Applied Soft Computing 48 (2016) 444–457

Contents lists available at ScienceDirect

Applied Soft Computing

journal homepage: www.elsevier.com/locate/asoc

Supplier selection in nuclear power industry with extended VIKOR method under linguistic information

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ARTICLE INFO

Article history:
Received 9 December 2015
Received in revised form 30 June 2016
Accepted 13 July 2016
Available online 26 July 2016

Keywords:
Quality-sensitive
Nuclear industry
Supplier selection
Cloud model
VIKOR

ABSTRACT

With Chinese nuclear power restarting, supplier selection in quality-sensitive nuclear power industry has become increasingly urgent and necessary. However, the current research on supplier selection in nuclear power industry is rather few. Moreover, there is still one great problem in the present methods: the description of the information uncertainty is inadequate. This paper proposes an extended VIsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) under linguistic information to evaluate the uncertainty of potential supplier quantitatively and scientifically. The cloud model is used to handle imprecise numerical quantities, which can give consideration to both fuzziness and randomness of uncertain information. An empirical example of a nuclear power plant in China illustrates an application to supplier selection in nuclear power industry, which proves the effectiveness of the proposed method. Finally, a comparative analysis with fuzzy VIKOR and sensitivity analysis of results are presented to verify the correctness and robustness of the extended method respectively.

1. Introduction

The nuclear power industry belongs to a quality-sensitive one, as nuclear power plants have an extremely high request for the security and reliability compared with the conventional ones. Once nuclear incidents appear, the consequences will be significantly catastrophic. And China put its nuclear power projects on hold to assess safety concerns due to Japan's Fukushima disaster. Chinese government approved the resumption of nuclear energy until the first quarter of 2015, facing triple pressure of environmental, energy and economic. Given the booming construction of nuclear plants and stricter security requirements in recent five years, supplier selection in nuclear power industry in China has become increasingly urgent and necessary. However, very few scholars, such as Yang, Huang and Lei [1], kept supplier selection in nuclear power industry in their study. Currently, the research on supplier selection mainly focus on manufacturing industry [2], automotive industry [3], household appliance industry [4], electronic industry [5], airline retail industry [6] and so forth.

Selecting the best supplier from a large number of alternatives involves many complex and time-consuming tasks [7]. Actually, many tasks may be meaningless and unnecessary due to invalid alternatives. To optimize decision process and improve the efficiency of management, we propose a two-stage methodology for the supplier selection in nuclear power industry. These two subsequent stages are defined as phase I (Qualification) and phase II (Ranking), respectively. Phase I aims to select the qualified suppliers, which firstly ensures the final selected supplier can meet requirements, and secondly reduces the complexity of decision-making by avoiding useless tasks. For phase II, we propose an extended VIsekriterijumska optimizacija i KOmpromisno Resenje (VIKOR) method under linguistic information.

When selecting the optimal supplier, quite a few criteria, including qualitative and quantitative ones, should be taken into consideration, such as quality, cost and technological capacity and the like. Thus, supplier selection is a multi-criteria decision-making (MCDM) problem. And the VIKOR method, based on an aggregating function representing "closeness to the ideal" using linear normalization, has been widely used for supplier selection [8–11]. It considers group utility maximization and individual regret minimization and fully reflects the decision makers' subjective preferences, which makes it superior to some traditional MCDM methods [12,13]. In decision situations, some problems present qualitative aspects that are complex to assess by means of

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http://dx.doi.org/10.1016/j.asoc.2016.07.023
1568-4946/

precise [14,15], and thus, the use of a linguistic approach is necessary [16,17]. For supplier selection in nuclear power industry, some performance values cannot be assessed precisely in a quantitative form but may be in a qualitative one, such as service, credit, environmental consciousness. By the use of a linguistic approach, the experts can easier express their perception preferences about the alternatives [18]. As the natural language is the standard representation of those concepts that humans use for communication [19], the application of the qualitative concept makes communication among experts comprehensive and cognitive, and also can largely facilitate experts' work [20]. However, natural languages usually involve ambiguity and uncertainty, so it is difficult to form an exact definition of linguistic information. Among the uncertainties involved in natural language, randomness and fuzziness are the two most important aspects [21]. Fortunately, the proposed extended VIKOR can express human fuzziness and randomness with cloud variables, which can effectively improve decision quality.

This paper aims to design an applicable method for supplier selection in nuclear power industry. The main contributions of this article are: Firstly, there is no investigation of supplier selection in nuclear power industry using extended VIKOR with cloud variables. Therefore, this is the first work attempting to use this technique to select the best supplier, which can enrich research idea and provide reference for practice. Secondly, the proposed method can promote the accuracy and quality of decision-making. The VIKOR method is applied to aggregate the whole criteria, which can fully consider the relative importance of the criteria, and a balance between total and individual satisfaction. And the cloud model is introduced to describe the information uncertainty, which can give consideration to both fuzziness and randomness to reduce information loss. Both efforts contribute to a better decision-making. Thirdly, the decision process and management efficiency can be improved. By designing the two-phase method, the unqualified suppliers will be excluded in an early stage, which avoids the unqualified ones to participate in the selection from beginning to end. The tasks related to the unqualified suppliers can be substantially decreased. And the final selected supplier must conform to the fundamental requirements.

The remainder of the paper is structured as follows. Section 2 reviews supplier selection methods and analyzes the detailed sub-criteria of criteria considered for the selection of suppliers in the nuclear industry. A two-phase extended VIKOR method under linguistic information is proposed in Section 3. In Section 4, a case study from China is evaluated. And results and discussion are shown in Section 5. Subsequently, final conclusion is provided in Section 6.

2. Literature review

2.1. Supplier selection methods

Currently, the research on supplier selection methods in nuclear industry is very few. Yang, Huang and Lei [1] proposed an integrated framework based on analytic hierarchy process (AHP) and technique for order preference by similarity to an ideal solution (TOPSIS) for selecting the suitable supplier. Besides, some MCDM methods used for supplier selection can be listed as follows: analytic network process (ANP) [22–24], preference ranking organization method for enrichment evaluations (PROMETHEE) [25] and elimination et choice translating reality (ELECTRE) [26,27] and other hybrid methods integrating fuzzy set theory [28,29], etc. A disadvantage of AHP and ANP is that exact numerical values are needed for the pair-wise comparison judgments, which is difficult for DMs to express due to the perceptual preference and uncertainty [4,6]. The TOPSIS method uses vector normalization to introduce two reference points, failing to consider the relative importance of the distances from these points [12,13]. PROMETHEE can't satisfy the independence from irrelevant alternatives. In other words, increasing or decreasing an alternative will influence the final results, which may limit its application. And ELECTRE can't make the best of decision information, which may lead to decision mistakes.

Based on the above analysis, The VIKOR method is used for supplier selection in nuclear industry. As VIKOR is applicable to rank and select a set of conflicting alternatives in MCDM problems. Compared with other MCDM methods, VIKOR has the following advantages: ① By using linear standardization, it is not affected by individual indicators unit [12]; ② Sorting theory is reasonable. It can give consideration to both group utility maximization and individual regret minimization [10,30–32]. Therefore, the final optimal solution is a compromise with priority, which is more likely to be accepted by DMs. Also because of the advantages, VIKOR has been widely used in many areas, such as selection of supplier [9,11,33,34], site [35], material [36,37], project [38,39], assessment of risk [40,41], entrepreneurial intensity [42], quality [43,44] and so on. All above research have proved the effectiveness and correctness of VIKOR.

Decision quality is greatly influenced by the MCDM methods. However, traditional VIKOR has displayed limitation in describe criteria or sub-criteria information under linguistic environment, which will lead to loss of information and accuracy. Many research proposed extended VIKOR method to solve that problem. Jahan and Edwards [45] extended VIKOR to interval numbers for material selection; literature [46] proposed an integrating VIKOR with interval numbers. Kuo and Liang [43], Bazzazi, Osanloo and Karimi [47] and Rezaie, Ramiyani, Nazari-Shirkouhi and Badizadeh [48] proposed extended VIKOR with triangular fuzzy number for MCDM problems. Girubha and Vinodh [36] integrated trapezoidal fuzzy number with VIKOR to select the best material of an automotive component; and Ju and Wang [49] extended VIKOR to trapezoidal fuzzy number to solve MCDM problems. By integrating with fuzzy set theory, the extended VIKOR can reduce the uncertainty to some extent. In order to exactly and fully describe the information uncertainty, some scholars introduced fuzzy sets and 2-tuple linguistic fuzzy sets into their research. Wei and Zhang [50] proposed an extended VIKOR method based on hesitant fuzzy set; Devi [51] proposed extended VIKOR with triangular intuitionistic fuzzy number for robot selection; Qin, Liu and Pedrycz [52] and Ghorabaee, Amiri, Sadaghiani and Zavadskas [53] extended VIKOR to interval 2-tuple linguistic fuzzy sets to solve MCDM problems. Although the latter ones can reduce more information uncertainty compared with the former ones, they still only work from the perspective of fuzziness. Actually, randomness and fuzziness are the most important and fundamental in all kinds of uncertainty [54]. In other words, the randomness of the information has not been paid attention in above research.

As to the analysis above, cloud theory put forward by Deyi, Haijun and Xuemei [55] is introduced in this paper. Cloud theory can give consideration to the randomness and fuzziness of information, which can reduce greatly loss of information. It has been extensively studied and applied by scholars. Wang, Xu and Li [56] proposed a 2nd-order generic normal cloud model and carried on the thorough analysis and discussion; Wang, Peng, Zhang, Liu and Chen [57] proposed an uncertain linguistic MCDM method based on a cloud model; Li, Liu, Yang and Li [58] applied cloud model for the comprehensive evaluation of smart distribution grid. Besides, some researchers applied it for risk management [59,60] and route assessment [61]. The above mentioned researches proved the effectiveness and correctness of cloud theory from two aspects of theory and practice. In conclusion, the combination of cloud and VIKOR is meaningful and beneficial work, which will contribute to a

Table 1
Supplier selection criteria and related literature.

Criterion or sub-criterion	Related literature	Remarks
(Q) Quality assurance ability		
(Q_1)The condition of quality management	[1,9,80,81]	The condition of quality management, a key premise requirement for the supplier selection, mainly considers whether the quality management for systemizing system and organization of the supplier is able to fulfill commitments.
(Q_2)Training program	[1,9,82]	Managers and workers have a close relation with the product quality. Suppliers should provide them with well-defined training programs to reduce efficiently negative influence of human error.
(Q_3)Non-conformance control	[1,6,8,70,80,81]	Non-conformance control is the most fundamental requirement of quality assurance. For the supplier, it refers to effective prevention against quality deviation and procedures to identify the cause and correct the non-conformance terms.
(Q_4)Feedback and improvement	[9,68,78]	The supplier should have thorough experience feedback mechanism through various channels to prevent the same quality defect from occurring repeatedly and improve the quality standard continually.
(Q_5)Reject rate	[6,69,73,80,81]	Reject rate can reflect the quality history directly. It can be defined as at what percentage the supplied equipment is rejected by the quality control.
(C_1) Technological capacity		
(C_{11})Technology level	[1,8,67,70,75,78,80,81,83]	Technology level means the supplier's ability to meet the current needs of the nuclear power plant. It is a key parameter to control the requirements related to customer needs.
(C_{12})Capability of R & D	[1,65,68,71,78,80,82]	Suppliers must be technologically capable to adapt themselves for innovations. Carrying out research and development work to incorporate innovations in technology helps to adapt with the present market and technological turbulences.
(C_2) Cost		
(C_{21})Purchasing price	[65–68,70,71,79,80,82–84]	Lower product price without compromising the quality is preferred by the customer. For suppliers, reasonable cost control is a great way to achieve cooperation success with more competitive price.
(C_{22})Maintenance and repair cost	[6,65,67,70,80,81,83,84]	For purchasers, both maintenance and repair become ineluctable expenditure in the stage of quality assurance. Competitive maintenance and repair cost could are beloved and help to establish a long-term relations of cooperation.
(C_3) Service		
(C_{31})Rate of processing order form	[78,80,84]	Rate of processing order form reflects the supplier's management level and the cooperative desire.
(C_{32})After-sales service quality	[6,65,70,76,77,80–82]	After-sales service mainly refers to the frequency and measures for maintenance and repair in nuclear industry. A good after-sales service can improve the credibility of suppliers and expand product market share.
(C_{33})Desire for business	[6]	Desire for business reflects the supplier's motivation to enter into and foster a long-term relationship with the nuclear industry. A supplier's desire for business is essential to nuclear power plant because of advanced equipment demand exceeding supply.
(C_4) Reliability		
(C_{41})Lead time	[6,64,65,78,80,84]	Lead time refers to the time interval from sending out an order to placing the goods to the warehouse. It is a critical parameter controlling delivery time and other requirements related to customer needs.
(C_{42})Rate of delivery in time	[6,65–68,70,80–84]	Rate of delivery in time implies the accuracy of the response to every agreement with the customer, which can impart the reliability of suppliers.
(C_{43})Ability of disruption management	[8,67,70,71,73,78,80,82]	Supplier should have the ability to resist uncertainty and risk which may cause disruption. There should be an operation planning process for suppliers to identify and react to sources of disruptions.
(C_5) Credit		
(C_{51})Corporate social responsibility	[6,85–88]	Corporate social responsibility (CSR) in a general sense reflects obligations to society and stakeholders within societies impacted by the firm. It contributes to a company's credibility, and may serve as an enabler of trustful business relationships.
(C_{52})Financial stability	[6,8,66,67,71,76,78,81,82]	Financial stability directly affects the production operation long-term development. A poor situation may lose customers' confidence in credit. So it is an important factor to be considered.
(C_{53})Reputation	[6,9,68,70,71,74,77,78,81,82]	A supplier's reputation shows its "performance history", which is based on its own experiences and opinions from other parties within the industry. A good industry reputation contributes to collecting information on new suppliers.
(C_6) Environmental consciousness		
(C_{61})Supplier's energy efficiency	[9,66,68,69,77,80,82,83]	The energy efficiency of a supplier's operation compared with the other suppliers in the same equipment is used to determine whether the supplier is operating below or above industry norm.
(C_{62})Environmental measures	[9,66,68,69,80,83]	A supplier with environmental consciousness should use appropriate greenhouse gases reduction technologies and install needful pollution control equipment during production and operation.

Table 2
Linguistic variables for the importance weights of criteria.

Linguistic variables	Corresponding normal clouds
Very Low (VL)	$Y_{-3}(0,2.598,0.125)$
Low(L)	$Y_{-2}(0.225,2.655,0.226)$
Medium Low (ML)	$Y_{-1}(0.385,2.1,0.411)$
Medium (M)	$Y_{0}(0.5,1.922,0.47)$
Medium High (MH)	$Y_{1}(0.615, 2.1,0.411)$
High (H)	$Y_{2}(0.775, 2.655,0.226)$
Very High (VH)	$Y_{3}(1, 2.598,0.125)$

Table 3
Linguistic variables for the performance ratings of alternatives.

Linguistic variables	Corresponding normal clouds
Very Poor (VP)	$Y_{-3}(0,2.598,0.125)$
Poor(P)	$Y_{-2}(2.25,2.655,0.226)$
Medium Poor (MP)	$Y_{-1}(3.85,2.1,0.411)$
Fair (F)	$Y_{0}(5,1.922,0.47)$
Medium Good (MG)	$Y_{1}(6.15, 2.1,0.411)$
Good (G)	$Y_{2}(7.75, 2.655,0.226)$
Very Good (VG)	$Y_{3}(10, 2.598,0.125)$

high-quality and reasonable decision for supplier selection in nuclear industry.

2.2. Nuclear power equipment supplier selection criteria

- Quality assurance ability. Nuclear power plant equipment can be mainly divided into three categories: nuclear island equipment, conventional island equipment and equipment for balance of plant (BOP). Currently, many studies [62–67] pointed out that high quality has a positive impact directly upon profitability. Actually, for nuclear power equipment, quality is most expected to ensure safety and reliability. Given that quality is the most fundamental requirement for providing safe operation [68–73], there should be no compensation for a supplier not meeting the minimum requirements in the quality criterion. In other words, quality has the veto power and cannot be compensated, which is also used to filter the qualified alternatives in this paper.
- Technological capacity. Technological capacity has deserved an abundant amount of attention in supplier selection literature [62,74,75]. Generally, there is a positive correlation between technological capacity and quality assurance ability. Technological capacity of supplier should meet the current and future market demand with a competitive advantage. The competitive advantage is often shown as high-quality, low-cost and low-risk products or equipment.
- Cost. According to many scholars [6,63,69,74,76,77], cost is regarded as a critical factor when selecting an optimal suppliers. The equipment cost in nuclear power plant, a significant expenditure, contributes nearly half the total cost. For the purchaser, controlling cost helps to realize high profit. And for suppliers, purchasing prices can be seen as a major determinant of a company's ability to be competitive.
- Service. Service is one of the most used criteria in supplier selection [6,68]. Services reflect a supplier's abilities and attitude on customers and products, which can be divided into pre-sale and after-sale service. Pre-sale service refers to a series of efforts provided for the customers before selling the product. And after-sale service can be considered as the continuous responsibility.
- Reliability. One of the major concerns in supplier selection is that whether equipment would be delivered in time [8,62,63,68,69,73]. A delayed delivery may cause great negative impact and losses, such as cost overruns due to project delay, even project failure. Hence, reliability is an important factor in supplier selection [9,63,74,76,77].
- Credit. Both suppliers and buyers expect to establish a long term sourcing relation, not a one-off business. Credit reflects the supplier's history status. A supply chain partner who has poor credit histories will be less suitable for such a relationship [6,62,70,74,76]. A good credit can not only show the supplier's level of responsibility and authority, but also led the purchasers to believe a long-term cooperation is reliable and feasible. Therefore, it is important to consider credit when selecting a supplier.
- Environmental consciousness. A nuclear power plant that wants to operate as a sustainable and environmentally responsible company cannot limit its environmental consciousness just to its own operations. It has become increasingly important to make sure the suppliers and vendors are also environmentally responsible [73,74,78,79].

Through the above analysis and literature summary, detailed sub-criteria of criteria considered for the selection of suppliers in the nuclear industry and the related literatures involving them are shown in Table 1.

3. Proposed supplier selection methodology

For the purpose of supplier selection, a two-phase methodology is proposed: Phase I: qualification and Phase II: rank the alternatives. Phase I screens the alternatives in accordance with quality, while Phase II proposes the application of an innovative methodology based on the cloud model and VIKOR to rank the alternatives. The individual phase is explained in the greater detail below, shown in Fig. 1.

3.1. Phase I: qualification

Qualification is imperative which can improve the efficiency and quality of decision making. The objective of the qualification phase is to reduce the total number of initial potential suppliers to a number of "qualified" suppliers, prior to the more comprehensive final choice phase. The benefits would be twofold, the complexity and difficulty of decision-making can be reduced partly and useless work can be avoided. The useless work refers to all efforts taken to the unqualified suppliers, for example, collecting data. The detailed five steps for qualification are as follows:

Step 1: Set up the review and decision committee (hereafter referred to as the committee). The review and decision committee consists of multiple experts with extensive industry background and excellent professional skills. The committee will define and describe a finite set of relevant criteria.

Step 2: Identify appropriate linguistic variables. Li, Liu and Gan [21] and Wang, Xu and Li [56] noted that randomness and fuzziness are the two most important uncertainties inherent in human cognition. Traditional quantification methods fail to depict the intension of a concept reasonably, which always ignores the randomness, and sometimes both. Fortunately, the cloud model can effectively integrate the randomness and fuzziness of concepts and describe the overall quantitative property of a concept by three numerical characteristics, namely, Expectation (*Ex*), Entropy (*En*), and Hyper entropy (*He*). Here, *Ex* is the mathematical expectation of the cloud drops belonging to a concept in the universe and is the most representative and typical sample of the qualitative concept; *En* represents the fuzziness measurement of a qualitative concept, which is determined by both the randomness and the fuzziness of the concept; *He* is the uncertain degree of *En*, which reflects the dispersion of the cloud drops. These linguistic variables can be denoted by normal clouds [89], as shown in Tables 2 and 3.

Step 3: Determine the uncertain importance weights of evaluation criteria and sub-criteria. Different evaluation criteria of supplier selection have different impacts on the final goal, not all of which hold the same importance. Because the committee evaluates the weights relying on personal knowledge, experience or intuition, this study utilizes λ to represent the credibility or confidence of an evaluator in evaluating a criterion. Suppose there are n evaluators in the committee, this paper uses the weighted mean method to aggregate the different evaluators' opinions.

Let the uncertain importance weight $\widetilde{W_i}$ of criterion C_i be denoted as:

$$\widetilde{W_i} = \frac{\lambda_1 \otimes W_i^1 \oplus \lambda_2 \otimes W_i^2 \oplus \cdots \oplus \lambda_n \otimes W_i^n}{\lambda_1 + \lambda_2 + \cdots + \lambda_n}, (0 \le \lambda_n \le 1), (0 \le i \le m) \quad (1)$$

Where W_i^n is the uncertain importance weight of criterion C_i measured by nth evaluator and $W_i^n = (Ex_i^n, En_i^n, He_i^n)$; $\widetilde{W_0}$ is the uncertain importance weight of criterion Q; m is the number of the criteria.

Then the uncertain importance weight $\widetilde{W_i}$ can be normalized to local weights W_i, given by:

$$W_i = \frac{S(\widetilde{W_i})}{\sum_{i=0}^{m} S(\widetilde{W_i})} \quad (2)$$

Where S is the score function, and $S(\widetilde{W_i})$ is the corresponding overall score of cloud variable $\widetilde{W_i}$. The score function can be transferred into crisp number (CN) through the forward normal cloud generator CG (Ex,En,He,n) proposed by Li, Liu and Gan [21], which is displayed in Algorithm 1.

Algorithm 1. Forward normal cloud generator

Input: three parameters Ex, En, He and the number of cloud drops n.

Output: n cloud drops and their certainty degree.

(i) Generate a normally distributed random number En_i' with expectation En and variance He^2.

(ii) Generate a normally distributed random number x_i with expectation Ex and variance En_i'.

(iii) Calculate $y_i = e^{-\frac{(x_i - Ex)^2}{2(En_i')^2}}$.

(iv) x_i is a cloud drop in the universe and y_i is the degree of certainty of x_i belonging to the concept T.

(v) Repeat steps (i)–(iv) until n cloud drops have been generated.

Let the uncertain importance weight $\widetilde{W_{ij}}$ of criterion C_{ij} be denoted as:

$$\widetilde{W_{ij}} = \frac{\lambda_1 \otimes W_{ij}^1 \oplus \lambda_2 \otimes W_{ij}^2 \oplus \cdots \oplus \lambda_n \otimes W_{ij}^n}{\lambda_1 + \lambda_2 + \cdots + \lambda_n}, (0.5 \le \lambda_n \le 1), (0 \le i \le m) \quad (3)$$

Where W_i^n is the uncertain importance weight of sub-criterion C_{ij} measured by nth evaluator and $W_i^n = (Ex_i^n, En_i^n, He_i^n)$; $\widetilde{W_{0j}}$ is the uncertain importance weight of sub-criterion Q_j; if $\lambda_n < 0.5$, then $\lambda_n = 0$.

Then the uncertain importance weight $\widetilde{W_{ij}}$ can be normalized to global weights W_{ij}, given by:

$$W_{ij} = W_i * \widetilde{W_{ij}} \quad (4)$$

Step 4: Collect the data and information of quality and rank. A quality team will be built to perform field research and conduct some market research, so that the quality information obtained from both internal to the corporation and external is impartial and comprehensive. Then, the committee uses the weighted mean method to evaluate the whole alternatives. Let the cloud variable Y_i^m of the mth evaluation criterion with respect to alternative A_i and the quality score Sq_i of alternative A_i be denoted as:

$$Y_i^m = \frac{\lambda_1 \otimes E_i^{1m} \oplus \lambda_2 \otimes E_i^{2m} \oplus \cdots \oplus \lambda_n \otimes E_i^{nm}}{\lambda_1 + \lambda_2 + \cdots + \lambda_n}, 0 \le \lambda_n \le 1 \quad (5)$$

$$Sq_i = W_1 \otimes Y_i^1 \oplus W_2 \otimes Y_i^2 \oplus \cdots \oplus W_m \otimes Y_i^m \quad (6)$$

Where E_i^{nm} is the performance of the mth evaluation criterion with respect to alternative A_i rated by the nth group of experts.

Step 5: Select the whole qualified alternatives. In order to filter out the unqualified alternatives, a threshold value is set by the committee. Only when the alternative reaches or exceeds the threshold value can it enter the second phase.

3.2. Phase II: rank the alternatives

In this phase, the data and information needed are collected. And an innovative methodology based on the cloud model and VIKOR is applied to rank the alternatives to select the best supplier. The detailed 10 steps for ranking the alternatives are as follows:

Step 1: Collect the remaining data and information of all qualified alternatives. The committee constructs a research group to collect the remaining information for supplier selection. The data

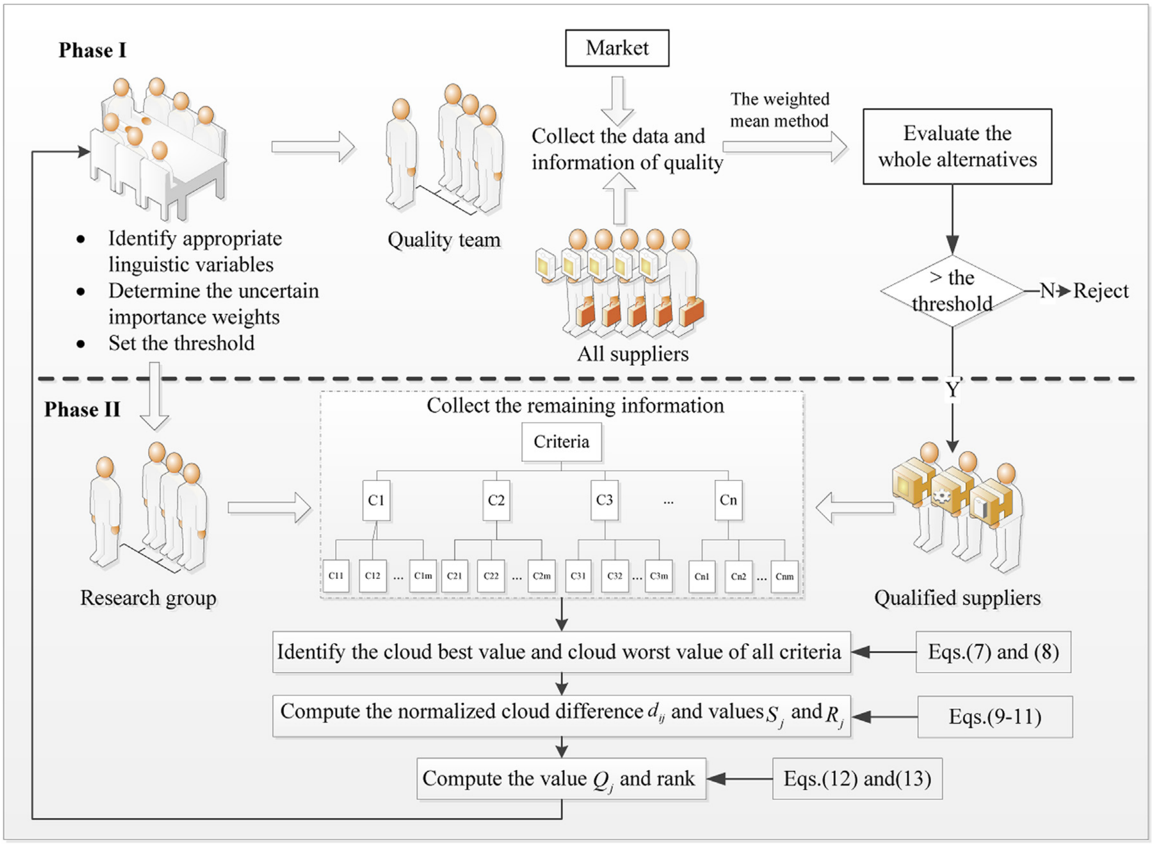

Fig. 1. The two-phase decision framework for supplier selection.

and information will be evaluated as shown in the decision matrix D.

$$D = \begin{bmatrix} Y_1^1 & Y_2^1 & \cdots & Y_m^1 \\ Y_1^2 & Y_2^2 & \cdots & Y_m^2 \\ \vdots & \vdots & \ddots & \vdots \\ Y_1^n & Y_2^n & \cdots & Y_m^n \end{bmatrix}, i = 1, 2, \ldots, n; \quad j = 1, 2, \ldots, m$$

Where Y_m^n is the cloud variable of the nth evaluation criterion with respect to alternative A_m.

Step 2: Identify the cloud best value f_i^* and cloud worst value f_i^- of all criteria. The cloud best value $f_i^* = (Ex^*, En^*, He^*)$ and cloud worst value $f_i^- = (Ex^-, En^-, He^-)$ are defined respectively as follows:

$$f_i^* = \left[\max_j D_{ij}\right], \forall i \quad (7)$$

$$f_i^- = \left[\min_j D_{ij}\right], \forall i \quad (8)$$

Where j is the alternative, and $i$is the evaluation criterion.

Step 3: Compute the normalized cloud difference d_{ij}. The cloud difference d_{ij}between D_{ij} and cloud best value f_i^* can be obtained as:

$$d_{ij} = (f_i^* \ominus D_{ij})/S(f_i^* \ominus f_i^-) \quad (9)$$

Step 4: Compute the values S_j and R_j.

$$S_j = \sum_{i=1}^{n} W_{ij} \otimes d_{ij}, \forall j \quad (10)$$

$$R_j = \max_i(W_{ij} \otimes d_{ij}), \forall j \quad (11)$$

Where S_j refers to the overall benefits of the jth alternative. The smaller the value S_j, the bigger the benefits. And R_j refers to the individual regret of the jth alternative. The smaller the value R_j, the smaller the individual regret. n refers to the number of the sub-criteria.

Step 5: Compute the value $\widetilde{Q}_j$.

$$\widetilde{Q}_j = \upsilon \otimes \left(S_j \ominus S^*\right) / S\left(S^- \ominus S^*\right) + (1-\upsilon) \otimes \left(R_j \ominus R^*\right) / S\left(R^- \ominus R^*\right), \forall j \quad (12)$$

Where $S^* = \min_j S_j$, $S^- = \max_j S_j$, $R^* = \min_j R_j$, $R^- = \max_j R_j$. And υ refers to the decision-making mechanism coefficient. υ is for the strategy of "the majority of criteria"(when $\upsilon > 0.5$), "the minimum regret" (when $\upsilon < 0.5$) and both (when $\upsilon = 0.5$).

Step 6: Transfer $\widetilde{Q}_j$,S_j and R_j into CN. The process is similar to the defuzzify converting a fuzzy number into a best nonfuzzy performance (BNP) value.

Step 7: Rank the alternatives. Two judgment standards are proposed to compare the alternatives and rank, which are listed as follows:

Standard 1: Acceptable utility threshold value.

$$S(\widetilde{Q^{(2)}} \ominus \widetilde{Q^{(1)}}) \geq 1/(J-1) * S(\widetilde{Q^{(*)}} \ominus \widetilde{Q^{(-)}}) \quad (13)$$

Where $\widetilde{Q^{(2)}}$ is the order of alternatives as second sorting by Q, and $\widetilde{Q^{(1)}}$ as first. $J$is the number of the alternatives.

Standard 2: Acceptable reliability of decisions.

When sorting by $\widetilde{Q}$, the alternatives can sort as follows: $A_{\widetilde{Q^{(1)}}} \succ A_{\widetilde{Q^{(2)}}} \succ \cdots \succ A_{\widetilde{Q^{(J)}}}$. And the corresponding the values S_j and R_j are respectively denoted by$S_{\widetilde{Q^{(1)}}}(R_{\widetilde{Q^{(1)}}})$, $S_{\widetilde{Q^{(2)}}}(R_{\widetilde{Q^{(2)}}})$, $\cdots$, $S_{\widetilde{Q^{(J)}}}(R_{\widetilde{Q^{(J)}}})$. $S_{\widetilde{Q^{(1)}}} \succ S_{\widetilde{Q^{(2)}}}$ (or/and $R_{\widetilde{Q^{(1)}}} \succ R_{\widetilde{Q^{(2)}}}$). Others are in the same way.

According to the following rules, we can rank the alternatives.

Table 4
Importance weights of evaluation criteria and sub-criteria.

Criteria	Sub- criteria	Weight rating					Local weight	Global weight
		E_1	E_2	E_3	E_4	E_5		
Q		VH[0.9]	VH[0.7]	VH[0.1]	VH[0.2]	VH[0.6]	0.1699	
	Q_1	MH[0.9]	VH[0.7]			VH[0.6]	0.2026	0.0344
	Q_2	VH[0.9]	ML[0.7]			M[0.6]	0.1604	0.0273
	Q_3	VH[0.9]	H[0.7]			H[0.6]	0.2076	0.0353
	Q_4	M[0.9]	VH[0.7]			VH[0.6]	0.1920	0.0326
	Q_5	VH[0.9]	VH[0.7]			VH[0.6]	0.2374	0.0403
C_1		VH[1.0]	H[0.6]	VH[0.2]	VH[0.3]	VH[0.6]	0.1599	
	C_{11}	H	H			H	0.4737	0.0757
	C_{12}	VH	H			H	0.5263	0.0842
C_2		VH[0.8]	VH[0.9]	VH[1.0]	VH[0.4]	VH[0.8]	0.1707	
	C_{21}	VH	VH	H		VH	0.6126	0.1046
	C_{22}	MH	H	M		M	0.3874	0.0661
C_3		MH[0.9]	H[0.9]	M [0.7]	H[0.3]	MH[0.8]	0.1077	
	C_{31}	MH	L	M		MH	0.2265	0.0244
	C_{32}	VH	H	VH		H	0.4088	0.0440
	C_{33}	H	H	MH		VH	0.3647	0.0393
C_4		H[0.4]	VH[1.0]	VH[1.0]	VH[0.2]	VH[1.0]	0.1658	
	C_{41}		VH	H		VH	0.3149	0.0522
	C_{42}		VH	VH		VH	0.3392	0.0562
	C_{43}		VH	VH		VH	0.3459	0.0573
C_5		M[0.4]	VH[0.8]	H[0.9]	H[0.3]	MH[1.0]	0.1257	
	C_{51}		M	MH		M	0.2334	0.0293
	C_{52}		VH	VH		VH	0.4318	0.0543
	C_{53}		VH	H		MH	0.3347	0.0421
C_6		M[0.2]	L[0.2]	ML[0.4]	H[1.0]	MH[0.7]	0.1003	
	C_{61}				MH	H	0.4011	0.0402
	C_{62}				VH	VH	0.5989	0.0601

Note: Bracket [.] denotes λ.

Table 5
Quality performance of the alternatives.

Sub-criteria	Performance rating					Groups of experts
	A_1	A_2	A_3	A_4	A_5	
Q_1	MG	VG	G	MG	F	E_1[0.9]
Q_2	VG	VG	G	VG	G	
Q_3	VG	VG	VG	MG	VG	
Q_4	G	G	F	VG	MG	
Q_5	G	VG	G	F	MG	
Q_1	F	VG	G	MG	MP	E_2[0.7]
Q_2	VG	G	G	VG	MG	
Q_3	VG	VG	VG	MG	VG	
Q_4	G	G	MG	VG	MG	
Q_5	G	VG	G	MP	F	
Q_1	F	VG	MG	MG	MP	E_5[0.6]
Q_2	VG	G	G	VG	MG	
Q_3	VG	VG	VG	MG	VG	
Q_4	MG	MG	F	VG	MG	
Q_5	G	VG	G	F	MG	

(i) If any two alternatives (such as $A_{\widetilde{Q^{(i)}}} \succ A_{\widetilde{Q^{(i+1)}}}$) can meet the above both judgment standards, $A_{\widetilde{Q^{(i)}}}$ is accepted as the optimal alternative.

(ii) If the alternatives (such as $A_{\widetilde{Q^{(i)}}} \succ A_{\widetilde{Q^{(i+1)}}}$) only can meet the second judgment standards, $A_{\widetilde{Q^{(i)}}}$ and $A_{\widetilde{Q^{(i+1)}}}$ come close. $A_{\widetilde{Q^{(i)}}}$ is weakly superior to $A_{\widetilde{Q^{(i+1)}}}$.

4. A case study

A nuclear power plant 'H' locating in China was expected to further improve the production ability of complete sets of equipment, and encourage the formation of a complete self-independence nuclear power industry system. H's plan aimed for six nuclear power units with mega kilowatt during two phases. The first phase of the project including four nuclear power units was completed in 2015. And the second phase approved in 2015 decided to use ACPR1000. ACPR1000 refers to the self-developed third generation nuclear technology by a Chinese nuclear power group co., LTD.

In order to select an appropriate equipment supplier for nuclear island, a review meeting was hold in Beijing on May 2015. Five suppliers (labeled as A_1–A_5) from home and abroad actively participated in the meeting and submitted the respective business and technical requirements. And the corresponding supply data was collected to evaluate them. The case study is conducted to select the best supplier for a nuclear power plant, which enables us to evalu-

Table 6
Criteria performance of the alternatives.

Alternatives	Sub-criteria	Performance rating				
		E_1	E_2	E_3	E_4	E_5
A_1	C_{11}	MG	F			MG
	C_{12}	VG	VG			G
	C_{21}	VG	VG	VG		VG
	C_{22}	VG	VG	G		VG
	C_{31}	VG	VG	VG		VG
	C_{32}	G	VG	G		VG
	C_{33}	VG	VG	VG		VG
	C_{41}		MG	MG		F
	C_{42}		VG	G		G
	C_{43}		G	VG		VG
	C_{51}		VG	VG		G
	C_{52}		VG	MG		VG
	C_{53}		VG	VG		VG
	C_{61}				G	G
	C_{62}				VG	VG
A_2	C_{11}	G	G			G
	C_{12}	G	G			MG
	C_{21}	G	G	VG		G
	C_{22}	F	F	F		F
	C_{31}	VG	VG	G		G
	C_{32}	MG	MG	F		F
	C_{33}	G	G	MG		G
	C_{41}		MG	F		MG
	C_{42}		G	G		MG
	C_{43}		MG	F		MP
	C_{51}		MG	MG		F
	C_{52}		MG	G		MG
	C_{53}		F	MG		MG
	C_{61}				MG	MG
	C_{62}				MG	F
A_3	C_{11}	MG	MG			F
	C_{12}	MG	MG			G
	C_{21}	G	VG	VG		G
	C_{22}	MP	F	MP		F
	C_{31}	VG	G	G		G
	C_{32}	MP	F	F		F
	C_{33}	P	F	MP		F
	C_{41}		G	G		MG
	C_{42}		MG	F		MG
	C_{43}		G	MG		G
	C_{51}		F	MG		F
	C_{52}		MG	MG		MG
	C_{53}		F	MG		F
	C_{61}				MG	F
	C_{62}				F	F
A_4	C_{11}	F	F			F
	C_{12}	VG	VG			VG
	C_{21}	F	F	MP		F
	C_{22}	G	G	VG		G
	C_{31}	MG	F	F		MG
	C_{32}	G	MG	MG		G
	C_{33}	F	MG	G		G
	C_{41}		MG	MG		F
	C_{42}		G	G		G
	C_{43}		VG	G		G
	C_{51}		G	MG		G
	C_{52}		VG	VG		G
	C_{53}		G	G		VG
	C_{61}				MG	G
	C_{62}				VG	G

ate the supplier in the context of practice. The detailed procedure is shown as follows.

4.1. Qualification phase

Step 1: The committee consisting of five groups of experts (labeled as E_1–E_5) whose academic backgrounds were technological, engineering, economic, environmental and logistics fields respectively was set up. The committee defined and described a finite set of relevant criteria shown in Table 1. Then the committee used the linguistic variables defined in Table 2 to express their preferences for the importance weight of each evaluation criterion or sub-criterion. Next, the linguistic variables were transferred into corresponding normal clouds. Eqs. (1)–(2) were used to calculate the weights listed in Table 4.

This study adopts the Algorithm 1 to transfer each aggregated cloud variable into a CN. To make the computational procedures more comprehensive, this study gives example calculations for

Table 7
The normalized cloud difference d_{ij} of the remaining alternatives.

	A_1	A_2	A_3	A_4
Q_1	(1.4047,1.8247,0.2584)	(0,2.0460,0.0984)	(0.8331,2.0139,0.1751)	(1.1939,1.8603,0.2392)
Q_2	(0,2.9139,0.1402)	(0.8363,2.9329,0.1812)	(1.4152,2.9460,0.2048)	(0,2.9139,0.1402)
Q_3	(0,2.2270,0.1071)	(0,2.2270,0.1071)	(0,2.2270,0.1071)	(1.4144,2.0248,0.2604)
Q_4	(0.8213,1.9997,0.1738)	(0.8213,1.9997,0.1738)	(1.4168,1.8063,0.2593)	(0,2.0315,0.0977)
Q_5	(0.5864,1.8963,0.1318)	(0,1.8756,0.0902)	(0.5864,1.8963,0.1318)	(1.3984,1.6677,0.2394)
C_{11}	(0.9778,2.3991,0.3459)	(0,2.6840,0.2285)	(0.9778,2.3991,0.3459)	(1.4052,2.3430,0.3728)
C_{12}	(0.2577,2.3880,0.1311)	(1.1280,2.3435,0.2037)	(1.4334,2.2334,0.2530)	(0,2.3808,0.1146)
C_{21}	(0,1.9025,0.0915)	(0.4309,1.9176,0.1232)	(0.2758,1.9122,0.1128)	(1.4288,1.6897,0.2438)
C_{22}	(0,1.9816,0.1216)	(1.2516,1.7391,0.2662)	(1.4215,1.7693,0.2513)	(0.2770,1.9909,0.1384)
C_{31}	(0,2.0845,0.1003)	(0.3292,2.0950,0.1235)	(0.5267,2.1013,0.1355)	(1.4187,1.8656,0.2598)
C_{32}	(0,2.1536,0.1486)	(1.1038,1.9217,0.2753)	(1.4203,1.9045,0.2838)	(0.6508,2.0639,0.2178)
C_{33}	(0,1.7936,0.0863)	(0.6171,1.7762,0.1478)	(1.4285,1.6562,0.2066)	(0.8189,1.7026,0.1860)
C_{41}	(1.4145,3.1760,0.5194)	(1.4145,3.1760,0.5194)	(0,3.4693,0.4199)	(1.4145,3.1760,0.5194)
C_{42}	(0,2.6928,0.2024)	(0.6695,2.6162,0.2600)	(1.4260,2.4087,0.3430)	(0.3913,2.7024,0.2171)
C_{43}	(0,2.1336,0.1351)	(1.4124,1.9137,0.2665)	(0.6757,2.0800,0.1979)	(0.2492,2.1414,0.1489)
C_{51}	(0,2.2566,0.1461)	(1.2776,2.0210,0.2837)	(1.4041,2.0014,0.2936)	(0.7237,2.1990,0.2102)
C_{52}	(0.2104,2.4495,0.2113)	(1.1613,2.3837,0.2722)	(1.4107,2.2958,0.3040)	(0,2.5331,0.1640)
C_{53}	(0,2.0358,0.0979)	(1.2866,1.8333,0.2478)	(1.4174,1.8110,0.2594)	(0.4349,2.0500,0.1282)
C_{61}	(0,3.0937,0.2633)	(1.0862,2.7891,0.3865)	(1.4077,2.7530,0.4048)	(0.6389,2.9184,0.3412)
C_{62}	(0,1.9620,0.0944)	(1.2329,1.7602,0.2423)	(1.4258,1.7257,0.2597)	(0.2642,1.9709,0.1143)

Table 8
The values S_j and R_j of the remaining alternatives.

	A_1	A_2	A_3	A_4
Q_1	(0.0511,0.3480,0.0493)	(0,0.3903,0.0188)	(0.0303,0.3841,0.0334)	(0.0434,0.3548,0.0456)
Q_2	(0,0.4786,0.0230)	(0.0226,0.4817,0.0298)	(0.0382,0.4839,0.0336)	(0,0.4786,0.0230)
Q_3	(0,0.4259,0.0205)	(0,0.4259,0.0205)	(0,0.4259,0.0205)	(0.0517,0.3873,0.0498)
Q_4	(0.0274,0.3654,0.0318)	(0.0274,0.3654,0.0318)	(0.0473,0.3301,0.0474)	(0,0.3713,0.0179)
Q_5	(0.0245,0.3880,0.0270)	(0,0.3837,0.0185)	(0.0245,0.3880,0.0270)	(0.0585,0.3412,0.0490)
C_{11}	(0.0685,0.6350,0.0916)	(0,0.7104,0.0605)	(0.0685,0.6350,0.0916)	(0.0984,0.6201,0.0987)
C_{12}	(0.0222,0.7010,0.0385)	(0.0972,0.6880,0.0598)	(0.1235,0.6557,0.0743)	(0,0.6989,0.0336)
C_{21}	(0,0.6090,0.0293)	(0.0442,0.6138,0.0394)	(0.0283,0.6121,0.0361)	(0.1464,0.5409,0.0780)
C_{22}	(0,0.5190,0.0319)	(0.0859,0.4555,0.0697)	(0.0975,0.4634,0.0658)	(0.0190,0.5214,0.0363)
C_{31}	(0,0.3264,0.0157)	(0.0081,0.3281,0.0193)	(0.0129,0.3291,0.0212)	(0.0348,0.2922,0.0407)
C_{32}	(0,0.4557,0.0314)	(0.0494,0.4066,0.0583)	(0.0636,0.4030,0.0601)	(0.0291,0.4367,0.0461)
C_{33}	(0,0.3569,0.0172)	(0.0244,0.3534,0.0294)	(0.0565,0.3295,0.0411)	(0.0324,0.3388,0.0370)
C_{41}	(0.0731,0.7222,0.1181)	(0.0731,0.7222,0.1181)	(0,0.7888,0.0955)	(0.0731,0.7222,0.1181)
C_{42}	(0,0.6298,0.0473)	(0.0366,0.6119,0.0608)	(0.0780,0.5634,0.0802)	(0.0214,0.6321,0.0508)
C_{43}	(0,0.5085,0.0322)	(0.0802,0.4561,0.0635)	(0.0384,0.4957,0.0472)	(0.0142,0.5103,0.0355)
C_{51}	(0,0.3882,0.0251)	(0.0378,0.3477,0.0488)	(0.0416,0.3443,0.0505)	(0.0214,0.3783,0.0362)
C_{52}	(0.0116,0.5742,0.0495)	(0.0638,0.5588,0.0638)	(0.0775,0.5382,0.0713)	(0,0.5938,0.0384)
C_{53}	(0,0.4271,0.0206)	(0.0566,0.3846,0.0520)	(0.0624,0.3799,0.0544)	(0.0191,0.4301,0.0269)
C_{61}	(0,0.6122,0.0521)	(0.0425,0.5520,0.0765)	(0.0551,0.5448,0.0801)	(0.0250,0.5776,0.0675)
C_{62}	(0,0.4713,0.0227)	(0.0711,0.4228,0.0582)	(0.0823,0.4145,0.0624)	(0.0152,0.4734,0.0275)
S_j	(0.2785,2.2866,0.2058)	(0.8210,2.2305,0.2477)	(1.0265,2.1979,0.2638)	(0.7034,2.2377,0.2405)
R_j	(0.0685,0.6350,0.0916)	(0.0972,0.6880,0.0598)	(0.1235,0.6557,0.0743)	(0.1464,0.5409,0.0780)

uncertain importance weight and global weight of criterion Q_1. Three groups of experts (E_1, E_2 and E_5) ($\lambda > 0.5$) evaluated Q_1 by the linguistic variables in Table 2.

Uncertain importance weight of criterion Q_1

$$\widetilde{W_{Q_1}} = \frac{0.9 \otimes (0.615, 2.1, 0.411) \oplus 0.7 \otimes (1, 2.598, 0.125) \oplus 0.6 \otimes (1, 2.598, 0.125)}{0.9 + 0.7 + 0.6} = (0.8425, 2.4068, 0.2799)$$

In order to gain a stable result, we ran Algorithm 1 three times and took the average, shown as follows:

$$CN_{\widetilde{W_{Q_1}}} = \frac{0.6054 + 0.5980 + 0.5960}{3} = 0.5998$$

Local weight of criterion Q_1

$$W_{Q_1} = \frac{0.5998}{0.5998 + 0.4750 + 0.6148 + 0.5684 + 0.7030} = 0.2026$$

Global weight of criterion Q_1

$$W_{Q_1} = 0.1699 * 0.2026 = 0.0344$$

According to Table 4, the importance degree order of quality criteria follows: reject rate (Q_5), non-conformance control (Q_3), the condition of quality management (Q_1), feedback and improvement (Q_4), training program (Q_2). And for the criteria in phase II, the five most important criteria for evaluating the supplier are: purchasing price (C_{21}), capability of R & D (C_{12}), technology level (C_{11}), maintenance and repair cost (C_{22}), environmental measures (C_{62}).

Step 2: Collect the information of quality criteria of all alternatives and determine the qualified ones. A quality team performed field research and conducted some market research to collect the whole required information. Then the committee evaluated the quality performance of all alternatives by the linguistic variables in Table 3, shown in Table 5. And the committee set the threshold as 5.0.

According to Eqs. (3)–(4) and Algorithm 1, the quality score of A_1–A_5 can be transferred into CNs as follows:

$$Sq_1 = 0.2026 \otimes (5.4705, 1.9967, 0.4468) \oplus \cdots \oplus 0.2374 \otimes (4.3205, 2.0291, 0.4361) = (8.0520, 2.4878, 0.2713)$$

$$CN_{Sq_1} = 5.7457; CN_{Sq_2} = 6.5753; CN_{Sq_3} = 5.4409;$$
$$CN_{Sq_4} = 5.0531; CN_{Sq_5} = 4.6622$$

Given that the pre-set threshold set, A_5 was excluded from the qualified alternatives. The remaining alternatives, A_1A_4, entered into the next phase.

4.2. Ranking phase

Step 1: A research group was constructed to collect the remaining information for supplier selection. Then the committee evaluated the criteria performance of the remaining alternatives by the linguistic variables in Table 3, shown in Table 6.

According to Eq. (5), the decision matrix D can be gained as following.

$$D=\begin{bmatrix} & A_1 & A_2 & A_3 & A_4 \\ Q_1 & (5.4705,1.9967,0.4468) & (10.0000,2.5980,0.1250) & (7.3136,2.5158,0.2885) & (6.1500,2.1000,0.4110) \\ Q_2 & (10.0000,2.5980,0.1250) & (8.6705,2.6318,0.1912) & (7.7500,2.6550,0.2260) & (10.0000,2.5980,0.1250) \\ Q_3 & (10.0000,2.5980,0.1250) & (10.0000,2.5980,0.1250) & (10.0000,2.5980,0.1250) & (6.1500,2.1000,0.4110) \\ Q_4 & (7.3136,2.5158,0.2885) & (7.3136,2.5158,0.2885) & (5.3659,1.9804,0.4521) & (10.0000,2.5980,0.1250) \\ Q_5 & (7.7500,2.6550,0.2260) & (10.0000,2.5980,0.1250) & (7.7500,2.6550,0.2260) & (4.6341,1.9804,0.4521) \\ C_{11} & (5.8364,2.0530,0.4279) & (7.7500,2.6550,0.2260) & (5.8364,2.0530,0.4279) & (5.0000,1.9220,0.4700) \\ C_{12} & (9.3864,2.6137,0.1590) & (7.3136,2.5158,0.2885) & (6.5864,2.2649,0.3698) & (10.0000,2.5980,0.1250) \\ C_{21} & (10.0000,2.5980,0.1250) & (8.3929,2.6388,0.2024) & (8.9714,2.6242,0.1784) & (4.6714,1.9745,0.4539) \\ C_{22} & (9.3571,2.6144,0.1605) & (5.0000,1.9220,0.4700) & (4.4086,2.0155,0.4406) & (8.3929,2.6388,0.2024) \\ C_{31} & (10.0000,2.5980,0.1250) & (8.9773,2.6241,0.1782) & (8.3636,2.6396,0.2035) & (5.5924,2.0157,0.4406) \\ C_{32} & (8.9091,2.6258,0.1811) & (5.6273,2.0210,0.4388) & (4.6864,1.9721,0.4547) & (6.9742,2.4020,0.3290) \\ C_{33} & (10.0000,2.5980,0.1250) & (7.4106,2.5474,0.2758) & (4.0061,2.1820,0.4044) & (6.5636,2.3269,0.3599) \\ C_{41} & (5.7667,2.0424,0.4316) & (5.7667,2.0424,0.4316) & (7.2167,2.4838,0.3006) & (5.7667,2.0424,0.4316) \\ C_{42} & (8.5000,2.6361,0.1981) & (7.2167,2.4838,0.3006) & (5.7667,2.0424,0.4316) & (7.7500,2.6550,0.2260) \\ C_{43} & (9.2500,2.6171,0.1657) & (5.0000,2.0424,0.4316) & (7.2167,2.4838,0.3006) & (8.5000,2.6361,0.1981) \\ C_{51} & (9.1667,2.6193,0.1696) & (5.7241,2.0359,0.4338) & (5.3833,1.9831,0.4512) & (7.2167,2.4838,0.3006) \\ C_{52} & (8.7167,2.4433,0.2583) & (6.6833,2.2999,0.3601) & (6.1500,2.1000,0.4110) & (9.1667,2.6193,0.1696) \\ C_{53} & (10.0000,2.5980,0.1250) & (5.8093,2.0489,0.4293) & (5.3833,1.9831,0.4512) & (8.5833,2.6340,0.1948) \\ C_{61} & (7.7500,2.6550,0.2260) & (6.1500,2.1000,0.4110) & (5.6765,2.0286,0.4363) & (6.8088,2.3445,0.3470) \\ C_{62} & (10.0000,2.5980,0.1250) & (5.6765,2.0286,0.4363) & (5.0000,1.9220,0.4700) & (9.0735,2.6216,0.1738) \end{bmatrix}$$

Step 2: Identify the cloud best value f_i^* and cloud worst value f_i^- of all criteria.

$$f_i^*=\begin{bmatrix} Q_1 & (10.0000,2.5980,0.1250) \\ Q_2 & (10.0000,2.5980,0.1250) \\ Q_3 & (10.0000,2.5980,0.1250) \\ Q_4 & (10.0000,2.5980,0.1250) \\ Q_5 & (10.0000,2.5980,0.1250) \\ C_{11} & (7.7500,2.6550,0.2260) \\ C_{12} & (10.0000,2.5980,0.1250) \\ C_{21} & (10.0000,2.5980,0.1250) \\ C_{22} & (9.3571,2.6144,0.1605) \\ C_{31} & (10.0000,2.5980,0.1250) \\ C_{32} & (8.9091,2.6258,0.1811) \\ C_{33} & (10.0000,2.5980,0.1250) \\ C_{41} & (7.2167,2.4838,0.3006) \\ C_{42} & (8.5000,2.6361,0.1981) \\ C_{43} & (9.2500,2.6171,0.1657) \\ C_{51} & (9.1667,2.6193,0.1696) \\ C_{52} & (9.1667,2.6193,0.1696) \\ C_{53} & (10.0000,2.5980,0.1250) \\ C_{61} & (7.7500,2.6550,0.2260) \\ C_{62} & (10.0000,2.5980,0.1250) \end{bmatrix} \quad f_i^-=\begin{bmatrix} Q_1 & (5.4705,1.9967,0.4468) \\ Q_2 & (7.7500,2.6550,0.2260) \\ Q_3 & (6.1500,2.1000,0.4110) \\ Q_4 & (5.3659,1.9804,0.4521) \\ Q_5 & (4.6341,1.9804,0.4521) \\ C_{11} & (5.0000,1.9220,0.4700) \\ C_{12} & (6.5864,2.2649,0.3698) \\ C_{21} & (4.6714,1.9745,0.4539) \\ C_{22} & (4.4086,2.0155,0.4406) \\ C_{31} & (5.5924,2.0157,0.4406) \\ C_{32} & (4.6864,1.9721,0.4547) \\ C_{33} & (4.0061,2.1820,0.4044) \\ C_{41} & (5.7667,2.0424,0.4316) \\ C_{42} & (5.7667,2.0424,0.4316) \\ C_{43} & (5.0000,2.0424,0.4316) \\ C_{51} & (5.3833,1.9831,0.4512) \\ C_{52} & (6.1500,2.1000,0.4110) \\ C_{53} & (5.3833,1.9831,0.4512) \\ C_{61} & (5.6765,2.0286,0.4363) \\ C_{62} & (5.0000,1.9220,0.4700) \end{bmatrix}$$

Step 3: Compute the normalized cloud difference d_{ij} of the remaining alternatives by using Eq. (9) and Algorithm 1, which are shown in Table 7. We take d_{11} as an example to explain the computation.

$$d_{11}=\frac{(10.0000,2.5980,0.1250)\ominus(5.4705,1.9967,0.4468)}{S(4.5295,3.2767,0.4640)}=(1.4047,\ 1.8247,\ 0.2584)$$

Step 4: Compute the values S_j and R_j of the remaining alternatives by using Eqs. (10)–(11) and Algorithm 1, which are shown in Table 8. We take S_1 as an example to explain the computation.

$$\begin{aligned} S_1 = {} & [0.0344\otimes(1.4047,\ 1.8247,\ 0.2584)\oplus 0.0273\otimes(0,\ 2.9139,\ 0.1402)\oplus\cdots \\ & \oplus 0.0403\otimes(0.5864,\ 1.8963,\ 0.1318)\oplus 0.0757\otimes(0.9778,\ 2.3991,\ 0.3459)\oplus \\ & 0.0842\otimes(0.2577,\ 2.3880,\ 0.1311)\oplus\cdots\oplus 0.0601\otimes(0,\ 1.9620,\ 0.0944)] \\ = {} & (0.2785,2.2866,0.2058) \end{aligned}$$

Step 5: Compute the value $\widetilde{Q}_i$ by Eq. (12) and Algorithm 1, which are shown as follows. In this case, the committee thought the overall benefit was as important as the individual regret, i.e. $v=0.5$. We take $\widetilde{Q}_1$ as an example to explain the computation.

$$\widetilde{Q_1} = \frac{0.5 \otimes [(0.2785, 2.2866, 0.2058) - (0.2785,2.2866,0.2058)]}{S(0.7480,2.2155,0.3346)} \oplus \frac{0.5 \otimes [(0.0685, 0.6350, 0.0916) - (0.0685,0.6350,0.0916)]}{S(0.0779,0.5452,0.1203)} = (0,4.0846,0.4725)$$

$\widetilde{Q_2} = (0.7525, 4.1293, 0.4467)$; $\widetilde{Q_3} = (1.1705, 4.0673, 0.4732)$; $\widetilde{Q_4} = (1.0667, 3.9402, 0.46$

Step 6: Transfer $\widetilde{Q_j}$,S_j and R_j into CN and rank the alternatives. We use Algorithm 1 to convert the cloud variables into CN shown in Table 9. According to the corresponding CNs of $\widetilde{Q_j}$,S_j and R_j, the final ranking is as follows.

$$A_{\widetilde{Q(1)}} > A_{\widetilde{Q(2)}} > A_{\widetilde{Q(4)}} > A_{\widetilde{Q(3)}}$$

$$S_{\widetilde{Q(1)}} > S_{\widetilde{Q(2)}} > S_{\widetilde{Q(4)}} > S_{\widetilde{Q(3)}}$$

5. Results and discussion

The utility threshold value is $1/(J-1) * S(\widetilde{Q^{(*)}} \ominus \widetilde{Q^{(-)}}) = 0.2877$. According to the aforementioned judgment standards and rules, it is found that A_1 is weakly superior to A_2, A_2 significantly superior to A_4, and A_4 weakly superior to A_3. That is to say, the final order relation is:$A_1 > A_2 > A_4 > A_3$, with A_1 the best supplier.

5.1. Comparison analysis

In this study, we propose an extended VIKOR method under linguistic information for supplier selection in quality-sensitive industry. The results gained by the proposed method are reasonably creditable and approved by the DMs. In order to verify the correctness and advantages of the proposed method, we make a comparison with an extended VIKOR with TFNs proposed by Opricovic [90]. We use the method [90] to solve the supplier selection in quality-sensitive industry for further explaining the importance of using cloud variables to express the criteria or sub-criteria information. The weights of criteria or sub-criteria in Table 4 are used to ensure the comparability of results. Based on the data and information in Section 4, the results and ranking are gained and shown in Table 10 by using the method [90].

According to Table 10, the ordering of the alternatives is prioritized as $A_1 > A_2 > A_3 > A_4$. It is found that A_1 is the best alternative, followed by A_2, which is consistent with the results gained by the extended method in this paper. However, the worst alternative is changed to A_4 instead of A_3.

From Tables 5 and 6, A_1 has the second best quality performances. And compared with other alternatives, A_1's overall performances of the non-quality criteria are the best, with the performances of many sub-criteria the best, such as C_{21}, C_{22}, C_{62}, C_{31}, C_{33} and C_{53}, etc. Only C_{11} and C_{41} show poor and need to be improved greatly. Thus, A_1 has a considerable advantage and competitiveness. For A_2, it has the best quality performances. However, A_2's overall performances of the non-quality criteria are poor, especially maintenance and repair cost (C_{22}) and ability of disruption management (C_{43}). When comprehensive consideration, A_2's quality advantage would be weakened. A_3 has poor quality performances. And A_3's maintenance and repair cost (C_{22}), after-sales service quality (C_{32}) and desire for business (C_{33}) are the worst aspects, with the overall performance of the non-quality criteria the worst. Thus, A_3 becomes pretty poor. Although A_4 has the worst quality performances, A_4's overall performances of the non-quality criteria are the second best, with capability of R & D (C_{12}), environmental measures (C_{62}) and financial stability (C_{52}) better.

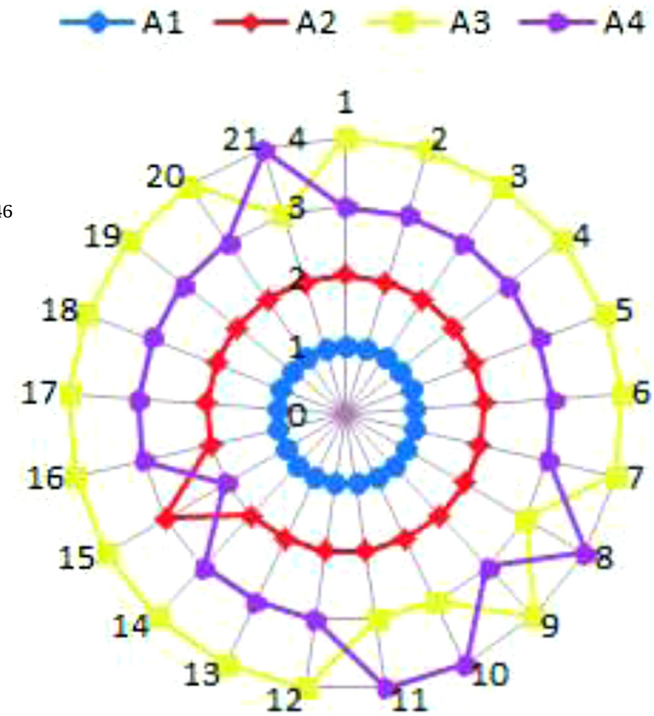

Fig. 2. Sensitivity analysis.

The disadvantage of quality performances in A_4 can be compensated by the advantages of non-quality criteria.

Based on the above analysis, it is found that the ranking gained by the extended method in this paper, i.e., $A_1 > A_2 > A_4 > A_3$, is more precise and reliable than the result produced in the comparison. We can explain the above results as follows: the method in the comparison ignores the randomness, which means it assesses the alternatives out of considering the average level as the sole criterion. However, the cloud variable considers not only the average levels of evaluation information but also the fluctuation and stability which are depicted by *En* and *He*, respectively.

5.2. Sensitivity analysis

In order to evaluate the stability of the evaluation model, the committee analyzed the sensitivity by switching any two weights of Q, C_1–C_6, with the others being the same as before [91]. The whole results of sensitivity analysis are shown in Table 11. According to Fig. 2, It is found that A_1 and A_2 are always the best and the second best suppliers respectively except the situation (NO.15). Under the situation (NO.15), the weight of C_6 increases by about seventy percent, which strengthens the advantages of A_4 compared with A_2. Overall, the evaluation results are almost $A_1 > A_2 > A_4 > A_3$. Based on the above analysis, DMs can draw a conclusion that the evaluation model in this paper has a strong robustness to choose the best one from multiple alternatives.

6. Conclusions

In this study, the paper proposes the extended VIKOR based on cloud model for supplier selection in nuclear power industry, which is the first work attempted to use this technique for supplier selection. The extended VIKOR can rank and select the best one from a set of alternatives. The cloud variable is used to define criteria, sub criteria and their uncertain weights, which can handle well imprecise information. The extended method is based on the aggregating

Table 9
The corresponding CNs of $\widetilde{Q}_j$, S_j and R_j.

	A_1	A_2	A_3	A_4
$\widetilde{Q}_j$	0.0291	0.5371	0.8119	0.7530
S_j	0.1996	0.5965	0.7217	0.5094
R_j	0.0469	0.0708	0.0848	0.1055

Table 10
The results of all alternatives.

	A_1	A_2	A_3	A_4
$\widetilde{Q}_j$	0	0.4491	0.7230	0.7857
S_j	0.0936	0.2833	0.3911	0.2636
R_j	0.0268	0.0378	0.0456	0.0691
Ranking	A1 > A2 > A3 > A4			

Table 11
The whole results of sensitivity analysis.

No.	Weight of criteria	Ranking
	Q(0.1699);C1(0.1599);C2(0.1707);C3(0.1077);C4(0.1658);C5(0.1257);C6(0.1003)	A1 > A2 > A4 > A3
1	Q(0.1599);C1(0.1699);C2(0.1707);C3(0.1077);C4(0.1658);C5(0.1257);C6(0.1003)	A1 > A2 > A4 > A3
2	Q(0.1707);C1(0.1599);C2(0.1699);C3(0.1077);C4(0.1658);C5(0.1257);C6(0.1003)	A1 > A2 > A4 > A3
3	Q(0.1077);C1(0.1599);C2(0.1707);C3(0.1699);C4(0.1658);C5(0.1257);C6(0.1003)	A1 > A2 > A4 > A3
4	Q(0.1658);C1(0.1599);C2(0.1707);C3(0.1077);C4(0.1699);C5(0.1257);C6(0.1003)	A1 > A2 > A4 > A3
5	Q(0.1257);C1(0.1599);C2(0.1707);C3(0.1077);C4(0.1658);C5(0.1699);C6(0.1003)	A1 > A2 > A4 > A3
6	Q(0.1003);C1(0.1599);C2(0.1707);C3(0.1077);C4(0.1658);C5(0.1257);C6(0.1699)	A1 > A2 > A4 > A3
7	Q(0.1699);C1(0.1707);C2(0.1599);C3(0.1077);C4(0.1658);C5(0.1257);C6(0.1003)	A1 > A2 > A4 > A3
8	Q(0.1699);C1(0.1077);C2(0.1707);C3(0.1599);C4(0.1658);C5(0.1257);C6(0.1003)	A1 > A2 > A3 > A4
9	Q(0.1699);C1(0.1658);C2(0.1707);C3(0.1077);C4(0.1599);C5(0.1257);C6(0.1003)	A1 > A2 > A4 > A3
10	Q(0.1699);C1(0.1257);C2(0.1707);C3(0.1077);C4(0.1658);C5(0.1599);C6(0.1003)	A1 > A2 > A3 > A4
11	Q(0.1699);C1(0.1003);C2(0.1707);C3(0.1077);C4(0.1658);C5(0.1257);C6(0.1599)	A1 > A2 > A3 > A4
12	Q(0.1699);C1(0.1599);C2(0.1077);C3(0.1707);C4(0.1658);C5(0.1257);C6(0.1003)	A1 > A2 > A4 > A3
13	Q(0.1699);C1(0.1599);C2(0.1658);C3(0.1077);C4(0.1707);C5(0.1257);C6(0.1003)	A1 > A2 > A4 > A3
14	Q(0.1699);C1(0.1599);C2(0.1257);C3(0.1077);C4(0.1658);C5(0.1707);C6(0.1003)	A1 > A2 > A4 > A3
15	Q(0.1699);C1(0.1599);C2(0.1003);C3(0.1077);C4(0.1658);C5(0.1257);C6(0.1707)	A1 > A4 > A2 > A3
16	Q(0.1699);C1(0.1599);C2(0.1707);C3(0.1658);C4(0.1077);C5(0.1257);C6(0.1003)	A1 > A2 > A4 > A3
17	Q(0.1699);C1(0.1599);C2(0.1707);C3(0.1257);C4(0.1658);C5(0.1077);C6(0.1003)	A1 > A2 > A4 > A3
18	Q(0.1699);C1(0.1599);C2(0.1707);C3(0.1003);C4(0.1658);C5(0.1257);C6(0.1077)	A1 > A2 > A4 > A3
19	Q(0.1699);C1(0.1599);C2(0.1707);C3(0.1077);C4(0.1257);C5(0.1658);C6(0.1003)	A1 > A2 > A4 > A3
20	Q(0.1699);C1(0.1599);C2(0.1707);C3(0.1077);C4(0.1003);C5(0.1257);C6(0.1658)	A1 > A2 > A4 > A3
21	Q(0.1699);C1(0.1599);C2(0.1707);C3(0.1077);C4(0.1658);C5(0.1003);C6(0.1257)	A1 > A2 > A3 > A4

cloud merit $\widetilde{Q}_j$ representing the distance of an alternative to the ideal solution.

When applied to a case from China, the extended method shows excellent suitability. The DMs can well understand the decision-making process and results through the linguistic (cloud) data. Finally, the best supplier received recognition from DMs. In conclusion, this proposed extended method can be utilized to solve the comprehensive and multi-constrained optimal selection problem with clear and effective management process. For the industry which needs to focus on some specific criteria, the two-phase extended method will show good practicability and advantage. In the practical management problems, the managers should pay more attention to the suitability of the methods and the efficiency of management process.

Acknowledgements

Project supported by the Fundamental Research Funds for the Central Universities (No.2015XS27), the National Nature Science Foundation of China (No.71271085).

Appendix A.

Basic concept and properties of the clouds are outlined.

Assume that there are two clouds$A(Ex_1, En_1, He_1)$ and $B(Ex_2, En_2, He_2)$, some operations between cloud A and cloud B can be defined as follows:

$$A+B=\left(Ex_1+Ex_2,\ \sqrt{En_1^2+En_2^2},\ \sqrt{He_1^2+He_2^2}\right) \quad \text{(i)};$$

$$A-B=\left(Ex_1-Ex_2,\ \sqrt{En_1^2+En_2^2},\ \sqrt{He_1^2+He_2^2}\right) \quad \text{(ii)};$$

$$A\times B=\left(Ex_1\times Ex_2,\ \sqrt{(En_1Ex_2)^2+(En_2Ex_1)^2},\ \sqrt{(He_1Ex_2)^2+(He_2Ex_1)^2}\right) \quad \text{(iii)};$$

$$\lambda A=\left(\lambda Ex_1,\ \sqrt{\lambda}En_1,\ \sqrt{\lambda}He_1\right) \quad \text{(iv)};$$

$$A^{\lambda}=\left(Ex_1{}^{\lambda},\ \sqrt{\lambda}Ex_1^{\lambda-1}En_1,\ \sqrt{\lambda}Ex_1^{\lambda-1}He_1\right) \quad \text{(v)}.$$

The cloud model represents linguistic concepts with three numerical characteristics, which realize the objective and interchangeable transformation between qualitative concepts and quantitative values.

Given the numerical characteristics and applied forward normal cloud generator, n cloud drops $\langle(x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)\rangle$ can be generated. Then the estimated $\hat{s}$ of cloud A is as follows. With regard to two clouds A and B, if $\hat{s}(A) \geq \hat{s}(B)$, then $A \geq B$.

$$\hat{s}(A) = \frac{1}{n}\sum_{i=1}^{n} x_i y_i$$

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