{(-1, 0.4), (0, 0.5)}
Sociological / Cultural (0.25)				
S/C 1	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
S/C 2	{(0, 1.0)}	{(-1, 0.65), (0, 0.3)}	{(-1, 1.0)}	{(0, 1.0)}
S/C 3	{(0, 0.5), (1, 0.5)}	{(-1, 1.0)}		{(0, 1.0)}
S/C 4	{(-2, 0.2), (-1, 0.8)}	{(2, 0.8), (3, 0.2)}	{(1, 1.0)}	{(0, 1.0)}
S/C 5	{(-2, 0.3), (-1, 0.7)}	{(3, 1.0)}	{(1, 1.0)}	{(1, 0.8)}
S/C 6	{(0, 1.0)}	{(1, 0.8), (2, 0.2)}	{(1, 0.5), (2, 0.5)}	{(0, 1.0)}
S/C 7	{(-2, 1.0)}	{(2, 1.0)}	{(1, 0.4), (2, 0.6)}	{(0, 1.0)}
S/C 8	{(1, 0.5), (2, 0.3)}	{(-1, 1.0)}	{(1, 1.0)}	{(-1, 1.0)}
S/C 9	{(0, 1.0)}	{(1, 1.0)}	{(0, 0.2), (1, 0.7)}	{(-1, 1.0)}
S/C 10	{(-1, 1.0)}	{(2, 1.0)}	{(2, 1.0)}	{(0, 1.0)}
Economical / Operational (0.15)				
E/O 1	{(2, 0.8)}	{(-1, 1.0)}	{(2, 0.9)}	{(0, 1.0)}
E/O 2	{(-2, 1.0)}	{(2, 1.0)}	{(0, 1.0)}	{(0, 1.0)}
E/O 3	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(-2, 1.0)}
E/O 4	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(-2, 1.0)}
E/O 5	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
E/O 6	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
E/O 7	{(0, 1.0)}	{(-1, 1.0)}	{(-1, 1.0)}	{(0, 1.0)}
E/O 8	{(-1, 1.0)}	{(3, 0.7)}	{(1, 1.0)}	{(0, 1.0)}

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TABLE VII
THE BELIEF DEGREE OF ALL THE ASSESSMENT GRADES UNDER EACH OPTION USING THE MODIFIED BELIEF MATRIX

Option	Factors	Belief degree assessed to each assessment grade											
		-E	-D	-C	-B	-A	N	A	B	C	D	E	H
Option 1	P/C	0	0.0532	0.1549	0.1674	0.1780	0.0484	0.1130	0.0617	0.0355	0	0	0.1879
	B/E	0	0	0.3242	0.3633	0	0	0	0	0	0	0	0.3125
	S/C	0	0	0	0.1280	0.4352	0.0010	0.3584	0.0256	0	0	0	0.0518
	E/O	0	0	0	0.0994	0.4313	0.0038	0.3875	0.0508	0	0	0	0.0272
Option 2	P/C	0	0	0.0631	0.1114	0.2103	0.0742	0.1816	0.1594	0	0	0	0.2000
	B/E	0	0	0	0.3038	0.2958	0.0157	0.1157	0	0	0	0	0.2690
	S/C	0	0	0	0	0.2048	0.0006	0.3844	0.3072	0.1000	0	0	0.0030
	E/O	0	0	0	0	0.3567	0.0029	0.4021	0.1127	0.0704	0	0	0.0552
Option 3	P/C	0	0	0	0	0.1572	0.0755	0.3895	0.2919	0.0859	0	0	0
	B/E	0	0	0	0.2159	0.4300	0.0302	0.2219	0	0	0	0	0.0984
	S/C	0	0	0	0	0.1536	0.0009	0.4611	0.3072	0	0	0	0.0772
	E/O	0	0	0	0	0.4481	0.0045	0.4102	0.1169	0	0	0	0.0203
Option 4	P/C	0	0	0	0	0	0.2222	0.5889	0.1889	0	0	0	0
	B/E	0	0	0	0	0.7043	0.0784	0	0	0	0	0	0.2173
	S/C	0	0	0	0	0.5376	0.0019	0.4352	0	0	0	0	0.0253
	E/O	0	0	0	0.2545	0.7340	0.0115	0	0	0	0	0	0

TABLE IX
THE SUBJECTIVE WEIGHTS, OBJECTIVE WEIGHTS AND AGGREGATION WEIGHTS FOR FACTORS

Environmental factors	entropy	divergence	objective weights	subjective weights	aggregation weights
Physical/Chemical	0.2204	0.7796	0.2731	0.3500	0.3790
Biological/Ecological	0.3543	0.6457	0.2262	0.2500	0.2242
Sociological/Cultural	0.2868	0.7132	0.2499	0.2500	0.2477
Economical/Operational	0.2843	0.7157	0.2508	0.1500	0.1491

TABLE X
THE RANKING RESULTS USING VIKOR METHOD BY S, R AND Q VALUES

S, R, Q	Option 1	Option 2	Option 3	Option 4	Ranking
S	0.9143	0.2804	0.1422	0.3704	
R	0.3790	0.2160	0.0742	0.2168	$O3 \succ O2 \succ O4 \succ O1$
Q	1.0000	0.3221	0	0.3817	

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