



A Logarithmic lp Distance-Based Hybrid VIKOR-TOPSIS Decision-Making Method for Interval-Valued Fermatean Fuzzy Sets with Application to Battery Swap Station Site Selection for New Energy Vehicles

Zirui Li¹ and Huayong Zhang^{1,*}

¹ Engineering Ecology and Nonlinear Science Research Center, North China Electric Power University, Beijing 102206, China

SUMMARY: *This research provides a new distance measure, named logarithmic lp distance, for interval-valued Fermatean fuzzy sets (IVFFSs), which is utilized in a hybrid model of VIKOR-TOPSIS in order to solve the problem of multiple criteria decision-making regarding battery swap station location selection in new energy vehicle systems. This distance measure considers the membership and non-membership values cubed using logarithmic conversion, where the value of parameter p provides sensitivity adjustment capability. The measure strictly satisfies the properties of a conventional metric distance measure of non-negative values, symmetry, finiteness, and the triangular rule. Combining the closeness concept typical of TOPSIS and the regret approach associated with VIKOR leads to the application of the developed combined model to assess five station locations using six performance indices, two of which are related to NEV conditions, including NEV ownership coverage and charging facilities complementarity. It has been demonstrated that the optimal location for the station construction is the highway service area junction ($F = 1.0000$), regardless of different parameters and weights used. Cross-method comparisons further reveal that the proposed measure achieves finer discrimination among closely evaluated alternatives than its Euclidean and Hamming counterparts.*

KEYWORDS: *interval-valued Fermatean fuzzy sets; logarithmic lp distance; VIKOR-TOPSIS; multi-criteria decision-making; battery swap station site selection*

1 Introduction

The growing trend towards sustainable transport has led to the popularity of NEVs across the globe. Currently, China is the largest consumer of NEVs with sales amounting to 12.87 million units in 2024, reflecting an annual growth rate of 35.5%. Moreover, NEV sales represented approximately 41% of the total vehicle sales within the country. The growing number of EVs has resulted in concerns regarding the availability and distribution of energy replenishment facilities. The concept of battery swapping can be considered an alternative method of energy supply for NEVs, with notable benefits, such as shorter service times of approximately three minutes for each process and separation of ownership between the battery and the vehicle [1]. Despite the deployment of 4,443 battery swapping stations in China by the end of 2024, significant deficiencies still exist in terms of their geographical distribution relative to the demand for NEVs [2]. In this context, the selection of locations for

*vdc5636@outlook.com

<https://doi.org/10.65102/is20261276>

such stations poses a highly significant problem [3].

With respect to methodology, the choice of locations for battery swap stations is inherently an MCDM problem where several conflicting criteria such as traffic access, power supply capability, land cost, and environmental effect have to be considered together. The traditional MCDM methods include TOPSIS approach and the VIKOR approach, which have been widely used for facility location problems under the conditions of crisp environment and classical fuzzy environment [4, 5]. However, the uncertainty inherent in experts' subjective judgments during site assessment exceeds the representational capacity of conventional fuzzy sets. Although intuitionistic fuzzy sets and Pythagorean fuzzy sets have alleviated certain limitations of conventional fuzzy sets, their inherent constraints restrict the feasible evaluation space when decision-makers assign high degrees of membership and non-membership simultaneously. In order to overcome this drawback, FFS was developed with the restriction that the sum of the cubic forms of the membership grade and non-membership grade is less than or equal to one. IVFFS is an extended version of FFS and provides a much wider scope for modeling uncertain information. It allows membership grade and non-membership grade to be considered as intervals instead of crisp numbers [6, 7].

In the field of IVFFSs, several types of aggregation operators and decision-making approaches have emerged. Specifically, score functions, weighted aggregation operators [8], and multi-criteria decision making approaches like WASPAS and COPRAS [9] were designed within the scope of IVFFSs. Distance measures play a critical role in multi-criteria decision-making models, especially in TOPSIS and VIKOR approaches where distance measures determine the ordering of alternatives based on the distance from the ideal solution. Distance measures of Fermatean fuzzy sets, which consist of Hamming, Euclidean, and Hellinger-based measures [10], have demonstrated effectiveness in practical applications like green port assessment and low-carbon city evaluation [11]. However, these measures exhibit limited discrimination capability when distinguishing between alternatives with nearly similar values of their fuzzy assessments. Moreover, the ability to vary parameters of these models to suit varying circumstances is also not very flexible [12]. A logarithmic distance with a tunable parameter can address this limitation by enhancing discrimination among alternatives with closely valued assessments.

In light of this scenario, this paper presents an approach for the logarithmic l_p distance measure that operates in the domain of IVFFSs, along with a novel hybrid approach for decision-making by combining the VIKOR and TOPSIS methods, whereby the latter provides a ranking based on the closeness coefficient, whereas the former ensures optimization by maximizing the group utility and minimizing individual regrets. The proposed method is applied to the site selection problem of battery swap stations for new energy vehicles. The highlights of the research are listed below: (i) a new logarithmic l_p distance between IVFFSs that has proven to be a metric; (ii) an innovative application of the hybrid VIKOR-TOPSIS model which involves the use of the distance measure developed; and (iii) a realistic case study that shows the effectiveness of the hybrid VIKOR-TOPSIS method for designing the EV charging facilities for NEV implementation. The structure of the rest of this paper is outlined as follows: Methodology is explained in Section 2, the results are presented in Section 3, followed by the discussion and conclusions in Sections 4 and 5, respectively.

2 Methods

2.1 Interval-Valued Fermatean Fuzzy Sets and Logarithmic lp Distance

An interval-valued Fermatean fuzzy set (IVFFS) on a universe of discourse X is defined as A , where the interval membership degree $[\mu_a^L(x), \mu_a^U(x)] \subseteq [0,1]$ and interval non-membership degree $[v_a^L(x), v_a^U(x)] \subseteq [0,1]$ satisfy the constraint $(\mu_a^U)^3 + (v_a^U)^3 \leq 1$. This cubic constraint is more relaxed than the quadratic condition of interval-valued Pythagorean fuzzy sets and the linear condition of interval-valued intuitionistic fuzzy sets, substantially enlarging the feasible evaluation space. For an interval-valued Fermatean fuzzy number (IVFFN) $\alpha = ([\mu^L, \mu^U], [v^L, v^U])$, the score function and accuracy function are defined as:

$$(\mu_A^U(x))^3 + (v_A^U(x))^3 \leq 1 \quad (1)$$

$$S(\alpha) = \frac{(\mu^L)^3 - (v^L)^3 + (\mu^U)^3 - (v^U)^3}{2} \quad (2)$$

$$H(\alpha) = \frac{(\mu^L)^3 + (v^L)^3 + (\mu^U)^3 + (v^U)^3}{2} \quad (3)$$

The score function stands for the difference between the support of membership and non-membership, while the accuracy function indicates the general level of confidence. In comparison between two IVFFNs, α_1 is considered superior to α_2 if $S(\alpha_1) > S(\alpha_2)$; in the case where $S(\alpha_1) = S(\alpha_2)$, the superiority belongs to the α with a higher accuracy level. Basic operations under the framework of IVFFS are commutative and associative.

Building upon this framework, a logarithmic lp distance measure is introduced. For $\alpha_1 = ([\mu_1^L, \mu_1^U], [v_1^L, v_1^U])$ and $\alpha_2 = ([\mu_2^L, \mu_2^U], [v_2^L, v_2^U])$, the proposed measure is defined as:

$$d_{\log^p}(\alpha_1, \alpha_2) = \left\{ \frac{1}{4} \left[\left| \ln(1 + (\mu_1^L)^3) - \ln(1 + (\mu_2^L)^3) \right|^p + \left| \ln(1 + (\mu_1^U)^3) - \ln(1 + (\mu_2^U)^3) \right|^p \right] + \left[\left| \ln(1 + (v_1^L)^3) - \ln(1 + (v_2^L)^3) \right|^p + \left| \ln(1 + (v_1^U)^3) - \ln(1 + (v_2^U)^3) \right|^p \right] \right\}^{\frac{1}{p}} \quad (4)$$

where $p \geq 1$ is an adjustable parameter. Setting $p = 1$ yields a logarithmic Manhattan-type distance, while $p = 2$ produces a logarithmic Euclidean-type distance.

These criteria are based on four axioms that define the validity of this criterion. Non-negativity is implied by the non-negativity of absolute values and the monotonicity of the p-th root; $d_{\log^p} = 0$ equals zero when and only when $\alpha_1 = \alpha_2$. The symmetry axiom is built into the absolute value function. The boundedness criterion is provided by the Fermatean condition, limiting $\ln(1 + \mu^3)$ and $\ln(1 + v^3)$ to the range $[0, \ln 2]$; hence, the largest distance is $\ln 2$. For the triangle inequality, denoting the component-wise differences as ξ_k for $k = 1, \dots, 4$, the Minkowski inequality for lp norms yields $(\sum \xi_k^p)^{1/p} \leq (\sum |\xi_k - \eta_k|^p)^{1/p} + (\sum \eta_k^p)^{1/p}$, from which $d_{\log^p}(\alpha_1, \alpha_3) \leq d_{\log^p}(\alpha_1, \alpha_2) + d_{\log^p}(\alpha_2, \alpha_3)$ follows.

The logarithmic form offers two structural benefits over LP-distance formulations in general. Firstly, the nature of the logarithm as a concave function shrinks the effect of differences that are large and increases the effect of small differences, thus improving discrimination where options produce similar numerical results. Secondly, the parameter p

controls the extent to which the difference measure is sensitive to the biggest differences: the higher the value of p , the closer the behavior resembles Chebyshev distance.

2.2 Hybrid VIKOR-TOPSIS Method under IVFFSs

The TOPSIS approach rates alternatives based on how close they are to both the positive ideal solution and the negative ideal solution; hence, the technique provides a geometrical meaning. The VIKOR technique focuses on finding an acceptable solution which minimizes the utility loss of the whole community while minimizing the maximum regret of each individual. Each approach has some weaknesses when used individually. For example, the TOPSIS technique is purely compensatory and can therefore ignore bad rating in one important attribute, while VIKOR depends on the weight used in the technique. By combining the two techniques, compensatory aspect of TOPSIS and the non-compensatory nature of VIKOR are enhanced.

The proposed hybrid method is implemented through the following steps.

Step 1. Construct the interval-valued Fermatean fuzzy decision matrix $D = (d_{ij})_{m \times n}$, where m candidate sites are evaluated against n criteria. Each element $d_{ij} = ([\mu_{ij}^{\wedge}L, \mu_{ij}^{\wedge}U], [v_{ij}^{\wedge}L, v_{ij}^{\wedge}U])$ represents the aggregated IVFFN evaluation of site A_i under criterion C_j . When multiple experts participate, individual assessments are aggregated using the IVFFWA operator with Fermatean parameter $q = 3$.

Step 2. Determine the attribute weight vector $w = (w_1, w_2, \dots, w_n)$, satisfying $w_j \in [0,1]$ and $\sum w_j = 1$, reflecting the relative importance of each criterion.

Step 3. Identify the positive ideal solution (PIS) A^+ and negative ideal solution (NIS) A^- . For benefit-type criteria, the PIS component is the IVFFN with the highest score value across all alternatives and the NIS component is the one with the lowest; for cost-type criteria, the assignments are reversed.

Step 4. Compute the weighted logarithmic l_p distances from each alternative to the PIS and NIS:

$$D_i^+ = \sum_{j=1}^n w_j \cdot d_{\log^p}(d_{ij}, d_j^+), \quad D_i^- = \sum_{j=1}^n w_j \cdot d_{\log^p}(d_{ij}, d_j^-) \quad (5)$$

Step 5. Calculate the TOPSIS relative closeness coefficient:

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (6)$$

where values closer to 1 indicate stronger preference.

Step 6. Compute the VIKOR group utility value S_i , individual regret value R_i , and compromise index Q_i :

$$\begin{aligned} S_i &= \sum_{j=1}^n w_j \cdot \frac{d_{\log^p}(d_{ij}, d_j^+)}{d_{\log^p}(d_j^-, d_j^+)} \\ R_i &= \max_j \left[w_j \cdot \frac{d_{\log^p}(d_{ij}, d_j^+)}{d_{\log^p}(d_j^-, d_j^+)} \right] \\ Q_i &= v \cdot \frac{S_i - S^*}{S^- - S^*} + (1-v) \cdot \frac{R_i - R^*}{R^- - R^*} \end{aligned} \quad (7)$$

where $S^* = \min S_i$, $S^- = \max S_i$, $R^* = \min R_i$, $R^- = \max R_i$, and $v \in [0,1]$ balances group utility against individual regret. In this study, $v = 0.5$ is adopted, reflecting equal emphasis on both objectives.

Step 7. Derive the final integrated ranking score by combining both measures through linear fusion:

$$F_i = \lambda \cdot CC_i + (1 - \lambda) \cdot (1 - \tilde{Q}_i) \tag{8}$$

where $\tilde{C}C_i$ and \tilde{Q}_i are min-max normalized values, and $\lambda \in [0,1]$ controls the relative contribution of TOPSIS and VIKOR. The baseline value $\lambda = 0.5$ is adopted, and sensitivity to variations in λ is examined in Section 3.2. The alternative with the highest F_i is selected as the optimal site.

The complete procedure of the proposed method is illustrated in Figure 1.

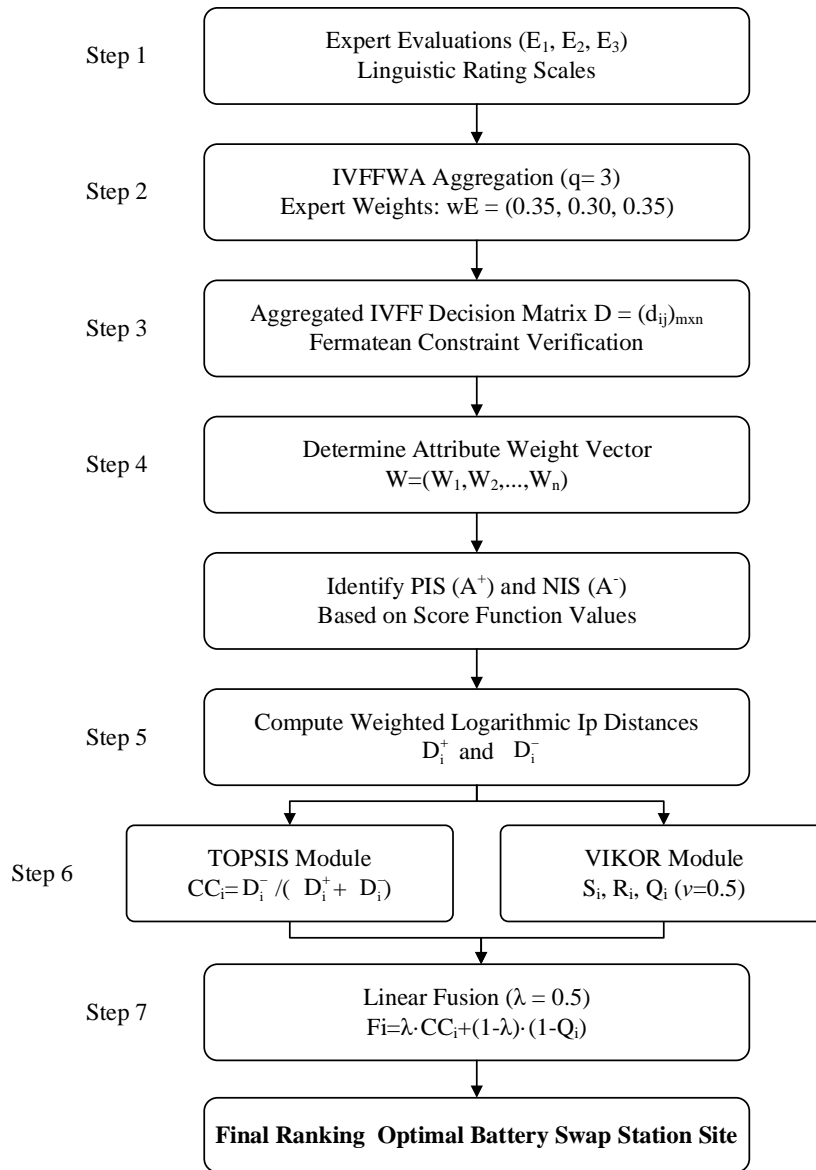


Figure 1: Flowchart of the proposed logarithmic lp distance-based hybrid VIKOR-TOPSIS decision-making method under interval-valued Fermatean fuzzy sets.

2.3 Case Description: Battery Swap Station Site Selection for NEVs

The application of the above methodological framework in practice can be demonstrated by using the example of a case study that aims to determine the optimal location for building battery swap stations for NEVs (new energy vehicles). Five potential locations were selected in the context of a medium-sized city in east China, taking into account the particularities of each location within an urban area and the corresponding scenario of the urban function: A_1 (city center commercial district), A_2 (suburban industrial park), A_3 (highway service area junction), A_4 (residential new town development), and A_5 (logistics and freight hub).

The evaluation criteria system is tailored to battery swap station planning requirements. As shown in Table 1, six criteria are adopted. Traffic accessibility (C_1) measures proximity to arterial roads and transit nodes. Power grid capacity (C_2) assesses available electrical load and network stability. Land cost (C_3) is the cost related to land acquisition. NEV ownership density (C_4) evaluates the number of registered new energy vehicles within the service radius defined. Complementarity of charging infrastructure (C_5) analyzes the compatibility with current charging facilities. Environmental impact (C_6) covers aspects including noise and environmental disruption. Among these criteria, C_1 , C_2 , C_4 , and C_5 are benefit-type criteria, while C_3 and C_6 are cost-type criteria.

Table 1: Evaluation criteria system for battery swap station site selection for new energy vehicles

| Criterion | Symbol | Type | Description |
|---------------------------------|--------|---------|----------------------------------------------------------------------|
| Traffic accessibility | C_1 | Benefit | Proximity to arterial roads, highway interchanges, and transit nodes |
| Power grid capacity | C_2 | Benefit | Available electrical load and distribution network stability |
| Land cost | C_3 | Cost | Acquisition or leasing expense of the candidate site |
| NEV ownership coverage | C_4 | Benefit | Density of registered NEVs within the projected service radius |
| Charging infra. complementarity | C_5 | Benefit | Synergy with existing charging piles and energy stations |
| Environmental impact | C_6 | Cost | Noise, visual intrusion, and ecological disruption |

Evaluation of the five potential sites by three domain specialists in urban transportation planning, power systems engineering, and NEV market analysis is carried out independently by means of linguistic scales transformed to IVFFNs. Expert weights $w_E = (0.35, 0.30, 0.35)$ are applied to aggregate expert judgments by means of IVFFWA ($q = 3$). After obtaining an aggregated matrix that complies with condition $(\mu^U)^3 + (v^U)^3 \leq 1$, it is entered as input data into the VIKOR-TOPSIS hybrid algorithm. Attribute weights $w = (0.20, 0.18, 0.12, 0.22, 0.15, 0.13)$ allocate the highest importance to NEV ownership rate because of demand-driven reasons.

3 Results

3.1 Ranking Results

The aggregated interval-valued Fermatean fuzzy decision matrix generated using the

IVFFWA operator, which considers the weight vector of experts as $w_E = (0.35, 0.30, 0.35)$, will serve as input for the proposed hybrid VIKOR-TOPSIS approach. All 30 numbers adhere to the Fermatean property, thereby validating the fuzzy information. The ideal solutions are defined using the score function of each criterion.

For $p = 2$, $v = 0.5$, and $\lambda = 0.5$, the lp distances, TOPSIS proximity measures, VIKOR values, and combined ranks for the decision alternatives were evaluated. These results are summarized in Table 2.

Table 2: Comprehensive ranking results of the proposed hybrid VIKOR-TOPSIS method ($p = 2, v = 0.5, \lambda = 0.5$)

| Alternative | D_i^+ | D_i^- | CC_i | S_i | R_i | Q_i | F_i | Rank |
|----------------|---------|---------|--------|--------|--------|--------|--------|------|
| A ₁ | 0.0766 | 0.1765 | 0.6974 | 0.3236 | 0.1322 | 0.1208 | 0.8946 | 2 |
| A ₂ | 0.1496 | 0.1088 | 0.4210 | 0.6042 | 0.1441 | 0.4663 | 0.4295 | 3 |
| A ₃ | 0.0658 | 0.1872 | 0.7400 | 0.2651 | 0.1200 | 0.0000 | 1.0000 | 1 |
| A ₄ | 0.1627 | 0.0899 | 0.3558 | 0.6369 | 0.2000 | 0.7792 | 0.2041 | 4 |
| A ₅ | 0.1819 | 0.0663 | 0.2672 | 0.7554 | 0.2200 | 1.0000 | 0.0000 | 5 |

As seen from Table 2, the resulting ranking is $A_3 > A_1 > A_2 > A_4 > A_5$. Thus, the junction of a highway service area (A₃) has the best overall rating ($F = 1.0000$) together with the greatest closeness coefficient ($CC = 0.7400$) and minimum compromise index ($Q = 0.0000$). This proves its higher effectiveness in terms of traffic access (C_1) and complementarity of charging facilities (C_5). A₁ Central business district represents the second priority area ($F = 0.8946$), being characterized by outstanding achievement with regard to the criterion of NEV coverage (C_4) but being burdened by expensive land (C_3) and negative impact on the environment (C_6). A₂ Suburban industrial park is situated in the median group ($F = 0.4295$), performing moderately and having no special strength. The residential new town (A₄) ranks as fourth ($F = 0.2041$), being mainly inhibited by low accessibility of traffic due to poor connectivity to arterials. The logistics hub (A₅) is ranked last ($F = 0.0000$), affected by the low NEV penetration rate (C_4), indicating that there is low demand for passenger vehicles in a goods-dominated environment.

To conclude, it is evident that the suggested hybrid VIKOR-TOPSIS model based on the logarithmic lp distance has concluded that A₃ is the ideal choice for establishing a battery swap station owing to its maximum total score, while A₅ is the least preferred because it fails to cater to the demands of the NEV fleet.

3.2 Sensitivity and Comparative Analysis

To verify the validity of the ranking, sensitivity analysis with respect to two variables is carried out. With an increase in p from 1 to 5, the aggregate value of A₁ increases from 0.8802 to 0.9115, while the value of A₂ decreases from 0.4727 to 0.3970, suggesting that a greater p value emphasizes the preference of better ranked alternatives. The entire ranking order, $A_3 > A_1 > A_2 > A_4 > A_5$, stays constant at any p value considered, implying stability concerning the distance variable.

Weight sensitivity analysis is conducted using five weight settings: W1 (base weight setting), W2 (dominance of traffic accessibility), W3 (dominance of power grid capacity), W4 (dominance of land cost), and W5 (dominance of NEV ownership). In the case of settings W3 and W5, the highest-ranked alternative changes from A₃ to A₁, consistent with the favorable assessment of grid capacity and NEV ownership at the central city location. All other settings

keep A3 as the optimal alternative. Such results imply that ranking is dependent on weight allocation in a sensible way.

Comparison of TOPSIS methods based on Euclidean and Hamming distances is performed using the same decision matrix. In case of the original vector of weights W1, all three methods produce the same result. In the case of vector W2, the proposed method evaluates alternative A2 as more preferable than A5, while Euclidean-based TOPSIS assigns preference to alternative. A similar disparity is noticed in case W5, where the ranking order according to the new approach ranks A4 better than A2, whereas the rankings according to Euclidean and Hamming TOPSIS approaches rank A2 ahead of A4. This is due to the logarithmical modification in the distance formula, which magnifies the minute differences between criteria when alternatives have close scores, especially for the cost-based criteria C3 and C6. The hybridization of VIKOR and TOPSIS makes the ranking process more stable through the incorporation of the VIKOR approach, which punishes those options that show weakness in some particular criterion. The sensitivity and comparative analysis are illustrated in Figure 2.

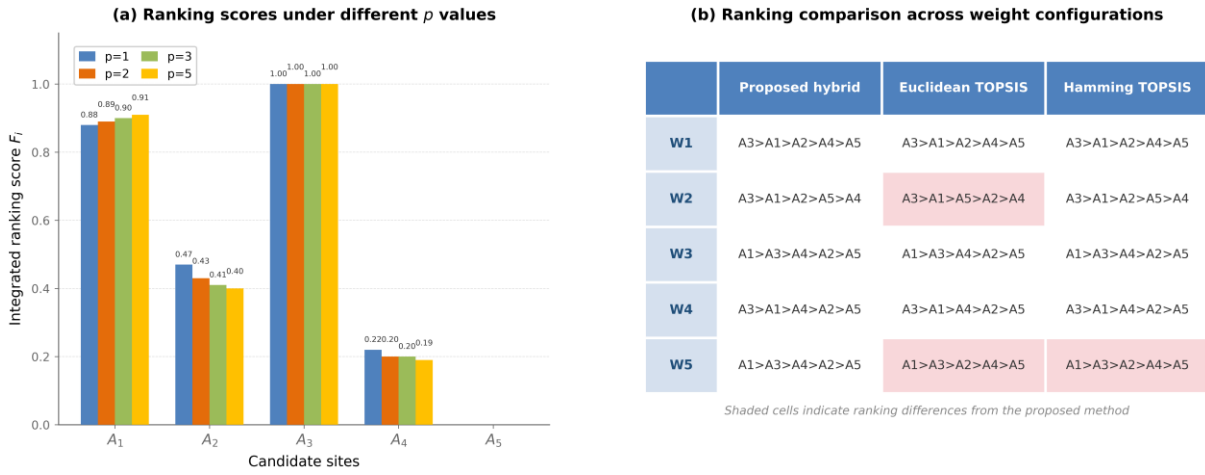


Figure 2: Ranking comparison of the proposed method and alternative distance-based TOPSIS methods across five weight configurations.

To sum up, the ranking is quite stable in all considered values for the distance parameter p and fusion parameter λ , proving the effectiveness of the developed approach. The comparison conducted for different weight settings shows a difference in ranking provided by the developed approach from that of the existing approaches based on the distance method of TOPSIS, which confirms the better discriminability of the new measure.

4 Discussion

The ranking results identify the highway service area junction (A3) as the optimal battery swap station site with an integrated score of $F = 1.0000$, followed by the city center commercial district (A1) at $F = 0.8946$. This outcome aligns with the practical logic of NEV infrastructure deployment, as highway service areas combine high traffic accessibility with complementary charging facilities. The finding that A1 ranks second despite its highest NEV ownership coverage (C4) reflects the balancing effect of the hybrid VIKOR-TOPSIS mechanism. Under weight vector W5, Euclidean TOPSIS ranks A2 above A4, while the proposed method reverses this order, consistent with observations in interval-valued Fermatean fuzzy risk assessment where ranking reversals were attributed to distance measure

sensitivity [13]. The regret-based VIKOR component penalizes alternatives with extreme underperformance on any single criterion, producing more balanced outcomes, a complementarity also recognized in Fermatean fuzzy facility location studies [14].

The ranking $A_3 > A_1 > A_2 > A_4 > A_5$ holds true for all p values investigated, indicating the reliability of the logarithmic l_p distance. In sensitivity analysis, the change in weights produces understandable results: When the capacities of power grids or number of NEVs outweigh each other, the optimal location changes from A_3 to A_1 , reflecting the nature of downtown areas. The differences noted between W_2 and W_5 support the idea that the logarithmic function can indeed identify variations between close IVFFN assessments, which cannot be captured by traditional methods, as evidenced by previous research on distance measure development using integrated weighted distances [15] and Einstein operator-based approaches [16]. This discriminative capacity is relevant when expert evaluations cluster within narrow intervals [17].

Theoretically, the new l_p logarithmic distance metric adds a non-linear element to the equation in that it shrinks large distances while magnifying small distances, which gives more options than the current Hamming and Euclidean distance equations in the context of IVFFS. The development of new distance metrics is seen as an important area of future work within the context of Fermatean fuzzy MCDM [18], and this study fulfills this requirement. The case study highlights the real-world relevance of the IVFFS model in infrastructure planning, besides its established use in wheelchair analysis [19] and humanitarian logistics [20].

The current study contains several shortcomings. First, the case study uses expert assessments created artificially, as opposed to empirical data gathered in the field, thus limiting the applicability of conclusions drawn to practical decision-making processes. Second, attribute weights are calculated based on expert opinion and not using objective criteria, potentially creating subjectivity issues. Third, the model evaluates a steady-state situation, whereas a time-based process, such as changing levels of NEV usage, is disregarded. This research highlights areas for further investigation, such as using objective weight determination techniques, for example, entropy and CRITIC, collecting empirical data through municipal planning questionnaires, and developing a dynamic approach to decision-making.

5 Conclusion

In this paper, a logarithmic l_p distance measure is proposed for IVFFNS and further a VIKOR-TOPSIS hybrid approach has been designed which is applied in the selection of battery swap stations sites for new energy vehicle application. Logarithmic l_p distance is computed by taking the natural log of cubes of membership function and non-membership functions of IVFFNs. This distance measure is proven to be a metric measure as it possesses properties of positivity, symmetry, boundedness, and the triangular inequality. The variable parameter p allows the decision-makers to adjust the measure in line with the characteristics of the problem being solved, ranging from the Manhattan approach as p approaches 1 to the Chebyshev approach as p approaches infinity. The combined VIKOR-TOPSIS technique takes advantage of both the TOPSIS' closeness ranking and the VIKOR's compromise ranking through a linear combination approach; hence the procedure is able to consider both closeness to ideal solutions and regret minimization simultaneously.

Validation of the technique occurs through a case study involving the evaluation of five potential locations for battery swap stations on the basis of six different parameters. It turns out that the location at the highway service area junction is the best location choice for a

battery swap station, regardless of any change in the configuration of parameters used. This finding proves the robustness of the ranking process, as the sensitivity of weights indicates a logical response.

Weight sensitivity analysis shows that whenever the dominance in the weighting scheme belongs to criteria like capacity of power grids or NEVs owned, the best location changes accordingly. Such findings confirm that the rankings change in accordance with variations in criteria importance, which is logical. The new model also has more discrimination ability compared to other methods that use Euclidean and Hamming distances, especially when there are similar values among competing options.

The theoretical contribution is achieved by proposing a logarithmic lp distance, which is analyzed regarding its metric properties in the context of IVFFS research. The methodological contribution lies in formulating a hybrid model that combines the features of compensatory and non-compensatory ranking approaches. The practical contribution is illustrated by its implementation in solving a strategic issue related to the location choice of battery exchange stations. This approach can also be applied to other IVFFS-based decision-making cases, including the assessment of renewable energy sources, the selection of sustainable suppliers, and smart cities' infrastructure design.

About the Author

Zirui Li is currently pursuing a master's degree at North China Electric Power University, which is located in Beijing, China. His research interests lie in the field of data mining and statistics.

References

- [1] Wang R, Li X, Xu C, et al. Study on location decision framework of electric vehicle battery swapping station: Using a hybrid MCDM method. *Sustainable Cities and Society*. 61: 102149.
- [2] Zu S, Sun L. Research on location planning of urban charging stations and battery-swapping stations for electric vehicles. *Energy Reports*. 8: 508-522.
- [3] Ghosh A, Ghorui N, Mondal S P, et al. Application of hexagonal fuzzy MCDM methodology for site selection of electric vehicle charging station. *Mathematics*. 9(4): 393.
- [4] Gul M, Lo H W, Yucesan M. Fermatean fuzzy TOPSIS-based approach for occupational risk assessment in manufacturing. *Complex & Intelligent Systems*. 7(5): 2635-2653.
- [5] Akram M, Muhiuddin G, Santos-García G. An enhanced VIKOR method for multi-criteria group decision-making with complex Fermatean fuzzy sets. *Mathematical Biosciences and Engineering*. 19(7): 7201-7231.
- [6] Jeevaraj S. Ordering of interval-valued Fermatean fuzzy sets and its applications. *Expert Systems with Applications*. 185: 115613.
- [7] Sergi D, Sari I U, Senapati T. Extension of capital budgeting techniques using interval-valued Fermatean fuzzy sets. *Journal of Intelligent & Fuzzy Systems*. 42(1):

365-376.

- [8] Qin H, Peng Q, Ma X, et al. A new multi-attribute decision making approach based on new score function and hybrid weighted score measure in interval-valued Fermatean fuzzy environment. *Complex & Intelligent Systems*. 9(5): 5359-5376.
- [9] Rani P, Mishra A R. Interval-valued Fermatean fuzzy sets with multi-criteria weighted aggregated sum product assessment-based decision analysis framework. *Neural Computing and Applications*. 34(10): 8051-8067.
- [10] Deng Z, Wang J. New distance measure for Fermatean fuzzy sets and its application. *International Journal of Intelligent Systems*. 37(3): 1903-1930.
- [11] Yang S, Pan Y, Zeng S. Decision making framework based Fermatean fuzzy integrated weighted distance and TOPSIS for green low-carbon port evaluation. *Engineering Applications of Artificial Intelligence*. 114: 105048.
- [12] Kirişci M. New cosine similarity and distance measures for Fermatean fuzzy sets and TOPSIS approach. *Knowledge and Information Systems*. 65(2): 855-868.
- [13] Kirişci M. Interval-valued Fermatean fuzzy based risk assessment for self-driving vehicles. *Applied Soft Computing*. 152: 111265.
- [14] Görçün Ö F, Ulutaş A, Topal A, et al. Telescopic forklift selection through a novel interval-valued Fermatean fuzzy PIPRECIA–WISP approach. *Expert Systems with Applications*. 255: 124674.
- [15] Zeng S, Gu J, Peng X. Low-carbon cities comprehensive evaluation method based on Fermatean fuzzy hybrid distance measure and TOPSIS. *Artificial Intelligence Review*. 56(8): 8591-8607.
- [16] Rani P, Mishra A R, Deveci M, et al. New complex proportional assessment approach using Einstein aggregation operators and improved score function for interval-valued Fermatean fuzzy sets. *Computers & Industrial Engineering*. 169: 108165.
- [17] Mishra A R, Liu P, Rani P. COPRAS method based on interval-valued hesitant Fermatean fuzzy sets and its application in selecting desalination technology. *Applied Soft Computing*. 119: 108570.
- [18] Büyüközkan G, Uztürk D, Ilıcak Ö. Fermatean fuzzy sets and its extensions: a systematic literature review. *Artificial Intelligence Review*. 57(6): 138.
- [19] Hezam I M, Rani P, Mishra A R, et al. Assessment of autonomous smart wheelchairs for disabled persons using hybrid interval-valued Fermatean fuzzy combined compromise solution method. *Sustainable Energy Technologies and Assessments*. 57: 103169.
- [20] Korucuk S, Aytekin A, Görçün Ö, et al. Warehouse site selection for humanitarian relief organizations using an interval-valued Fermatean fuzzy LOPCOW-RAFSI model. *Computers & Industrial Engineering*. 192: 110160.