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Hexagonal Fuzzy-AHP with TOPSIS and COPRAS for Site Suitability Analysis of Electric Vehicle Charging Stations Management

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ABSTRACT

In this rapidly evolving urban mobility, strategic deployment of Electric Vehicle Charging Stations (EVCS) holds the key to sustainable transportation systems, especially in the era of escalating demand for changes to environmental sustainability. The uneven distribution of existing EVCS causes several challenges such as range anxiety for users. Hence, it is important to identify the suitable location for EVCS development. However, current practice shows limitations such as it may be prone to human errors. To address this matter, the integration of Hexagonal Fuzzy-AHP, Geographical Information Systems (GIS), and the ideal solution method of Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Complex Proportional Assessment (COPRAS) to analyse the best potential site of EVCS. This approach involves five (5) stages considering criteria; Perceived Safety, Accessibility, Public Facilities, and Population Density. Spatial data representing the criteria were collected to establish criterion maps. Weightage criteria were calculated with pairwise comparison matrices obtained from experts. Site suitability analysis was then conducted. TOPSIS and COPRAS were employed to rank potential areas and identify suitable EVCS sites. Ultimately, this research aims to evaluate the integration of Hexagonal Fuzzy-AHP with TOPSIS and COPRAS for EVCS site suitability, thereby supporting sustainable urban transportation initiatives.

Keywords: COPRAS, EVCS, Hexagonal Fuzzy-AHP, Spatial-MCDA, TOPSIS

INTRODUCTION

Electric vehicles (EVs) represent the changes in transportation toward sustainability by providing economic savings and environmental benefits compared to using Internal Combustion Engine (ICE) vehicles (Schoettle & Sivak, 2016). Despite having a higher upfront expense, EVs have economic benefits in the long term due to reducing the expenses for fuel and maintenance requirements. It plays an important role in mitigating climate change and promoting sustainable transportation worldwide. However, choosing a suitable site for

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Electric Vehicle Charging Stations (EVCS) requires a thorough evaluation of numerous factors such as social, economic, environmental, operational, and urban planning challenges (Ghosh et al., 2021). This research focuses on using the Hexagonal Fuzzy GIS-MCDA approach to identify suitable EVCS sites. The combination of Multi-Criteria Decision Analysis (MCDA) and Geographical Information Systems (GIS) techniques enables data-driven decision-making, resulting in a more pleasant and sustainable transportation system while delivering environmental and economic advantages.

Since the transportation sector grows, carbon emissions rise, encouraging the deployment of sustainable options, EVs appear as a solution with lower fuel use and emissions but the users are facing a range of anxiety due to long-distance travel as the EVCS are not well-distributed (Wang et al., 2021). Range anxiety may be eased by properly establishing charging stations and increasing the adoption of EVs and sustainable mobility. However, obstacles remain to developing efficient and accessible EVCS. The integration of MCDA and GIS is useful in determining suitable EVCS locations.

Therefore, to address this problem, the research aims to answer three (3) research questions that are related to EVCS starting with how to measure the degree of importance for each criterion, potential sites, and suitability index model performance using Analytical Hierarchical Process-Technique for Order of Preference by Similarity to Ideal Solution and Complex Proportional Assessment (AHP-TOPSIS and COPRAS). In identifying the most suitable sites for EVCS, both non-GIS and GIS-based approaches are used. Important site suitability criteria are obtained from Malaysia’s Energy Commission guidelines. These factors are divided into four (4) main criteria which are perceived safety, accessibility, public facilities, and population.

Integration of GIS and MCDA for Site Suitability Analysis

Using the combination of GIS and MCDA it helps in improves the process of evaluating site suitability for EVCS. A spatial decision support system (SDSS) has been developed. SDSS uses geospatial data and GIS capabilities to offer decision-makers tools for location-based decision-making (Longley et al., 2015). SDSS allows for the evaluation of various criteria and scenarios resulting in the selection of suitable EVCS locations. GIS provides an effective computer-based solution for managing spatial data by allowing users to view, change, analyse, and manage data related to the Earth’s surface. According to Jankowski (1995), GIS are normally known for its ability to support decision-making system. However, there is a debate regarding the sufficiency of GIS results which brings some uncertainties and is partially sufficient for decision-making.

Malczewski and Rinner (2015) stated that Spatial-MCDA is employed for evaluating specified alternatives using spatial data based on chosen criteria with three basic approaches which are the conventional MCDA, spatially explicit MCDA, and spatial multi-objective optimization. Conventional MCDA involves evaluating and ranking numerous alternatives depending on certain criteria established for the study objective. However, when these requirements are applied to a geographic format using GIS, the spatial characteristics are taken into account. Comprehensive evaluation is carried out using approaches such as AHP, Ideal Point, and complex proportional assessment.

Each method uses various calculation concepts and methodologies. AHP and Analytic Network Process (ANP) employ hierarchical frameworks to organize goals, criteria, and alternatives. Similarly, TOPSIS, COPRAS, and Grey Relational Analysis and Visekriterijumsko Kompromisno Rangiranje (GRA-VICOR) deal with decision model complexity, ambiguity, and dependency by employing distance-based analysis to quantify the distances between alternatives and ideal solutions. Fuzzy logic-based MCDA handles uncertainty, while techniques like Elimination and Choice Expressing Reality (ELECTRE) and COPRAS aid in ranking and preference modelling.

Uncertainty in MCDA weighting approaches, as highlighted by Malczewski and Rinner in 2015, plays an important role in decision analysis, especially throughout the decision-making process. The evaluation of criteria importance is usually unpredictable when it involves experts' choices. This unpredictability will have an impact on the weight choices and has the potential to change the analysis results. To ensure a reliable decision-making process, it is important to deal with uncertainty. To address this, Malczewski & Rinner (2015) recommended numerous methods including sensitivity analysis which helps identify the most sensitive criteria for weight adjustments. Other than that, techniques like fuzzy logic and group decision-making provide several value representations and combine expert perspectives. Using these approaches, decision-makers may effectively manage uncertainty, resulting in more consistent and better-informed decision results.

AHP is a common approach in conducting MCDA (Saaty, 1980). It starts with the creation of a hiera Xrchical structure that divides the decision problem-solving into different levels and pairwise comparisons based on experts' ratings of each criterion. It has the adaptability and ability to interact with other approaches such as fuzzy logic, making it better at handling complicated decision-making problems. However, AHP alone may not be sufficient to manage uncertainty leading to the creation of Fuzzy-AHP which extends the conventional method to deal with fuzziness in decision-making by allowing decision-making criteria to have different values for each level allowing for more precise analysis using membership functions. While the procedures in Fuzzy-AHP are similar to those in AHP, the main difference is that Fuzzy-AHP handles fuzziness by using three values for each criterion which helps in solving uncertainty.

Hexagonal fuzzy numbers (HFN) are a more precise representation of uncertainty in decision-making compared to usual fuzzy numbers such as triangular, trapezoidal, and pentagon fuzzy numbers. While traditional fuzzy numbers often use three (3) numbers to represent uncertainty, HFN uses six (6) numbers resulting more accurate method. Gazi et al. (2023) suggested that HFN could be used to suitably depict the imprecise uncertain environment using its distance measure and defuzzification to deal with the hesitancy and impreciseness of the decision-makers. HFN uses hexagons to indicate several details including upper and lower boundaries as well as the degree of membership for different values within a given range.

TOPSIS and COPRAS are two outstanding MCDA methods that uses different methodologies to determine difficulty and ranking. TOPSIS developed by Hwang and Yoon in 1981 helps to evaluate and rank alternatives based on its proximity to ideal and anti-ideal solutions. Its dependency on precise data makes it less adaptive to unexpected situations. To address this, a Fuzzy-TOPSIS are utilized by using fuzzy membership functions. While COPRAS was established by Zavadskas and Kaklauskas in 1994 helps in solving complex issues by assessing the performance of alternatives in numerous situations. Its ability to use fuzzy logic improves its efficiency in dealing with uncertain or unclear information which is common in real-world decisions.

The integration of fuzzy in MCDA techniques has been implemented in several studies related to site suitability analysis (Seyedmohammadi & Navidi, 2022; Seyedmohammadi et al., 2019). Alzahrani et al. (2023) stated that if TOPSIS and COPRAS can be applied for ranking of the sites then, comparative and sensitivity analyses could be conducted to check the steadiness of the techniques used for site suitability analysis. The method also had been applied by Seyedmohammadi et al. (2018) as it was revealed that in the study, the fuzzy TOPSIS method was able to provide more accurate results than the Simple Additive Weightage (SAW) method that was also tested.

METHODOLOGY

Figure 1 illustrates the flow of methodology in identifying suitable locations for EVCS in Shah Alam. This process integrates two different techniques which are Hexagonal Fuzzy-AHP and GIS. Hexagonal Fuzzy-AHP calculates the weights for each criterion, while GIS analysis is employed to generate spatial data and identify suitable sites for EVCS development.

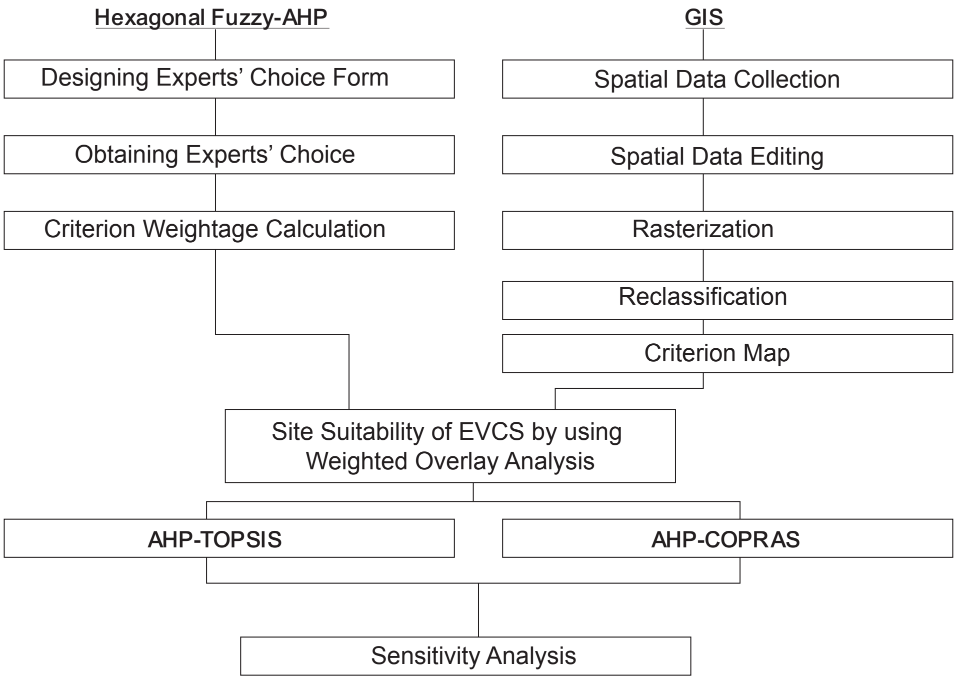


Figure 1. Research methodology

This study proposed a model integrating HFN within AHP for GIS modelling to find suitable sites for EVCS. This approach leverages the precision and flexibility of HFN to handle inherent uncertainties and subjective judgments in the decision-making process. AHP is employed to decompose complex problems into a hierarchy, allowing for a systematic evaluation of criteria influencing site suitability. Each criterion's importance is assessed using pairwise comparisons, and the fuzziness helps to capture the ambiguity in expert opinions. The suitability index derived from the AHP was then ranked using TOPSIS and COPRAS. The former identifies the optimal sites by measuring the geometric distance from an ideal solution, while the latter evaluates the sites based on their relative importance and performance across all criteria. Combining these methods ensures a comprehensive and robust ranking of the most suitable sites for EV charging stations, facilitating informed and effective decision-making in urban planning.

To perform the GIS operation, the criteria that had been chosen need to be represented as spatial data. It is evaluated and verified by using the primary data collection from gathering the expert's choice. The experts helped in engaging the decision-makers by structuring a decision into main criteria and subcriteria. The research used a hierarchical structure to represent criteria and subcriteria. The hierarchical structure of AHP has a very important role in this process as explained by Saaty (2001). AHP effectively manages complex decision-making by organizing selected criteria into a logical hierarchy.

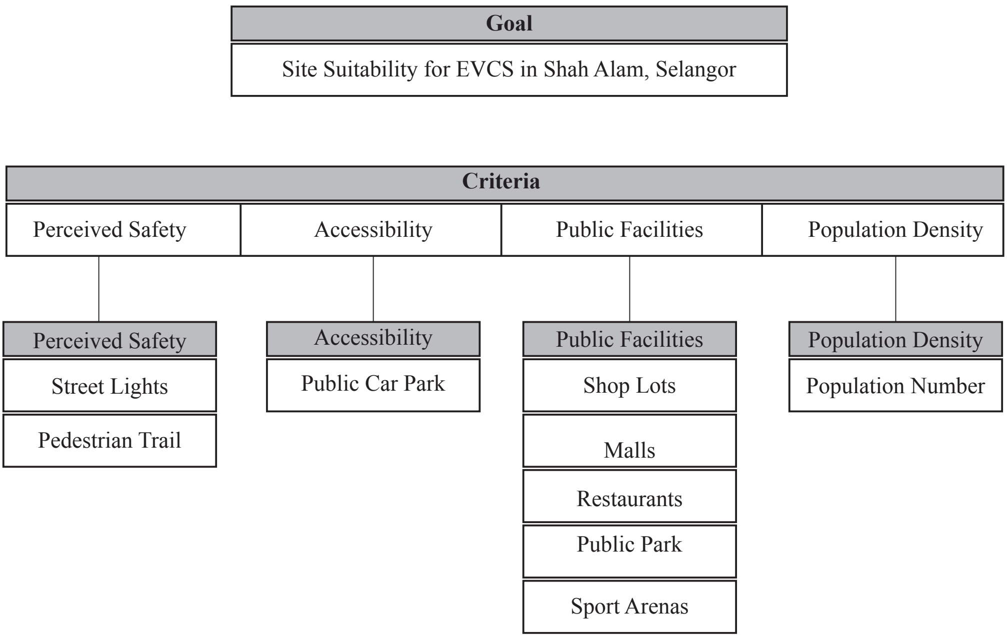


Figure 2. Hierarchical structure

This structure comprises three (3) different levels as illustrated in Figure 2 which is the goal in the first level indicates the site suitability of EVCS in Shah Alam, the second level is the criteria which includes four (4) main criteria and their respective subcriteria and the third level is the alternatives that is represented by the selection of existing malls, public car park, and petrol stations.

Next, experts' choice on the criteria and the subcriteria were conducted to determine their weightage. The experts' choice form was distributed to the experts to obtain their opinions regarding each criterion and subcriteria. As mentioned previously, this study used Fuzzy-AHP to address the inconsistency and uncertainty in decision-making. For that, linguistic terms are used to replace the fuzzy numbers as shown in Table 1 to make them easier to understand.

Table 1

Linguistic terms and Hexagonal Fuzzy number

Linguistic Terms	Scale	Hexagonal Fuzzy Number
Equally Important (EI)	1	(1, 1.5, 2.5, 3.5, 5, 6)
Less Important (LI)	3	(3, 4, 4.5, 5.5, 6.5, 7)
Moderate Important (MI)	5	(3.5, 4.5, 5, 6.5, 7, 8)
Strongly Important (SI)	7	(5.5, 6, 7, 7.5, 8, 8.5)
Very Strongly Important (VSI)	9	(6, 7, 7.5, 8, 8.5, 9)

In the process of obtaining criterion weights, a combination of the AHP method and Hexagonal Fuzzy logic was used. This process involved in creating a comparison matrix based on the evaluation that has been obtained from a group of decision makers. Next, the weights of each criterion were calculated using a combined Hexagonal Fuzzy-AHP method. These obtained weights were utilized to determine potential sites for the EVCS. The Hexagonal Fuzzy-AHP approach served to represent uncertainty and inconsistency in decision-making processes, aiming to produce a reliable and precise outcome for site selection. The criterion weighing involved six (6) different and continuous steps as illustrated in Figure 3.

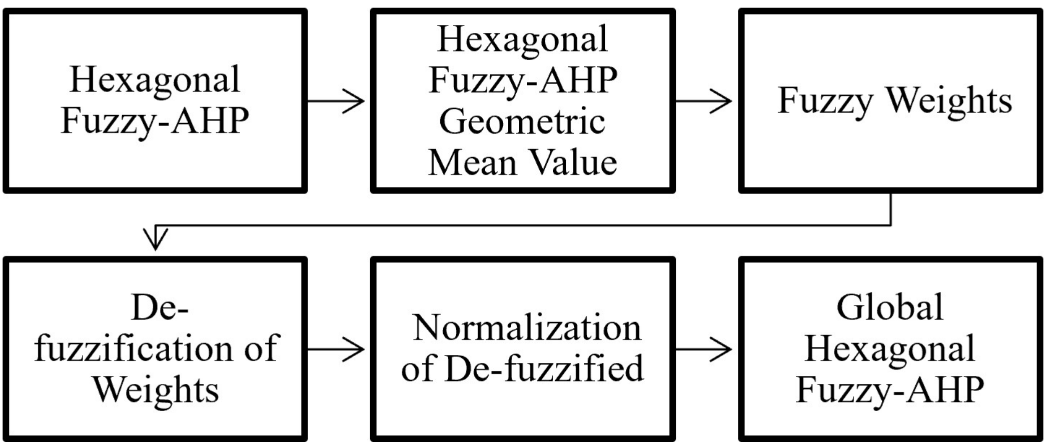


Figure 3. Process for criterion weighing

This process included obtaining the Hexagonal Fuzzy-AHP geometric mean value, determining fuzzy weights, de-fuzzification of weights, normalization of de-fuzzified weights, and global Hexagonal Fuzzy-AHP. All calculations were made by using Microsoft Excel.

The third step is to derive site suitability with index model. In this step, the spatial data representing the criteria were obtained from secondary data sources as well as field data collection. The data was then transformed into criterion maps using rasterization and reclassification methods. The raster values represent the suitability to develop EVCS which were based on the HFN. The weightage calculated in the previous steps then was used as attributes in the index modelling. The process was conducted in selected GIS software.

The next stage is to rank the potential sites which were extracted from the output of the highest level of suitability in the site suitability analysis, the highest influential criteria which is malls and public car parks, and the additional data of existing petrol stations. These features are merged into a single layer for the representation of the data. The layers are overlaid to display potential sites, highlighting locations in which all criteria overlap indicating suitability. The ranking is only applied to the potential locations with the highest suitability level as it helps to methodological test the method.

Finally, sensitivity analysis was conducted to analyse the ranks derived by using both TOPSIS and COPRAS method. This is to validate the model to find the potential sites for EVCS using Hexagonal Fuzzy-AHP which this study used.

RESULTS AND DISCUSSION

Weightage of Criteria for EVCS Development

The Hexagonal Fuzzy-AHP approach was used to calculate weightage and prioritize overall priorities as shown in Table 2, resulting in higher priorities having a larger impact on choosing the best location for EVCS development. The results may differ from a normal percentage distribution due to factors such as fuzzy logic, subjective evaluation, group judgments, and inconsistencies in Pairwise Comparisons. The study's findings are crucial for determining the most suitable location for EVCS development.

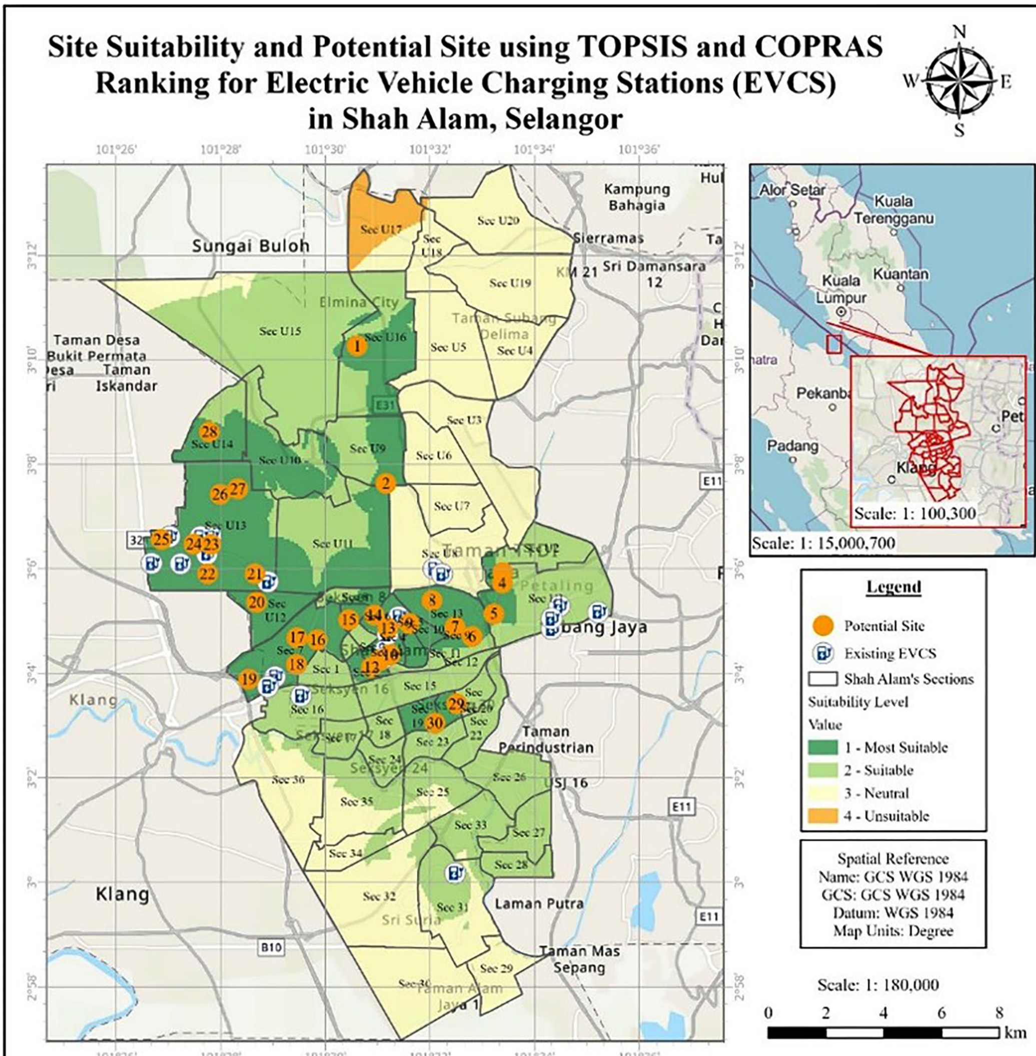
Table 2

Overall priorities of criteria and subcriteria

Main Criteria	Subcriteria	Weightage	Overall Priority	Percentage (%)
Perceived Safety	Street Lights	0.515	0.026	3
	Pedestrian Trail	0.485	0.024	2
Accessibility	Public Car Park	0.145	0.145	15
Public Facilities	Shop Lots	0.190	0.074	8
	Malls	0.315	0.124	12
	Restaurants	0.212	0.083	8
	Public Park	0.096	0.038	4
	Sport Arenas	0.187	0.073	7
Population	Population/Crowd	0.412	0.412	41

Site Suitability for EVCS

Figure 4 shows a site suitability map for EVCS by using GIS index model. The map shows four levels of suitability, with orange, yellow, light green, and dark green symbols indicating the least suitable to the highest level. The analysis reveals three sections are least suitable for EVCS development, due to lower population density and availability of existing public facilities.



Indicator

No	Name	TOPSIS	COPRAS	No	Name	TOPSIS	COPRAS
1	Petronas Bukit Subang	30	30	16	Shell Jalan Lazuardi Sec 7	15	15
2	Shell Persiaran Mokhtar Dahari	28	28	17	Taman Tasik Sec 7 Car Park	15	15
3	Shell TTDI Jaya	14	14	18	Petronas Sec 7	23	23
4	Petronas Glenmarie TTDI Jaya	3	3	19	Pharmaniaga Logistic Car Park	15	15
5	Shell Jalan Subang Sec 13	3	3	20	Ardence Crest Car Park	23	25
6	Petronas Sec 13	3	3	21	Acres Lake Car Park	15	15
7	Stadium Shah Alam Car Park	3	3	22	Shell Setia Alam	26	23
8	Sultan Abdul Aziz Shah Golf & Country Club Car Park	3	3	23	Setia City Convention Centre Car Park	15	15
9	Shell Sec 9	3	3	24	Top Glove Tower Car Park	15	15
10	Wisma MBSA	3	3	25	Petronas Setia Murni	15	15
11	PKNS Complex Shah Alam	3	3	26	Caltex Setia Alam	23	25
12	Auditorium Dato Yahaya Ahmad Car Park	3	3	27	Petron Setia Alam	27	27
13	Sultan Idris Shah Building Car Park	1	1	28	Fairy Park Heritage City Car Park	29	29
14	Jalan 5/1 Car Park	3	3	29	Petronas Persiaran Tengku Ampuan	2	2
15	Petronas Sec 6	3	3	30	Shell Sec 19	15	15

Figure 4. Map of site suitability of EVCS in Shah Alam, Selangor, Malaysia

On the other hand, the most suitable sites for EVCS development are spread across 20 sections, with most located near highly developed areas with higher population densities and city attractions. The final output had been verified by using two different approaches. The first verification involves consultation with experts as their expertise provides valuable insights and validation to ensure the accuracy and reliability of the results. The second method of verification is being made by field verification. This process involves physically inspecting the locations and conditions identified in the analysis.

Ranking Potential Sites with Hexagonal Fuzzy AHP-TOPSIS and COPRAS

The Hexagonal Fuzzy AHP-TOPSIS and AHP-COPRAS approaches were then used to rank 30 locations for EVCS development. Findings revealed that both methods consistently rank potential sites as shown in Figure 5, considering factors like criteria and existing buildings. This reliability helps in enhancing confidence in the research and underscores the robustness of the methodologies used.

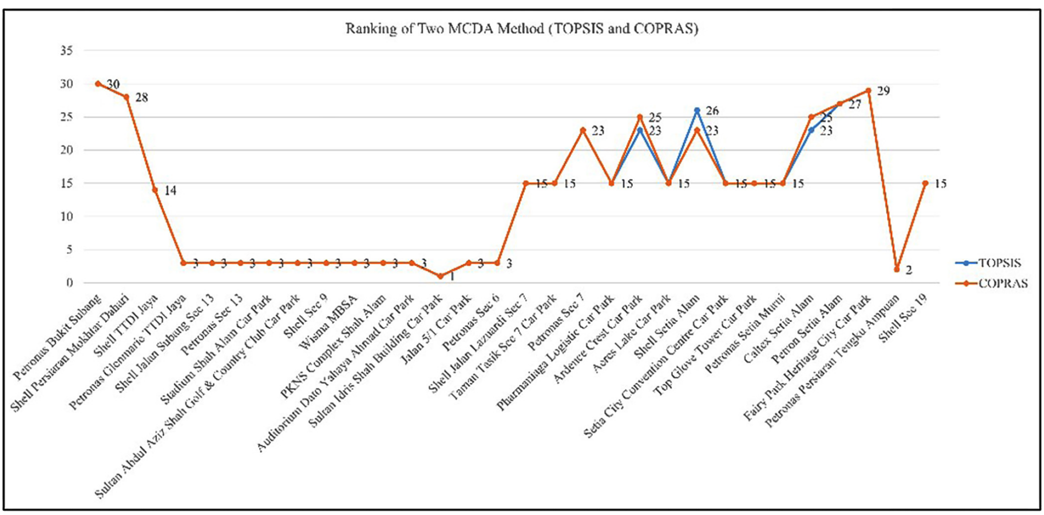


Figure 5. Graph of potential site for EVCS in Shah Alam, Selangor, Malaysia

Sensitivity Analysis

A sensitivity analysis evaluates the impact of variations in conditions on the final ranking of alternatives. In this study, several tests had been conducted. The first test focuses on the most influential subcriteria of Public Car Parks and Potential Density and the least influential subcriteria of Public Parks and Pedestrian Trails.

As shown in Figure 6, the sensitivity analysis revealed that initially, the weightage for Public Car Parks is lower than Population Density with values of 15% and 41% respectively. However, in the sensitivity analysis, this arrangement is reversed making changes towards the Public Car Parks to be higher in weightage compared to Population Density. The results show that this adjustment causes changes in the rankings of possible sites. This adjustment causes changes in site rankings, but only in four locations. The overall effect is minor, indicating the overall ranking remains stable and suitable for use.

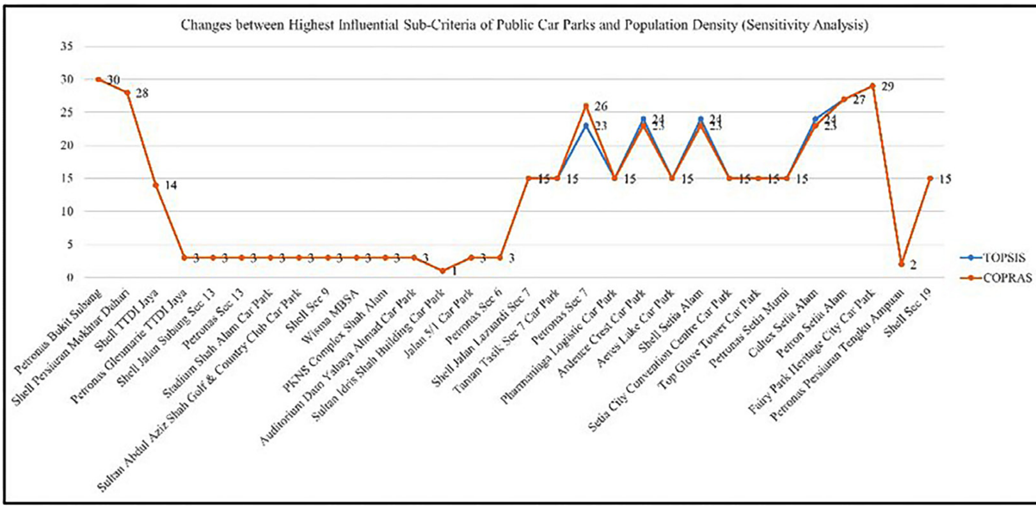


Figure 6. Graph of sensitivity analysis on highest influential subcriteria

The test is run again where the results revealed in Figure 7 shows consistent ranking of lowest subcriteria using interchanged methods, indicating robustness of methods used for EVCS station ranking. Changes occur at three locations or alternatives, demonstrating stability and accuracy. The majority of rankings remain consistent, increasing confidence in the approaches used.

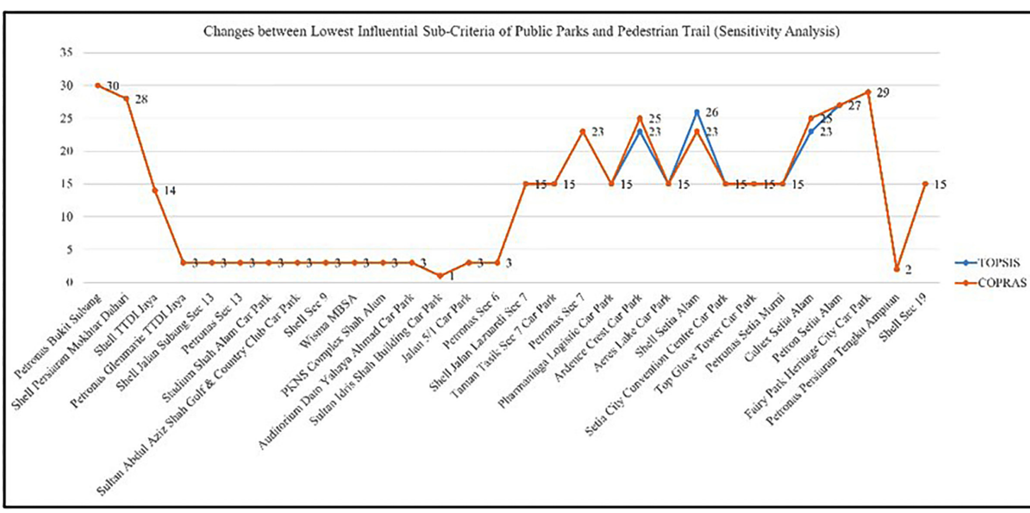


Figure 7. Graph of sensitivity analysis on lowest influential subcriteria

CONCLUSION

In conclusion, the research integrates Hexagonal Fuzzy-AHP with GIS to determine EVCS locations effectively addressing challenges like range anxiety and inadequate charging infrastructure. The study highlights Hexagonal Fuzzy-AHP's effectiveness in handling uncertainty in criteria weighting. In addition, this study proposed a step in the site selection study which is to rank the potential by using Ideal Points solutions which are TOPSIS and COPRAS which also act as validation of the model developed to find the potential location for EVCS.

This study highlights several recommendations for future studies. First, it is recommended to further refine and validate the AHP-TOPSIS and COPRAS methodologies for the site suitability analysis of EVCS. The robustness and reliability of these methods should be further explored through sensitivity analysis, including altering criterion weightage, interchanging criteria, and using different percentages or null values. Second, future research should focus on advancing technologies in the GIS environment, such as developing dashboards or web applications for better visualization for users and stakeholders. Adopting these recommendations can improve decision-making processes and accelerate the transition to a sustainable transportation system, particularly in Malaysia.

NOVELTY

This study presents a novel approach to identifying suitable sites for EVCS by integrating HFN in AHP for the GIS model, a methodology not previously explored in depth. This innovative use of HFN enhances the precision and reliability of the decision-making process by better handling the uncertainties in expert judgments. The study also employs employing TOPSIS and COPRAS, to rank the suitability of potential sites, providing a comprehensive evaluation framework. By combining these advanced techniques, the study not only improves the accuracy of site suitability analysis but also offers a robust methodology for future research and practical applications in urban planning and sustainable transportation infrastructure.

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