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Comparison Of Analytic Hierarchy Process And Fuzzy Analytic Hierarchy Process: Allocation Of Photovoltaic Electric Vehicle Charging Stations In Malaysia

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ABSTRACT
The siting of photovoltaic electric vehicle charging stations (PEVCS) requires careful evaluation of multiple criteria, which necessitates reliable methods for criteria weighting. This study compares two widely used multi-criteria decision-making (MCDM) methods—Analytic Hierarchy Process (AHP) and Fuzzy Analytic Hierarchy Process (FAHP)—in determining criteria weights for allocating ideal PEVCS locations in Malaysia. In this study, a total of six main criteria and twelve sub-criteria are considered based on the evaluation of seven experts. Generally, the AHP method provides a straightforward hierarchical framework, and FAHP integrates fuzzy logic to address vagueness and imprecision in expert judgments. To avoid getting the null weight in the FAHP results, a modified version of Chang's Extent Analysis Method (Approach #4) is employed. The resulting global weights from both methods are applied in a Geographic Information System (GIS) environment to generate final suitability maps. Hence, the results showed significant differences in criteria priorities between the two methods, with FAHP offering more stable and realistic weight distributions. However, the study contributes to the growing field of GIS-based MCDM in sustainable infrastructure planning, and both methods are used to predict the ideal locations of PEVCS. Future work may explore additional weighting techniques, broader study areas, or integration with data-driven approaches.
Keywords: *Analytic Hierarchy Process (AHP), Fuzzy Analytic Hierarchy Process (FAHP), criteria, weight, photovoltaic electric vehicle charging stations (PEVCS), Malaysia*

1 INTRODUCTION

In this era, the adoption of electric vehicles (EVs) is remarkably increasing in Malaysia. However, the lack of electric vehicle charging stations (EVCS), especially those integrated with photovoltaic systems, poses a major barrier for drivers transitioning from fuel-based vehicles to EVs. Due to its eco-friendliness, lessening the transportation problem, photovoltaic electric vehicle charging stations (PEVCS) have been highlighted as an inspiration for sustainable mobility (Farah & Syahirah, 2024). Thus, PEVCS should be strategically located by considering multiple criteria. To determine which criteria should be taken into account when allocating PEVCS, a multi-criteria decision-making (MCDM) method should be employed (Syahirah & Farah, 2024). When dealing with a variety of criteria, objectives, or alternatives to determine the optimal outcome, the MCDM method is considered a subfield of operational research (OR) (Kumar et al., 2017).

Besides, the evaluation of criteria is represented by their weights, which quantitatively express the importance of each criterion in the decision-making process (Vinogradova et al., 2018). Significantly, the criteria weights are important to focus on, as they affect the outcome of the decision-making process (Odu, 2019). Moreover, there are three approaches to weighting: subjective (which needs decision makers (DMs) to assign the weights), objective (which relies solely on mathematical algorithms without involving DMs), and combinative (which integrates both subjective and objective approaches) (Busra et al., 2023).

In addition, there are a variety of criteria weighting methods, such as the Analytic Hierarchy Process (AHP), Fuzzy Analytic Hierarchy Process (FAHP), Best-Worst Method (BWM), Full Consistency Method (FUCOM), and others. Hence, AHP is the most commonly used method for calculating criteria weights among these methods (Taherdoost & Madanchian, 2023). To handle the ambiguity in the evaluations provided by decision makers (DMs), fuzzy sets are applied through the FAHP method, as subjective judgments can often be imprecise (Liu et al., 2020). On the other hand, there are limited studies that focus on comparing the AHP and FAHP methods, particularly in the context of allocating ideal locations for PEVCS. For instance, discovering suitable areas for drinking water harvesting (Khashei-Siuki et al.,

2020), assessing cash crop suitability (Rodcha et al., 2019) and prioritizing sub-watersheds (Meshram et al., 2019) have been conducted in previous comparisons.
To address this gap, this study goals to compare the AHP and FAHP methods in determining the criteria weights in allocating ideal locations for PEVCS in Malaysia. This study is organized into five sections. Section 2 provides a detailed explanation of the AHP and FAHP methodologies and highlights the case study involved. Section 3 presents the comparison results, which are further discussed in Section 4. Finally, Section 5 concludes the study.

2 MATERIALS AND METHODS

This section highlighted the case study, which includes the pilot areas and DMs, and the application of both AHP and FAHP methods.

2.1 CASE STUDY: PAHANG

First and foremost, this study focuses on Pahang (3.9743° N, 102.4381° E), the largest state in Peninsular Malaysia, as the study area for determining ideal locations for PEVCS. The selection of Pahang is based on its diverse geographical features, availability of open land, solar potential, and increasing focus on green transportation initiatives. To determine ideal locations for PEVCS, six main criteria and twelve sub-criteria are identified through an extensive review of existing literature, thorough need analysis (Farah et al., 2023) and instrument validation (Raja Ma'amor Shah et al., 2024). Seven domain experts known as DMs are involved in the evaluation process. These experts come from academic, governmental, and industry backgrounds related to renewable energy, EVs, and spatial planning. Their judgments were used to construct the pairwise comparison matrices required for both AHP and FAHP analyses.

2.2 AHP METHOD

The AHP method was developed by Thomas Saaty in the 1970s. In fact, AHP operates in a hierarchical structure consisting of three levels: the top level (goal), the middle level (main criteria and sub-criteria), and the bottom level (alternatives) (Genevois & Kocaman, 2018). Basically, the AHP method is implemented through four key steps (Al Amin et al., 2019; Bedir et al., 2016; Islam et al., 2024; Norddin et al., 2012; Saaty, 2008; Sun, 2020; Yagmahan & Yılmaz, 2023):
Define the problem. The problem is structured into three levels: goal, criteria, and alternatives. In this study, the problem is determining the ideal locations for PEVCS in Malaysia. From Figure 1, the analysis involves one goal, six main criteria, and twelve sub-criteria (Azmar et al., 2024).

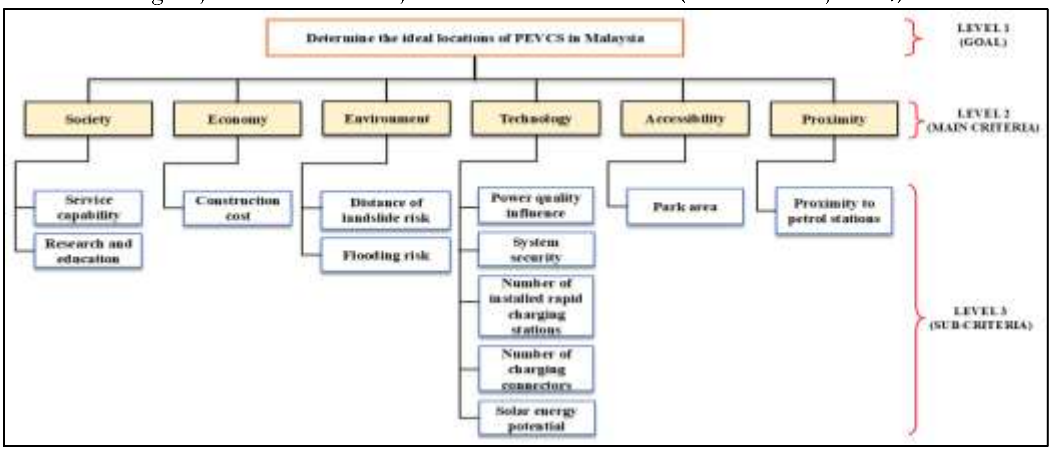

Figure 1. The hierarchy of determining the ideal locations for PEVCS in Malaysia

Construct a pairwise comparison matrix. Pairwise comparisons are made using Saaty's ratio scale from 1 to 9, as shown in Table 1.

Table 1 Saaty's scale (Saaty, 2008)

Intensity of Importance	Definition	Explanation
1	Equal Importance	The two criteria are of equal importance.
3	Moderate importance	One criterion is slightly more important than the other

5	Strong importance	One criterion is strongly more important than the other
7	Very strong importance	One criterion is very strongly more important than the other
9	Extreme importance	One criterion is extremely more important than the other
2, 4, 6, 8	An intermediate value between two adjacent considerations	When compromise is needed

Determine the criteria weights. The higher of criteria's weight indicates a more important criterion (Malczewski & Rinner, 2015).

Calculate the consistency ratio (CR). The CR is used to assess the consistency of the pairwise comparisons. If the CR is 0.1 or less, the level of consistency is considered acceptable.

However, as the most efficient method for consolidating multiple pairwise comparisons into a single representative result, the weighted geometric mean is used to account for the judgments of seven experts in weighting the criteria (Aczél & Alsina, 1986; Aczél & Saaty, 1983; Brunelli, 2019). Alternatively, the Aggregating Individual Judgments (AIJ) technique can be applied by computing the geometric mean of individual judgments for each element in the pairwise comparison matrices (Yagmahan & Yılmaz, 2023).

2.3 FAHP METHOD

To deal with uncertainty and vagueness often present in expert judgments, the FAHP method enhances the traditional AHP by incorporating fuzzy set theory. In this study, triangular fuzzy numbers (TFNs) are used to represent the subjective assessments of the DMs. To capture the range of possible judgments with a degree of confidence, each TFN is defined by three values: the lower (l), middle (m), and upper (u) bounds.

Chang's Extent Analysis Method is widely recognized in decision-making applications due to its effectiveness in handling complex problems (Eroğlu, 2021). Chang's extent analysis method is employed to derive fuzzy synthetic extent values for each criterion. Furthermore, this method involves calculating the degree of possibility for each criterion to be greater than the others, which is then used to compute the normalized weights (Chang, 1996). To integrate the evaluations from all seven experts, the fuzzy pairwise comparison matrices are aggregated by calculating the geometric mean for each corresponding fuzzy element. MATLAB is used to implement the full procedure, including the aggregation of expert inputs, the calculation of fuzzy synthetic extents, and the final derivation of criteria weights. The following steps outline the procedure of the extent analysis method (Ahmed, 2014; Bilgen & Şen, 2012; Chang, 1996; Feng, 2022; Ju et al., 2019; Ku et al., 2010; Nguyen, 2021; Ramanayaka et al., 2019; Vahidnia et al., 2009):

Convert linguistic judgments into triangular fuzzy numbers using a predefined linguistic scale, as shown in Table 2, to construct the fuzzy pairwise comparison matrix.

Table 2 TFN scale for pairwise comparison

Linguistic scale	Crisp value	TFN (l, m, u)
Extremely strong	9	(9, 9, 9)
Intermediate	8	(7, 8, 9)
Very strong	7	(6, 7, 8)
Intermediate	6	(5, 6, 7)
Strong	5	(4, 5, 6)
Intermediate	4	(3, 4, 5)
Moderately strong	3	(2, 3, 4)
Intermediate	2	(1, 2, 3)
Equally	1	(1, 1, 1)

Compute the fuzzified pairwise comparison matrix by aggregating the individual judgments of DMs using the geometric mean for each fuzzy element.

Comparing fuzzy synthetic extent values by determining the degree of possibility for each criterion, which evaluates the extent to which one criterion is greater than the others.

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Calculate the fuzzy weight vector based on the minimum degree of possibility for each criterion across all comparisons.
Normalize the fuzzy weight vector to obtain the final relative weights of the criteria, ensuring that the weights sum to one.

3 RESULTS

Figures 2 and 3 present the results of global weights obtained from both the AHP and FAHP methods. Thus, these values reflect the relative importance of each criterion in the process of decision-making and illustrate the differences in weight distribution across the six main criteria and twelve sub-criteria. Although the overall ranking remains relatively consistent between the two methods, slight variations can be observed in the magnitude of the weights.
The global weights of the six main criteria derived from both the AHP and FAHP methods are displayed in Figure 2. While the general ranking of criteria remains consistent between the two approaches, noticeable differences in weight magnitudes can be observed. In addition, though its weight is slightly reduced in FAHP (from 0.22621 to 0.20864), the "Economy" criterion holds the highest importance in both methods. On the other hand, the "Environment" and "Accessibility" criteria show an increase in importance under the FAHP method, referring that the inclusion of fuzzy logic slightly shifts expert judgments. Overall, FAHP tends to distribute the weights more evenly, reducing the dominance of individual criteria compared to AHP. These findings suggest that a more balanced evaluation framework may be achieved by incorporating uncertainty through the FAHP method.

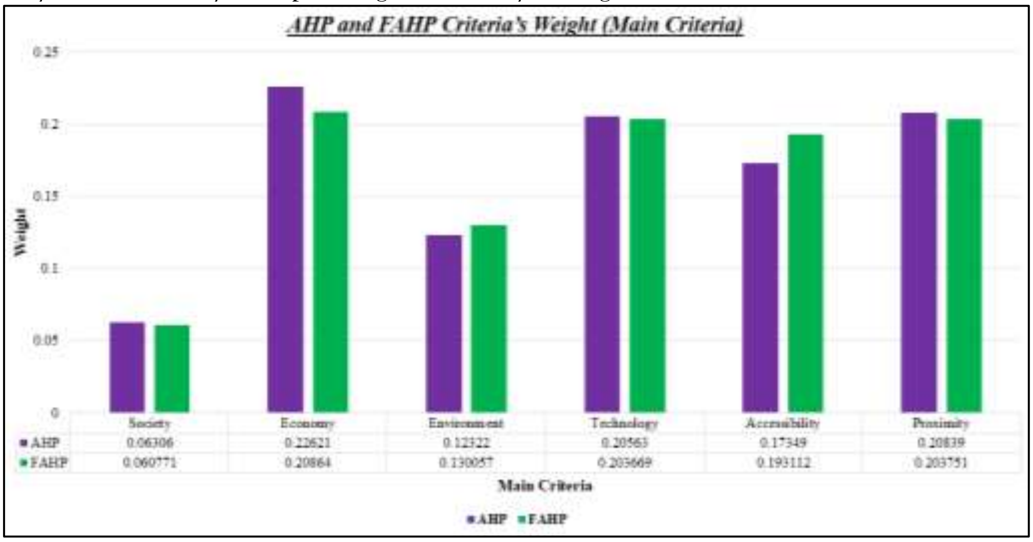

Figure 2. Main criteria's weight for AHP and FAHP methods

Furthermore, Figure 3 presents a comparison of global weights for the twelve sub-criteria as determined by both methods. The construction cost remains the greatest sub-criterion across both methods, though its relative importance is slightly lower in FAHP (from 0.22621 to 0.208640). Moreover, the remarkable changes are also observed for criteria such as "Park areas" and "Proximity to petrol stations," which acquire slightly more weight under FAHP. Similarly, fuzzy logic may gain experts' uncertainty more sensitively when the weights for "Flooding risk," "System security," and "Number of installed rapid charging stations" are marginally higher in the FAHP method. Overall, while both methods provide consistent prioritization patterns, FAHP introduces subtle adjustments that lead to a more nuanced distribution of weights across sub-criteria.

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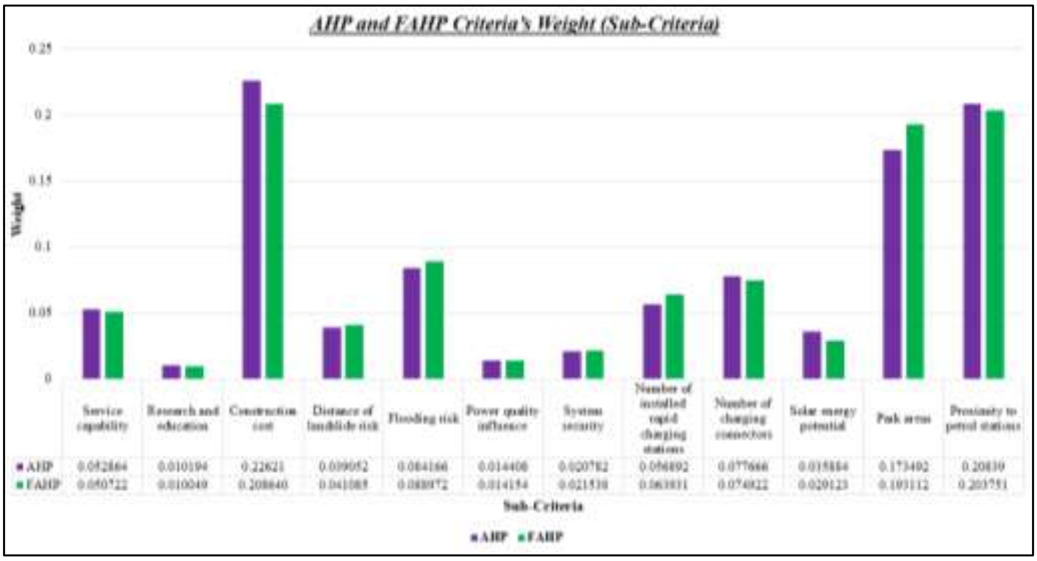

Figure 3. Sub-criteria's weight for AHP and FAHP methods

4 DISCUSSION

The divergence between AHP and FAHP weights is mainly due to how both methods handle expert judgments. Owing to that, the AHP method employed crisp numbers, while the FAHP used TFNs to represent ambiguity in expert opinions. The FAHP method is used to overcome the weaknesses of the AHP method and increase the reliability (Guler & Yomralioglu, 2020). In fact, this means FAHP can better reflect the natural hesitation and vagueness that experts may feel when comparing different criteria. FAHP also helps to reduce the impact of extreme or biased values. For example, in AHP, criteria like construction cost and proximity to petrol stations received higher weights, but in FAHP, their influence was slightly balanced. Hence, this makes the results more stable and reliable, especially when expert opinions vary.

In this study, the original version of Chang's Extent Analysis Method was not used by itself because it sometimes gives null weight to some criteria. It is also supported in evaluating Chang's algorithm for calculating weights, attention is drawn to the potential for the criteria to receive null weight since the lower bound (l) exceeds the upper bound (u), often due to the limited range of the TFN scale (Zinkevič et al., 2021). To overcome this problem, this study used a modified version (Approach #4) (Lima-Junior, 2020). This is because Approach #4 is based on (Chang, 1996), but it uses a better normalization process from (Wang et al., 2008) and a mean calculation method from (Lima Junior et al., 2014). This helps ensure that all criteria have meaningful weights.

However, by considering the criteria weights derived from both AHP and FAHP methods, these weights are applied in the GIS-based analysis using the Raster Calculator to map the ideal locations for PEVCS. As displayed in Figure 4, the suitability maps are generated using the Raster Calculator tool that combines the reclassified raster layers based on the respective AHP and FAHP weights. This process demonstrates how differences in weighting methods influence the spatial prediction of optimal sites, emphasizing the practical implications of methodological choice in location decision-making.

Figure 4. The final suitability maps for PEVCS in Pahang

5 CONCLUSION

In conclusion, this study compared the AHP and FAHP methods in determining criteria weights for the allocation of PEVCS in Malaysia. The AHP method provides a structured and widely adopted method, the FAHP method is used to address uncertainty in expert judgments by encompassing fuzzy logic. Besides, the findings showed noticeable distinctions in criteria weights between AHP and FAHP methods, especially due to FAHP's ability to capture expert vagueness and lessen the influence of extreme values. Moreover, the modified Chang's Extent Analysis Method with Approach #4 is used for FAHP to overcome the issues of getting the null weight, improving reliability, and consistency. In addition, the calculated weights are then employed in a GIS environment through the Raster Calculator tool to generate final suitability maps, which demonstrate how the chosen weighting method can directly affect spatial decision-making results. However, future studies can expand this study by comparing other MCDM methods such as BWM, FUCOM, and so on. Other researchers can also explore the integration of machine learning with GIS-based MCDM methods to enhance prediction accuracy.

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