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Comparative Multi-Criteria Analysis to Determine Optimal Construction Locations for Electrical Vehicle Charging Stations

Elektrikli Araç Şarj İstasyonlarının En Uygun İnşaat Yerinin Belirlenmek için Karşılaştırmalı Çok Kriter Analizi

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Abstract

A key step taken at the 26th United Nations Climate Change Summit, held in Glasgow, Scotland, in October 2021, was addressing carbon dioxide (CO2) emissions. Thirty countries, including Turkiye, signed an agreement that calls for reducing carbon dioxide emissions by 2040. The agreement stipulates that these countries will use zero-emission minibuses and cars by 2040 at the latest. Those who signed the agreement committed to providing the necessary conditions for converting cars with internal combustion engines to non-carbon dioxide-emitting vehicles. The current situation has become a major step in the transition to electric vehicles from diesel and gasoline vehicles. According to this agreement, Türkiye's first domestic and national electric vehicle, TOGG, is being produced. Since electric vehicles will replace diesel and gasoline vehicles, charging stations and units will be required to provide electric power to these vehicles. Having charging stations in strategic locations is an important part of promoting the use of electric vehicles. The purpose of this study is to propose a model using multicriteria decision-making techniques to solve the installation location problem of charging stations containing charging units to popularize the use of electric vehicles.

Keywords: Electric vehicles, Charging stations, Charging units, Multicriteria decision-making.

Öz

Ekim 2021'de İskoçya'nın Glasgow kentinde düzenlenen 26. Birleşmiş Milletler İklim Değişikliği Zirvesi'nde atılan önemli bir adım, karbondioksit (CO2) emisyonlarının ele alınmasıydı. Türkiye'nin de aralarında bulunduğu 30 ülke, 2040 yılına kadar karbondioksit emisyonlarının azaltılmasını öngören anlaşmaya imza attı. Anlaşmaya göre, bu ülkeler en geç 2040 yılına kadar sıfır emisyonlu minibüs ve otomobil kullanmaya başlayacaklar. Anlaşmaya imza atanlar, içten yanmalı motorlu araçların karbondioksit salınımı yapmayan araçlara dönüştürülmesi için gerekli koşulları sağlamayı taahhüt ettiler. Mevcut durum, dizel ve benzinli araçlardan elektrikli araçlara geçişte önemli bir adım olmuştur. Bu anlaşmaya göre Türkiye'nin ilk yerli ve milli elektrikli aracı TOGG üretilmektedir. Elektrikli araçların dizel ve benzinli araçların yerini alacağından bu araçlara elektrik enerjisi sağlayacak şarj istasyonları ve ünitelerine ihtiyaç duyulacaktır. Elektrikli araç kullanımının yaygınlaştırılmasında şarj istasyonlarının stratejik noktalarda bulunması önemli bir yer tutmaktadır. Bu çalışmanın amacı, elektrikli araçların kullanımını yaygınlaştırmak amacıyla şarj üniteleri içeren şarj istasyonlarının kurulum yeri problemini çözmek için çok kriterli karar verme tekniklerini kullanan bir model önermektir.

Anahtar Kelimeler: Elektrikli araçlar, Şarj istasyonları, Şarj üniteleri, Çok kriterli karar verme.

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1. Introduction

In most countries, fossil fuels are used as the primary source of energy (Shojaabadi et al., 2016). The increasing human population has led to increased vehicle use, which has increased CO2 emissions and caused global warming (Karaşan et al., 2018). As reported in the Key World Energy Statistics, 65.5% of 2018 oil consumption was used for transportation, while fuel-related CO2 emissions accounted for 34.1% (Birol, 2020). The pollution caused by fossil fuels in transportation negatively affects our quality of life. As a result of these adverse conditions and limited fossil fuel reserves, alternative energy has become more popular.

Over the past few years, electric vehicles (EVs) have become increasingly popular (Bi et al., 2025) due to a growing emphasis on sustainable development and the shift to clean energy around the world (Feng et al., 2021; Karaşan et al., 2018; W. Liu et al., 2019). Several factors have contributed to this transformation, including environmental concerns (Oranpairoj et al., 2025) like climate change and air pollution, rapid progress in battery technology, policy incentives, and shifts in consumer preferences. With the increase in demand for EVs, the EV charging station market has grown dramatically (Ecer et al., 2025). Charging infrastructure, however, remains a significant challenge to the widespread adoption of EVs, and the strategic placement of EV charging stations is crucial to efficient mobility (Erbaş et al., 2018; Xu et al., 2018; Kaya et al., 2020).

One of the most critical management decisions is determining the optimal locations of EV charging stations, which plays an important role in promoting the development of the EV industry (Guler & Yomralioglu, 2020; Meng et al., 2013; Ju et al., 2019; Y. Zhang et al., 2022). It requires considering multiple alternatives and conflicting qualitative and quantitative criteria, making it a complex multi-criteria decision-making (MCDM) problem (Cui et al., 2018; Wu et al., 2016). MCDM techniques are a structured and systematic approach to evaluating, ranking, and selecting competing alternatives based on predefined criteria, integrating expert judgment, stakeholder preferences, and quantitative data to facilitate informed and transparent decision-making. Several techniques can be used to address the complexity and uncertainty of infrastructure planning, including DEMATEL, Grey Relational Analysis, MOORA, and Vikor.

On the other hand, improperly located charging stations can cause underutilization, inconvenience, inefficiency in power distribution, and congestion in urban areas. Selection results will affect not only the construction costs, but also the operating and maintenance costs (Ren et al., 2019; H. -C. Liu et al., 2019). A comprehensive, systematic, and data-informed approach is therefore essential when planning EV charging station deployment. The purpose of this study is to identify optimal locations for EV charging stations by evaluating multiple potential sites against a set of relevant criteria using four MCDM techniques. This comparative analysis enhances decision quality as well as supports sustainable urban mobility planning by ensuring equitable and efficient infrastructure deployment. Study results can provide strategic insights into EV infrastructure expansion for stakeholders, including policymakers, urban planners, and utility providers.

2. Literature Review

Several studies have examined different models and methodologies for selecting the most suitable EV charging station locations. They can be divided into three main categories: mathematical models or heuristic/metaheuristic methods, mathematical programming methods, and integrated MCDM-mathematical programming methods (Kalender et al., 2020). In traditional approaches, Geographic Information Systems (GIS) are used to analyze spatial factors and identify areas with heavy traffic or dense populations; however, GIS-based approaches may not be able to handle qualitative criteria or conflicting stakeholder preferences. MCDM techniques have been used to address these limitations by incorporating both quantitative and qualitative data. GIS and MCDM are powerful methods of site selection because they enable the management of geographical data, local characteristics, and stakeholder preferences (Hisoğlu et al., 2025). Additionally, several studies have explored the use of fuzzy logic to reduce uncertainty and manage linguistic variables in expert evaluations. A fuzzy-based MCDM approach may prove particularly useful in situations with subjective judgment and ambiguity.

The location of the electric vehicle fast charging station for an electric vehicle was selected using a geographical information system (GIS), an analytical hierarchy process (AHP) and fuzzy AHP methods, and this approach is demonstrated in Istanbul, Türkiye (Guler & Yomralioglu, 2020).

Wu et al. (2016) proposed the use of the cloud model and preference ranking organization method for enrichment evaluation (PROMETHEE) method to choose an optimal location. Beijing, China, was used to verify the scheme's effectiveness and validity (Wu et al., 2016). A cloud model proposed by Tian et al. (2018) was used to predict the charging behavior of drivers, and then a dwell time-based optimization model was proposed for optimizing charging station locations by minimizing the time cost of electric vehicle drivers, which was solved using the Shuffled Complex Evolution (SCE-UA) algorithm. GLDS II (gained and lost dominance score II) was utilized in Chengdu, China, for optimum location selection. The main advantage of the GLDS II method is that it takes into account the uncertainty of the expert group's assessments (Liang et al., 2020).

An analysis of the EV charging station location problem was conducted by A. Liu et al. (2020) using a fuzzy multi-criteria group decision-making model based on Gray relation analysis (GRA). The most important factors were found to be the number of roads, population density, greenhouse gas emissions, road potency, construction investment cost, and operation and management cost (A. Liu et al., 2020). For the selection of the most suitable location for the EV charging station, Rani and Mishra (2021) used an integrated Fermatean fuzzy-MULTIMOORA approach. It was recommended that the most important criteria be ease of expansion and future reconstruction, greenhouse gas emission reduction, fine particulate matter reduction, and destruction of urban vegetation and landscapes, respectively (Rani & Mishra, 2021). The study conducted by Feng et al. (2021) chose a suitable location in Chengdu, China, using linguistic entropy weight (LEW) and fuzzy axiomatic design (FAD). Based on the fuzzy Delphi method and the fuzzy GRA-VIKOR method, optimum locations were determined in Tianjin, China (Zhao & Li, 2016). A case study conducted in Shanghai, China, demonstrated how the Pythagorean Fuzzy VIKOR method could be used to determine the most suitable location among the alternatives (Cui et al., 2018). An interval fuzzy set enhanced by simulated annealing (SA) was used by Türk et al. (2021) to select the best locations for electric bus charging stations based on the existing infrastructure in Istanbul, Türkiye.

Based on a total social cost model and genetic algorithm, Zhou et al. (2022) established a location optimization model that covers construction costs, operating costs, and carbon dioxide emission costs. A user satisfaction function was developed by Yi et al. (2019) for EV charging station location and capacity optimization using an artificial immunity algorithm in Beijing, China, based on factors such as ease of charging, charging cost, and charging time for the user. An improved whale optimization algorithm (IWOA) was proposed by H. Zhang et al. (2019) to reduce social costs associated with the location of electric vehicle charging stations based on service risk factors, such as capacity issues and user anxiety, establishing an EV charging station site selection model. A location problem for EV charging stations was examined in the article by Q. Liu et al. (2019) to minimize the overall CO2 emissions of the entire traffic network in Chengdu, China. This study examined the location problem in a data-driven smart optimization framework based on particle swarm optimization (Q. Liu et al., 2019). In the study of Janjić et al. (2021), AHP is used for possible location comparison. Greedy heuristics are applied to minimize the walking distances from the charging station location, and the optimum number of locations is determined by minimizing the total distance and total costs. Hosseini and Sarder (2019) developed a Bayesian network (BN) model to identify the most suitable location in Tehran, Iran.

A variety of evaluation criteria have been used in the studies mentioned above to identify the most suitable location. These criteria are based on seven main categories, including Economic, Energy, Environmental, Management, Reliability & Safety, Social, and Traffic. The criteria used in these studies are summarized in Table 1.

Table 1. An overview of commonly used evaluation criteria for selecting locations for EV charging station heading.

Criteria	Sub-criteria	Criteria	Sub-criteria
Economic	Construction investment cost	Management	Possibility of capacity expansion and reconstruction in the future
Economic	Operating and/or maintenance costs	Management	Harmonization of EV charging station with urban development planning and power grid.
Economic	Service radius	Management	Government support
Economic	Predicted economic benefit	Management	Policy environment
Economic	Investment payoff period	Reliability & Safety	Electricity stability and quality
Economic	Land cost/value	Reliability & Safety	Safety of the construction site
Economic	Fixed costs	Reliability & Safety	Electricity grid security implications
Economic	Transportation costs	Reliability & Safety	Reliability in the future
Energy	Substation/transportation stations capacity	Reliability & Safety	Security and ability to tackle with the emergency in the future
Energy	Voltage stability/Transmission of electricity	Reliability & Safety	Fire and explosion prevention
Energy	Average charging frequency by region	Social	Population density of the service area
Energy	Distance to frequent power cut areas	Social	Charging Service/Station capacity
Energy	Electricity supply and technical superiority	Social	Traffic convenience/conditions
Energy	Number of installed rapid charging stations	Social	Adverse impact on living quality of local people
Energy	Number of transformed conventional vehicles into electric vehicles	Social	Consumption level around the service area
Energy	Solar energy potential	Social	Attractiveness
Energy	Station harmonic pollution problem	Social	Convenience of accessing public transportation; Charging station accessibility
Energy	System reliability	Social	Distance to the substation/transportation stations
Energy	System security	Social	Distance to petrol stations
Energy	Time to power outage (failure)	Social	Parking areas/lots and fee
Environmental	Destruction degree on surrounding environment	Social	Average income rate of residents
Environmental	Energy-saving benefits and air pollutants reduction	Social	Fulfillment of drivers' convenience
Environmental	Available resources	Social	Job opportunities
Environmental	Slope of land	Social	Distance to park areas
Environmental	Available space for disposal of waste	Social	Number of mass rapid transit stations
Environmental	Distance to landslide areas	Social	Size of traffic conditions
Environmental	Distance to water resources like rivers and lakes	Traffic	Road network
Environmental	Distance to surrounding environment	Traffic	Number of roads
Environmental	Resource recycling	Traffic	Distance to junctions
Environmental	Resource utilization	Traffic	Distance to main roads
Environmental	Topographic conditions	Traffic	Main road number
Environmental	Weather conditions	Traffic	Number of highway exit

Most studies use various techniques to evaluate EV site location problems, focusing on a comprehensive set of environmental, economic, technical, and social factors to evaluate EV site location problems. Although various MCDM methods have been applied to EV charging station planning, few studies offer a comparative analysis of multiple MCDM techniques to assess the consistency and reliability of site selection results. A more comprehensive evaluation of the final decision can be made by analyzing the consistency among the different methods' outcomes. Spatial data or Geographic Information Systems (GIS) are incorporated into this study along with comparative MCDM analysis, which is essential to accurate location analysis in real-world urban or regional contexts.

3. Materials and Methods

This study is intended to conduct a comparative MCDM analysis to identify the most suitable locations for EV charging stations, integrating expert judgment with spatial and technical information. The study evaluates a range of critical social factors to determine optimal locations for EV infrastructure that are efficient, accessible, and sustainable. This research utilizes and compares multiple MCDM techniques to ensure robust, validated decision-making outcomes. A selection procedure aims to identify suitable selection characteristics and make the best decision about the actual requirements (Chakraborty, 2010). Key steps in the methodology are as follows:

- Criteria identification: Location selection criteria are identified through literature review and expert consultation. These include exclusive accessibility to social amenities such as malls, places of worship, schools, family health centers and municipalities (in this case, Sultanbeyli Municipality).
- Data collection: Data for each criterion is collected from reliable sources, including expert surveys, remote sensing and GIS databases, and satellite imagery. The data is compiled into a decision matrix for each potential site.
- MCDM application: The selected MCDM techniques, including VIKOR, MOORA, GRA (Grey Relation Analysis), and DEMATEL, are used to assign weights to criteria and rank alternative locations based on their performance.
- Sensitivity analysis: Testing results robustness is performed by varying the criteria weights and comparing the ranking outcomes.
- Result interpretation and recommendations: The analysis identifies optimal charging station locations and provides policy recommendations for planners and decision-makers.

The selection of these specific methods is based on their ability to provide distinct analytical perspectives and to enable comparative analysis among multiple approaches. This, in turn, enhances the reliability of the findings and strengthens the robustness of the decision-making process. This approach supports strategic urban planning and contributes to the broader adoption of EVs by addressing infrastructure challenges related to charging station deployment.

3.1. Vikor Method

VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje), proposed by Opricovic (1998), is a method that seeks a compromise solution by identifying alternatives that are closest to the ideal solution. It is particularly effective in situations where a consensus among decision-makers is required. To reach the consensus solution, the VIKOR method uses an aggregation function based on "closeness to the ideal" and linear normalization. VIKOR creates a consensus result that is accepted by decision-makers because it maximizes group benefit for the majority and minimizes personal regret for the minority (Opricovic & Tzeng, 2004; Opricovic & Tzeng, 2007). However, one of its limitations lies in the use of subjective input parameters, such as the compromise parameter (v), which may affect the objectivity of the results.

The steps of the VIKOR method are as follows:

Step 1: Determining the criteria values.

Determining the best and worst values according to the benefit and cost of the criteria.

This may include sub-headings within/under main headings.

$$f_i^* = \max_j f_{ij} \tag{1}$$

$$f_i^- = \min_j f_{ij} \tag{2}$$

Step 2: Generating the normalized matrix.

$$r_{ij} = \frac{f_j^* - x_{ij}}{f_j^* - f_j^-} \tag{3}$$

Step 3: Weighting the normalized matrix. In the normalized decision matrix, the members are weighted based on the importance of the decision-makers.

$$v_{ij} = r_{ij} \times w_j \tag{4}$$

Step 4: Calculating the mean and worst scores of the alternatives.

$$S_i = \sum_{j=1}^{n} w_j \times \frac{f_j^* - x_{ij}}{f_j^* - f_j^-} \tag{5}$$

$$R_j = \max_j \left(w_j \times \frac{f_j^* - x_{ij}}{f_j^* - f_j^-} \right) \quad (6)$$

Step 5: Calculating the Qi values of the alternatives.

$$Q_i = \frac{q \times (S_i - S^*}{S^- - S^*} + \frac{(1-q) \times (R_i - R^*)}{R^- - R^*} \quad (7)$$

Step 6: Ranking of alternatives and deciding based on the Qi values of the alternatives.

3.2. MOORA Method

MOORA (Multi-Objective Optimization by Ratio Analysis), proposed as a new method for multi-objective optimization with discrete alternatives by Brauers and Zavadskas in 2006, offers a straightforward and computationally efficient approach based on normalization and ratio analysis. It is especially advantageous in situations where criteria are expressed in different units or scales, as it enhances comparability. Nonetheless, the assumption of equal weight for all criteria may limit the method's applicability in cases where the importance of criteria varies significantly.

The steps of the MOORA method are as follows:

Step 1: Creating a matrix of alternatives for goals.

$$(x_{ij}) \quad (8)$$

Step 2: Generating the normalized matrix.

$$N^{x_{ij}} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}} \quad (9)$$

Step 3: Addition in the case of maximization and subtraction in the case of minimization.

$$N^{y_i} = \sum_{i=1}^{i=g} N^{x_{iy}} - \sum_{i=g+1}^{i=n} N^{x_{ij}} \quad (10)$$

Step 4: To measure the distance between alternatives and the reference point, the Tchebycheff Min-Max metric is used.

$$\min_{(j)} \left\{ \max_{(i)} |r_i - N^{x_{ij}}| \right\} \quad (11)$$

Step 5: Calculation of the importance levels of criteria for ranking.

$$\ddot{N}^{y_i} = \sum_{i=1}^{i=g} s_j N^{x_{iy}} - \sum_{i=g+1}^{i=n} s_j N^{x_{ij}} \quad (12)$$

3.3. GRA

A Gray relational analysis is a grading, classification and decision-making technique developed by Ju Long Deng in the 1980s to solve problems with small sample sizes and limited information (Liu et al., 2011). In MCDM problems, gray relational analysis can be used alone or in combination with other methods to create hybrid models. Both qualitative and quantitative datasets can be analyzed using this approach (Ju-Long, 1982). It serves as a powerful tool when information is limited or partially known. However, the method involves a grey relational coefficient determined by a distinguishing coefficient (commonly set to 0.5), the selection of which may introduce subjectivity and influence the results.

Gray relational analysis steps are as follows;

Step 1: The preparation of the data set and the establishment of the decision matrix.

$$x_i = \left(x_i(j), \dots, x_i(n)\right), \qquad i = 1,2,\dots,m \quad j = 1,2,\dots,n \tag{13}$$

$$X = \begin{bmatrix} x_1(1) & x_2(2)\cdots & x_1(n) \\ x_2(1) & x_2(2)\cdots & x_2(n) \\ \vdots & \vdots \quad \ddots & \vdots \\ x_m(1) & x_m(2) \quad \cdots & x_m(n) \end{bmatrix} \tag{14}$$

Step 2: Creation of reference series and comparison matrix.

$$x_0 = (x_0(j)) \qquad j = 1,2,\dots,n \tag{15}$$

Step 3: Creation of the normalization matrix.

$$x_i^* = \frac{x_i(j) - \min_j x_i(j)}{\max_j x_i(j) - \min_j x_{i(J)}} \tag{16}$$

$$x_i^* = \frac{\max_j x_i(j) - x_i(j)}{\max_j x_i(j) - \min_j x_{i(J)}} \tag{17}$$

$$x_i^* = \frac{|x_i(j) - x_{0b}(j)|}{\max_j x_i(j) - x_{0b}(j)} \tag{18}$$

$$X = \begin{bmatrix} x_1^*(1) & x_1^*(2)\cdots & x_1^*(n) \\ x_2^*(1) & x_2^*(2)\cdots & x_2^*(n) \\ \vdots & \vdots \quad \ddots & \vdots \\ x_m^*(1) & x_m^*(2) \quad \cdots & x_m^*(n) \end{bmatrix} \tag{19}$$

Step 4: Creation of the absolute value table.

$$\Delta_{0i} = |x_0^*(j) - x_i^*(j)| \qquad i = 1,2,\dots,m \quad j = 1,2,\dots,n \tag{20}$$

$$X = \begin{bmatrix} \Delta_{01}(1) & \Delta_{02}(2)\cdots & \Delta_{01}(n) \\ \Delta_{02}(1) & \Delta_{02}(2)\cdots & \Delta_{02}(n) \\ \vdots & \vdots & \ddots & \vdots \\ \Delta_{0m}(1) & \Delta_{0m}(2) & \cdots & \Delta_{0m}(n) \end{bmatrix} \quad (21)$$

Step 5: Generating the gray relational coefficient matrix.

$$\gamma_{0i}(j) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(j) + \zeta\Delta_{max}} \quad (22)$$

$$\Delta_{max} = \max_i \max_j \Delta_{0i}(j) \quad (23)$$

$$\Delta_{min} = \min_i \min_j \Delta_{0i}(j) \quad (24)$$

Step 6: Calculation of gray associative degrees.

$$\Gamma_{0i} = \frac{1}{n}\sum_{j=1}^{n} \gamma_{0i}(j) \qquad i = 1,2,\ldots,m \quad (25)$$

$$\Gamma_{0i} = \sum_{j=1}^{n}[w_i(j).\gamma_{0i}(j)] \qquad i = 1,2,\ldots,m \quad (26)$$

3.4. DEMATEL Technique

For solving economic, political and scientific problems, Fontela and Gabus developed the DEMATEL (Decision-Making Trial and Evaluation Laboratory) in 1976 (Fontela & Gabus, 1976), which is an important method for visualizing complex causal relations using matrices or digraphs. The system can be modeled in an intelligible structural way based on the causes and effects of criteria (Falatoonitoosi et al., 2013).

As described in Fontela and Gabus (1976), the DEMATEL method consists of the following steps.

Step 1: Establishing the direct-relation matrix.

At this stage, the relationship between the criteria is evaluated. Using a four-level scale, the decision maker scores the criteria in pairs. Table 2 shows the definition of the scoring scale.

Table 2. Scoring scale and definition.

Linguistic Expression	Numeric Values
No influence	0
Low influence	1
High influence	2
Very high influence	3

Following the decision of the decision maker, **A** direct relationship matrix in dimension *nxn* is obtained to represent the number of criteria a_{ij} in matrix **A** and to show the degree to which criterion *i* affects criterion *j*.

Step 2: Obtaining the normalized direct-relation matrix.

With the help of the following equations, we can obtain the normalized direct relationship matrix denoted by **X** from the direct relationship matrix **A**.

$$\mathbf{X} = k.\mathbf{A} \tag{27}$$

$$k = \frac{1}{maks \sum_{j=1}^{n} a_{ij}}, \qquad i,j=1,2,3,......,n \tag{28}$$

The sum of the direct relation matrix's rows and columns is calculated by Equations 27 and 28. A maximum value is chosen from the totals in the columns and rows. Matrix **A** elements are divided by this number. The result is a normalized direct correlation matrix **X**, each element of which has a normalized value between 0 and 1.

Step 3: Calculate the total-relation matrix.

The total relationship matrix **T** is derived from equation 29 shown below by the unit matrix **I**.

$$\mathbf{T} = \mathbf{X}(\mathbf{I} - \mathbf{X})^{-1} \tag{29}$$

Step 4: Determination of affecting and affected criterion groups.

The **D***i* matrix in dimension *nx1* is derived from the **T** total relationship matrix. Column totals of the total relationship matrix **T**, then the transpose of these total values is taken. By transposing *1xn* column totals, we will get an **R** matrix with *nx1* dimensions.

$$\mathbf{T} = \left[t_{ij}\right]_{nxn}, i,j = 1,2,\dots,n \tag{30}$$

$$\mathbf{D}_i = \left[\sum_{j=1}^{n} t_{ij}\right]_{nx1} = [t_i]_{nx1}, i = 1,2,\dots,n \tag{31}$$

$$\mathbf{R}_i = \left[\sum_{i=1}^{n} t_{ij}\right]_{1xn}^{t} = \left[t_j\right]_{nx1}, j = 1,2,\dots,n \tag{32}$$

Step 5: Determination of threshold values.

The sum of rows and sum of columns of the total relation matrix **T** in Equation 30 are computed as an **D** and **R** *nx1* vectors. As a result, while *i = j* the sum (*Di + Ri*) that is called "Prominence'' proves the degree of importance role of criterion *i* in the system and also gives an index that shows the total effects both given and received by criterion *i*. Likewise, the (*Di, Ri*) that is called "Relation" shows the net effect that criterion *i* donates to the system. When (*Di, Ri*) is positive, criterion *i* will belong to the cause group and when (*Di, Ri*) is negative, criterion *i* is a net receiver (Falatoonitoosi et al.,2013).

3.5. Methods Comparison: Pros and Cons

The comparison of selected MCDM techniques based on Brauers and Zavadskas (2012) is shown in Table 3.

Table 3. Comparison of selected MCDM techniques

	VIKOR	GRA	MOORA
Calculation time	Low	Moderate	Very low
Applicability	Simple	Critic	Simple
Mathematical operation	Moderate	Moderate	Low
Reliability	Moderate	Moderate	Good
Data type	Quantitative	Quantitative	Quantitative

Every method has its strengths, making it suitable for different decision contexts. The VIKOR is an ideal solution for situations that require a compromise between group satisfaction and individual preferences. The GRA is appropriate when data are incomplete or uncertain, such as when early-stage planning is taking place in developing regions. For the rapid evaluation of many alternatives with clearly defined quantitative data, MOORA is an excellent tool. DEMATEL adds value by modeling criteria interdependencies, making it especially suitable for model development's early stages. An analysis of these methods in parallel or a comparative analysis can enhance the accuracy, transparency, and resilience of urban mobility and infrastructure planning.

4. Results

4.1. Criteria Identification

A site selection model is developed for EV charging stations based on accessibility to social amenities such as malls, places of worship, schools, family health centers, and the Sultanbeyli District Municipalities of Istanbul. The rationale behind this focused approach is grounded in the increasing recognition that user convenience and experiential quality are key determinants of charging behavior, particularly in urban and peri-urban environments.

Although technical and infrastructural factors—such as energy availability, grid access, and land suitability—are essential for operational feasibility, the presence of proximate social amenities plays a substantial role in influencing user preferences and station utilization. EV users are more likely to favor charging locations that offer opportunities to engage in auxiliary activities during the charging process, thereby increasing the attractiveness and competitiveness of the station.

By limiting the model's scope to social accessibility criteria, the study aims to isolate and quantitatively evaluate the spatial impact of user-centric variables on site suitability. This methodological choice allows for a more streamlined and interpretable analysis, reducing the complexity and multicollinearity often associated with MCDM models that incorporate heterogeneous factors.

While this constitutes a deliberate simplification of the broader site selection process, it provides valuable insights for urban planners, policymakers, and investors seeking to enhance user satisfaction and optimize the spatial integration of EV infrastructure in densely populated or strategically significant areas.

4.2. Criteria Weights Assignment

Weights were calculated using the Analytic Hierarchy Process (AHP) and confirmed through expert judgment. Table 4 below shows the final normalized weights assigned to each criterion.

Table 4. Criteria weights for the models presented.

#	Criterion	Weights
K1	Malls	0.4
K2	Places of worship	0.1
K3	Schools	0.1
K4	Family health centers	0.1
K5	Sultanbeyli Municipality	0.3

4.3. Alternative Selection and Data Collection

Gas stations and green areas are considered possible site locations for electric vehicle charging stations. There are several strategic infrastructure compatibility factors at gas stations, such as existing transportation nodes, grid connectivity, alignment of user behavior, space availability, and synergy between business models. Green areas have several benefits for sustainable and smart urban integration, including environmental harmony, reduced land conflict, synergy with recreation and dwell time, and public sector control.

Expert surveys, remote sensing and GIS databases, and satellite imagery are used to collect data for each criterion. Table 5 shows the decision matrix for each potential site based on the data compiled. This table shows alternative locations for EV charging stations in the Sultanbeyli District Municipality of Istanbul, of which 12 are gas stations and the rest are green areas.

Table 5. Electric charging station location alternatives and criteria

Alt.	Location	Distances to (in meter)				
		malls	places of worship	schools	family health centers	the Sultanbeyli Municipality
GS_01	https://goo.gl/maps/AAKrHG7LqqRHmyKn7	810	111	750	680	1490
GS_02	https://goo.gl/maps/cc6cY77V4aHVjKLx6	295	313	321	288	917
GS_03	https://goo.gl/maps/hN7thNsCNf8Na6RM9	1140	618	273	505	613
GS_04	https://goo.gl/maps/fADxaDki7m4RJDKf8	380	90	960	827	226
GS_05	https://goo.gl/maps/kPiv1qKJ9KuPtAxA8	1190	438	210	544	678
GS_06	https://goo.gl/maps/MbX8fMowLdH5h8oWA	1070	562	785	695	1450
GS_07	https://goo.gl/maps/SvE46BBmv7EGgZu8A	1240	368	832	701	1570
GS_08	https://goo.gl/maps/afvgNDoYhzbrMVQAA	2080	505	810	645	2450
GS_09	https://goo.gl/maps/hNWqKy8WbqMXKJb38	2780	215	880	525	3140
GS_10	https://goo.gl/maps/kWzPHB2eBdC6onR86	1830	161	401	413	2160
GS_11	https://goo.gl/maps/mEKHqzcz99XVzwk56	1730	248	109	489	1680
GS_12	https://goo.gl/maps/1PFuUgqTTiGvT89p7	2680	107	455	420	2670
GA_01	https://goo.gl/maps/ZmLvzjhrNiPrx6Ap9	782	149	590	478	2030
GA_02	https://goo.gl/maps/pwyZyBZ3Q2nCMyS89	1110	237	327	296	1810
GA_03	https://goo.gl/maps/rgH3srPg6RK3go929	1170	104	538	463	1480
GA_04	https://goo.gl/maps/4pg8T8jcJHTqndaD6	1620	490	253	557	1940
GA_05	https://goo.gl/maps/shoUaWAA4heKbtdM9	2050	360	290	661	2370
GA_06	https://goo.gl/maps/7vLZCoSYw1EQ2e1P9	2230	112	899	907	2560
GA_07	https://goo.gl/maps/bdM8uMcB2oy4YiLz8	4540	452	358	312	4876
GA_08	https://goo.gl/maps/2t9ccWmFRzMwH7kP6	4370	269	85	623	4690
GA_09	https://goo.gl/maps/ovqKRQfu5saqQLLb6	5530	313	125	234	5850
GA_10	https://goo.gl/maps/9BygnejBq1sEiFd97	2940	227	3240	253	3243
GA_11	https://goo.gl/maps/qE3bAPh2WimzCPFP8	4500	167	472	885	4818
GA_12	https://goo.gl/maps/1Uv4PcwrQ4dFzniy9	3700	169	226	757	3900
GA_13	https://goo.gl/maps/W4QvHH8tHg6ZrrL5A	1000	53	111	192	1200
GA_14	https://goo.gl/maps/vV1cdjhFrtCpewK1A	5400	103	650	1320	5200
GA_15	https://goo.gl/maps/nSiDeQ573KxAhwzW6	5100	178	694	794	5000
GA_16	https://goo.gl/maps/qHaa2cZyA5iCLzzW7	4400	283	391	203	4300
GA_17	https://goo.gl/maps/hAkqdmnhtvpvxbyb6	3100	242	1100	509	3300
GA_18	https://goo.gl/maps/VWksE2vDcpSZuhzQ7	2500	438	616	734	2600
GA_19	https://goo.gl/maps/Rtwkpp9UbkGsqqop8	2400	163	378	409	2200
GA_20	https://goo.gl/maps/FfPPrUcEiZ6Sezv37	2000	123	207	472	1900
GA_21	https://goo.gl/maps/vxELH5Fh6DFWWEE57	2400	198	144	216	2300
GA_22	https://goo.gl/maps/FsKufB1EJG3h1w9KA	2100	211	165	549	2000
GA_23	https://goo.gl/maps/dyT5VvaVip5tM3Gk9	2700	249	283	1370	2600
GA_24	https://goo.gl/maps/B3NmgXfrBWgyjUG3A	2800	121	375	122	2700
GA_25	https://goo.gl/maps/cQWHmBD6BFw9qNEg9	3700	767	314	250	3600
GA_26	https://goo.gl/maps/Gk4EBrC6fQmRAoPB8	4900	316	335	1270	4800
GA_27	https://goo.gl/maps/q2BykZ3NxzjQUksT7	3700	79	200	118	3600
GA_28	https://goo.gl/maps/NkHw4a3cD1N3rpYo6	4100	795	865	1310	4000
GA_29	https://goo.gl/maps/yrTZh8s5GqTfL2YG9	3400	533	56	356	3300
GA_30	https://goo.gl/maps/d3ZDrzvW3gXRaiop7	3500	191	395	270	3300
GA_31	https://goo.gl/maps/Z2VrzB3HLYD3qYxC6	3400	382	214	713	3300
GA_32	https://goo.gl/maps/mAerSde2os2SCqZi8	3200	290	630	1080	3100
GA_33	https://goo.gl/maps/e75e3kFKz5YuPhMt7	2800	518	270	697	2600

GA_34 https://goo.gl/maps/9Fg14Arj4M6GuWgu6	3300	192	283	757	3200
GA_35 https://goo.gl/maps/y68Qk9ocTY5W5pjGA	1900	213	738	803	1700
GA_36 https://goo.gl/maps/tjdxjnYfuQkidaQe9	1100	306	178	277	1000
GA_37 https://goo.gl/maps/3qhsXcf5fpVRZErp8	1300	205	510	251	1200
GA_38 https://goo.gl/maps/aFvPfRxCEZNHB5dBA	2400	124	212	828	2300

Alt: Alternatives; GS: Gas station; GA: Green area.

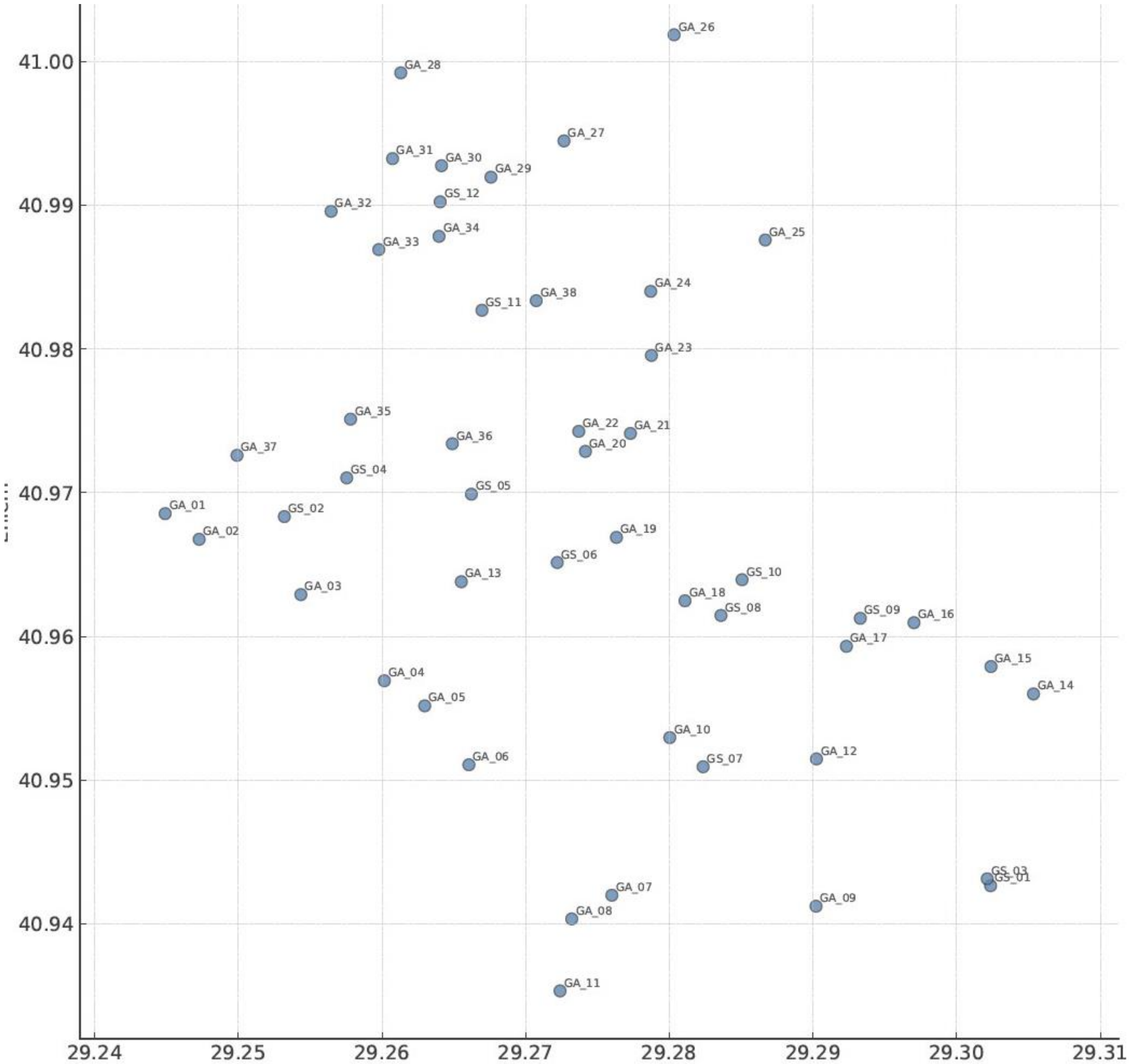

Figure 1. The geographic distribution of the evaluated alternatives.

Figure 1 shows the geographic distribution of the evaluated alternatives was examined based on their latitude and longitude coordinates. This spatial analysis enabled a detailed understanding of the locational patterns of the candidate points, highlighting potential clustering tendencies and proximity to urban infrastructure. Mapping these alternatives provided valuable insights into spatial accessibility, regional equity, and the potential effectiveness of selected locations in meeting service delivery objectives.

4.4. MCDM Application

4.4.1. VIKOR Results

When the problem is solved with the VIKOR method, it can be seen from Table 6 that the most suitable alternative (location) is Gas station_02.

Table 6. Solution results of the VIKOR method

Alt.	Qi (*q=0*)	Qi (*q=0.25*)	Qi (*q=0.5*)	Qi (*q=0.75*)	Qi (*q=1*)	Alt.	Qi (*q=0*)	Qi (*q=0.25*)	Qi (*q=0.5*)	Qi (*q=0.75*)	Qi (*q=1*)
GS_01	3	4	5	5	7	GA_17	33	33	32	33	32
GS_02	1	1	1	1	1	GA_18	26	27	28	29	30
GS_03	12	13	11	11	14	GA_19	23	24	22	21	20
GS_04	5	5	4	4	3	GA_20	18	17	17	16	13
GS_05	9	10	10	10	10	GA_21	23	22	21	19	16
GS_06	10	11	13	15	18	GA_22	21	19	18	18	17
GS_07	11	12	12	14	15	GA_23	28	30	30	34	35
GS_08	20	21	24	27	27	GA_24	30	28	26	23	21
GS_09	29	29	29	28	29	GA_25	39	41	41	41	42
GS_10	16	16	15	13	11	GA_26	47	47	48	49	48
GS_11	15	15	14	12	12	GA_27	39	39	35	30	28
GS_12	27	26	27	25	24	GA_28	42	44	46	48	49
GA_01	2	2	3	3	3	GA_29	36	37	37	36	36
GA_02	6	6	6	6	5	GA_30	38	36	34	32	31
GA_03	8	8	8	8	8	GA_31	36	38	39	38	38
GA_04	14	14	16	17	19	GA_32	34	35	38	40	40
GA_05	19	20	20	22	23	GA_33	30	31	31	31	34
GA_06	22	23	23	26	26	GA_34	35	34	36	35	33
GA_07	46	46	44	44	44	GA_35	17	18	19	20	22
GA_08	43	43	43	43	43	GA_36	6	7	7	7	6
GA_09	50	49	49	47	46	GA_37	13	9	9	9	9
GA_10	32	32	33	37	39	GA_38	23	25	25	24	25
GA_11	45	45	45	45	45	Q (A^2)	0.0274	0.0519	0.0763	0.1008	0.1253
GA_12	39	40	40	39	37	Q (A^1)	0	0	0	0	0
GA_13	4	3	2	2	2	Q (A^2) -Q (A^1)	0.0274	0.0519	0.0763	0.1008	0.1253
GA_14	49	50	50	50	50	DQ	0.0204	0.0204	0.0204	0.0204	0.0204
GA_15	48	48	47	46	47	Cond_1	True	True	True	True	True
GA_16	44	42	42	42	41	Cond_2	True	True	True	True	True

Alt: Alternatives; GS: Gas station; GA: Green area; Cond: Condition.

As a result of the ranking and control of the conditions in Table 6, Gas station_02 was determined as the best alternative since it satisfies both conditions at the same time.

4.4.2. MOORA Results

When the problem is solved with the MOORA method, it can be seen from Table 7 that the most suitable alternative (location) is Gas station_02.

Table 7. Solution results of the MOORA method

Alt.	K1	K2	K3	K4	K5	Maxs	RNG	Alt.	K1	K2	K3	K4	K5	Maxs	RNG
	min	min	min	min	min				min	min	min	min	min		
GS_01	0.010	0.002	0.014	0.012	0.018	0.018	6	GA_14	0.098	0.002	0.012	0.026	0.070	0.098	49
GS_02	0.000	0.011	0.006	0.004	0.010	0.011	1	GA_15	0.093	0.005	0.013	0.014	0.068	0.093	48
GS_03	0.016	0.024	0.005	0.008	0.005	0.024	12	GA_16	0.079	0.010	0.007	0.002	0.058	0.079	44
GS_04	0.002	0.002	0.019	0.015	0.000	0.019	7	GA_17	0.054	0.008	0.022	0.008	0.043	0.054	32
GS_05	0.017	0.016	0.003	0.009	0.006	0.017	4	GA_18	0.042	0.016	0.012	0.013	0.034	0.042	26
GS_06	0.015	0.022	0.015	0.012	0.017	0.022	10	GA_19	0.041	0.005	0.007	0.006	0.028	0.041	23
GS_07	0.018	0.013	0.016	0.012	0.019	0.019	8	GA_20	0.033	0.003	0.003	0.008	0.024	0.033	18
GS_08	0.034	0.019	0.016	0.011	0.031	0.034	20	GA_21	0.041	0.006	0.002	0.002	0.029	0.041	23
GS_09	0.048	0.007	0.017	0.009	0.041	0.048	29	GA_22	0.035	0.007	0.002	0.009	0.025	0.035	21
GS_10	0.030	0.005	0.007	0.006	0.027	0.030	16	GA_23	0.046	0.008	0.005	0.027	0.034	0.046	28
GS_11	0.028	0.008	0.001	0.008	0.021	0.028	15	GA_24	0.048	0.003	0.007	8.571	0.035	0.048	30
GS_12	0.046	0.002	0.008	0.006	0.035	0.046	27	GA_25	0.066	0.031	0.005	0.003	0.048	0.066	38
GA_01	0.009	0.004	0.011	0.008	0.026	0.026	13	GA_26	0.089	0.011	0.006	0.025	0.065	0.089	47
GA_02	0.016	0.008	0.006	0.004	0.022	0.022	11	GA_27	0.066	0.001	0.003	0.000	0.048	0.066	38
GA_03	0.017	0.002	0.010	0.007	0.018	0.018	5	GA_28	0.073	0.032	0.017	0.026	0.053	0.073	42
GA_04	0.026	0.019	0.004	0.009	0.024	0.026	14	GA_29	0.060	0.021	0.000	0.005	0.043	0.060	35
GA_05	0.034	0.013	0.005	0.012	0.030	0.034	19	GA_30	0.062	0.006	0.007	0.003	0.043	0.062	37
GA_06	0.037	0.003	0.018	0.017	0.033	0.037	22	GA_31	0.060	0.014	0.003	0.013	0.043	0.060	35
GA_07	0.082	0.017	0.006	0.004	0.066	0.082	46	GA_32	0.056	0.010	0.012	0.021	0.041	0.056	33
GA_08	0.079	0.009	0.001	0.011	0.063	0.079	43	GA_33	0.048	0.020	0.004	0.012	0.034	0.048	30
GA_09	0.101	0.011	0.001	0.002	0.080	0.101	50	GA_34	0.058	0.006	0.005	0.014	0.042	0.058	34
GA_10	0.051	0.007	0.066	0.003	0.043	0.066	41	GA_35	0.031	0.007	0.014	0.015	0.021	0.031	17
GA_11	0.081	0.005	0.009	0.016	0.065	0.081	45	GA_36	0.016	0.011	0.003	0.003	0.011	0.016	3
GA_12	0.066	0.005	0.004	0.014	0.052	0.066	38	GA_37	0.019	0.007	0.009	0.003	0.014	0.019	9
GA_13	0.014	0.000	0.001	0.002	0.014	0.014	2	GA_38	0.041	0.003	0.003	0.015	0.029	0.041	23

Alt: Alternatives; GS: Gas station; GA: Green area.

4.4.3. GRA Results

The data in Table 5 were applied to the steps of the Gray relational analysis and the results in Table 8 below were obtained.

Table 8. Solution results of the Gray relational analysis

wi	0.4	0.1	0.1	0.1	0.3	r_{0i}	RNG	wi	0.4	0.1	0.1	0.1	0.3	r_{0i}	RNG
	K1	K2	K3	K4	K5				K1	K2	K3	K4	K5		
GS_01	0.836	0.865	0.696	0.527	0.690	0.750	7	GA_14	0.339	0.881	0.728	0.342	0.361	0.439	48
GS_02	1.000	0.588	0.857	0.786	0.803	0.864	2	GA_15	0.353	0.748	0.714	0.481	0.371	0.447	47
GS_03	0.756	0.396	0.880	0.618	0.879	0.756	6	GA_16	0.389	0.617	0.826	0.880	0.408	0.511	42
GS_04	0.969	0.909	0.638	0.469	1.000	0.889	1	GA_17	0.483	0.663	0.604	0.616	0.478	0.525	37
GS_05	0.745	0.491	0.912	0.595	0.862	0.756	5	GA_18	0.543	0.491	0.740	0.504	0.542	0.553	31
GS_06	0.772	0.422	0.686	0.520	0.697	0.680	13	GA_19	0.554	0.771	0.832	0.683	0.588	0.627	22
GS_07	0.735	0.541	0.672	0.518	0.677	0.670	14	GA_20	0.606	0.841	0.913	0.639	0.627	0.670	15
GS_08	0.595	0.451	0.679	0.543	0.558	0.573	28	GA_21	0.554	0.719	0.948	0.865	0.576	0.647	17
GS_09	0.513	0.696	0.659	0.606	0.491	0.549	33	GA_22	0.592	0.701	0.936	0.592	0.613	0.644	19
GS_10	0.630	0.775	0.822	0.680	0.592	0.657	16	GA_23	0.521	0.654	0.875	0.333	0.542	0.557	30
GS_11	0.646	0.655	0.968	0.628	0.659	0.681	12	GA_24	0.511	0.845	0.833	0.994	0.532	0.631	21
GS_12	0.523	0.873	0.800	0.675	0.535	0.605	25	GA_25	0.435	0.342	0.861	0.826	0.455	0.513	40
GA_01	0.843	0.794	0.749	0.635	0.609	0.738	9	GA_26	0.362	0.585	0.851	0.352	0.381	0.438	49
GA_02	0.763	0.668	0.855	0.779	0.640	0.727	11	GA_27	0.435	0.935	0.917	1.000	0.455	0.595	26
GA_03	0.749	0.879	0.768	0.645	0.692	0.736	10	GA_28	0.408	0.333	0.663	0.344	0.427	0.425	50
GA_04	0.664	0.459	0.890	0.588	0.621	0.646	18	GA_29	0.457	0.436	1.000	0.725	0.478	0.542	34
GA_05	0.599	0.547	0.872	0.536	0.567	0.605	24	GA_30	0.450	0.729	0.824	0.805	0.478	0.559	29
GA_06	0.575	0.863	0.654	0.442	0.546	0.590	27	GA_31	0.457	0.530	0.910	0.513	0.478	0.522	38
GA_07	0.381	0.482	0.841	0.763	0.377	0.474	44	GA_32	0.474	0.610	0.735	0.394	0.495	0.512	41
GA_08	0.391	0.632	0.982	0.553	0.386	0.489	43	GA_33	0.511	0.444	0.882	0.520	0.542	0.552	32
GA_09	0.333	0.588	0.958	0.844	0.333	0.472	45	GA_34	0.466	0.727	0.875	0.495	0.486	0.542	35
GA_10	0.497	0.681	0.333	0.823	0.482	0.527	36	GA_35	0.620	0.699	0.700	0.477	0.656	0.632	20
GA_11	0.384	0.765	0.793	0.449	0.380	0.468	46	GA_36	0.765	0.595	0.929	0.797	0.784	0.773	4
GA_12	0.435	0.762	0.904	0.495	0.434	0.520	39	GA_37	0.723	0.709	0.778	0.825	0.743	0.743	8
GA_13	0.788	1.000	0.967	0.894	0.743	0.824	3	GA_38	0.554	0.839	0.911	0.469	0.576	0.616	23

GS: Gas station; GA: Green area.

As shown in Table 8, Gas Station 2 is ranked second, contrary to VIKOR and MOORA, while Gas Station 4 was ranked first.

4.4.4. Comparison of the Results of VIKOR, MOORA and GRA Methods

The data in Table 5 were solved by VIKOR, MOORA and Gray relational methods and the results were compared in Table 9.

Table 9. Comparison of the results of the three methods

Alt.	Methods			Alt.	Methods		
	VIKOR	MOORA	GR		VIKOR	MOORA	GR
GS_01	7	6	7	GA_14	50	49	48
GS_02	1	1	2	GA_15	47	48	47
GS_03	14	12	6	GA_16	41	44	42
GS_04	3	7	1	GA_17	32	32	37
GS_05	10	4	5	GA_18	30	26	31
GS_06	18	10	13	GA_19	20	23	22
GS_07	15	8	14	GA_20	13	18	15
GS_08	27	20	28	GA_21	16	23	17
GS_09	29	29	33	GA_22	17	21	19
GS_10	11	16	16	GA_23	35	28	30
GS_11	12	15	12	GA_24	21	30	21
GS_12	24	27	25	GA_25	42	38	40
GA_01	4	13	9	GA_26	48	47	49
GA_02	5	11	11	GA_27	28	38	26
GA_03	8	5	10	GA_28	49	42	50
GA_04	19	14	18	GA_29	36	35	34
GA_05	23	19	24	GA_30	31	37	29
GA_06	26	22	27	GA_31	38	35	38
GA_07	44	46	44	GA_32	40	33	41
GA_08	43	43	43	GA_33	34	30	32
GA_09	46	50	45	GA_34	33	34	35
GA_10	39	41	36	GA_35	22	17	20
GA_11	45	45	46	GA_36	6	3	4
GA_12	37	38	39	GA_37	9	9	8
GA_13	2	2	3	GA_38	25	23	23

Alt: Alternatives; GS: Gas station; GA: Green area; GR: Gray relational

4.4.5. DEMATEL Results

The solutions shown in Table 9 were rearranged according to the first 5 rankings and 38 alternatives were reduced to five, and a new data set was created as shown in Table 10, which is one of the MCDM methods to guide the decision maker, DEMATEL technique, which is a method for determining the interaction between the variables affecting the decision in the decision-making environment, was utilized.

Table 10. The top 5 locations for alternative locations

Alt.	Distances to (in meter)				
	malls	places of worship	schools	family health centers	the Sultanbeyli Municipality
GS_02	295	313	321	288	917
GS_04	380	90	960	827	226
GA_02	1110	237	327	296	1810

GA_13	1000	53	111	192	1200
GA_36	1100	306	178	277	1000

Alt: Alternatives; GS: Gas station; GA: Green area.

Using the DEMATEL method, the data set in Table 9 was processed and the results shown in Table 11 were obtained.

Table 11. Solution results of the DEMATEL method

Alt.	Distances to (in meter)					Influences/Relations			
	malls	Places of worship	schools	family health centers	the Sultanbeyli Municipality				
	K-1	K-2	K-3	K-4	K-5	D	R	D+R	D-R
GS_02	1	0	0	$6.66*10^{-11}$	$8.88*10^{-11}$	1	1	2	0
GS_04	$1.04*10^{-12}$	1	$3.47*10^{-13}$	$6.66*10^{-11}$	$-1.22*10^{-10}$	1	$3.82*10^{-12}$	1	1
GA_02	$-2.78*10^{-12}$	$2.78*10^{-12}$	1	$-8.88*10^{-11}$	$8.88*10^{-11}$	1	$2.78*10^{-12}$	1	1
GA_13	0	$2.22*10^{-11}$	$1.11*10^{-11}$	1	$8.88*10^{-11}$	1	$5.55*10^{-12}$	1	1
GA_36	$5.55*10^{-12}$	0	$1.11*10^{-11}$	$-8.88*10^{-11}$	1	1	$5.55*10^{-12}$	1	1

Alt: Alternatives; GS: Gas station; GA: Green area.

By determining the threshold value, an effect-relationship diagram was drawn. A threshold value was suggested by Li & Tzeng (2009) after calculating the interaction between the variables in the DEMATEL method. In this case, the threshold value was accepted as 0.4 as indicated by Li & Tzeng (2009).

An effect-relationship diagram using *Di+Ri* and *Di-Ri* values is shown in Figure 2.

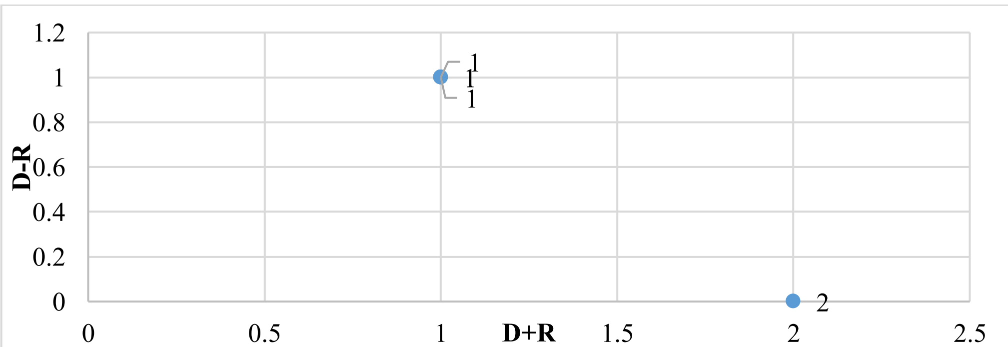

Figure 2. Effect-relationship diagram.

Gas Station 2 appears to be the optimum location according to the DEMATEL method.

Gas station 2 was found to be the most suitable EV location based on the results of MCDM methods. Figure 3 shows on the Sultanbeyli map the location of the gas station_02 obtained using the DEMATEL method.

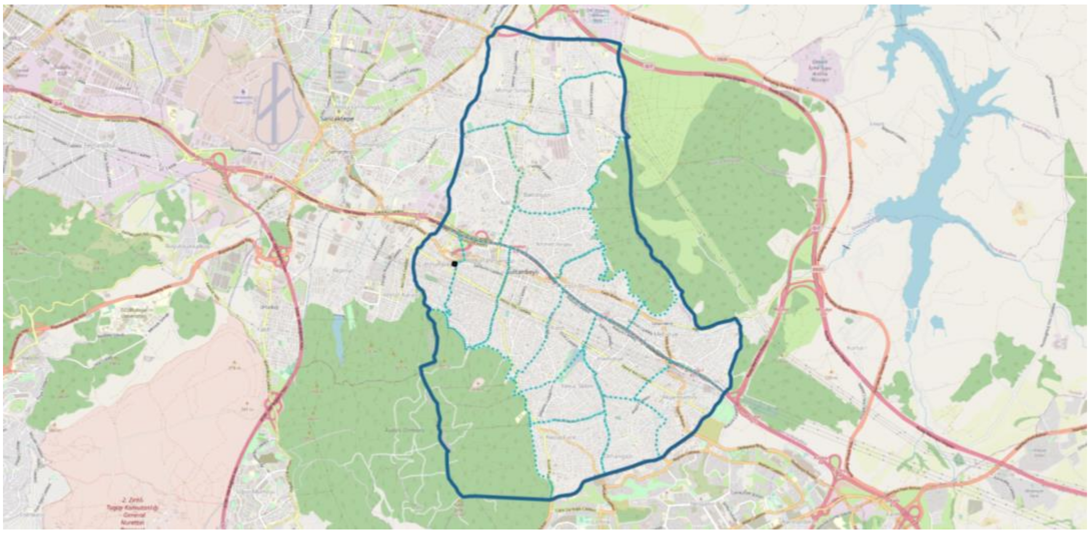

Figure 3. Location of the Gas station_02 on the Sultanbeyli map.

The GS_02 alternative ranked highest among all options based on the applied multi-criteria decision-making (MCDM) methods. This outcome is primarily attributed to its close proximity to key urban amenities, including shopping centers, workplaces, schools, family health centers, and the municipal building. Such locational advantages significantly enhance the alternative's overall utility and accessibility, thereby increasing its desirability in the context of urban planning and service distribution.

4.5. Sensitivity Analysis

A comprehensive sensitivity analysis was conducted to evaluate the reliability and consistency of the results obtained from ranking the alternatives using three different multi-criteria decision-making (MCDM) methods: VIKOR, MOORA, and Grey Relational Analysis (GRA).

4.5.1. Ranking Consistency Among Methods

To assess the comparability of ranking results across the methods, Spearman's rank correlation coefficient was calculated. Spearman's correlation is a non-parametric measure that assesses the strength of the monotonic relationship between ranked variables (Spearman, 1904)

Method Pair	Spearman Correlation
VIKOR – MOORA	0.9135
VIKOR – GRA	0.8732
MOORA – GRA	0.9279

Interpretation: A high level of positive correlation was observed between all three methods (ρ > 0.87), indicating that the ranking results are highly consistent across methods (Kendall & Gibbons, 1990).

4.5.2. Ranking Discrepancies

To further examine the differences in rankings, the absolute ranking gaps (|VIKOR–MOORA|, |VIKOR–GRA|, |MOORA–GRA|) were calculated for each alternative. The average and median values of these differences are presented below:

Ranking Gap Pair	Mean Difference	Median Difference
VIKOR – MOORA	6.12	5
VIKOR – GRA	6.84	6
MOORA – GRA	5.29	5

Interpretation: The relatively low average differences (<7) suggest that the rankings are largely similar. However, in some cases, the differences reached values of 10 or more, signaling potential divergences in specific alternatives.

4.5.3. Variance Analysis per Alternative

The variance and standard deviation of the rankings assigned to each alternative by the three methods were computed to evaluate ranking stability. High variance and standard deviation indicate that an alternative's rank is sensitive to the choice of method.

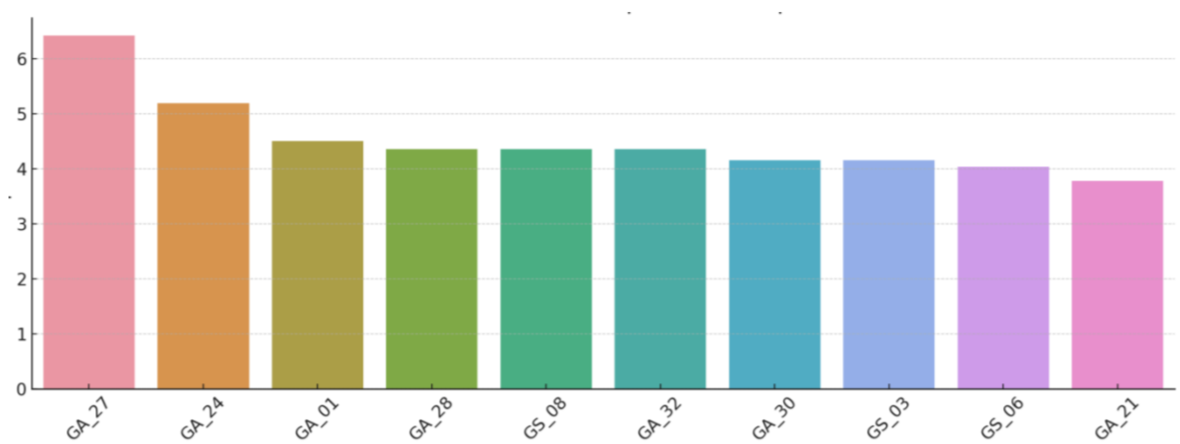

Figure 4. Illustrates the 10 alternatives with the highest ranking standard deviations.

4.5.4 Comparative Performance of Methods

For each alternative, the method providing the lowest (i.e., best) ranking was identified. This analysis highlights which method most frequently ranked alternatives in the top positions.

Method	Number of Times Ranked Best
GRA	23
VIKOR	14
MOORA	11
Shared	2

Interpretation: The GRA method yielded the best ranking for the largest number of alternatives. This may suggest that GRA is more advantageous in certain types of decision problems (Deng, 1989).

4.5.5. Visualization and Correlation Matrix

Figure 5 presents a heatmap showing the Spearman correlations among the three methods.

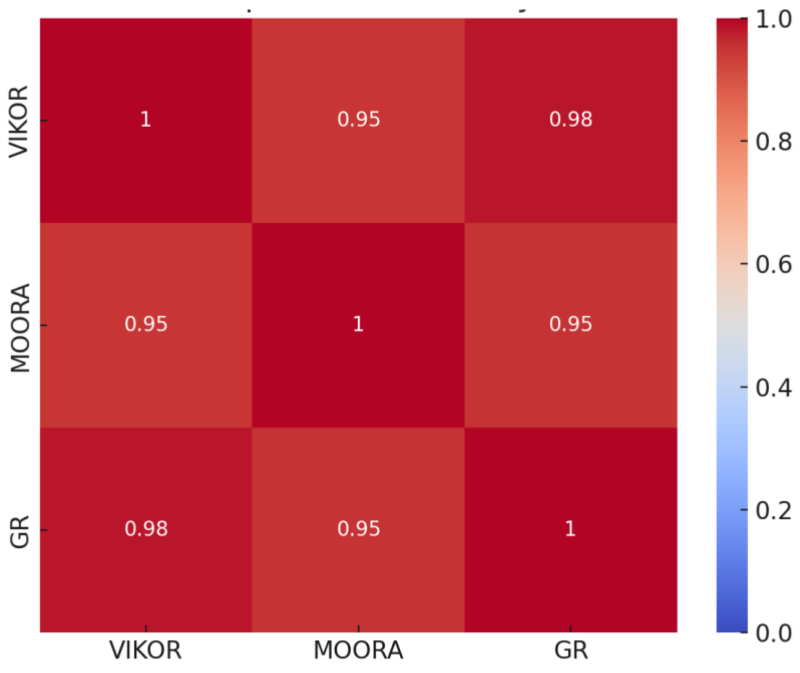

Figure 5. Heatmap of the Spearman correlations among the three methods.

Figure 6 provides scatter plots of the rankings between each method pair.

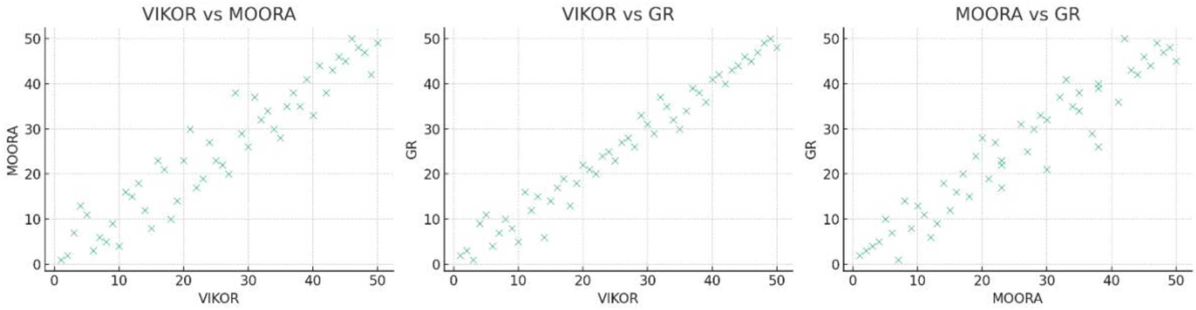

Figure 6. The rankings between each method pair.

GRA most frequently provided the top-ranked alternatives overall. VIKOR and MOORA displayed a more balanced distribution, but differed particularly at the extremes (very high or very low ranks). These differences may reflect the methodological priorities of each technique. For instance, GRA may prioritize certain alternatives more favorably, while VIKOR or MOORA may emphasize others.

5. Findings and Discussion

This section discusses the implications, significance, and interpretation of the findings obtained through the application of VIKOR, GRA, MOORA, and DEMATEL methods in determining optimal EV charging station locations.

The VIKOR method uses an aggregation function based on "closeness to the ideal" and linear normalization to reach the consensus solution. Gray relational analysis, the second method used in this study, is also capable of intuitively comparing and ranking alternatives based on the decision data. MOORA was chosen as the third method for solving this problem due to its low computation time, simple application, minimum mathematical operations, and high reliability. The DEMATEL method, which provides a graphical evaluation to decision-makers, was preferred after determining the interaction between the five most suitable alternative locations and the criteria selected from 38 alternatives using the VIKOR, GRA and MOORA methods.

There is a high degree of consistency between the VIKOR, MOORA, and DEMATEL methods, with GS_02 consistently ranking high. It should be noted, however, that while GS_04 ranked first on the GRA, it ranked second on the DEMATEL.

With its findings, urban planners, energy providers, and transport authorities can identify data-driven, spatially optimized locations for the deployment of EV charging infrastructure. Providing a replicable framework that can be applied to other cities or regions with appropriate local data, the paper demonstrates the utility of integrating multiple decision-making techniques to minimize bias and avoid reliance on a single method.

Comparative MCDM offers many benefits, including increased robustness of results due to multi-method validation, increased transparency in decision-making, as stakeholders can see the rationale behind certain locations' selection, and flexibility and scalability—the model can be adapted to other regions, criteria sets, or technologies.

The study has several limitations, despite its strengths. Expert-based weighting (e.g., AHP) can introduce bias due to subjectivity. Machine learning or big data-driven weight estimation techniques may be used in future studies. Data based on static criteria may fail to reflect future changes in urban dynamics, EV adoption rates, or traffic patterns. For adaptive decision-making, future research could explore hybrid models combining MCDM and machine learning. Social equity and user preferences can be incorporated into the decision-making process through stakeholder engagement frameworks.

The observed consistency among the VIKOR, MOORA, and DEMATEL methods—particularly the consistently high ranking of GS_02—is in line with findings in the existing literature, where multiple MCDM methods often converge in ranking top-performing alternatives due to shared underlying data structures and criteria weightings.

Several studies have demonstrated that when criteria are clearly defined and weighted appropriately, methods such as VIKOR, MOORA, and even hybrid methods involving DEMATEL tend to produce converging results at the top end of the ranking list:

Opricovic & Tzeng (2004) found that VIKOR and TOPSIS yielded nearly identical rankings for high-priority alternatives in a resource allocation problem, especially when the compromise solution aligned with the ideal vector.

Zavadskas et al. (2016) reported strong alignment between MOORA and other utility-based methods in site selection problems, where criteria weights derived from DEMATEL reinforced ranking consistency.

Li et al. (2011) demonstrated that the integration of DEMATEL with VIKOR and AHP improved ranking stability and yielded highly consistent top rankings in urban transport planning scenarios.

The consistent ranking of GS_02 across all methods reflects a similar pattern, where an alternative with a clear multi-criteria advantage (e.g., central location, accessibility to public services, etc.) maintains its superiority regardless of the MCDM method applied.

On the other hand, the divergence observed in the case of GS_04—ranked first by GRA but second by DEMATEL—can be interpreted through method-specific sensitivity. This phenomenon is also widely discussed in the literature:

Deng (1989) emphasized that GRA is particularly sensitive to the relative closeness of alternatives across all criteria, and may favor options that show uniform performance, even if they do not strongly dominate in any one criterion.

In contrast, DEMATEL-based rankings, when used in conjunction with other methods, often emphasize inter-criteria causal relationships, which may penalize alternatives that perform well on output criteria but have less influence in the system structure (Tseng, 2009).

Brauers & Zavadskas (2006) noted that MOORA may shift rankings slightly when alternatives are highly clustered in performance, introducing minor deviations in mid-tier options but usually preserving top-rank consistency.

Thus, the case of GS_04 illustrates a classic instance of methodological divergence caused by differing conceptual foci:

GRA → favors alternatives with overall closeness to the ideal.

DEMATEL → incorporates systemic influence and may adjust rankings accordingly.

The combination of inter-method consistency (e.g., GS_02) and selective divergence (e.g., GS_04) suggests a robust decision environment, where:

Top-ranked alternatives can be considered stable choices across various decision logic frameworks.

Minor divergences call for further expert judgment or qualitative evaluation, especially in borderline cases. This aligns with the argument made by Belton and Stewart (2002) that MCDM outputs should not be seen as absolute solutions, but as tools for structured dialogue and justification in decision processes.

6. Conclusions and Recommendations

The Methods of MCDM are used to evaluate more than one criterion in complex decision-making processes and choose the best alternative among them. By using these techniques, different options can be evaluated objectively and methodically, and are more structured than subjective or heuristic methods. A variety of fields use multicriteria decision-making techniques, including business and economics, engineering, health, and public policy. As a result of these techniques, the decision-making process becomes more systematic and objective, resulting in better results. Nevertheless, accurate results can only be obtained by correctly applying the techniques and evaluating the data. It is important to note that both VIKOR and MOORA are MCDM methods; they are used for ranking and selecting alternatives in problems according to multiple criteria; however, there are important differences between them.

The goal of VIKOR is to find the best compromise among alternatives; it aims to find that one alternative has the best average values compared to the others and that the distance between the best alternatives is reasonable. MOORA, on the other hand, aims to identify the alternatives that perform the best based on all criteria to choose the best among them. In the VIKOR method, alternatives are categorized into best and worst performers as opposed to a ranking, while in the MOORA method, the best alternative has the highest ranking. The VIKOR method can also be used when weights and preference weights are not fully specified, so it may be preferable when that information is not fully known, but MOORA would be better used when the weights and preference weights are clearly defined. VIKOR is a multi-objective optimization method and focuses on finding the best compromise solution by maintaining a balance between alternatives, whereas MOORA is a multi-objective classification method aimed at selecting the best alternatives by sorting them in a precise order. In general, the VIKOR method seeks to balance multiple criteria to find the best compromise, while the MOORA method ranks the alternatives and selects the best one. The choice of method will vary depending on the nature of the decision problem and the available data.

Regarding the problem addressed in this study, GS_2 was determined to be the best alternative after taking into account the weights of the criteria from both methods.

In comparison to MOORA and VIKOR, the third method, Gray relational analysis, has some differences. The Gray relational analysis tries to reduce the impact of uncertainties on data sets by evaluating the relationships between different criteria. Nevertheless, MOORA attempts to solve problems involving MCDM as well as to select the best alternative by examining the effects of different criteria. VIKOR aims to achieve both optimal and compromising solutions in MCDM, namely to maintain a balance between all criteria and to find the best solution. MOORA utilizes exact, real-number data and makes direct comparisons between criteria, whereas gray relational analysis utilizes imprecise, gray data. Furthermore, VIKOR produces more effective results with precise data, especially with ordinal data. The Gray relational analysis converts gray data into the range 0-1 and evaluates it against a reference series of data. Mostly, MOORA works with normalized values and expresses criteria values in the same unit. Vikor converts the criteria values into a range between 0 and 1 and compares them with some target values. With gray relational analysis, weights are automatically calculated based on datasets, giving it a more flexible approach to weight determination. Experts or predetermined weights are usually used in the MOORA method. With VIKOR, the solutions are ranked using a weighting method based on the priority of the different criteria. Each method can be chosen according to specific problem types and data conditions. MOORA and VIKOR work more effectively when there is no uncertainty in the dataset, as they work with precise data. Gray Relational Analysis is more effective for datasets with uncertainty.

In this study, Gas Station 2, which came out on top using the first two methods, took second place using the Gray relational analysis, and Gas Station 4 took first place using this method. Gas station 2 is actually in the top two, even though the criteria are greyed out. As a consequence, we recalculated the solution, which was reduced to five alternatives from the first three methods.

The DEMATEL method is an MCDM method with features different from VIKOR, MOORA and Gray Relational Analysis. A DEMATEL model is used to understand and analyze cause-effect relationships in complex decision problems; this model is preferred to analyze the decision-making process and evaluate the factors influencing it. To understand cause-effect relationships, DEMATEL relies primarily on prior knowledge and experience gained by a specific group of experts. DEMATEL does not transform data because it explains cause-and-effect relationships. DEMATEL does not perform weighting while determining cause-effect relationships; weights are not determined by prior knowledge and expert opinions.

Under five different decision criteria, 38 different alternative sites for the installation of electric charging stations in the Sultanbeyli district of Istanbul were analyzed. In addition, the study can be solved with different optimization methods, and the results compared.

Authors' Contributions

All authors contributed equally to the study

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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