A multi-criteria decision-making framework for electric vehicle supplier selection of government agencies and public bodies in China

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Abstract
Electric vehicle deployment shows promising potentials in promoting cleaner energy utilization and reducing carbon emission. Due to increasing carbon neutral pressure and market competition from transportation sector, government agencies and public bodies (GAPBs) have emphasized the significance of electric vehicle adoption through supplier selection. Consequently, GAPBs must consider a reasonable criteria system and a comprehensive supplier selection framework and rationally select the electric vehicle supplier that matches their practical needs in terms of economic, social, environmental, and technical factors. This paper provides insights into electric vehicle supplier selection (EVSS) from the perspective of GAPBs using an integrated multi-criteria decision-making (MCDM) framework based on best–worst method (BWM) and fuzzy ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR). Initially, 14 critical factors from economic, social, environmental, and technical dimensions are identified as the criteria by literature review and experts’ opinions. Then, a comprehensive decision framework using the integrated MCDM approach is proposed. To validate the applicability and feasibility of the proposed framework, a case study is launched and analyzed. It emerges that bad environmental record, cost, quality, service, and environmental initiatives are the most important criteria in EVSS for GAPBs with the weight values of 0.1995, 0.1172, 0.1219, 0.0708, and 0.2553. The comparative analysis and the sensitivity analysis are performed for verifying the reliability of the proposed framework. The work helps to understand the electric vehicle supplier selection criteria and makes methodological decision-making support for GAPBs.

Keywords Multi-criteria decision-making · Electric vehicle · Supplier selection

Introduction
Transportation sector electrification is believed to be an effective solution to reduce greenhouse gas emission and raise the environmental awareness of residents (Zhang and Fujimori 2020; Zhang and Hanaoka 2021). Countries around the world have built a series of policies and regulations to support renewable energy development concerning electric vehicle (EV), including China (Xiong et al. 2021), USA (Linn and McConnell 2019), Ghana (Ayetor et al. 2020), and so on. Global EV sales increased by more than 40% to 3 million by 2020 accompanied by powerful policy support and incentives from European Union and China (IEA 2021). As the largest CO2 emitter of the world, China has set a carbon neutral target by 2060, which releases an overwhelming signal for transportation electrification and clean energy utilization.

Apart from strong encouraging policies for automakers and consumers, obligations have been imposed on government agencies and public bodies (GAPBs) to promote the electrifying process of the public sector (Ziemba 2020). According to Implementation Plan of New Energy Vehicles Purchase of Government Agencies and Public Bodies, GAPBs in China are encouraged to choose several technology alternatives to promote and apply EVs, including
battery EVs, plug-in hybrid EVs and fuel-cell EVs (The State Council of the PRC 2014). The implementation plan also pointed out that battery EVs were recommended in relatively fixed routes of urban areas and plug-in hybrid EVs were recommended in alpine areas. Faced with available EVs and their suppliers, building a structure to evaluate EV supplier’s performance and accordingly select the suitable supplier remains one of the urgent challenges for GAPBs. Studies have investigated relevant problems for GAPBs concerning government investment in charging infrastructure (Dwyer et al. 2021), market penetration with government incentives (Gong et al. 2020), and so on. Nevertheless, there is a research gap in discussing the determining factors and decision-making processes that influence whom the GAPBs select as the most appropriate EV supplier from available competing alternatives, or whether the supplier selection (SS) decision of GAPB are impacted by economic, social, environmental, or technical factors. In this context, we try to answer the following research questions: (1) What are the influencing factors in decision-making process of EVSS? (2) How to weight the criteria and rank the alternative suppliers with a multi-criteria decision-making method?

To address problems mentioned above, it is necessary to propose an appropriate model for EVSS of GAPBs to identify internal and external influencing factors in decision-making and recognize the outstanding suppliers from the perspective of long-term partnership. The paper is innovative in terms of the following aims:

- This paper aims to identify multiple dimension of influencing factors of EVSS through a comprehensive literature review and experts’ opinions. The proposed criteria system can strongly support the practical decision-making of GAPBs when selecting a proper EV supplier. No previous research has been found to study the EVSS problem from the perspective of GAPBs.
- This paper aims to rank the influencing factors in the basis of the criteria system of EVSS for GAPBs, the criteria and sub-criteria weights are determined with the best–worst method (BWM). In this way, decision makers of GAPBs are able to set or adjust their judgements on the criteria and sub-criteria accordingly.
- This paper aims to select the optimal EV supplier for GAPBs in the basis of their economic, social, environmental, and technical performance with the integrated decision framework using BWM and fuzzy ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), which provides an applicable and suitable decision-making tool for both the suppliers and the decision makers from the GAPBs.

Selecting potential alternatives for the government can be depicted with bundles of characteristics or attributes (Melese and Fan, 2020), which make it a typical multi-criteria decision-making (MCDM) question (Schramm et al. 2020) involving various criteria, including EV encouraging incentives, environment impact, research and development investment, economy, etc. Incomplete consideration of such criteria might impede the rational application of EV fleet in GAPBs, and a poor decision over the EVSS may further affect residents’ EV purchasing choices. To address this problem, a widespread application of MCDM techniques has been found their applicability and advantages (Abdel-Basset et al. 2021; Wang et al. 2018a), which can finely processed the ambiguity of linguistic criteria and uncertainty of criteria weights (Liu et al. 2019) and solve different types of complex problems. Hernandez et al. (2020) used a MCDM framework to select the order picking strategies. Hosseinzadeh et al. (2020) provided an investigation on service selection with the MCDM method.

MCDM has proved its capability and robustness in evaluation or selection decision-making problems, including sustainability performance assessment (Niu et al. 2018; Wu et al. 2019a), site selection (Li et al. 2020; Zhang et al. 2019a) and SS (Ambrin et al. 2021; Baki 2021). With respect to SS, different methods have been adopted. Liaqait et al. (2021) combined an analytical hierarchy process (AHP) and the technique for order of preference by similarity to ideal solution (TOPSIS) to choose the sustainable supplier. Wu et al. (2019b) discussed the green SS problem with the BWM and the VIKOR methods. Nevertheless, current research may still be limited on EVSS concerning the urgent needs of GAPBs. Thus, it is of great importance to establish a scientific framework to reasonably address this problem.

Even though quantities of researches on SS have been processed with MCDM, there still exist some difficulties in practical applications. On one hand, information loss exists in traditional selection methods that use linguistic terms to express the uncertain and random evaluation information since the decision-making of mankind is naturally fuzzy (Lu et al. 2019). On the other hand, most of the decision-making procedures of GAPBs are started with experts’ judgements over both the criteria system and the evaluation, but difficulties exist for experts to present their preference degrees with crisp numbers. Therefore, fuzzy logic theory is necessary to convert linguistic variables into crisp numbers and solve the MCDM problems. Additionally, a comprehensive MCDM method helps to select the most appropriate supplier based on the evaluation results, but efforts should be made to launch a deep discussion on major criteria as well. For example, one supplier ranks the first among all alternatives does not mean that it performs the best in terms of the key criteria.

Consequently, several improvements have been made from following aspects: (1) We construct a comprehensive criteria system for EVSS with a literature review and expert
interview, which can help understand the cause-effect relationship between factors and supplier performance; (2) We investigate the EVSS problem for GAPBs with a rational MCDM-based framework, wherein the BWM and the fuzzy VIKOR are respectively used to obtain the criteria weights and achieve the solution; (3) To deal with uncertain and fuzzy information, fuzzy set theory put forward by Zadeh (1975) is applied to process linguistic variables. The paper’s main objective is identifying the SS criteria in accordance with practical EV adoption requirements of GAPBs and constructing a comprehensive EVSS framework to help recognize the outstanding suppliers from alternatives with a MCDM method. Obtained criteria system provides a deep understanding among various factors and the constructed model provides a selection framework for decision makers of GAPBs.

Contributions of the work are some folds: First, since rare literature regards the EVSS needs of GAPBs, the paper can fill in the research gap and enrich the investigation perspectives of SS and EV. Second, identifying influencing factors and determining the relationships between criteria can help to form a clearer and more specific understanding of indicators of EVSS, which contributes to increasing decision-making efficiency of GAPBs and satisfies the practical needs of GAPBs. Third, a MCDM approach is proposed wherein the BWM provides the criteria weights and the fuzzy VIKOR is adopted to prioritize and select the EV suppliers, then a case study in China is applied to implement the proposed approach and assess the performance of alternatives through providing a ranking order. Last but not the least, criteria identification and the proposed approach would be more suitable in GAPB domain and more general in complicated MCDM fields.

The rest of the work is established as follows. A literature review is introduced in the “Literature review” section concerning criteria and methodologies of EVSS. The “Method” section discusses the criteria system of EVSS for GAPBs. The “Decision framework of EVSS” section illustrates the research framework and related methodologies. A case study using the proposed model and the discussions are presented in the “Results and discussions” section. The conclusions are obtained in the “Conclusions” section.

Literature review

Criteria for supplier selection

The requirements for sustainable and green practices in EV industry and public service administrations are becoming urgent and acute. GAPBs are responsible for promoting transportation section electrification and improving sustainable and environmental awareness as a whole; thus, EVSS for GAPBs has to face cost and quality pressures alongside with potential environmental and social benefits of clean production application. As a result, the conventional SS field should be extended considering specific requirements of GAPBs, including economic, social, environmental, and technical attributes.

Criteria identification and criteria system construction must be done before evaluation procedure. With the global awareness of clean and sustainable environmental development, SS has become an important issue and the green-related and environmental criteria were widely discussed. Therefore, the attention of the EVSS for GAPBs should not only focus on traditional selection criteria but also consider new environmental and sustainable needs. Usually, scholars prefer determining the criteria for SS problem from economic, environmental, and social aspects (Baki 2021; Gören 2018; Liaqait et al. 2021). Kumar and Barman (2021) believed that environment friendly materials and environment friendly technology were necessary indicators in criteria construction. Saputro et al. (2022) figured out that quality, cost, and delivery are usually adopted criteria, and technology factors and environment-related factors were measured as well. Rahman et al. (2022) believed that there was a need to improve green-related factors with the increasing awareness of environment sustainability. Table 1 outlines the criteria used in decision problems related to SS.

Previous studies have made numerous attempts in SS field or green/sustainable-related field, but there is no research has been found to construct a criteria system for EVSS decision-making regarding specific consideration of GAPBs, which makes the paper innovative. Thus, this paper constructs a comprehensive EVSS criteria system from four abovementioned aspects, wherein the sub-criteria would satisfy the specific requirements and actual demands of GAPBs. The details of criteria and sub-criteria will be discussed in the “Decision framework of EVSS” section.

MCDM methods about supplier selection

Since the SS remains a complex MCDM problem involving multiple aspects of attributes, numerous MCDM methodologies have been used to solve this kind of problems. Most of the related research about SS focus on three perspectives, i.e., methods to determine the criteria weights, methods to select the optimal supplier, and methods to handle data description. Therefore, different methodology combinations were found to get the appropriate solutions.

With respect to weights determination methods, subjective methods and objective methods are commonly used (Wu et al. 2020b). Du and Gao (2020) used the entropy weight method and the analytical hierarchy process (AHP) to calculate the criteria weights. Wei (2021) applied the AHP in multi-criteria weight calculation process. Since
the decision makers of GAPBs prefer to express their knowledge and expertise with ambiguity and uncertainty, an applicable and flexible method for weight determination can better fit the data processing requirements of EVSS. The BWM identifies the best (most satisfactory or most important) and the worst (most unsatisfactory or least important) criteria as the base, and then conducts pairwise comparisons to describe the significance of different criteria. The BWM was put forward in 2015 (Rezaei 2015); it has achieved much attention for its advantages in short pairwise comparison time and high consistency performance. Dwivedi et al. (2021) constructed a performance assessment model for insurance company with the BWM method. Subotić et al. (2020) tried to solve location selection problem with the help of the integrated BWM-based approach. Hosseini Dehshiri et al. (2022) proposed a MCDM approach using BWM for assessing the criteria in automotive industry supply chain. Previous results indicated that BWM technique performed better in consistency ratio, conformity, and other indicators. What is more, BWM method is able to extra criteria weights under fuzziness (Ecer and Pamucar 2020), which is in line with the needs of EVSS. Furthermore, to the best of our knowledge, no previous literature introduces BWM method in calculating the weights of SS problem for the GAPBs. As a result, the paper uses the BWM method in EVSS to fulfill the research gap and constructs a BWM-based evaluation framework for EVSS of GAPBs.

After determining the criteria weights, the problem comes to selecting the optimal solution from alternatives. Various MCDM techniques are used to deal with SS, such as VIKOR (Kumar and Barman 2021; Wu et al. 2019a), TOPSIS (Afrasiabi et al. 2022; Ambrin et al. 2021), ANP (Khan et al. 2018), and so on. Yu et al. (2019) used TOPSIS technique to rank the alternatives from the perspective of sustainability. Fei et al. (2019) proposed an elimination and choice translating reality (ELECTRE)-based method to analyze the relations among different alternatives. Table 2 illustrates the MCDM methods used in SS field. Among them, VIKOR approach has been commonly used in MCDM field and its application has been diversified in various fields. Therefore, the paper chooses VIKOR as the MCDM algorithm to address the SS problem of GAPBs. The paper first follows the steps of multi-criteria decision-making and then integrates the BWM and VIKOR methods to construct the evaluation framework for EVSS of GAPBs.
feasibility were verified. Abdulkareem et al. (2020) suggested that using VIKOR in solving MCDM problems was highly recommended. Thus, it is reasonable for the paper to introduce VIKOR in EVSS to rank the alternatives.

Regarding SS using BWM and VIKOR, researchers have found its applicability. Gul et al. (2022) used Bayesian BWM and fuzzy VIKOR to study the control measures in risk assessment. Li et al. (2018) chose a AHP-VIKOR method to evaluate the competition ability of power generation companies considering fuzzy conditions. Celik et al. (2021) combined BWM and TODIM for selecting green supplier for textile industry. Yucesan et al. (2019) adopted an integrated BWM-TOPSIS method to help make decisions. Karami et al. (2021) applied a VIKOR-based approach to evaluate and select the supplier in the garment supply chain. Shang et al. (2022) explored the use of BWM method for SS problem in sustainable supply chains. Vardin et al. (2021) integrated BWM and VIKOR into a decision support model for choosing the optimal contractor in construction projects. Although BWM and VIKOR are used in solving SS problem in various fields, their application in determining criteria weights and ranking suppliers in EVSS field for GAPBs remains nebulous.

According to the research operational modeling of EVSS, we propose a MCDM method integrated by the BWM and the fuzzy VIKOR to provide a structured multi-criteria modeling framework. The methods we adopted in this paper has several advantages:

- **BWM helps decision makers obtain a proper understanding of the items on the basis of the best and worst factors before determining the pairwise comparison, which improves the procedure’s precision and efficiency. Compared with AHP, which is another popular weighting method but has some drawbacks, such as lack of consistency (Mi et al. 2019) and relatively complicated comparison procedures (Yucesan et al. 2019), BWM uses simple vectors to construct pairwise comparisons and calculate the consistency effectively.**
- **Researches showed that VIKOR can obtain the ranking orders of alternatives considering immeasurable and conflicting criteria (Li et al. 2022) and objectivity in decision-making (Gao et al. 2020), which makes it an appropriate choice in the presence of EVSS decision-making.**
- **The MCDM framework based on combination of BWM and fuzzy VIKOR helps to make the EVSS of GAPBs reliable and flexible, which provides a powerful and proper tool for decision makers of GAPBs.**

Regarding decision-making procedures of GAPBs, experts’ opinions are usually considered and their preferences are expressed along with inherent ambiguity and vagueness. Thus, linguistic variables, such as **Very High, High, Medium, Low,** and **Very Low,** are introduced. Consequently, many problems, including criteria information processing, importing data fuzziness and criteria weights determination, should be carefully handled (Liu et al. 2019). To better decrease the adverse impacts of information ambiguity, the work utilizes the fuzzy theory and triangular fuzzy numbers (TFNs) to make it easier to represent supplier’s performances. In recent literature about decision making, TFN has been used as the most popular method among fuzzy numbers in a series of fields. Meanwhile, integrating TFN with VIKOR as the ranking method, i.e., fuzzy VIKOR, also finds it application in previous research. Ecer and Pamucar (2020) believed that the BWM approach was a suitable decision-making tool. Hosseini et al. (2021) developed a fuzzy VIKOR framework to evaluate several recovery solutions for ecotourism centers with respect to complex attributes during the COVID-19 pandemic. Koppiahraj et al. (2021) used the fuzzy VIKOR method to effectively select ergonomics assessment methods.

### Table 2 The main MCDM techniques used in supplier selection

| Methods                          | Application fields                                      | Authors                  |
|----------------------------------|--------------------------------------------------------|--------------------------|
| VIKOR                            | Electric vehicle charging infrastructure supplier selection | Zhang et al. 2019b       |
| VIKOR-Sort                       | Green supplier selection regarding environmental performance | Demir et al. (2018)     |
| Interval type-2 fuzzy BWM, VIKOR | Green supplier selection                               | Wu et al. (2019b)        |
| BWM, fuzzy TOPSIS               | Organization performance assessment                     | Gupta (2018)             |
| BWM, TOPSIS                     | Green supplier selection of steel industry             | Ooroonji Mohammad Javad et al. (2020) |
| HCA, VIKOR                      | Water resources carrying capacity evaluation            | Yang et al. (2021)       |
| ELECTRE                         | Supplier selection under vague environment             | Lu et al. (2018)         |
| Fuzzy AHP, PROMETHEE            | Sustainable supplier selection of transportation section | Roy et al. (2020)        |
| Interval type-2 fuzzy sets, AHPSort II | Sustainable supplier selection under fuzzy environment | Xu et al. (2019b)        |
The analysis shows that BWM and fuzzy VIKOR methods are suitable for solving MCDM problems. However, the research on using MCDM methods in SS field related to EVs is limited and there is no detailed analysis of available research focused on specific characteristics of GAPBs. What is more, the EVSS problem regarding GAPBs has not yet been investigated by an integrated approach involving ambiguity/inaccuracy input variables, criteria weights determination with the BWM and alternative ranking with the fuzzy VIKOR. This makes the paper’s novelty regarding the present research. Thus, this paper tries to address the gaps and enrich the application range by implementing BWM and fuzzy VIKOR in dealing with EVSS problem of GAPBs.

Method

TFN

Fuzzy set theory was proposed by Zadeh in 1965 to deal with linguistic terms in practical applications. In a fuzzy set, various membership functions are available for use (such as TFN, interval type-2 fuzzy numbers, etc.). One major advantage of TFN is ability to transform criteria significance into fuzzy numbers, which is more practical since specific data and information of EVSS problem in real world is unknown and uncertain (Xu et al. 2019a). Let $\tilde{m}$ be the a TFN, then $\tilde{m} = [m^L, m^M, m^U]$ and $0 \leq m^L \leq m^M < m^U \leq 1$. The membership function of $\tilde{m}$ is denoted by $\mu_{\tilde{m}}(y)$ and expressed as follows (Zhou et al. 2019):

$$
\mu_{\tilde{m}}(x) = \begin{cases} 
0, & \text{if } x < m^L \\
(x - m^L) / (m^M - m^L), & \text{if } m^L \leq x \leq m^M \\
(m^U - x) / (m^U - m^M), & \text{if } m^M \leq x \leq m^U \\
0, & \text{if } x > m^U
\end{cases}
$$

(1)

where $m^L$, $m^M$, $m^U$ represent the lower, mean, and upper limits of $\tilde{m}$, respectively.

The operations of TFNs $\tilde{m} = [m^L, m^M, m^U]$ and $\tilde{n} = [n^L, n^M, n^U]$ can be obtained as follows (Kumar and Barman 2021):

\[
\tilde{m} + \tilde{n} = (m^L + n^L, m^M + n^M, m^U + n^U)
\]

(2)

\[
\tilde{m} - \tilde{n} = (m^L - n^L, m^M - n^M, m^U - n^U)
\]

(3)

\[
\tilde{m} \times \tilde{n} = (m^L \times n^L, m^M \times n^M, m^U \times n^U)
\]

(4)

\[
\tilde{m} \times n = (m^L \times n^L, m^M \times n^M, m^U \times n^U)
\]

(5)

After determination of criteria and sub-criteria, the next step comes to calculate the criteria weights. A series of methods have been investigated in weight calculation, including AHP, ANP, DEMETAL, etc. (Celik and Akyuz 2018; Fei et al. 2019). The BWM was developed by Rezaei to provide more reliable results with fewer comparisons and less importing data (Rezaei, 2015). This method has shown brilliant performance on applications (Sagnak et al. 2021; Wankhede and Vinodh 2021). The BWM considers ambiguity and certainty exit in human qualitative judgments, and uses a 1–9 scale for pairwise comparison and calculation, i.e., “1” and “9” respectively represents the best and the worst preference rating (Dwivedi et al. 2021; Oroojeni Mohammad Javad et al. 2020). The executing steps of BWM are illustrated as follows (Guo and Zhao 2017; Rezaei 2015):

Step 1: Suppose the criteria set of $n$ criteria is $C_j (j = 1, 2, \ldots, n)$, then respectively denote the best and the worst criteria with $C_B$ and $C_W$.

Step 2: Give preference rating on $C_B$ over other criteria (the best-to-others) with pairwise comparison considering the scale of 1–9 (Oroojeni Mohammad Javad et al. 2020). Therefore, the comparison matrix can be constructed as follows:

$$
\tilde{A}_{BTO} = (\tilde{a}_{BTO1}, \tilde{a}_{BTO2}, \ldots, \tilde{a}_{BTON})
$$

(7)

where $\tilde{A}_{BTO}$ represents the best-to-others comparison matrix. $\tilde{a}_{BTOj} (j = 1, 2, \ldots, n)$ is the preference rating of criterion $C_B$ over criterion $C_j$. According to Rezaei (2015), $\tilde{a}_{BTOj} = 1$ shows that $C_B$ and $C_j$ are equally important and $\tilde{a}_{BTOj} = 9$ shows that criterion $C_B$ is extremely important than criterion $C_j$.

Step 3: Similarly, construct the others-to-worst pairwise comparison matrix $\tilde{A}_{OTW}$ as:

$$
\tilde{A}_{OTW} = (\tilde{a}_{1OTW}, \tilde{a}_{2OTW}, \ldots, \tilde{a}_{nOTW})
$$

(8)
where $\tilde{A}_{OTW}$ is the others-to-worst comparison matrix and $\tilde{a}_{OTW1}$ is the preference rating of criterion $C_j$ over the worst criterion $C_W$.

Step 4: Calculate the criteria weights $\tilde{W} = (w_1, w_2, \cdots, w_n)$. The optimal weight of criterion $C_i$ should satisfy certain conditions, namely $w_B/w_j = \tilde{a}_{BTOW}$ for pair $w_B/w_j$ and $w_W/w_j = \tilde{a}_{OTW}$ for pair $w_W/w_j$ (Liang et al. 2021). Consequently, it is necessary to achieve a solution $\theta$ that satisfies conditions of all criteria and addresses the following Eqs. (9)–(10):

$$\min \max_j \theta$$

$$\theta = \left\{ \left| w_B/w_j - \tilde{a}_{BTOW} \right|, \left| w_W/w_j - \tilde{a}_{OTW} \right| \right\}$$

where the sum of all criteria weights is 1 and the criteria weight should be a real number range between $[0, 1]$, $\sum \theta_i = 1$.

Step 5: Solve Eqs. (9)–(10) to obtain the criteria weights $\tilde{W}$ and solution $\theta$, where $\theta$ is the consistency ratio. Besides, the smaller $\theta$ value is, the more reliable result becomes.

### Fuzzy VIKOR

VIKOR was developed by Opricovic (1998) and has been widely used in various fields, such as sustainability evaluation (Tian et al. 2020), etc. VIKOR is capable of achieving a compromise solution regarding multiple dimensions of criteria by measuring the alternatives’ closeness to the ideal solution with easy computation steps. The compromise solution is the closest solution to the ideal one and it indicates this technique ranks the alternatives by compromising between the most expected and unexpected solutions (Cah and Balaman, 2019). Generally, it is difficult to select an optimal subject that satisfies all criteria simultaneously, so obtaining an appropriate compromise solution with VIKOR might be preferred (Wang et al. 2018b). Since linguistic terms are introduced in providing experts’ preferences on alternatives, uncertainty and ambiguity should be well handled. Thus, TFN is combined and the fuzzy VIKOR method is then applied to handle the uncertain and fuzzy multi-criteria EVSS problem considering different conflicting criteria. Fuzzy VIKOR takes the LP-metric as the original formula for starting operations, as Eq. (11) illustrates:

$$M_{Pi} = \left\{ \sum_{i=1}^{n} w_i (S^+_j - S^-_j)/(S^+_j - S^-_j) \right\}^{1/p}$$

s.t.

$$1 \leq p \leq +\infty$$

Here, $M_{Pi}$ represents the dimension between $i$ $\text{-th}$ alternative and the ideal solution; $S^+_j$ is the solution of $i$ $\text{-th}$ alternative over criterion $C_j$; $(S^+_j$ and $S^-_j$ is respectively the positive and negative ideal solutions over criterion $C_j$; $w_j(i = 1, 2, \cdots, n)$ is the weight of criterion $C_j$.

Step 1: Denote the supplier alternative set, the criteria set and the initial judgement matrix by $A = A_i(i = 1, 2, \cdots, m)$, $C = C_j(j = 1, 2, \cdots, n)$, and $D = D_i(i = 1, 2, \cdots, m)$. Normalize matrix $D_i$ and get the normalized judgement matrix $F_i$ as follows:

$$F_i = \begin{bmatrix}
A_1 & f_{11} & f_{12} & \cdots & f_{1n} \\
A_2 & f_{21} & f_{22} & \cdots & f_{2n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
A_n & f_{n1} & f_{n2} & \cdots & f_{nn}
\end{bmatrix}$$

where $f_{ij} = (\tilde{f}_{ij}^L, \tilde{f}_{ij}^M, \tilde{f}_{ij}^U)$ is the TFN transformed from linguistic term and represents the assessment judgement on $i$ $\text{-th}$ alternative respecting $j$ $\text{-th}$ criterion.

Step 2: Determine the positive ideal $f^*_i = (\tilde{f}_{ij}^{L^*}, \tilde{f}_{ij}^{M^*}, \tilde{f}_{ij}^{U^*})$ and negative ideal $f^-_i = (\tilde{f}_{ij}^{L^-}, \tilde{f}_{ij}^{M^-}, \tilde{f}_{ij}^{U^-})$ values of all criteria. Since criteria types can be divided into the cost type and the benefit type, the computation of different criteria types should be distinguished to eliminate interference:

$$f^*_i = \max_j f_{ij}$$

and

$$f^-_i = \min_j f_{ij}$$

with Eqs. (15)–(16):

$$S_i = \sum_{j=1}^{n} (w_j \otimes \tilde{a}_{ij})$$

$$R_i = \max_j (w_j \otimes \tilde{d}_{ij})$$

Step 3: Calculate $S_i = (\tilde{S}^L_i, \tilde{S}^M_i, \tilde{S}^U_i)$ and $R_i = (\tilde{R}^L_i, \tilde{R}^M_i, \tilde{R}^U_i)$ with Eqs. (15)–(16):

$$\tilde{d}_{ij} = \frac{d(f^*_i, f_{ij})}{d(f^*_j, f^-_j)}$$

where $\tilde{d}_{ij}$ is the difference of $f_{ij}$ and $f^*_i$, as Eq. (17) shows. The distance $\tilde{d}_{ij}$ between TFNs $f_{ij}$ and $f^*_i$ is obtained with Eq. (18).

$$d(f^*_i, f_{ij}) = \sqrt{\frac{1}{3} \left[ (\tilde{Q}^{L^*}_i - \tilde{Q}^{L}_{ij})^2 + (\tilde{Q}^{M^*}_i - \tilde{Q}^{M}_{ij})^2 + (\tilde{Q}^{U^*}_i - \tilde{Q}^{U}_{ij})^2 \right]}$$

Step 4: Compute the value $Q_i = (\tilde{Q}^L_i, \tilde{Q}^M_i, \tilde{Q}^U_i)$ in the basis of $S_i$ and $R_i$.
\[ Q_j = v \frac{S_i - S^*}{S^* - S^-} + (1 - v) \frac{R_i - R^*}{R^- - R^*} \]

Here, \( S^* = \min_i R_i \), \( S^- = \max_i S_i \), \( R^* = \min_i R_i \), and \( R^- = \max_i R_i \); \( v \) is used to represent the maximum group utility as the weight while \((1 - v)\) indicates that of the individual section. Let \( v = 0.5 \) in the work.

Step 5: Rank alternatives \( A_i (i = 1, 2, \cdots, m) \) with \( S_i, R_i \), and \( Q_i \) values in an ascending order. Since \( Q_i \) measures the magnitude separated from the optimal one (Liang et al. 2021), the smaller \( Q_i \) value is believed to be a better choice. According to the ranking order with respect to \( Q_i \) value, obtain the order denoted by \( Q_{1 \leq i \leq 6} \).

Step 6: \( Q(Q_{p2}) - Q(Q_{p1}) \geq 1/(m - 1) \)

Step 7: \( Q_{p1} \) remains the optimal solution according to ranking orders of \( S_i \) or/and \( R_i \).

It is noteworthy that if condition 1 and condition 2 cannot be fully met, the optimal solution contains a set of alternatives:

(i) If condition 2 is not satisfied, set \( Q_{p1} \) and \( Q_{p2} \) as the optimal solutions;
(ii) If condition 1 is not satisfied, calculate \( Q_{p1} - Q_{p2} < 1/(m - 1) \) to get the maximum \( r \) and determine the number of the optimal solutions, i.e. \( Q_{p1}, Q_{p2}, Q_{p2}, Q_{p2} \).

**Decision framework of EVSS**

There exists limited research on EVSS for GAPBs; thus, it is absolutely necessary to build a feasible decision framework for this objective considering practical needs of GAPBs. This section proposes an integrated MCDM framework in the basis of theoretical methods and application steps

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**Results and Discussions**

1. Results analysis based on criteria ranking results and supplier selection results.
2. Comparative analysis with other techniques.
3. Sensitivity analysis regarding criteria weight variations.

**Fig. 1** Flowchart of the proposed decision framework of EVSS
discussed in previous sections, and its flowchart is shown in Fig. 1. The proposed framework uses a MCDM approach composed by BWM and fuzzy VIKOR to conduct efficient analysis, and the procedure steps of the proposed BWM-fuzzy VIKOR method are discussed as follows:

Step 1: Identify the criteria and sub-criteria

Before selecting the EV supplier for GAPBs, a panel of experts are invited to obtain consistency in the research’s purpose. Therefore, literature review, target group interview and experts’ opinions are simultaneously conducted to check and confirm the criteria. The premises and assumptions for identifying the criteria system and EV suppliers are based on several points:

1. Traditional criteria for SS problem and criteria used in general industry should be considered, such as cost, quality, service, and so on.
2. Green-related and sustainable-related criteria and sub-criteria should be given enough attention since promoting clean energy application from the transportation section and public section are irreversible trends.
3. The criteria system should comprehensively consider specific characteristics of EV companies, GAPBs, and SS problems.
4. Alternative suppliers should restrain good records in providing public service and easy availability of EVs.

As a result, four groups of criteria with a total of 14 sub-criteria $C = C_j (j = 1, 2, \ldots, n)$ are identified, as Table 3 illustrates, and their brief descriptions are provided as well.

Step 2: Compute the criteria weights with the BWM method

On the basis of the criteria system, experts reach consensus on the significance of each criterion and figure out the best criterion $C_B$ and the worst criteria $C_W$ over other criteria.
with respect to the paper’s purpose. Then, construct the best-to-others pairwise comparison matrix $\tilde{A}_{BTO}$ and the others-to-worst pairwise comparison matrix $A_{OTW}$ with a scale of 1–9. Solve Eqs. (9)–(10) to compute the criteria weights and analyze corresponding consistency ratio.

Step 3: Construct the decision matrix and process data with TFNs.

Three experts $Ek (k = 1, 2, 3)$ from local government, transportation organization and research institute are invited to make decisions on the alternatives $A = A_i (i = 1, 2, \cdots, m)$ with linguistic terms (see Table 4). Process the obtained data with TFNs, construct the decision matrix $D_i^k$ of expert $Ek$ and then aggregate each expert’s decision into one matrix $D_i$ with Eq. (20).

$$D_i = (D_i^1 + \cdots + D_i^k)/k$$

Step 4: Select the optimal solution with the fuzzy VIKOR.

Generally speaking, traditional VIKOR method can only solve complicated MCDM problems with crisp variables, so it is crucial to transform linguistic terms into TNFs to make them fit in. Therefore, the fuzzy VIKOR presented in previous section is introduced to address the problem more fluently and efficiently.

On the basis of step 3, normalize the aggregated decision matrix $D_i$ and get the normalized matrix $F_i = (f_{ij})$, wherein $f_{ij} = (\tilde{f}_{ij}^L, \tilde{f}_{ij}^M, \tilde{f}_{ij}^U)$. Compute the positive ideal $f^*_i = (\tilde{f}_{i}^L, \tilde{f}_{i}^M, \tilde{f}_{i}^U)$ and negative ideal $f^-_i = (\tilde{f}_{i}^L, \tilde{f}_{i}^M, \tilde{f}_{i}^U)$ of all criteria with Eq. (13). According to Eqs. (14)–(17), calculate the values of $S_i = (\tilde{S}_{i}^L, \tilde{S}_{i}^M, \tilde{S}_{i}^U)$. $R_i = (\tilde{R}_{i}^L, \tilde{R}_{i}^M, \tilde{R}_{i}^U)$ and $Q_i = (\tilde{Q}_{i}^L, \tilde{Q}_{i}^M, \tilde{Q}_{i}^U)$. Rank the alternative suppliers $A_i (i = 1, 2, \cdots, m)$ in an ascending order, and finally decide the optimal solution/solutions considering certain conditions.

Step 5: Further discussions.

To verify the feasibility and robustness of proposed framework, sensitivity analysis, and comparative analysis are conducted. As to the sensitivity analysis, it is carried to simulate the influences caused by criteria weight changes, and the results help to understand different criteria and their significance in selecting a qualified supplier. The comparative analysis adopts two widely-used MCDM methods, i.e., TOPSIS and PROMETHEE II, to recalculate the importing data and then compares the results.

Results and discussions

Background information

The upward development of EVs is irreversible and determined, GAPBs as one major representative role in electrification of public sector are accelerated to make EVSS problem more reliable and feasible. The promotion speed of EV application has been raised, and the significance of SS issue has been further emphasized. In the case, the GAPBs are the direct customer and the EV manufacturers are the alternative suppliers. For reasonable and feasible EVSS, decision makers must use a reliable framework to assess all necessary requirements of GAPBs and understand how each manufacturer can satisfy corresponding requirements. Under this background, applying a EVSS framework to rank alternative suppliers can help GAPBs to make reasonable choices and encourage EV suppliers to improve economic, social, environmental, and technical performances.

In this case, three suppliers $A_i (i = 1, 2, 3)$ are chosen as alternatives. Supplier A1 is a domestic EV brand in China, it supplies 4 major models currently and its annual revenue in 2020 reached 16.258 billion yuan. A1 has showed outstanding market attraction and has been listed in the sentinel procurement catalogue for municipal administrative institutions of Beijing. Alternative A2 is a Sino-Japan joint company and mainly sales fuel vehicles, it supplies one EV model in China and has released its ambition in promoting electrification. A3 is developed by Chinese traditional vehicle brand and focuses on open-style designs, it sold 12,745 cars in 2020 and the number increased by 380.4%. Although all alternatives have their unique characteristics, it is necessary to carry out a comprehensive decision-making to rank alternative suppliers for GAPBs with the proposed BWM-fuzzy VIKOR approach.

Results

Data acquisition

Setting up a panel of experts is an effective and common way to choose the optimal supplier for GAPBs, thus experts’ opinions and choices are important to the results. We strictly invite experts with wide academic
background or rich management experience to obtain opinions and judgements based on several characteristics with the topic’s concern: (i) managing and processing relevant purchasing issues in the local government, (ii) working as a manager/supervisor in the transportation organization with rich experience on EV, and (iii) owning outstanding scientific research ability and several research findings about EV. Subsequently, three experts $Ek(k = 1, 2, 3)$ from local government, transportation organization and research institute are invited to provide their opinions.

Although several criteria (such as cost, charging time, and so on) can be illustrated with quantitative numbers, their accuracy might be ambiguous to some degree (Wu et al. 2020a). Therefore, this work collects the data with the help of linguistic terms and then transform them into computable data with TFNs. Experts determine the opinions from two perspectives: (i) weight determination with the BWM method. On the basis of the criteria system, experts need to compare criteria’s significance and reach consensus on the best criteria $C_B$ and the worst criteria $C_W$. After that, they are asked to conduct pairwise comparisons with a scale of 1–9. (ii) Supplier assessment with the proposed BWM-fuzzy VIKOR approach. As a result, the criteria/sub-criteria pairwise comparison results and the assessment results of alternatives’ performance are obtained (the details of the results are shown in the Appendix section).

**Supplier selection**

Step 1: Compute criteria weights with BWM.

As discussed above, experts’ opinions were collected and pairwise comparisons with respect to criteria were built, where the best and worst criteria among main criteria and sub-criteria were also identified. Accordingly, construct the comparison matrix and use Eqs. (9)–(10) to compute the criteria weights; thus, the results are obtained as illustrated in Table 5.

Based on the criteria weights, the information about the significance and the relationship among 4 main criteria and 14 sub-criteria can be observed. With respect to main criteria, the economic factor (C1) is believed to be the most significant one and has the greatest impacts on EVSS, and its weight is 0.4703. Besides, the economic factor is a vital indicator for purchasers to assess relevant productions and suppliers. The environmental factor (C3) remains the second one with a weight of 0.3533 and this is because GAPBs attach importance to environment issues. As a result, decision makers should pay enough attention to these criteria to select EV suppliers rationally. Meanwhile, the difference between these two criteria is not so obvious. The technical factor (C4) ranks the third with the weight of 0.1176. Compared with traditional vehicles, EV shows unique technical requirements, including reasonable battery lifetime and flexible charging period. The least important main criterion is social factor (C2). In regard to sub-criteria, bad environmental record (C32) under environmental dimension is the most critical one in the criteria

| Criteria | Sub-criteria | Weights | Global weights | Ranking | Global ranking |
|----------|--------------|---------|----------------|---------|----------------|
| Economic (C1) | Cost (C11) | 0.4242 | 0.1995 | 1 | 2 |
| | Service (C12) | 0.2493 | 0.1172 | 3 | 4 |
| | Quality (C13) | 0.2591 | 0.1219 | 2 | 3 |
| | Flexibility (C14) | 0.0674 | 0.0317 | 4 | 8 |
| Social (C2) | Responsibility (C21) | 0.4476 | 0.0263 | 1 | 10 |
| | Satisfaction (C22) | 0.2238 | 0.0132 | 4 | 13 |
| | Trust (C23) | 0.3286 | 0.0193 | 3 | 11 |
| Environmental (C3) | Environmental initiatives (C31) | 0.2004 | 0.0708 | 2 | 5 |
| | Bad environmental record (C32) | 0.7226 | 0.2553 | 1 | 1 |
| | Environment friendly performance (C33) | 0.0769 | 0.0272 | 3 | 9 |
| Technical (C4) | Security (C41) | 0.3048 | 0.0358 | 2 | 7 |
| | Battery lifetime (C42) | 0.5133 | 0.0604 | 1 | 6 |
| | Charging time (C43) | 0.124 | 0.0146 | 3 | 12 |
| | Innovation capability (C44) | 0.0579 | 0.0068 | 4 | 14 |
system. It can be seen from global ranking result that cost
(C11), quality (C13), and service (C12) under economic
dimension respectively ranks the second to the fourth. That
is to say, these criteria make contributions to choosing a
proper vehicle and selecting the corresponding suppliers.
Environmental initiatives (C31) and battery lifetime (C42)
also have nonnegligible impacts on determining the opti-
mal alternative.

Step 2: Construct and process the decision matrix with
TFNs.

On the basis of the supplier performance assessment
results, transform each expert’s decision into TFNs
with the linguistic scale in Table 4. Aggregate them
with Eq. (20) and thus the processed decision results
are obtained (see Table 6).

Step 3: Select the optimal solution with fuzzy VIKOR.

First of all, apply Eqs. (13) and (14) in calculating the
positive and negative ideal values with the aggregated deci-
sion matrix (the obtained values are listed in the Appendix
section).

Second, compute the distance \(d_{ij}\) with Eqs. (14)–(17), and
then obtain \(S_i, R_i\), and \(Q_i\) values of each alternative with Eqs.
(15) and (16), and the results are shown in Table 7.

Finally, rank the alternative suppliers with an ascending
order of \(Q_i\), namely \(Q_2 < Q_1 < Q_3\); thus, \(Q_2\) has the mini-
mum value. According to the ranking, obtain the new order
\(Q_i(i = 1, 2, 3) = (Q_2, Q_1, Q_3)\). Since \(Q(Q_{g2}) - Q(Q_{g1}) \geq 0.5\)
and \(Q_{g1}\) still has the minimum value regarding ranking order
of \(S_i\); conditions (1) and (2) are fully satisfied; A2 can be
determined the optimal EV supplier. A2 owns an efficient
EV supply chain and rich automobile production experience,
it provides high quality vehicles with relatively low price.

### Table 6 Aggregated decision matrix with TFNs

| Criteria | A1         | A2         | A3         |
|----------|------------|------------|------------|
| C11      | (0.40, 0.60, 0.80) | (0.20, 0.40, 0.60) | (0.33, 0.53, 0.73) |
| C12      | (0.40, 0.60, 0.80) | (0.73, 0.93, 1.00) | (0.20, 0.40, 0.60) |
| C13      | (0.33, 0.53, 0.73) | (0.60, 0.80, 0.93) | (0.13, 0.33, 0.53) |
| C14      | (0.27, 0.47, 0.67) | (0.67, 0.87, 0.93) | (0.07, 0.27, 0.47) |
| C21      | (0.20, 0.40, 0.60) | (0.60, 0.80, 0.93) | (0.27, 0.47, 0.67) |
| C22      | (0.40, 0.60, 0.80) | (0.47, 0.67, 0.87) | (0.20, 0.40, 0.60) |
| C23      | (0.27, 0.47, 0.67) | (0.47, 0.67, 0.87) | (0.33, 0.53, 0.73) |
| C31      | (0.47, 0.67, 0.87) | (0.73, 0.93, 1.00) | (0.33, 0.53, 0.73) |
| C32      | (0.07, 0.20, 0.40) | (0.00, 0.00, 0.20) | (0.07, 0.27, 0.47) |
| C33      | (0.27, 0.47, 0.67) | (0.60, 0.80, 1.00) | (0.27, 0.47, 0.67) |
| C41      | (0.67, 0.87, 0.93) | (0.67, 0.87, 1.00) | (0.40, 0.60, 0.80) |
| C42      | (0.33, 0.53, 0.73) | (0.60, 0.80, 0.93) | (0.33, 0.53, 0.73) |
| C43      | (0.00, 0.13, 0.33) | (0.00, 0.00, 0.20) | (0.20, 0.40, 0.60) |
| C44      | (0.33, 0.53, 0.73) | (0.60, 0.80, 1.00) | (0.40, 0.60, 0.80) |

### Table 7 Calculation results of alternative supplies

|   | A1         | A2         | A3         |
|---|------------|------------|------------|
| \(S_i\) | 0.6454 | 0.0 | 0.8403 |
| \(R_i\) | 0.1995 | 0.0 | 0.2553 |
| \(Q_i\) | 0.7748 | 0.0 | 1.00    |

Facing the environmental, economic, and technical chal-
denges, A2 has shown outstanding responsiveness and flex-
ibility. Therefore, the EVSS result is in line with the practi-
cal situation. On the basis of \(Q_i\), it can be concluded that the
selection priority of alternative suppliers is \(A2 > A1 > A3\).

### Discussions

EVSS currently receives attentions from GAPBs because of
the increasing global concerns for developing clean energy
and reducing environmental pollutions. Meanwhile, EVSS
can effectively help to increase public satisfaction by pro-
moting electrification, reducing cost and improving deci-
sion-making efficiency. The results offer evidence support-
ing that the proposed criteria system and decision framework
are capable to select proper EV suppliers concerning charac-
teristics of GAPBs. To further analyze the robustness of the
proposed method, the paper conducts a sensitivity analysis
and a comparative analysis.

### Sensitivity analysis

The sensitivity analysis is carried out by assigning differ-
ent criteria weights. Compared with the original weights,
criteria and corresponding sub-criteria will be increased or
decreased by 10% and 15%. Thus, 5 groups of weights are
used: (i) group G1, criteria weights remain unchanged and
G1 is used as the reference group; (ii) group G2, sub-criteria
weights of economic dimension decrease and increase by
15%; (iii) group G3, sub-criteria weights of social factors
decrease and increase by 15%; (iv) group G4,
sub-criteria weights of environmental factors decrease and increase by 15%; and (v) group G5, sub-criteria weights of technical dimension respectively decrease and increase by 15%. Thus, the weights are changed (the details of criteria weights variation are displayed in the Appendix section).

After setting different groups of weights, compute the SS results with the proposed decision framework of EVSS to get the \( S_j \) and \( R_i \) values; the results are shown in Fig. 2. Calculate \( Q_i \) value of each group and rank the suppliers for all groups, thus the results are obtained and the detail is shown in Fig. 3. The ranking orders of alternatives are achieved due to multiple criteria weights and the results change under different groups. As can be observed from Fig. 3, the supplier ranking orders under most of the groups remain the same and alternative A2 are believed to be the best choice when the criteria weight changes. Thus, the sensitivity results illustrate that the proposed decision framework of EVSS and the used methods are reliable and robust. Bearing in mind that the ranking of alternatives A1 and A3 are different considering the sub-criteria weights in G2 (State -15%), where cost (C11), service (C12), quality (C13), and flexibility (C14) of economic dimension decrease by 15%. Therefore, EV supplier A3 shows better performance than A1 if the significance of economic criteria is reduced. Except for this group, A1 has priority in decision-making of EVSS compared with A3.

Comparative analysis

To prove that the proposed decision framework is available and feasible, a comparative analysis based on the same case and importing data is carried out. For the sake of comparative discussion, two MCDM techniques including BWM-TOPSIS (Oroojeni Mohammad Javad et al. 2020) and BWM-PROMETHEE II (Kheybari et al. 2021) are applied. TOPSIS and PROMETHEE II are widely used in making complicated decisions, such as sustainability analysis (Samaie et al. 2020). According to data acquisition results, respectively apply BWM-TOPSIS and BWM-PROMETHEE II to rank the suppliers. Thus, the results are obtained and alternative EV suppliers are ranked (see Table 8). According to the comparative results, the ranking orders remain the same among three assessment techniques. To sum up, the proposed methodology considering BWM and fuzzy VIKOR can be employed to accurately select the suitable suppliers in real-world EVSS applications.

Although the ranking results in this case remain the same, but the proposed approach has showed novelties and advantages in addressing EVSS:

1. The VIKOR decides a compromise solution by offering a maximum group utility and a minimum regret (Kumar and Barman 2021), while the TOPSIS determines the optimal solution in the basis of the closeness coefficients. Particularly, the optimal one obtained by VIKOR methods always remains the closest to the ideal solution, i.e., the value of \( Q_i \) of the optimal alternative is always equal to 0, but the optimal one with the TOPSIS method is determined by the value of closeness coefficient, which cannot ensure that the obtained one is the closest to the optimal solution (Xu et al. 2017). Moreover, results obtained from TOPSIS ignore the relative significance between the ideal and the negative solutions (Wu et al. 2018), thus the calculation and results from VIKOR provide richer and more specific information about the alternative solutions. Last but not the least, traditional TOPSIS method has a significant shortcoming that changes of the alternatives, including alternative addition, removal and replacement, might lead to ranking order fluctuation, but this problem can be resolved by using a VIKOR-based framework (Raj Mishra et al. 2022).

2. The comparative analysis reveals that both the VIKOR and the PROMETHEE II have a distinct potential in selecting an optimal supplier for EVSS. It is noteworthy that only the maximum value of group utility is taken into account during the assessment calculation steps of

| Table 8 Comparative results |
|--------------------------------|
| BWM-VIKOR | Ranking order | BWM-TOPSIS | Ranking order | BWM-PROMETHEE II | Ranking order |
|-----------|---------------|------------|---------------|-----------------|---------------|
| A1        | 0.7748        | 2          | 0.4536        | 2               | -0.1611       | 2             |
| A2        | 0.0000        | 1          | 0.7378        | 1               | 0.5080        | 1             |
| A3        | 1.0000        | 3          | 0.3773        | 3               | -0.3469       | 3             |
PROMETHEE II method. Comparatively, the VIKOR method makes up for this disadvantage by considering both the maximum utility and the minimum regret simultaneously. Therefore, a VIKOR-based framework can better describe decision makers’ preference and have more trustworthiness.

3. In other pairwise comparison-based techniques, single vector or full vector matrices are introduced, wherein the former tries to simplify data collection and the latter wants to provide richer information. However, we can neither check the consistency ratio of a single vector-based comparison matrix nor improve the calculation efficiency since a full vector matrix might ask too many questions and make decision makers confused (Hosseini Dehshiri et al. 2022). On the contrary, the BWM can perfectly solve these problems since it simplifies the complexity of data collection and enables clear computation of the consistency of the comparison matrix (Rezaei 2020). In addition, the BWM helps to identify the best and the worst criteria among all the criteria and sub-criteria, which offers clear and unambiguous descriptions on various influencing factors of EVSS.

In conclusion, the new findings of this paper contributing to EV studies are outlined as follows:

1. We construct a comprehensive and stable criteria system for EVSS of GAPBs, which enriches the research perspective of EV studies and satisfies practical decision-making needs of GAPBs. The criteria system focuses not only on the traditional factors of decision making of SS and EV, such as quality, cost, charging time, etc., but also on some specific characteristics the government, thus factors like trust and bad environmental record are taken into consideration.

2. The present paper proposes an effective and efficient decision framework with the integrated MCDM approach for EVSS of GAPBs, which remained nebulous in previous studies. Since the decision-making environment of EVSS in GAPBs is ambiguous and uncertain, the linguistic terms are used to help describe the alternative’s performance. Meanwhile, the proposed methodologies show advantages in simplified criteria weighting and robust alternative ranking; thus, the decision framework can be easily applied for decision making for EVSS.

3. Since EVs play a positive role in greenhouse gas emission reduction and climate change mitigation, EVSS is becoming the norm for GAPBs across the world, generating demand for related proposals. Thus, we provide some policy implications based on the findings of the paper.

Policy implications

The present study not only contributes to providing an effective framework of EVSS for GAPBs but also offering a reference for decision making in related SS and EV studies. This is important to help making strategies timely of GAPBs and avoiding probable decision-making errors. Based on the findings, we put forward some policy implications as follows.

1. The proposed decision framework within an integrated MCDM method is able to select the proper EV supplier for GAPBs. Herein, literature review, group interview and experts’ opinions can be applied to explore and identify the criteria regarding EVSS practices and characteristics of GAPBs. Experts also assess alternative suppliers’ performances based on their experience and knowledge and express their judgments with linguistic variables, and a flexibility application of the integrated MCDM methodology combing the BWM and fuzzy VIKOR can be conducive to EVSS by making use of their advantages.

2. Since different decision makers have different preferences and understandings, the comprehensive and easy-to-follow criteria set we constructed helps to ensure the smooth implementation of EVSS. Regarding the critical factors, economic, social, environmental, and technical criteria should be considered simultaneously, wherein their weights are 0.4703, 0.0588, 0.3533, and 0.1176, respectively.

3. As climate change mitigation has become a worldwide consensus, bad environmental record (C32) from environmental dimension with a global weight of 0.2553 is believed to be the most significant criterion in EVSS. Similar to various SS-related research, economic performance is always the key to constructing a criteria system, cost (C11), quality (C13) and service (C12) from economic aspect should be paid enough attention. Moreover, suppliers should be awareness of other important factors to improve the overall performance, including environmental initiatives (C31), responsibility (C21), battery lifetime (C42), security (C41), and so on. Compared with SS problem in other fields, criteria and sub-criteria of technical dimension related to EVs, including security (C41), battery lifetime (C42), charging time (C43), and innovation capability (C44), have received more attention.

4. It is noteworthy that EV-related and climate change-related environment and policies are changing all the time, policymakers and decision-makers need to adjust the criteria and criteria weights accordingly. Furthermore, the weights of criteria and sub-criteria and the results of EVSS are greatly affected by experts’ opinions and judgments; thus, some obvious gaps between these opinions and judgements should be carefully processed.
Conclusions

EV has received much attention along with the growing interest and encouragement of clean and sustainable development. As a result, more and more GAPBs are rapidly increasing the proportion of EV in the whole fleet so that EVSS becomes an important decision-making problem. Successfully selecting the better supplier is often determined by the proper MCDM method. We propose an integrated MCDM method for EVSS combining BWM and fuzzy VIKOR. First, a comprehensive criteria system for EVSS is constructed from economic, social, environmental and technical aspects. Second, a decision framework is proposed to evaluate the performance of alternative EV suppliers and provide the ranking orders for decision-making. In the framework, the TFN is used to deal with linguistic variables, the BWM helps to determine the significance of criteria and sub-criteria, and the fuzzy VIKOR selects and ranks the alternatives. Third, three representative EV suppliers in China are chosen as alternatives in the case study, then the criteria weights calculation results and comprehensive ranking results are obtained by using the proposed decision framework. Fourth, we observe the selection result changes of EVSS through applying the proposed method when the criteria weights changes in several setting groups, and then a comparative analysis with two other methods is conducted to discuss the ranking results. Finally, from the results of the sensitivity analysis and the comparative analysis, it is concluded that the proposed method is feasible and robust in solving EVSS problem for GAPBs. We also put forward some policy implications for policymakers and decision makers based on the findings.

One of the limitations of the work is that the criteria and sub-criteria used for EVSS are limited due to data inadequacy. Since China’s policies and regulations about clean energy and EV are increasingly enhanced considering the challenges came from carbon neutral, the significance of different aspects of criteria will be dynamically influenced by more complicated factors (such as carbon reduction capability, responsiveness in market fluctuation, and so on). Meanwhile, more MCDM techniques can be employed for EVSS and comparative analysis, such as ELECTRE, Alpha-Discounting method, and so on. Therefore, future research may further discuss the internal relationships among different dimensions of criteria and improve the proposed methodology with other advanced techniques.

Appendix

Some tables are placed in this section to illustrate the data acquisition and supplier selection results (Tables 9, 10, 11, 12, 13, 14, 15 and 16).

| Table 9 | Main criteria pairwise comparison |
|---------|----------------------------------|
|         | Economic (C1) | Social (C2) | Environmental (C3) | Technical (C4) |
| Best-to-others | 1 | 7 | 2 | 5 | Best criteria: C1 |
| Others-to-worst | 9 | 1 | 7 | 3 | Worst criteria: C2 |

| Table 10 | Criteria pairwise comparison for economic (C1) |
|----------|-----------------------------------------------|
|          | Cost (C11) | Service (C12) | Quality (C13) | Flexibility (C14) |
| Best-to-others | 1 | 6 | 3 | 9 | Best criteria: C11 |
| Others-to-worst | 2 | 8 | 5 | 1 | Worst criteria: C14 |

| Table 11 | Criteria pairwise comparison for Social (C2) |
|----------|---------------------------------------------|
|          | Responsibility (C21) | Satisfaction (C22) | Trust (C23) |
| Best-to-others | 5 | 8 | 1 | Best criteria: C23 |
| Others-to-worst | 4 | 1 | 7 | Worst criteria: C22 |
### Table 12 Criteria pairwise comparison for environmental (C3)

| Criteria       | Environmental initiatives (C31) | Bad environmental record (C32) | Environment friendly performance (C33) |
|----------------|--------------------------------|---------------------------------|---------------------------------------|
| Best-to-others | 5                               | 1                               | 9                                     |
| Others-to-worst| 4                               | 8                               | 1                                     |

Best criteria: C32  
Worst criteria: C33

### Table 13 Criteria pairwise comparison for technical (C4)

| Criteria       | Security (C41) | Battery lifetime (C42) | Charging time (C43) | Innovation capability (C44) |
|----------------|----------------|------------------------|---------------------|-----------------------------|
| Best-to-others | 2              | 1                      | 5                   | 9                           |
| Others-to-worst| 6              | 8                      | 3                   | 1                           |

Best criteria: C42  
Worst criteria: C44

### Table 14 Supplier assessment results

| Criteria | A1 | A2 | A3 |
|----------|----|----|----|
|          | E1 | E2 | E3 | E1 | E2 | E3 | E1 | E2 | E3 | E1 | E2 | E3 | E1 | E2 | E3 |
| C11      | H  | M  | H  | H  | M  | M  | H  | M  | H  | C12 | H  | EH | M  | H  | EH | M  | H  | VH | M  |
| C12      | H  | EH | M  | H  | EH | M  | H  | VH | M  | C13 | H  | EH | L  | H  | VH | M  | H  | M  | C14 | M  | H  | M  | H  | EH | L  | M  | EH | L  |
| C21      | M  | EH | H  | L  | H  | M  | H  | VH | M  | C22 | VH | H  | M  | H  | VH | M  | H  | M  | C23 | H  | VH | H  | M  | H  | M  | H  | H  | M  |
| C31      | H  | EH | H  | H  | VH | H  | VH | EH | M  | C32 | L  | VL | M  | M  | VL | L  | M  | VL | L  |
| C32      | L  | VL | M  | M  | VL | L  | M  | VL | L  | C33 | H  | VH | H  | H  | VH | M  | M  | VH | M  |
| C41      | H  | VH | H  | H  | EH | H  | M  | VH | H  | C42 | M  | H  | M  | H  | VH | M  | H  | EH | H  |
| C42      | M  | H  | M  | H  | VH | H  | H  | EH | H  | C43 | VL | VL | M  | L  | VL | M  | L  | VL | M  |
| C43      | VL | VL | M  | L  | VL | M  | L  | VL | M  | C44 | M  | VH | H  | H  | VH | H  | H  | VH | H  |

### Table 15 Positive and negative ideal values

| Criteria | C11     | C12     | C13     | C14     | C21     | C22     | C23     |
|----------|---------|---------|---------|---------|---------|---------|---------|
| f<sup>+</sup><sub>i</sub> | (0.20, 0.40, 0.60) | (0.73, 0.93, 1.00) | (0.60, 0.80, 0.93) | (0.67, 0.87, 0.93) | (0.60, 0.80, 0.93) | (0.47, 0.67, 0.87) | (0.47, 0.67, 0.87) |
| f<sup>-</sup><sub>i</sub> | (0.40, 0.60, 0.80) | (0.20, 0.40, 0.60) | (0.13, 0.33, 0.53) | (0.07, 0.27, 0.47) | (0.20, 0.40, 0.60) | (0.20, 0.40, 0.60) | (0.27, 0.47, 0.67) |
| C31      | C32     | C33     | C41     | C42     | C43     | C44     |        |
| f<sup>+</sup><sub>i</sub> | (0.73, 0.93, 1.00) | (0.00, 0.00, 0.20) | (0.60, 0.80, 1.00) | (0.67, 0.87, 1.00) | (0.60, 0.80, 0.93) | (0.00, 0.00, 0.20) | (0.60, 0.80, 1.00) |
| f<sup>-</sup><sub>i</sub> | (0.33, 0.53, 0.73) | (0.07, 0.27, 0.47) | (0.27, 0.47, 0.67) | (0.40, 0.60, 0.80) | (0.33, 0.53, 0.73) | (0.20, 0.40, 0.60) | (0.33, 0.53, 0.73) |
Table 16  Criteria weights variation for sensitivity analysis

|       | G1 State 0% | G2 State 15% | G3 State 15% | G4 State 15% | G5 State 15% |
|-------|-------------|--------------|--------------|--------------|--------------|
| C11   | 0.200       | 0.170        | 0.229        | 0.201        | 0.198        | 0.216        | 0.183        | 0.203        | 0.196        |
| C12   | 0.117       | 0.100        | 0.135        | 0.118        | 0.116        | 0.127        | 0.108        | 0.120        | 0.115        |
| C13   | 0.122       | 0.104        | 0.140        | 0.123        | 0.121        | 0.132        | 0.112        | 0.124        | 0.119        |
| C14   | 0.032       | 0.027        | 0.036        | 0.032        | 0.031        | 0.034        | 0.029        | 0.032        | 0.031        |
| C21   | 0.026       | 0.030        | 0.023        | 0.022        | 0.030        | 0.028        | 0.024        | 0.027        | 0.026        |
| C22   | 0.013       | 0.015        | 0.011        | 0.011        | 0.015        | 0.014        | 0.012        | 0.013        | 0.013        |
| C23   | 0.019       | 0.022        | 0.017        | 0.016        | 0.022        | 0.021        | 0.018        | 0.020        | 0.019        |
| C31   | 0.071       | 0.080        | 0.061        | 0.071        | 0.070        | 0.060        | 0.081        | 0.072        | 0.069        |
| C32   | 0.255       | 0.289        | 0.221        | 0.258        | 0.253        | 0.217        | 0.294        | 0.260        | 0.250        |
| C33   | 0.027       | 0.031        | 0.024        | 0.027        | 0.027        | 0.023        | 0.031        | 0.028        | 0.027        |
| C41   | 0.036       | 0.041        | 0.031        | 0.036        | 0.036        | 0.039        | 0.033        | 0.030        | 0.041        |
| C42   | 0.060       | 0.068        | 0.052        | 0.061        | 0.060        | 0.065        | 0.055        | 0.051        | 0.069        |
| C43   | 0.015       | 0.017        | 0.013        | 0.015        | 0.014        | 0.016        | 0.013        | 0.012        | 0.017        |
| C44   | 0.007       | 0.008        | 0.006        | 0.007        | 0.007        | 0.007        | 0.006        | 0.006        | 0.008        |

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Data availability  The data used are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate  Not applicable.

Consent for publish  Not applicable.

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