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Article

A MULTIMOORA-Based Risk Evaluation Approach for CCUS Projects by Utilizing D Numbers Theory

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Abstract: As the global climate warms, carbon emissions must be reduced in order to alleviate the human climate crisis. Carbon capture, utilization and storage (CCUS) is an emerging technology that can reduce carbon emissions. However, most of the CCUS projects have ended in failure. The reason can be attributed to insufficient risk assessment. To this end, the purpose of this study is to construct a comprehensive risk assessment model for CCUS projects. The main body of this research is divided into two parts. First, in order to evaluate the CCUS project, a risk indicator system is constructed. In what follows, a decision-making framework for risk assessment under the D numbers environment is proposed, including two stages of decision-making preparation and decision-making process. The main task of the preparation stage is to gather evaluation experts and collect decision-making information. In the decision-making stage, this paper takes the D numbers theory as the core (acting on the effective expression and fusion of subjective evaluation information), respectively, proposes the method of determining the weight of risk evaluators, the fusion method of decision-making information from different experts, and the comprehensive decision model based on the MULTIMOORA method. In order to verify the effectiveness of the constructed model, the case of CCUS project site selection in *Shengli* power plant is analyzed, and the results showed that the third site is the best option. This study finds the importance of a comprehensive and timely risk assessment for the successful implementation of CCUS projects, and suggests that stakeholders carry out a risk assessment of CCUS projects prior to implementation based on the method presented in this paper, so as to improve the success rate.

Keywords: multi-criteria decision-making (MCDM); D numbers; MULTIMOORA; risk evaluation; CCUS

MSC: 68T37; 90B50

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1. Introduction

As the global climate warms, the concentration of carbon must be controlled, and there are two effective ways to do this. The first is to reduce carbon emissions, and the second is to deploy negative emissions technologies (NETs) [1] to remove carbon from the atmosphere and sequester it reliably. Carbon capture and storage (CCS) is the process of separating CO_2 from industrial or related energy sources and transporting it to a storage site, where it is isolated from the atmosphere for a long time. CCS technologies mainly fall into four categories [2–7]: pre-combustion capture, oxygen-containing fuel combustion [8], chemical chain combustion [9], and post-combustion capture. CCS technology is of great significance to achieve global climate goals [10].

In recent years, the global climate change situation has become increasingly serious [11]. According to the International Energy Agency (IEA), the higher the temperature rise, the more CO_2 reductions CCS will have to contribute [12]. The Intergovernmental Panel on Climate Change (IPCC) stressed the importance of achieving net zero CO_2 emissions by the middle of this century, and proposed that the large-scale application of CCS technology is the key to achieving zero carbon emissions, so CCS technology is of great significance to achieve global climate goals [10].

CCS is an important approach to deep CO_2 emission reduction, but the potential of capture and storage, implementation difficulty, and socio-economic benefits of different methods vary greatly [13]. With the development of CCS technology and the deepening of understanding, China first proposed Carbon Capture, Utilization and Storage (CCUS) technology at the Xiangshan Conference in Beijing in 2006, and introduced the technology of CO_2 resource utilization [14]. CCUS technology, after purifying captured CO_2, puts it into a new production process for recycling and reuse, and recycles CO_2. It can not only achieve carbon emission reduction, but also produce economic benefits, so it is more practical and operational. After years of development, CCUS technology has been accepted and used worldwide [15].

CCUS is an important carbon emission reduction technology, and more and more CCUS projects will be invested in because of its effectiveness in addressing climate change [16]. With the operation of CCUS project, more and more environmental risks as well as economic and social problems are being discovered [17], which can be attributed to the risk management lagging behind the development of CCUS technology [18,19]. The main obstacles facing CCUS projects in the commercialization stage are weak awareness of environmental risks, lack of legal constraints, and small financial support [20]. In addition to defects in basic research, supporting technology, and management policies, other factors that hinder the large-scale deployment of CCUS projects include immaturity of technology, law, economy, environment, and society [21]. The failure experience of many CCUS projects shows that environmental impact and risk are one of the key factors to determine whether CCUS projects can be successfully implemented, which is also the focus of public concern [22]. There is no practical process for assessing the risk of CCUS projects, from either the perspective of government or industry, particularly in critical areas such as the selection of carbon storage sites.

Risk assessment is a complete process composed of risk identification, risk analysis, and risk assessment. How the process is carried out depends not only on the background of the risk management process, but also on the methods and techniques used to execute the risk assessment work [23]. For CCUS projects, various risk assessment tools were proposed. A series of risk management processes were proposed by ISO 31000: 2018 [24], including determining assessment content → risk identification → analysis → evaluation → treatment → risk monitoring → review → communication → negotiation. OXAND conducts risk assessments for carbon storage projects based on the ISO 31000 risk management framework [25]. IFPEN, SINTEF, and TNO jointly developed the integrated carbon risk assessment tool [26]. IACRAS defined risk assessment as four modules: scenario definition, scenario analysis, impact assessment, and uncertainty assessment [27]. The CCS environmental risk assessment proposed by the UK Environment Agency uses a typical source → path → receptor model, and evaluates the possibility and consequences of exposure at four levels: high, medium, low, and very low [28]. Recently, Liu et al. [29] evaluated the risk of CCUS projects based on decision modeling, constructed risk indicators from the perspective of sustainable development, and proposed the risk assessment methods under intuitionistic fuzzy and linguistic environments.

Through the analysis of the existing literature on CCUS project risk assessment, it is found that there is not a complete evaluation index system, and especially few studies on measuring the implementation risk of CCUS project from the dimension of sustainable development. In addition, evaluation information generally comes from human subjective judgment, while existing evaluation methods do not provide flexible and effective information expression. For this problem, the theory of D numbers is a good choice [30,31], which has the ability to express uncertain information and provides broader conditions than the Dempster–Shafer theory. However, the fusion rules in the traditional D numbers theory have been questioned because they can not meet the characteristics of associative law, so this study proposes a new method to solve this problem. Furthermore, the current algorithm is more single-dimension assessment, which weakens the reliability of the assessment. Therefore, this paper will provide a comprehensive risk assessment method based on the MULTIMOORA method to provide integrated judgment for CCUS project risks.

This paper contributes to the risk evaluation for CCUS projects through three aspects of innovation. First, it introduces the D numbers to express the subjective judgment of the evaluators, and further proposes a new generation of fusion rule for D numbers to satisfy the associative law. Secondly, a comprehensive risk indicator system for evaluating CCUS projects is developed to guide the conduct of risk assessment. Thirdly, a MULTIMOORA-based decision-making model is proposed to characterize the degree of risk of the CCUS projects. The constructed model addresses the limitations of existing risk assessment approaches by optimizing evaluation indicators and improving evaluation algorithms.

The rest of this paper is organized as follows. Some preliminaries, such as the D numbers theory and MULTIMOORA method, are introduced in Section 2. Section 3 gives a complete description of the research methods, including the risk assessment index system and the comprehensive decision-making model. Section 4 shows the usage and effectiveness of the proposed decision-making method through an example of CCUS project risk assessment. The conclusion of this paper is given in Section 5, followed by some future research plans.

2. Preliminaries

In this section, the basic theory of D numbers and the MULTIMOORA method are introduced, respectively.

2.1. D Numbers

The D numbers theory is the expansion of the Dempster–Shafer theory [32,33]. It has more advantages to represent and handle uncertain information because the elements do not need to be mutually exclusive in D numbers and the completeness constraint is released in D numbers. As a generalization of evidence theory, the D numbers theory has a wide application, especially in linguistic assessment [34–37]. It is also been applied in other fields, such as healthcare waste management [38,39], risk assessment [40], and fuzzy decision-making [41]. The basic knowledge of D numbers will be introduced as follows.

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

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

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 below to show the D numbers.

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

$$D(\{b_1\}) = 0.2$$
$$D(\{b_3\}) = 0.6$$
$$D(\{b_1, b_2, b_3\}) = 0.1$$

where $b_1 = [0, 45]$, $b_2 = [38, 73]$, and $b_3 = [61, 100]$. Note that the set of $\{b_1, b_2, b_3\}$ is not 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 $\sum\limits_{i=1}^{n} v_i \leq 1$.

Some properties of D numbers are introduced as follows.

Definition 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 2. *If there are two D numbers:*

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

Then:

$$D_1 \Leftrightarrow D_2$$

Definition 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 $\sum\limits_{i=1}^{n} v_i \leq 1$.

Example 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 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:

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

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

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

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 the above equations is not exponent.*

Example 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:

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

2.2. MULTIMOORA Method

In 2006, Brauersand and Zavadskas [42] first proposed the MOORA (Multi-Objective Optimization on the basis of a Ratio Analysis) method, which includes two submethods, the ratio system method (RSM) and the reference point method (RPM). Subsequently, they extended MOORA and proposed the MULTIMOORA (Multi-Objective Optimizaion on the basis of a Ratio Analysis plus the full MULTIplicative form) method [43], which added a new submethod called the full-multiplicative form (FMF) on the basis of MOORA. The MULTIMOORA method is widely used in decision making [44–46] and evaluation [47–49]. Assuming X is the initial decision matrix, expressed as $X = (x_{ij})_{m \times n}$, where x_{ij} is the evaluation value of alternative A_i under attribute C_j, i = {1,2,...,m}, j = {1,2,...,n}. In order to facilitate comparison, the initial decision matrix needs to be standardized, and the standardized decision matrix $X^* = (x_{ij}^*)_{m \times n}$ is obtained, and x_{ij}^* is the standardized form of x_{ij} [43]:

$$x_{ij}^* = x_{ij} / \sqrt{\sum_{i=1}^{m} x_{ij}^2} \tag{9}$$

2.2.1. The Ratio System Method (RSM)

The evaluation value of alternative A_i under the ratio system method is:

$$y_i = \sum_{j=1}^{g} x_{ij}^* - \sum_{j=g+1}^{n} x_{ij}^* \tag{10}$$

where g and $n-g$ represent the number of benefit-type and cost-type attributes, respectively. The larger the value of y_i, the better the corresponding alternative. Therefore, the optimal scheme under the ratio system method is:

$$A^*_{RSM} = \{A_i | max_i y_i)\} \tag{11}$$

2.2.2. The Reference Point Method (RPM)

First, the optimal reference point r_j for each attribute is determined as:

$$r_j = \begin{cases} max_j(x^*_{ij}), & j \le g \\ min_j(x^*_{ij}), & j > g \end{cases} \tag{12}$$

The deviation of the attribute value x^*_{ij} from the corresponding reference point r_j can be represented as $r_j - x^*_{ij}$. Thus, the maximum bias of each alternative, i.e., the evaluation value of each alternative under the reference point method, can be expressed as:

$$z_i = max_j |r_j - x^*_{ij}| \tag{13}$$

The smaller the value of z_i, the better the corresponding alternative. Therefore, the optimal alternative under the reference point method is:

$$A^*_{RPM} = \{A_i | min_i z_i)\} \tag{14}$$

2.2.3. The Full-Multiplicative Form (FMF)

The evaluation value of each alternative under full-multiplicative form can be expressed as:

$$u_i = \frac{\prod_{j=1}^{g} x^*_{ij}}{\prod_{j=g+1}^{n} x^*_{ij}} \tag{15}$$

where $\prod_{j=1}^{g} x^*_{ij}$ is the product of standardized evaluation value of benefit-type attributes in alternative A_i and $\prod_{j=g+1}^{n} x^*_{ij}$ is the product of cost-type attributes in alternative A_i. The larger the value of the u_i, the better the corresponding alternative. Therefore, the optimal alternative under full-multiplicative form is:

$$A^*_{FMF} = \{A_i | max_i u_i)\} \tag{16}$$

3. Research Methodology

Figure 1 shows the structure of the proposed risk evaluation model. The proposed model consists of two parts, namely the decision-making preparation stage and the decision-making process stage of risk assessment. The former includes forming an expert team, constructing an evaluation index system, collecting evaluation information (represented by D numbers), and transforming it into several decision matrices. The latter mainly covers the determination of the weight of risk evaluators, the aggregation of multiple decision matrices (using the defined fusion rule), the determination of attribute weights, and the proposal of a decision model based on the weighted MULTIMOORA method. The specific methods are discussed as follows.

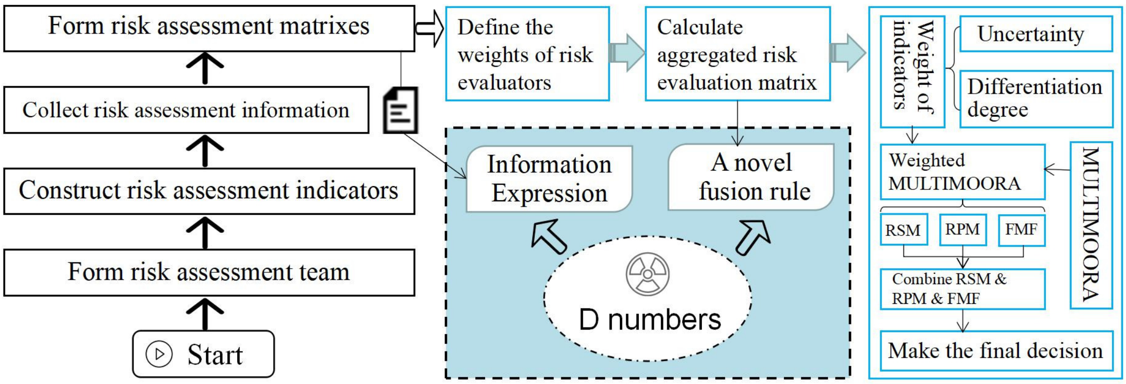

Figure 1. Process of the proposed risk assessment approach.

3.1. A Comprehensive Risk Indicator System for Evaluating CCUS Projects

In this paper, an indicator system is constructed to evaluate the risk of CCUS projects from five sustainability dimensions: economic, social, environmental, governance, and technology [50]. The sources of risk evaluation indicators mainly refer to the indicator system of Liu et al. [29], other references, and the opinions of relevant experts. In this paper, a two-layer evaluation indicator system is used. The specific content of the evaluation indicates are shown in Table 1, and the structure, explanation, and source are also given.

Table 1. The comprehensive risk indicator system for evaluating CCUS projects.

Dimension	Indicator	Meaning	References
Economy			
Cost	C_1	The economic cost of the CCUS project, including investment cost, operation and maintenance costs, unit capture costs, payback period uncertainty, and affordability.	[51]
Market	C_2	The economic system in CCUS market allocation that plays a fundamental role includes market obstacle, market uncertainty, market competition, and market maturity.	[52]
Industrial development	C_3	Technology, market size, and value of CO2 capture. It includes the development of the capture industry, transportation industry, storage industry, utilization industry, and monitoring industry.	[15,23]
Society			
Social acceptance	C_4	The degree to which CCUS projects are accepted by the public, stakeholders, governments, and NGOs, including fairness, equality, access, and so on.	[23]
Justice	C_5	Including equal management between regions and generations, equal availability for regions and generations, equal accessibility for regions and generations, and equal negative impacts for regions and generations	[52]
Social benefits	C_6	The contribution of the CCUS project to society.	Proposed by authors
Environment			
Climate pollution	C_7	The CCUS process causes certain substances to enter the atmosphere and, thus, endanger human health, including air pollution, soil pollution, water pollution, and so on.	[12]
Resources	C_8	Resources to meet human needs in CCUS projects, including the energy consumed during the life cycle of a CCUS and the diversity of energy sources.	[52,53]
Health and security	C_9	Including capture safety, transportation safety, storage safety, utilization safety, monitoring safety, alarm and management systems, impact on human health, catastrophic events, etc.	[52]
Governance			
Management	C_{10}	Participation degree of government, enterprises, research institutions, and the public in management.	[16,29]
Policy and regulation	C_{11}	National laws and local government support for CCUS programs, including domestic policies and regulations and international policies and regulations.	[29]
Demonstration	C_{12}	Demonstration to other industries in carbon capture, transportation, utilization, storage, and monitoring.	[16]
Technology			
Technological advancement	C_{13}	The maturity, flexibility, complexity, and reliability of CCUS technology. It also includes the adoption of technical processes and the use of equipment manufacturer process methods in CCUS.	[16]
Technological potential	C_{14}	The development of carbon transport technologies includes the application and expansion of technologies, knowledge created, and innovative breakthroughs.	[20]
Technology management	C_{15}	The process of efficiently collecting, storing, processing, and applying CCUS data using computer hardware and software technologies.	[29]

3.2. An Integrated Decision-Making Model

3.2.1. Problem Description of Risk Evaluation for CCUS Projects

The development alternatives of CCUS projects are represented as set $\mathbf{O} = \{o_1, o_2, \ldots, o_m\}$. In order to accurately measure the risk of each element and select the best alternative, experts in the field (represented as $\mathbf{E} = \{e_1, e_2, \ldots, e_q\}$, corresponding weight as $\mathbf{W}_E = \{\omega_{e_1}, \omega_{e_2}, \ldots, \omega_{e_q}\}$, $\omega_{e_k} \geq 0$, $\sum \omega_{e_k} = 1$) are invited to evaluate the alternatives against each risk indicator (denoted as $\mathbf{C} = \{C_1, C_2, \ldots, C_n\}$, corresponding weight as $\mathbf{W}_C = \{\omega_{C_1}, \omega_{C_2}, \ldots, \omega_{C_n}\}$, $\omega_{C_j} \geq 0$, $\sum \omega_{C_j} = 1$). The subjective judgment of expert e_k on alternative A_i against index c_j is expressed as a D number $(D_{ij}^k)_{m \times n}$, in which the evaluation level is defined in Table 2. That is, the frame of discernment is $\Omega = \{C^+, B^+, A^+, N, A^-, B^-, C^-\}$.

The ultimate goal of this paper is to complete the selection of optimal alternatives for CCUS project by calculating risks; to this end, the decision-making information from different experts needs to be aggregated first, then the MULTIMOORA method is used to sort all alternatives, and finally the optimal alternative can be selected.

Table 2. The assessment standard for D numbers.

Assessment Grade	Numerical Rating	Description
C^+	+3	Extremely good
B^+	+2	Good
A^+	+1	Somewhat good
N	0	Medium
A^-	−1	Somewhat poor
B^-	−2	Poor
C^-	−3	Extremely poor

3.2.2. The New Combination Rule for D Numbers

In Definition 4, the combination rule for two D numbers is given, but it must be pointed out that the combination operation defined in Definition 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 [54], but how to obtain μ_j has not been mentioned. To ensure 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 5. *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:

$$D_{AVG} = \{(b_1^{AVG}, v_1^{AVG}), \cdots, (b_t^{AVG}, v_t^{AVG}), \cdots, (b_q^{AVG}, v_q^{AVG})\} \tag{17}$$

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

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

$$D_1 \oplus D_2 \oplus \cdots \oplus D_C = \underbrace{D_{AVG} \oplus D_{AVG} \oplus, \cdots, \oplus D_{AVG}}_{c} \tag{18}$$

An example illustrates in detail the use of the proposed new fusion rule of D numbers, and more detailed steps are shown in Appendix A. It is clear that the new combination rule has no limit to the number of D numbers and it satisfies the associative property.

3.2.3. Define the Weights of the Risk Evaluators

In order to determine the weight of each evaluator, this study measures the entropy of all evaluation information made by each evaluator. Since the evaluation information is expressed by D numbers, the entropy function of D number proposed in the literature [55] is used in this paper, so the entropy of evaluator e_k is:

$$E(e_k) = \frac{1}{mn} \sum_{j=1}^{n} \sum_{i=1}^{m} E(D_{ij}^k), \tag{19}$$

where $E(D_{ij}^k)$ represents the entropy of D number D_{ij}^k, which is defined as follows.

Let $D = \{(b_1, v_1), (b_2, v_2), \cdots, (b_i, v_i), \cdots, (b_n, v_n)\}$ be a D number that contains n mutually exclusive and exhaustive hypotheses. When the information of D is incomplete, an operation is needed to complete it. Otherwise, skip this step.

$$\tilde{v}_i = v_i + \frac{1}{n}(1 - \sum_{j=1}^{n} v_j) \tag{20}$$

where v_i is the belief of proposition b_i. Thus, the complete D number can be denoted as $\tilde{D} = \{(b_1, \tilde{v}_1), (b_2, \tilde{v}_2), \cdots, (b_i, \tilde{v}_i), \cdots, (b_n, \tilde{v}_n)\}$, where $\tilde{v}_i > 0$ and $\sum_{i=1}^{n} \tilde{v}_i = 1$. Then, the entropy function of $\tilde{D}$ can be defined as

$$E(\tilde{D}) = \sum_{i=1}^{n} \tilde{v}_i \cdot I(\tilde{v}_i) \tag{21}$$

where $I(\tilde{v}_i)$ indicates the information content defined as:

$$I(\tilde{v}_i) = log(\frac{1}{\tilde{v}_i}) \tag{22}$$

According to the theory of belief entropy [55], entropy represents the magnitude of uncertainty. The greater the entropy provided by the evaluator, the greater the uncertainty, i.e., the less information, and the smaller the weight, and vice versa. Thus, the weight of evaluator can be defined as:

$$\omega_{e_k} = \frac{1 - E(e_k)}{q - \sum_{k=1}^{q} E(e_k)} \tag{23}$$

3.2.4. Calculate the Aggregated Risk Evaluation Matrix

In the above two subsections, the aggregation method of D numbers and the determination method of the evaluator's weight have been proposed, respectively. In what follows, the evaluation information of evaluators on different alternatives against each attribute needs to be aggregated, so a weighted average aggregation method should be proposed in this paper.

Definition 6. *Let the evaluation information for alternative A_i against attribute C_j by all the evaluators be represented as a set of D numbers $\{D_{ij}^1, D_{ij}^2, \ldots, D_{ij}^k\}$ on the frame of discernment $\Omega = \{E^+, D^+, C^+, B^+, A^+, N, A^-, B^-, C^-, D^-, E^-\}$. The weight vector of evaluators is $\mathbf{W}_E =$*

$\{\omega_{e_1}, \omega_{e_2}, \ldots, \omega_{e_q}\}$. The weighted average value of each proposition in D number is calculated as follows:

$$\widetilde{v}_{ij} = \sum_{k=1}^{q} \omega_{e_k} v_{ij}^k \quad (24)$$

so the weighted average D number is $\widetilde{D}_{ij} = (b_{ij}, \widetilde{v}_{ij})$. The fusion rule of D numbers is used to perform $q-1$ self-fusion for $\widetilde{D}_{ij}$, and the D number after aggregation of each evaluator can be obtained:

$$D_{ij} = \underbrace{\widetilde{D}_{ij} \oplus \widetilde{D}_{ij} \oplus, \cdots, \oplus \widetilde{D}_{ij}}_{q-1} \quad (25)$$

In order to lay a foundation for the use of the MULTIMOORA method [42,43], it is necessary to transform the decision matrix based on D number expression into numerical form, so the element I_{ij} in the decision matrix representing the risk evaluation of alternative A_i against attribute C_j is calculated as:

$$I_{ij} = \sum_{\theta \in \Omega} b_{ij}^{\theta} v_{ij}^{\theta} \quad (26)$$

where b_{ij}^{θ} indicates the numerical form of the grade (the second column in Table 2) for proposition θ and v_{ij}^{θ} represents its reliability. The decision matrix in numerical form has been obtained.

3.2.5. The MULTIMOORA-Based Risk Evaluation Approach

In order to evaluate CCUS projects, multiple risk indicators can be involved, and different indicators have different degrees of importance, so the weight of indicators needs to be determined. This subsection considers from two perspectives, namely, the uncertainty of evaluation information and the differentiation degree of indicators for alternatives.

Firstly, the weight of risk indicators is defined from the perspective of uncertainty (refer to the method in Section 3.2.3), and the entropy of indicator C_j is defined as:

$$E(C_j) = \frac{1}{m} \sum_{i=1}^{m} E(D_{ij}), \quad (27)$$

the weight of indicator C_j can be determined as:

$$\omega^{\dagger}(C_j) = \frac{1 - E(C_j)}{n - \sum_{j=1}^{n} E(C_j)} \quad (28)$$

Then, the weight of indicators can be defined from the perspective of discrimination degree based on entropy weight method.

(1) The decision matrix should be normalized as:

$$p_{ij} = \frac{I_{ij}}{\sum_{i=1}^{m} I_{ij}} \quad (29)$$

where I_{ij} is the numerical form of the decision matrix obtained by Equation (26).

(2) The entropy value can be calculated as:

$$e_j = -\frac{1}{ln(m)} \sum_{j=1}^{n} p_{ij} ln(p_{ij}) \quad (30)$$

(3) The degree of divergence of the risk indicator C_j can be calculated as:

$$div_j = 1 - e_j \quad (31)$$

where div_j represents the inherent contrast strength of risk indicator C_j, and the higher div_j is, the more important C_j is. Thus, the weight of indicator C_j can be determined as:

$$\omega^{\ddagger}(C_j) = \frac{div_j}{\sum_{j=1}^{n} div_j} \tag{32}$$

By combining the weights of the above two aspects, the final weight of indicator C_j can be obtained as:

$$\omega(C_j) = \frac{\omega^{\dagger}(C_j)\omega^{\ddagger}(C_j)}{\sum_{j=1}^{n} \omega^{\dagger}(C_j)\omega^{\ddagger}(C_j)} \tag{33}$$

Furthermore, combined with the MULTIMOORA method and the obtained weights, a weighted version of the MULTIMOORA method can be defined for risk evaluation. The decision matrix aggregated by multiple evaluators can be expressed as $\mathbf{I} = (I_{ij})_{m\times n}$, where I_{ij} is the numerical evaluation value of alternative A_i against attribute C_j, i = {1,2, . . . ,m}, j = {1,2, . . . ,n}. The standardized decision matrix $\mathbf{I}^* = (I^*_{ij})_{m\times n}$ of $\mathbf{I}$ can be obtained as:

$$I^*_{ij} = I_{ij} / \sqrt{\sum_{i=1}^{m} I^2_{ij}} \tag{34}$$

The evaluation value of alternative A_i under the ratio system method can be defined as:

$$Y_i = \sum_{j=1}^{g} \omega(C_j) I^*_{ij} - \sum_{j=g+1}^{n} \omega(C_j) I^*_{ij} \tag{35}$$

where g and $n-g$ represent the number of benefit-type and cost-type attributes, respectively. The larger the value of y_i, the better the corresponding alternative. Therefore, the optimal scheme under the ratio system method is $A^*_{RSM} = \{A_i | max_i Y_i)\}$.

The optimal reference point R_j for attribute C_j is determined as:

$$R_j = \begin{cases} \max_j (I^*_{ij}), & j \le g \\ min_j (I^*_{ij}), & j > g \end{cases} \tag{36}$$

The evaluation value of each alternative under the reference point method can be expressed as:

$$Z_i = max_j \{\omega_j * |R_j - I^*_{ij}|\} \tag{37}$$

The smaller the value of z_i, the better the corresponding alternative. Therefore, the optimal alternative under the reference point method is $A^*_{RPM} = \{A_i | min_i Z_i)\}$.

The evaluation value of each alternative under full-multiplicative form can be expressed as:

$$U_i = \frac{\prod_{j=1}^{g} (I^*_{ij})^{\omega_j}}{\prod_{j=g+1}^{n} (I^*_{ij})^{\omega_j}} \tag{38}$$

where $\prod_{j=1}^{g} x^*_{ij}$ is the product of standardized evaluation value of benefit-type attributes in alternative A_i and $\prod_{j=g+1}^{n} x^*_{ij}$ is the product of cost-type attributes in alternative A_i. The larger the value of the U_i, the better the corresponding alternative. Therefore, the optimal alternative under full-multiplicative form is $A^*_{FMF} = \{A_i | max_i U_i)\}$.

Finally, the decision results obtained by RSM, RPM, and FMF models are combined for comprehensive decision making. In this paper, the geometric mean method [56] is used for calculation:

$$S_i = \sqrt[3]{Y_i \times \frac{1}{Z_i} \times U_i} \tag{39}$$

where S_i represents the score index of each alternative, and the larger it is, the higher the alternative ranking will be.

4. Case Study

4.1. Case Description

This section selects the Shengli power plant as a case to illustrate the effectiveness of the proposed decision-making model in CCUS projects risk assessment. The site selection is of great significance for the smooth implementation of the CCUS project [57]. Due to the difficulty and high requirements of carbon storage, strict risk assessment is required for the selection of storage site. Based on the literature [29], considering six dimensions (i.e., geographical and climatic, geological conditions, drainage conditions, distance from cities, ecological protection standards, and land-use costs), four alternatives are selected for the CCUS project of the Shengli power plant. In what follows, the risk assessment model proposed in this paper will be utilized to determine the best one from the four alternative sites based on the constructed risk indicator system.

4.2. Decision-Making Process

The background of the risk assessment is introduced above, and the decision-making process is executed below.

Decision preparation: three experts in this field are invited to form an expert group, denoted as $E = \{e_1, e_2, e_3\}$. Experts judge the performance of the four alternative sites under various risk indicators based on their own experience, and give the evaluation information in the form of D numbers, as shown in Table 3, i.e., three decision matrices are obtained.

Decision process: firstly, determine the weight of the experts. According to the method proposed in Section 3.2.3, the weights of three experts are $\omega_{e_1} = 0.0347$, $\omega_{e_2} = 0.5473$, and $\omega_{e_3} = 0.4180$, respectively; secondly, the novel fusion rule for D numbers proposed in Section 3.2.2 is employed to aggregate the risk assessment results of multiple experts, and the results shown in Table 4 are obtained; thirdly, the MULTIMOORA-based risk evaluation approach is used to compare and sort multiple alternative sites. The last three columns of Table 5 give the weight calculation results of the indicators from the perspectives of uncertainty and differentiation degree. In addition, Table 5 also records the standardized matrix of D number. The weighted version of the MULTIMOORA method is enabled, and the results of RSM, PRM, and FMF are obtained, respectively, as shown in Table 6. For the final decision, the results of these three methods are aggregated through Equation (39) to obtain the scores shown in Table 6.

Table 3. The assessment information of CO_2 storage site selection represented by D numbers.

DMs/Indicates	Option 1	Option 2	Option 3	Option 4
e_1				
C_1	{(2, 0.3),(3, 0.5)}	{(1, 0.4),(2, 0.6)}	{(0, 0.4),(1, 0.6)}	{(−1, 0.5),(2, 0.5)}
C_2	{(1, 0.4),(2, 0.6)}	{(0, 0.3),(1, 0.7)}	{(1, 0.6)}	{(0, 0.8),(1, 0.2)}
...				
C_{15}	{(0, 0.5),(1, 0.5)}	{(1, 0.3),(2, 0.6)}	{(1, 0.5),(2, 0.5)}	{(1, 0.8),(2, 0.2)}
e_2				
C_1	{(2, 0.4),(3, 0.5)}	{(1, 0.2),(2, 0.8)}	{(0, 0.9),(1, 0.1)}	{(−1, 1.0)}
C_2	{(1, 0.7),(2, 0.3)}	{(0, 0.7),(1, 0.3)}	{(1, 0.7),(2, 0.2)}	{(0, 0.8),(1, 0.2)}
...				
C_{15}	{(0, 1.0)}	{(1, 0.1),(2, 0.9)}	{(1, 0.6),(2, 0.4)}	{(1, 0.6),(2, 0.4)}
e_3				
C_1	{(2, 0.6),(3, 0.3)}	{(1, 0.7),(2, 0.3)}	{(1, 1.0)}	{(−1, 0.7),(2, 0.3)}
C_2	{(1, 0.5),(2, 0.5)}	{(0, 0.8),(1, 0.2)}	{(1, 0.3),(2, 0.6)}	{(0, 1.0)}
...				
C_{15}	{(0, 0.8),(1, 0.2)}	{(1, 0.6),(2, 0.3)}	{(1, 0.3),(2, 0.7)}	{(1, 0.6),(2, 0.4)}

Table 4. The combined assessment information of CO_2 storage site selection.

Indicates	Option 1	Option 2	Option 3	Option 4
C_1	{(2, 0.09),(2.25, 0.26) (2.5, 0.33),(2.75, 0.24) (3, 0.08)}	{(1, 0.07),(1.25, 0.24) (1.5, 0.33),(1.75, 0.26) (2, 0.1)}	{(0, 0.15),(0.25, 0.32) (0.5, 0.33),(0.75, 0.19) (1, 0.01)}	{(−1, 0.14),(−0.125, 0.31) (0.5, 0.33),(1.25, 0.21) (2, 0.02)}
C_2	{(1, 0.1),(1.25, 0.27) (1.5, 0.33),(1.75, 0.23) (2, 0.07)}	{(0, 0.1),(0.25, 0.27) (0.5, 0.33),(0.75, 0.23) (1, 0.07)}	{(1, 0.1),(1.25, 0.26) (1.5, 0.33),(1.75, 0.24) (2, 0.07)}	{(0, 0.15),(0.25, 0.31) (0.5, 0.33),(0.75, 0.19) (1, 0.02)}
...				
C_{15}	{(0, 0.15),(0.25, 0.32) (0.5, 0.33),(0.75, 0.19) (1, 0.01)}	{(1, 0.06),(1.25, 0.22) (1.5, 0.33),(1.75, 0.28) (2, 0.11)}	{(1, 0.08),(1.25, 0.25) (1.5, 0.33),(1.75, 0.25) (2, 0.09)}	{(1, 0.1),(1.25, 0.27) (1.5, 0.33),(1.75, 0.23) (2, 0.07)}

Table 5. Intermediate results of the MULTIMOORA-based risk evaluation approach.

Indicates	Option 1	Option 2	Option 3	Option 4	$\omega^{\dagger}$	$\omega^{\ddagger}$	ω
C_1	2.49	1.52	0.40	0.29	0.0678	0.1028	0.1028
C_2	1.48	0.48	1.48	0.41	0.0589	0.0525	0.0456
C_3	2.36	1.31	3.28	1.83	0.0559	0.0665	0.0548
C_4	0.22	1.32	3.46	2.54	0.0661	0.1029	0.1004
C_5	0.54	0.79	3.92	1.92	0.0786	0.0436	0.0506
C_6	2.52	2.43	3.70	3.74	0.0481	0.0717	0.0509
C_7	1.41	4.12	4.24	4.53	0.0364	0.1237	0.0664
C_8	2.42	2.51	2.83	1.84	0.0928	0.0324	0.0444
C_9	1.72	0.38	3.61	1.54	0.0515	0.0080	0.0061
C_{10}	2.97	0.42	2.81	0.31	0.0988	0.0857	0.1249
C_{11}	0.84	0.52	2.28	3.52	0.0943	0.1028	0.1430
C_{12}	2.63	4.05	3.53	2.54	0.0369	0.0272	0.0148
C_{13}	2.61	3.38	3.63	3.50	0.0237	0.0668	0.0234
C_{14}	2.97	0.46	1.36	1.79	0.1129	0.0810	0.1349
C_{15}	0.39	1.54	1.50	1.48	0.0773	0.0324	0.0370

Table 6. The results from the weighted version of the MULTIMOORA method.

Options	RSM		PRM		FMF		Geometric Mean Method	
	Y_i	Ranking	Z_i	Ranking	U_i	Ranking	S_i	Ranking
Option 1	0.2612	3	0.0889	3	0.4358	3	1.0857	3
Option 2	0.1074	4	0.0996	4	0.2876	4	0.6771	4
Option 3	0.4528	1	0.0579	1	0.8210	1	1.8590	1
Option 4	0.3376	2	0.0806	2	0.5872	2	1.3497	2

4.3. Results and Analysis

The risk assessment results for the CCUS project site selection problem are shown in Table 6. The table indicates that the three sub-methods of the MULTIMOORA-based D numbers method (i.e., RSM, PRM, AND FMF) come to a consistent conclusion: Option 3 $\succ$ Option 4 $\succ$ Option 1 $\succ$ Option 2. In addition, the fusion result of the three methods is the same conclusion. In order to achieve further visualization of the risk assessment results, two of the results of the three methods (i.e., RSM, PRM, AND FMF), are, respectively, taken to establish two-dimensional coordinates, and the results shown in Figures 2–4 are obtained. In order to clearly compare different positions, the background of the coordinate system is set to a color that changes uniformly from bottom left to top right; the redder the color, the higher the risk, while the bluer the color, the lower the risk. From a geometric point of view, the closer to the origin, the higher the risk. In other words, from the origin to the upper right, the risk decreases. According to the above principles, the four alternative sites can be easily compared in terms of risk level from Figures 2 and 3. However, in Figure 4, Options 1, 3, and 4 are relatively close, indicating that the discrimination of the four alternatives is not obvious in the dimensions of PRM and FMF, but it still does not affect the acquisition of the final conclusion.

Based on the above analysis, the practical significance of this paper lies in: (1) the information expression and processing method of CCUS project risk assessment based on the D numbers theory can effectively represent the subjective judgment of experts and improve the flexibility of the assessment process; (2) the constructed assessment index system can effectively guide the risk assessment of CCUS projects and promote the systematization and standardization of the assessment; (3) the risk assessment method based on MULTIMOORA can analyze the results of risk assessment from different dimensions, which is conducive to the visualization of risks and novel discoveries.

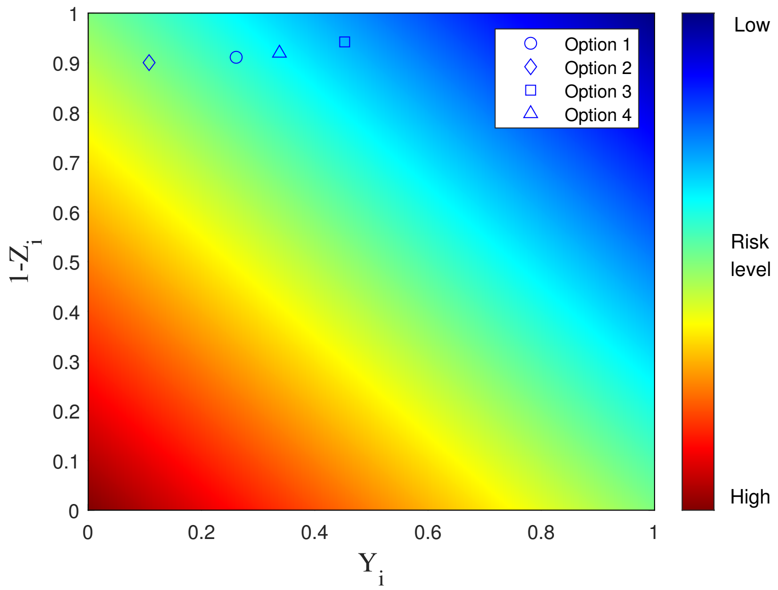

Figure 2. The risk level of each option in RSM and PRM coordinates.

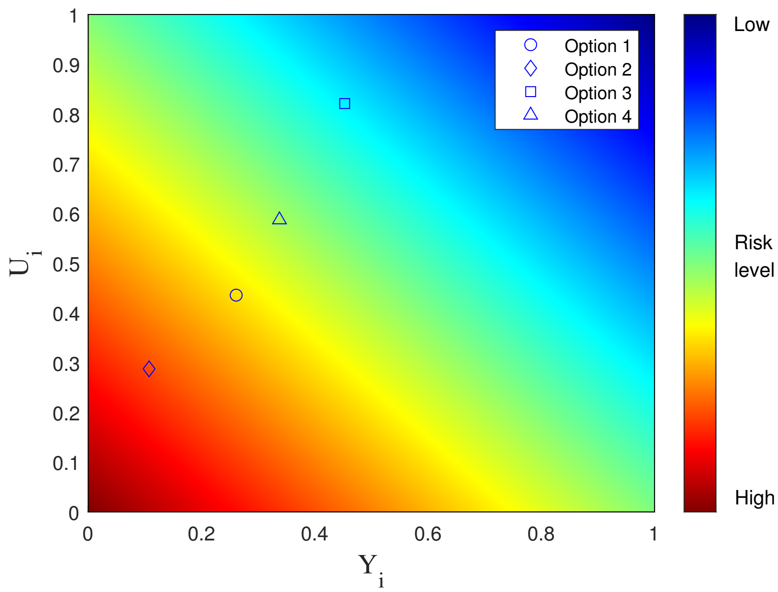

Figure 3. The risk level of each option in RSM and FMF coordinates.

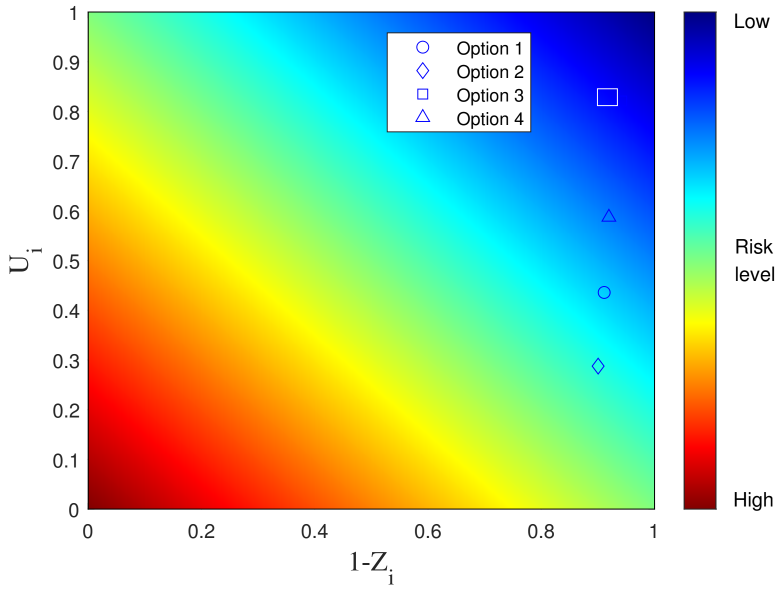

Figure 4. The risk level of each option in PRM and FMF coordinates.

4.4. Sensitivity Analysis

In this section, a sensitivity analysis is performed to verify the impact of changes in certain parameters on CCUS project risk assessment. The weight of the indicator is crucial to the result of the evaluation method. The weight of the indicator in Equation (33) comes from two aspects, namely uncertainty and differentiation. A new weight synthesis method is defined as: $\omega(C_j) = \omega^{\dagger}(C_j) * \beta + \omega^{\ddagger}(C_j) * (1-\beta)$. Parameter β is used to adjust the proportion of the two aspects. In this experiment, β is set to change from 0 to 1 at an interval of 0.1 to observe the final evaluation result, as shown in Figure 5.

Figure 5 shows that in RSM and FMF, the ranking results of the four options are very stable, while in PRM, there are some fluctuations. However, the best option is always in a stable state, and the final results of the MULTIMOORA method show that the ranking of the four options is stable, indicating that the evaluation method in this paper is robust under different indication weights.

4.5. Comparison and Analysis

In order to further demonstrate the effectiveness of the assessment method in this study, in this subsection, our method is compared and analyzed from both qualitative and quantitative aspects. The selected comparison methods are six multi-attribute decision-making methods based on the D numbers theory.

In terms of qualitative analysis, comparisons are made from the perspectives of the main contributions, applications, and aggregation method, and the analysis of the results are shown in Table 7.

Based on the results of comparative experiments, only our study essentially improves the fusion rules of D numbers, make its basic theory more perfect, and only our study has made a prominent contribution in terms of application, i.e., it constructs the indicator system of CCUS project risk evaluation. In addition, our study also obtains decision results from more perspectives, which is more robust. The above aspects can illustrate the effectiveness of the method in this paper.

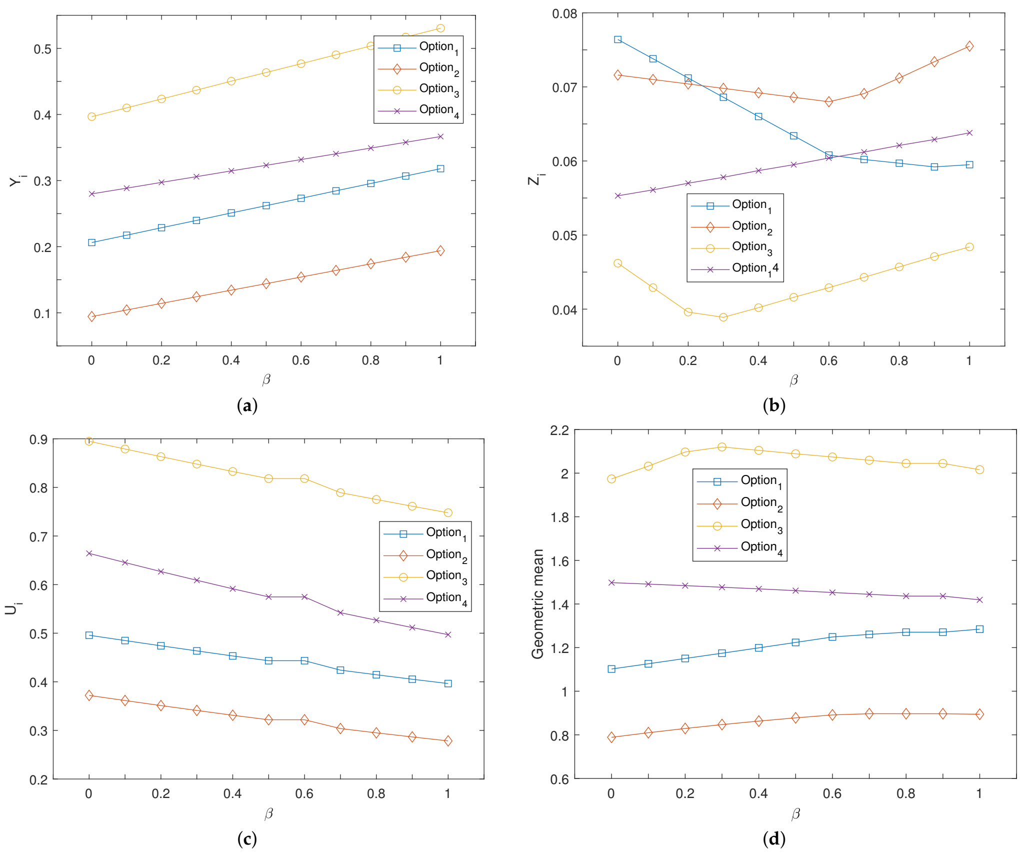

Figure 5. MULTIMOORA values under different weights, in which figure (**a**) corresponds to RSM, figure (**b**) corresponds to PRM, figure (**c**) corresponds to FMF and figure (**d**) is their geometric mean.

Table 7. Qualitative and quantitative comparison results.

Method	Main Contribution	Application	Aggregation Method	Ranking
[33]	Uncertainty quantification of D numbers	Feature evaluation for classification	-	$Option_3 \succ Option_4 \succ Option_2 \succ Option_1$
[34]	LDNs, DNMA, and CRITIC	Blockchain platform evaluation	Double normalization-based multiple aggregation	$Option_3 \succ Option_4 \succ Option_1 \succ Option_2$
[36]	Consider the attitudinal feature of decision makers	Car performance assessment	Power ordered weighted averaging operator	$Option_3 \succ Option_4 \succ Option_2 \succ Option_1$
[38]	Consider multi-granular linguistic terminology	Health-care waste management technologies assessment	Soft likelihood function	$Option_3 \succ Option_4 \succ Option_1 \succ Option_2$
[40]	Strengths-weaknesses-opportunities-threats	Assessment of safety risks in life cycle of wind turbine	Traditional fusion rules of D numbers	$Option_3 \succ Option_4 \succ Option_2 \succ Option_1$
[41]	Deal with uncertain information of D numbers	Investigation of the criminal case	Soft likelihood function	$Option_3 \succ Option_4 \succ Option_1 \succ Option_2$
Our method	Novel fusion rule A index system D_MULTIMOORA method	CCUS project risk assessment	Novel fusion rule	$Option_3 \succ Option_4 \succ Option_1 \succ Option_2$

In addition, we also made a quantitative comparison of the above methods, and the results are shown in Table 7. All methods identified Option 3 as the best, followed by Option 4. There are only differences in the ranking of the last two options, but this does not affect the selection of the final optimal option. The results of the quantitative analysis illustrate the availability and effectiveness of the proposed method.

5. Conclusions

Based on the D numbers theory and the MULTIMOORA method, this study puts forward a comprehensive decision-making model for the risk assessment of CCUS projects. This paper applies the theory of uncertain multi-attribute decision making (MADM) to the risk assessment of CCUS projects, which has the following novelties:

(1) Using the existing literature and relevant domain knowledge, this paper constructs a risk indicator system of CCUS project risk assessment, which lays the attribute foundation for the risk assessment based on the MADM method;

(2) The D numbers theory is used to express the evaluator's information, and a novel fusion rule is proposed, which not only solves the problem that the traditional fusion method does not meet the combination law, but also realizes the effective information expression and fusion of CCUS project risk assessment;

(3) From the perspective of information entropy, the weights of evaluators and risk factors are determined to capture valuable information and make the decision results more accurate;

(4) The traditional MULTIMOORA method is extended by using the D numbers theory, which not only effectively expresses the uncertainty of evaluators' assessment, but also makes the evaluation results more robust due to the use of three different functions for decision making.

In terms of practical significance, the CCUS project risk assessment model developed in this study examined a large number of indicators in the fields of economy, society, environment, governance, and technology, providing sufficient reference information and decision-making basis for stakeholders. Furthermore, the D numbers used in this study and the improved fusion rules can help decision-makers flexibly express their subjective judgments. In addition, the evaluation model based on the MULTIMOORA method can analyze risks from different dimensions, which is conducive to risk visualization and novel discovery.

This study also has some limitations. On the one hand, the constructed risk assessment index system is still relatively incomplete. On the other hand, using the constructed data to demonstrate and verify the method, its effectiveness needs to be further improved. This leads to the scope of future research: (1) more diversified expression methods of evaluation information are considered in order to more accurately express the subjective judgment of evaluators, (2) the indicator system of CCUS project risk assessment need to be further improved, (3) more extensive decision-making methods other than the MULTIMOORA method, such as ORESTE and PROMETHEE approaches, are employed to evaluate the risk of CCUS projects, and (4) experts could be invited to participate in the risk assessment of CCUS projects.

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Appendix A

Let D_1, D_2, D_3 be three D numbers that:

$$\begin{aligned} D_1 &= \{(0, 0.6), (1, 0.4)\}, \\ D_2 &= \{(0, 0.5), (1, 0.5)\}, \\ D_3 &= \{(0, 0.1), (1, 0.9)\} \end{aligned} \tag{A1}$$

The average D numbers of D_1, D_2, and D_3 can be obtained by Equation (17):

$$\begin{aligned} D_{AVG} &= \{(0, \frac{0.6 + 0.5 + 0.1}{3}), (1, \frac{0.4 + 0.5 + 0.9}{3})\} \\ &= \{(0, 0.4), (1, 0.6)\} \end{aligned} \tag{A2}$$

Then, the combination of D_1, D_2 and D_3 can be calculated by Equation (18) as follows:

$$\begin{aligned} D_1 \oplus D_2 \oplus D_3 &= D_{AVG} \oplus D_{AVG} \oplus D_{AVG} \\ &= \{(0, 0.4), (1, 0.6)\} \oplus \{(0, 0.4), (1, 0.6)\} \oplus \{(0, 0.4), (1, 0.6)\} \end{aligned} \tag{A3}$$

First, we calculate $\{(0, 0.4), (1, 0.6)\} \oplus \{(0, 0.4), (1, 0.6)\}$. Based on Equation (8):

$$\begin{aligned} C &= \frac{0.4 + 0.4}{2} + \frac{0.4 + 0.6}{2} + \frac{0.6 + 0.4}{2} + \frac{0.6 + 0.6}{2} \\ &= 2 \end{aligned} \tag{A4}$$

Based on Equations (6) and (7), $b_{11} = (0 + 0)/2 = 0$, $b_{12} = (0 + 1)/2 = 0.5$, $b_{21} = (1 + 0)/2 = 0.5$, $b_{22} = (1 + 1)/2 = 1$. $v_{11} = ((0.4 + 0.4)/2)/2 = 0.2$, $v_{12} = ((0.4 + 0.6)/2)/2 = 0.25$, $v_{21} = ((0.6 + 0.4)/2)/2 = 0.25$, $v_{22} = ((0.6 + 0.6)/2)/2 = 0.3$. So $\{(0, 0.4), (1, 0.6)\} \oplus \{(0, 0.4), (1, 0.6)\} = \{(0, 0.2), (0.5, 0.5), (1, 0.3)\}$.

So, $D_1 \oplus D_2 \oplus D_3 = \{(0, 0.2), (0.5, 0.5), (1, 0.3)\} \oplus \{(0, 0.4), (1, 0.6)\}$.

Based on Equation (8):

$$\begin{aligned} C &= \frac{0.2 + 0.4}{2} + \frac{0.2 + 0.6}{2} + \frac{0.5 + 0.4}{2} + \frac{0.5 + 0.6}{2} + \frac{0.3 + 0.4}{2} + \frac{0.3 + 0.6}{2} \\ &= 2.5 \end{aligned} \tag{A5}$$

Based on Equations (6) and (7), $b_{11} = (0 + 0)/2 = 0$, $b_{12} = (0 + 1)/2 = 0.5$, $b_{21} = (0.5 + 0)/2 = 0.25$, $b_{22} = (0.5 + 1)/2 = 0.75$, $b_{31} = (1 + 0)/2 = 0.5$, $b_{32} = (1 + 1)/2 = 1$. $v_{11} = ((0.2 + 0.4)/2)/2.5 = 0.12$, $v_{12} = ((0.2 + 0.6)/2)/2.5 = 0.16$, $v_{21} = ((0.5 + 0.4)/2)/2.5 = 0.18$, $v_{22} = ((0.5 + 0.6)/2)/2.5 = 0.22$, $v_{31} = ((0.3 + 0.4)/2)/2.5 = 0.14$, $v_{32} = ((0.3 + 0.6)/2)/2.5 = 0.18$. So $D_1 \oplus D_2 \oplus D_3 = \{(0, 0.2), (0.5, 0.5), (1, 0.3)\} \oplus \{(0, 0.4), (1, 0.6)\} = \{(0, 0.12), (0.25, 0.18), (0.50, 0.30), (0.75, 0.22), (1, 0.18)\}$.

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