ICONARP
International Journal of Architecture and Planning
Received: 14.08.2023 Accepted: 12.01.2025
Volume 13, Issue 1/ Published: 30.06.2025
Research Article *DOI: 10.15320 /ICONARP.2025.314 E- ISSN:2147-9380*
ICONARP

Parking Suitability and Site Selection Analysis Using GIS-Based Multi-Criteria Decision Analysis Techniques: AHP, TOPSIS, and VIKOR – A Case Study of Pendik District (Istanbul)

Arif Cağdaş Aydınoğlu *
Ahmad Shekib Iqbal **
Süleyman Şişman ***

Abstract

Demand for parking areas has increased with the growing population and increasing number of vehicles. Large cities are suffering from a lack of parking areas, which are one of the most significant parts of the modern urban transportation system and traffic management. Locating parking areas has become a major challenge for the urban transport planners, especially in the downtown of metropolises. Geographic Information Systems (GIS) with geographic analysis tools can provide a scientific approach to determine optimum locations for parking areas. In this paper, the essential factors affecting parking site selection were considered and data sets concerning these factors were created by GIS analysis techniques. The Analytical Hierarchy Process (AHP) as a Multiple-Criteria-Decision-Analysis (MCDA) method was applied to derive weights of the selected parameters. To conduct parking demand analysis, the parking suitability map was produced by integrating the GIS with AHP. Then, suitable parking areas were determined in a zoning plan that was based on the highest suitability on the map. Other MCDA techniques including TOPSIS and VIKOR were examined and compared to determine the order of preferences among suitable parking areas. Similar to the traditional AHP method, the same results were obtained in the ranking of parking areas with the other methods. Using GIS with these MCDA techniques appears to be a usable approach for better resource allocation as well as parking site selection.

Keywords:
Parking demand, Parking suitability, Site selection, GIS, MCDA.

* Department of Geomatics Engineering, Gebze Technical University (GTU), Kocaeli, Türkiye. (*Corresponding author*)
Email: aydinoglu@gtu.edu.tr

**Department of Geographical Information System & Remote Sensing, Faculty of Geomatics Engineering, Kabul Polytechnic University (KPU), Kabul, Afghanistan.
Email: shekibiqbal.si@kpu.edu.af

***Department of Geomatics Engineering, Gebze Technical University (GTU), Kocaeli, Türkiye.
Email: ssisman@gtu.edu.tr

To cite this article: Aydınoğlu, A. Ç, Iqbal, A. S, & Şişman, S. (2025). Parking Suitability and Site Selection Analysis Using GIS-Based Multi-Criteria Decision Analysis Techniques: AHP, TOPSIS, and VIKOR-A Case Study of Pendik District (Istanbul). *ICONARP International Journal of Architecture and Planning,* 13 (1), 22-50. DOI: 10.15320/ICONARP.2025.314

INTRODUCTION

The changes in lifestyle and working disciplines have led to an increase in urbanization with more people moving to urban areas (Alkan & Durduran, 2021). The increased number of people has negatively impacted urban transportation systems through a rapid increase in vehicle numbers. Therefore, most metropolitan and developed cities suffer from a lack of parking areas that play an important role in modern urban transportation and traffic management (Jonuzi et al., 2024).

Vehicle parking areas have an important part in the modern transportation system and play an essential role in reducing traffic congestion (Kazazi Darani et al., 2018). Traffic is considered one of the main challenges of urban transportation management (Hensher and King 2001). Optimal location of parking areas not only increases the efficiency of parking activity but also reduces the marginal parking (Jonuzi et al., 2024). This in turn will increase the width of the streets indirectly which would improve the traffic flow (Karimi et al. 2009). Wrong decisions may cause inefficient traffic management of urban transportation systems, economic loss, and increased environmental degradation (Hosseinlou et al. 2012).

Accurate decision-making for the determination of parking areas is vital especially in metropolitan cities associated with high vehicle ownership rates, to ensure the transportation of people without any disruption (Selcuk Demir et al., 2021). Determining optimum locations of parking areas is directly related to disparate parameters and their relative importance. Selecting parking areas using the traditional methods cannot give us reliable results because these methods are limited by the narrow spectrum of parameter evaluation during parking area allocation. In some cases, the use of traditional methods would result in parking areas being located far away from the travel absorption centers and far from busy streets, which have negative impacts on traffic loads. It is therefore essential to develop an approach that considers all the effective parameters simultaneously. An example of such an approach is the integration of a Geographic Information System (GIS) with a Multiple-Criteria-Decision-Analysis (MCDA) that has been extensively used in selecting suitable areas for the last two decades (Jelokhani-niaraki and Malczewski 2015).

GIS is widely recognized for its capability in performing geographic analysis (Butt et al., 2017), which is designed to manipulate and manage geographic data in various thematic applications (Wang et al. 2009). The ability of GIS analysis techniques is well captured in scientific literature. This increases the reliability of results for selecting suitable areas, particularly the parking areas (Aliniai et al. 2015).

MCDA is a set of processes for analyzing complex decision-making problems. It aims to establish a connection by dividing the decision problem into small, simple, and understandable parts so that a meaningful result can be obtained from these parts (Malczewski 1999).

DOI: 10.15320/ICONARP.2025.314

MCDA methods are used as a decision-support system for complex problems where environmental, economic, social, and technical objectives are involved (De Montis 2000).

Selecting a suitable location for the parking area is a multi-criteria decision-making problem, as it depends on various parameters. The GIS integrated with the MCDA approach allows for the study of complex problems and provides sufficient results to decision-makers. This approach has the ability to analyze multiple essential parameters simultaneously for selecting parking areas effectively. Numerous studies and research have focused on parking area selection problems by using GIS-based MCDA techniques. Jonuzi et al., (2024) used combined application of GIS and AHP techniques for the selection of new parking areas. Alkan & Durduran (2021) employed the GIS-AHP technique to identify optimum locations for parking facilities within the city of Konya. Demir et al., (2021) employed GIS-based Fuzzy AHP approach to determine optimum locations for parking supply in the four districts of Istanbul. Some authors used other MCDA methods related to parking site selections. Aydinoglu et. al., (2024) used Best Worst Method (BWM) and Fuzzy Logic (FL). Ozturk & Kilic-Gul, (2020), Aliniai et al, (2015), Jelokhani-niaraki and Malczewski (2015) used Ordered Weighted Average (OWA) method. Palevičius et al., (2013) employed the Complex Proportional Assessment (COPRAS). Darani et al., (2018) used the integration of Fuzzy AHP and the technique for order preference by similarity to ideal solution (TOPSIS) to locate a new public parking lot in Tuyserkan, Iran. And Samani et al., (2018) and Farzanmanesh et al., (2010) utilized AHP and Fuzzy Logic for parking site selection.

It's essential to develop an approach that considers all the effective parameters simultaneously and also to determine the best suitable parking areas in the transportation planning of metropolitan and developing cities. According to these considerations, the objective of this study is to design a geographic analysis method for determining suitable parking sites in urban metropolitan areas and to prioritize suitable parking sites. In the method section, the AHP technique was used for determining weights of effective criteria and TOPSIS and VIKOR techniques were examined for giving priority to the suitable parking areas. In the case study section, the Pendik district of Istanbul was explored to test the methods. A parking suitability map was produced, and priority was determined for the suitable parking areas by using GIS and MCDA methods. In the last section, as a new hybrid approach, these techniques and prioritizing results were examined and compared.

METHOD

The methodology used in this study is explained in Figure 1. Firstly, criteria for parking suitability were examined. The AHP method was considered to compute criteria weights as explained in this section. To create a pairwise comparison matrix among parking criteria, a

ICONARP – Volume 13, Issue 1 / Published: 30.06.2025

questionnaire survey was designed and distributed among researchers and experts from the Parking Authorities of Istanbul Metropolitans Municipality. According to the survey results, criteria weights were calculated using the comparative matrix. According to criteria weights developed from AHP, data sets were collected for the case study area, and a parking suitability map was created by using GIS analysis techniques. Then, suitable parking areas were determined in the zoning plan, based on the highest suitability on the map.

Other MCDA methods were examined, and TOPSIS and VIKOR were determined to prioritize suitable parking areas. The decision matrix used in both methods consists of alternatives as rows and criteria as columns. Suitable parking areas were used as Alternatives and parking criteria calculated with the AHP method were used as Criteria. Each criterion value of alternatives was calculated with GIS analysis techniques. Then, TOPSIS and VIKOR methods were processed and the results of these methods were compared to prioritize suitable parking areas. These MCDA techniques; AHP, TOPSIS, and VIKOR were examined in this section.

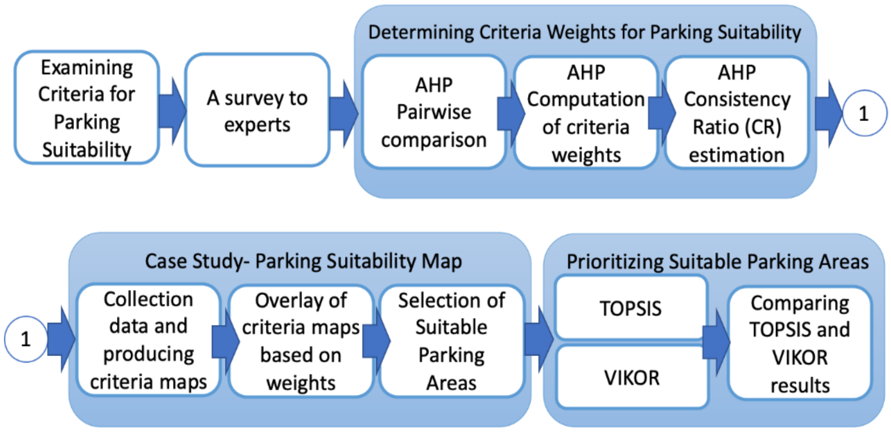

Figure 1. Methodology flow.

Criteria for Parking Suitability

All the criteria affecting physical, legal, and geographical suitability for parking areas have been examined to specify the areas suitable for vehicle parking. The criteria were divided into sub-criteria for the implementation of the MCDA method. Based on literature reviews, experts' opinions, and available data, all criteria were grouped into three main classes including transportation criteria, parking criteria, and travel absorption criteria. It is required to weight the data at the level of criteria and sub-criteria during the implementation of the MCDA technique. Figure 2 illustrates the hierarchy of criteria and sub-criteria for determining suitable parking areas.

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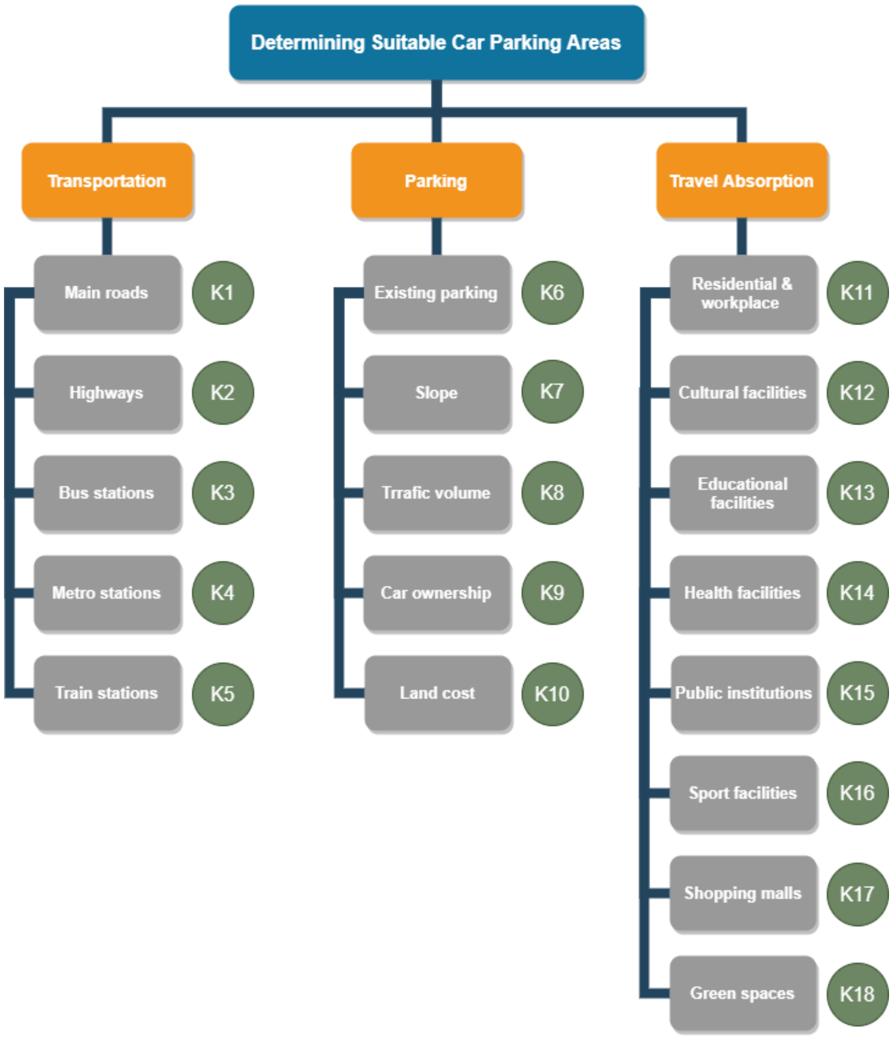

Figure 2. Hierarchy of criteria and sub-criteria.

Transportation criteria: These are significant for the selection of parking areas because transportation facilities attract more travelers than other criteria. Selecting parking locations near highways and transportation stations such as bus stations, train stations, and metro stations, which attract and absorb a massive group of travelers, is a vital factor in allocating parking areas. Moreover, some travelers may park their vehicles in proximity of stations and prefer to use public transport (Demir 2016; Jelokhani-niaraki and Malczewski 2015).

Parking criteria: These criteria include existing parking sites, slope, traffic volume, car ownership, and land cost. Further to these, a limitation factor, such as existing parking, is also included. The location of new parking areas should be far from the existing parking areas (Hosseinlou et al. 2012). Car ownership increases with the number of vehicles joining the traffic day by day. With increasing car ownership, demand for parking and traffic load also increases indirectly. Parking demand increases in places where vehicle mobility is at a high level. Accordingly, the traffic volume also increases in those places or routes. For building a parking area, land cost is one of the desirable factors for experts in transportation and urban management. Experts try to construct parking areas in places with low land prices. Slope criteria have an impact on accessibility and building a parking area. Thus, to build a new parking area we need to find areas with flat land considering that steep slopes are generally not suitable for building parking areas.

Travel absorption criteria: Travel absorption is related to determining demand for parking areas due to the increased frequency of absorbing travelers. These criteria include shopping malls, educational facilities, public institutions, residential and workplaces, administration buildings, hospital buildings, etc. Allocating parking areas near these facility centers can attract users due to the advantages of parking activities in these centers (Darani et al. 2018; Samani et al. 2018). The distance between the transportation system and these facility centers is also important in view of the experts (Ben-Joseph 2012). The distance should be in such a way that the passengers, employees, and clients reach their destinations from a parking location with minimum walking distance. In this study, regarding the defined criteria and experts' consultations, 1 km is the maximum acceptable distance and is classified into five categories (0-125 m, 125-250 m, 250-350 m, and 500-1000 m).

Analytical Hierarchy Process (AHP)

AHP is one of the Multi-Criteria-Decision-Analysis (MCDA) methods that was first proposed by Thomas L.Saaty in 1980. AHP is an extensively used method that is easy to understand and to manage multiple criteria. In addition, AHP does not require complex mathematics as it measures qualitative and quantitative data effectively (Saaty 1980). AHP allows individual judgments authentically and overlays all the classified criteria to select suitable locations (Ullah and Mansourian 2015).

AHP involves three main principles including decomposition of the problem, pair-wise comparison, and a combination of priorities (Malczewski 1999). In the AHP technique, the crucial issue is to develop a hierarchical structure that breaks down the problem into a hierarchy of goal, criteria, and sub-criteria (Taherdoost 2017). In this study, the hierarchical structure of AHP is illustrated in Figure 2, with the topmost level being the goal, followed by the three main criteria levels which lead to the sub-criteria that is the lowest point of hierarchical structure.

AHP technique can be described in three steps (Ibraheem and Atia 2016) in calculating the weights of criteria: I. Generating pairwise comparison matrix, II. Computation of criteria weights, and III. Evaluation of consistency ratio.

I. Generating pairwise comparison matrix

In this step, we perform the pairwise comparison between the related criteria. Each criterion must be at the same level. The pairwise comparison is undertaken on a qualitative scale where the scale ranges from 1 to 9, each number indicating the relative importance of one

DOI: 10.15320/ICONARP.2025.314

criterion over other criteria (Saaty 1980). The relative importance of the criteria can be seen in Table 1.

Table 1. The relative importance of pairwise comparison.

Value	Relative importance
1	Equally
3	Moderately
5	Strongly
7	Very strongly
9	Extremely

II. Computation of criteria weights

In this step, first, the sum of each column is calculated in the pairwise comparison matrix. Next, each sum is divided into the matrix by summation of its column where the result indicates the normalized pairwise comparison matrix. The average of weights is calculated in each row of the normalized matrix and the results provide weight of criteria.

III. Evaluation of consistency ratio

The consistency ratio (CR) of the n element is being estimated to ensure whether the judgment is consistent or not. If the CR does not reach the required level then the pairwise comparison should be revised (Lee, 2007). Equation 1 calculates the CR:

$$CR = \frac{CI}{RI} \tag{1}$$

In the above equation, CI is a consistency index that is derived from Equation 2 and RI is a random index that is acquired as given in Table 2 for several numbers of variables (n) (M. Kumar and Biswas 2013), and λ_{max} is the maximum eigenvalue of the pairwise comparison matrix.

$$CI = \frac{\lambda_{max} - \mathrm{n}}{n-1} \tag{2}$$

Table 2. Values of Random Index

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The concept of the CR is designed in such a way that if $CR \leq 0.10$ then the ratio expresses a validation of consistency in the pairwise comparisons; if $CR > 0.10$ then the ratio values are inconsistent and require reconsideration of pairwise comparison matrix (Al Garni and Awasthi 2017).

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS technique, being one of the MCDA methods, was first introduced by Hwang and Yoon in 1981. The technique allows for a priority ranking by evaluating alternative options according to certain criteria. The basic principle of the technique can be expressed as choosing the alternative closest to the positive ideal solution and the most distant to the negative ideal solution (Figure 3) (Tzeng and Huang 2011; Beskese et.al 2015).

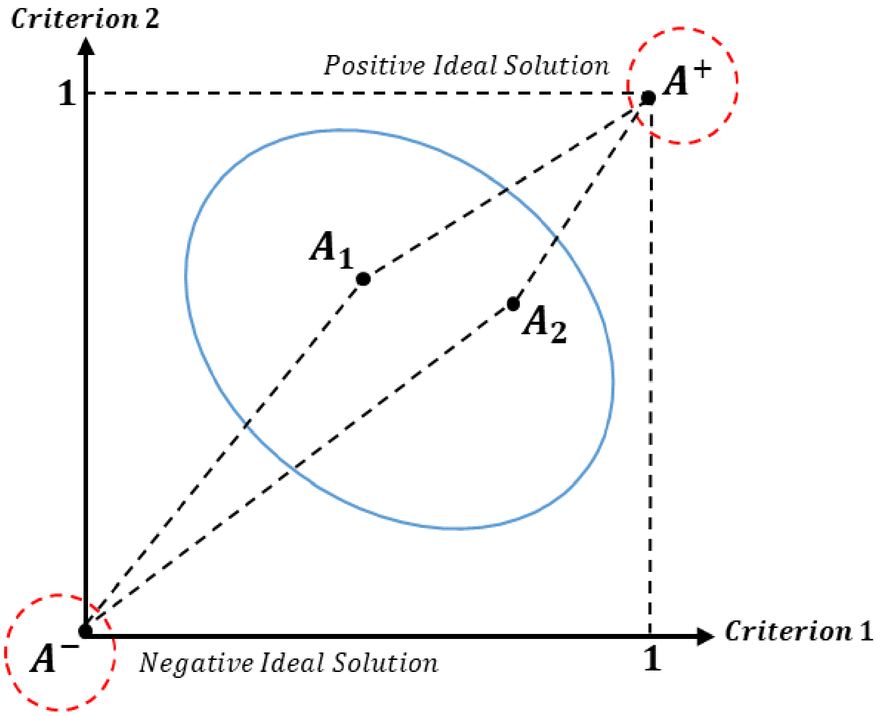

Figure 3. TOPSIS technique (Adapted from Balioti et.al 2018).

TOPSIS is an easy method to understand and interpret without any complicated mathematical expressions and complex algorithms when compared to other MCDA methods. It is also one of the most preferred MCDA techniques in the literature (Behzadian et.al 2012).

In addition, it is advantageous that the TOPSIS technique can work through integration with different MCDA methods such as AHP and FAHP. The TOPSIS technique procedure consists of the following steps. (Darani et.al 2018; García-Cascales and Lamata 2012):

I. Creating the decision matrix (A_{ij})

Firstly, a m x p dimensional matrix is created by the decision maker. While creating the decision matrix, alternative criteria are used in rows, and evaluation criteria are included in columns. The decision matrix can be seen in Equation 3.

$$A_{ij} = \begin{bmatrix} a_{11} & \cdots & a_{1p} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{np} \end{bmatrix} \tag{3}$$

II. Creating the normalized decision matrix (R_{ij})

DOI: 10.15320/ICONARP.2025.314

The normalized decision matrix is created using elements of matrix A in step 1 and Equation 4. The normalized decision matrix can be seen in Equation 5.

$$R_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}} \tag{4}$$

$$R_{ij} = \begin{bmatrix} r_{11} & \cdots & r_{1p} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mp} \end{bmatrix} \tag{5}$$

III. Creating the weighted normalized decision matrix (V_{ij})

Weighting is done by multiplying each element of the normalized matrix (R_{ij}) by a weighting factor such as Wi. The value of Wi mentioned here is calculated by the AHP method in this study. It should be noted that the sum of the weights of the criteria is one i.e. $W_i = 1$. The obtained weight coefficients are the only subjective parameter of the TOPSIS method. The matrix is created in Equation 6.

$$V_{ij} = \begin{bmatrix} w_1 r_{11} & \cdots & w_n r_{1p} \\ \vdots & \ddots & \vdots \\ w_1 r_{m1} & \cdots & w_n r_{mp} \end{bmatrix} = \begin{bmatrix} v_{11} & \cdots & v_{1p} \\ \vdots & \ddots & \vdots \\ v_{m1} & \cdots & v_{mp} \end{bmatrix} \tag{6}$$

IV. Determination of positive ideal (A^+) and negative ideal (A^-) solution values

After creating the V matrix, positive and negative ideal solution clusters are created in line to be achieved by considering the structure of the problem. Positive ideal and negative ideal solution values are created with Equations 7 and 8.

$$A^+ = \left\{\left(\max_j v_{ij} \middle| i \in I\right), \left(\min_j v_{ij} \middle| i \in J\right)\right\} = \{v_1^+, \dots, v_{1n}^+\} \tag{7}$$

$$A^- = \left\{\left(\min_j v_{ij} \middle| i \in I\right), \left(\max_j v_{ij} \middle| i \in J\right)\right\} = \{v_1^-, \dots, v_{1n}^-\} \tag{8}$$

where i represents benefit criteria, and J represents cost criteria.

V. Calculation of distances to positive ideal (S^+) and negative ideal (S^-) points

Distances from positive and negative ideal solution points are calculated with Equations 9 and 10. Euclidean distance is used when calculating the distances.

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_{ij}^+\right)^2} \tag{9}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_{ij}^-\right)^2} \tag{10}$$

VI. Calculation of relative proximity to the ideal solution (Ci^*)

The distances from the positive ideal and negative ideal points determined in step 5 are used in calculating the relative proximity to the ideal solution. Ci^* Value is calculated in Equation 11.

$$\boldsymbol{Ci^*} = \frac{\boldsymbol{S_i^-}}{\boldsymbol{S_i^-} + \boldsymbol{S_i^-}} \tag{11}$$

The Ci^* with a value in the range of 0≤ Ci* ≤1 indicates the relative proximity to the ideal solution. $Ci^* = 0$ indicates the absolute proximity of the relevant decision point to the negative ideal solution, whereas $Ci^* = 1$ indicates the absolute solution proximity of the relevant decision point to the ideal solution. Alternatives are listed with calculated Ci^* values.

VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)

VIKOR technique, one of the MCDA methods, was developed by Serafim Opricovic in 1998 for the solution of clash problems, which conflict with each other and consist of criteria in different units (Opricovic 1998). The VIKOR method aims to determine a compromised ranking and achieve a compromised solution under the specified weights. The compromise solution is to reach an agreement on all the criteria that are optimally achieved and joint acceptance. The compromise solution is the closest to the ideal solution. The idea of a compromise solution was introduced by Po-Lung Yu in 1973, and later by Milan Zeleny (Yu 1973; Zeleny 1982).

VIKOR prioritizes alternatives and determines the solution named ‘compromise’ that is the closest to the ideal. VIKOR method can work integrated with other MCDA methods such as the TOPSIS method. The VIKOR process consists of the following steps (Mohaghar et.al 2012; Sennaroglu and Celebi 2018; Opricovic and Tzeng 2004):

I. Creating the decision matrix (A_{ij})

The decision matrix of the VIKOR method is the same as the TOPSIS method. The decision matrix can be seen in Equation 12.

$$A_{ij} = \begin{bmatrix} a_{11} & \cdots & a_{1p} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{np} \end{bmatrix} \tag{12}$$

II. Determining the best and worst values of all criteria

According to the evaluation criteria of all alternatives, the best and the worst values are determined with the help of Equations 13 and 14.

DOI: 10.15320/ICONARP.2025.314

$$f_i^+ = max_j\, f_{ij} \qquad f_i^- = min_j\, f_{ij} \qquad \text{If the i-th function is benefit} \tag{13}$$

$$f_i^- = min_j\, f_{ij} \qquad f_i^+ = max_j\, f_{ij} \qquad \text{If the i-th function is cost} \tag{14}$$

III. Normalizing the decision matrix (R_{ij}) and creating a weighted normalized decision matrix (V_{ij})

Normalization is done with Equation 15 to make the decision matrix comparable. The generated normalized decision matrix is represented in Equation 16.

$$\mathrm{r}_{ij} = \frac{f_i^+ - f_{ij}}{f_i^+ - f_i^-} \tag{15}$$

$$\boldsymbol{R_{ij}} = \begin{bmatrix} \boldsymbol{r_{11}} & \cdots & \boldsymbol{r_{1p}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{r_{m1}} & \cdots & \boldsymbol{r_{mp}} \end{bmatrix} \tag{16}$$

The normalized decision matrix (R_{ij}) is multiplied by the relevant criterion weights (w_i) to obtain the weighted normalized decision matrix (V_{ij}) as seen in Equation 17.

$$V_{ij} = R_{ij}\, w_i = \begin{bmatrix} w_1 r_{11} & \cdots & w_n r_{1p} \\ \vdots & \ddots & \vdots \\ w_1 r_{m1} & \cdots & w_n r_{mp} \end{bmatrix} = \begin{bmatrix} v_{11} & \cdots & v_{1p} \\ \vdots & \ddots & \vdots \\ v_{m1} & \cdots & v_{mp} \end{bmatrix} \tag{17}$$

IV. Calculation of S_j, R_j and Q_j values

S_j and R_j values for each alternative can be calculated with the help of Equations 18 and 19. The w_i value in the equations represents the weighting coefficient determined for each criterion.

$$S_j = \sum_{i=1}^{m} \frac{w_i(f_i^+ - f_{ij})}{(f_i^+ - f_i^-)} \tag{18}$$

$$\boldsymbol{R_j = max\left[\frac{w_i(f_i^+ - f_{ij})}{(f_i^+ - f_i^-)}\right]} \tag{19}$$

After calculating S_j and R_j values, Q_j values are calculated with Equation 20. S^* and R^* values represent the minimum values calculated, while S^- and R^- represent the maximum values as seen in Equations 21 and 22. The value of v indicates the weight of the maximum group benefit and is determined by the group decision. For the maximum group benefit, $v > 0.5$ represents the majority preference, $v = 0.5$ is agreement, and $v < 0.5$ is veto (Opricovic and Tzeng, 2004). The value of v was used as 0.5 considering the compliance state.

$$Q_j = \frac{v\left(S_j - S^*\right)}{(S^- - S^*)} + \frac{(1-v)\left(R_j - S^*\right)}{(R^- - R^*)} \tag{20}$$

$$S^* = min\, S_i \;\; ; \;\; R^* = min\, R_i \tag{21}$$

$$S^- = max\, S_i \;\; ; \;\; R^- = max\, R_i \tag{22}$$

V. Ranking S_j, R_j and Q_j values

The S_j, R_j and Q_j values that are calculated for each alternative are sorted from small to large. Three different rankings are obtained for alternatives.

VI. Determining acceptable advantage (C1) and acceptable stability (C2) clusters in decision making

Acceptable advantage (C1) and acceptable stability (C2) clusters are determined by ranking the S_j, R_j, *and* Q_j values. One of the alternatives needs to provide equality to be included in cluster C1. Equations 23 and 24 are applied to all Q_j values to determine which of the alternatives are in the C1 set. The following two conditions must be satisfied to suggest a compromise solution (a').

C1: Acceptable advantage;

$$Q(a'') - Q(a') \geq DQ \tag{23}$$

$$DQ = \; 1/(1-m) \tag{24}$$

where; m represents the number of alternatives and a'' is the second alternative in the ranking list by Q(min) value, a' is the best alternative in the ranking list by Q(min) value.

C2: Acceptable stability in decision-making;

Alternative a' must also be the best ranked by S or/and R. Alternatives that exist in both the C1 and C2 clusters show stable decision points in a decision-making process.

If one of the conditions is not provided, then a set of compromise solutions is proposed, which consists of:

If condition-2 cannot be satisfied, alternatives a' and a'' are both determined as the best-compromised solution.

If condition-1 cannot be satisfied, alternatives $a', a'', \ldots\ldots, a^{(M)}$ and its value is determined by $Q\left(a^{(M)}\right) - Q(a') < DQ$ for maximum M. The best alternative, ranked by Q, is the one with the minimum value of Q (Opricovic and Tzeng 2004).

DOI: 10.15320/ICONARP.2025.314

CASE STUDY

Determining Study Area and Preparing Datasets

Pendik district of Istanbul was chosen as the case study for this research. Figure 4 displays Pendik district, surrounded by Tuzla from the east, Kartal and Sultanbeyli from the west, Sile from the north, and Marmara Sea from the south. The population of Pendik is 743.774 according to 2023 statistics and it is the third most populous district of Istanbul (TÜİK 2023) with an area of 190 km2, has a coastline of 7.5 km. In recent years the Pendik district has been developing rapidly in terms of transportation infrastructure and urbanization and accommodates different urban development dynamics as a metropolitan city. Railway infrastructure investments, road investments, and access to the sea are remarkable in the region. Due to these reasons, this district has become an attractive center and is faced with a lack of several city services including parking areas.

Figure 4. Location of Pendik district.

Concerning the parking suitability criteria in Figure 2, the required geographical datasets were obtained from the Istanbul Metropolitan Municipality (IMM) and Open Street Map (OSM) open data portal (OSM, 2023) and United States Geological Survey (USGS) Earth Explorer portal (USGS, 2023). Then, all datasets were imported to a geodatabase and organized for suitability analysis. Table 3 provides a detailed summary of these datasets, their corresponding sources, and the analytical techniques employed in the study. All the adopted dat sets were referenced and registered to the ITRF 96 coordinate system. All data were provided in a vector format, except the slope of the area, which was derived from a digital elevation model (DEM) in a raster format. In this study, the cell sizes of the analysis were set to 30 m x 30 m to analyze maximum details in urban areas. The criteria maps were rasterized and scored. The scoring process was done by the reclassifying tool with the rasterized criteria being classified.

Table 3. The dataset and analysis descriptions used in the study

Data	Source	Data Type	Year	Analysis
Main Roads	OSM	Vector (Polyline)	2023	Euclidean Distance
Highways	OSM	Vector (Polyline)	2023	Euclidean Distance
Bus Stations	IMM	Vector (Point)	2023	Euclidean Distance
Metro Stations	IMM	Vector (Point)	2023	Euclidean Distance
Train Stations	IMM	Vector (Point)	2023	Euclidean Distance
Existing Parking	IMM	Vector (Point)	2023	Euclidean Distance
DEM	USGS Earth Explorer	Raster (30x30 m)	2023	Slope
Traffic Volume	IMM	Polyline	2019	Linear Density
Car Ownership	IMM	Vector (Polygon)	2019	Feature to Raster
Land Cost	IMM	Vector (Polygon)	2019	Feature to Raster
Residential & Workplace	IMM	Vector (Point)	2023	Kernel Density
Cultural Facilities	IMM	Vector (Point)	2023	Euclidean Distance
Educational Facilities	IMM	Vector (Point)	2023	Euclidean Distance
Health Facilities	IMM	Vector (Point)	2023	Euclidean Distance
Public Institutions	IMM	Vector (Point)	2023	Euclidean Distance
Sport Facilities	IMM	Vector (Point)	2023	Euclidean Distance
Shopping Malls	IMM	Vector (Point)	2023	Euclidean Distance
Green Space	IMM	Vector (Point)	2023	Euclidean Distance

According to the transportation criteria in Figure 5 and travel absorption criteria in Figure 6, a driver should walk a minimum distance from the parking areas to their destinations. The walking distance to parking areas is one of the most considerable issues. Therefore, the

DOI: 10.15320/ICONARP.2025.314

walking distance from these criteria was calculated with the Euclidean distance technique, including 5 intervals; 0-125 m, 125-250 m, 250-350 m, 350-500 m, and 500-1000 m. which implies that the minimum distance has the higher score values.

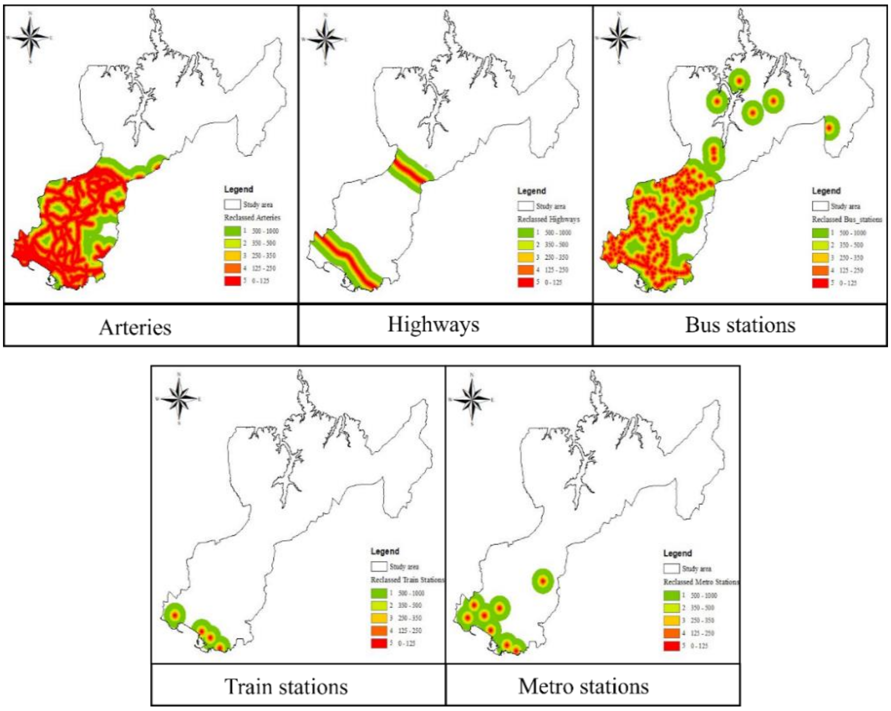

Figure 5. The classified maps of transportation criteria.

According to the parking criteria in Figure 7, it is more convenient to be far from existing parking areas. Therefore, distance to existing parking was scored with the Euclidean distance technique where the maximum distance has the higher score values.

The slope map was produced automatically with values between 0o to 39.56^{o} degrees and then the slope values were categorized according to the urban construction criterion. Land suitability is evaluated as 0^{o} - 5^{o}, 5^{o} -10^{o}, 10^{o}-15o, 15^{o}-25 ^{o} ,and >25^{o} (Xiaorui et al. 2013). The maximum values of the slope have the minimum scoring value. Steep slopes are generally not suitable for parking areas.

Land prices are high in areas with intensive transportation facilities, areas that are close to business and public services, and areas that experience modern urbanization. Considering the transportation conditions and public interest, parking investment should be supported despite the high land cost (Demir 2016). Land cost data were converted to raster data regarding their values at the neighborhood level and classified into 5 intervals.

Demand for parking areas in residential and workplaces is usually high due to increasing car ownership. This situation increases the traffic volume indirectly. Taking into account the density of residential areas and workplaces, car ownership, and traffic volume data were collected for districts and categorized into 5 intervals. Highly density places are suitable locations for selecting parking areas.

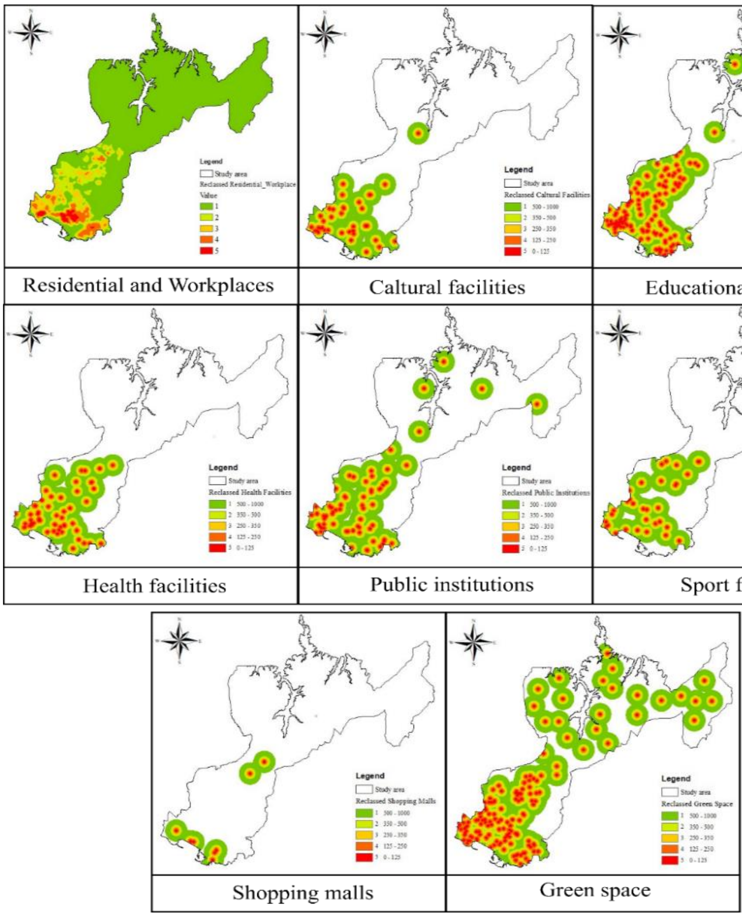

Figure 6. The classified maps of travel absorption criteria.

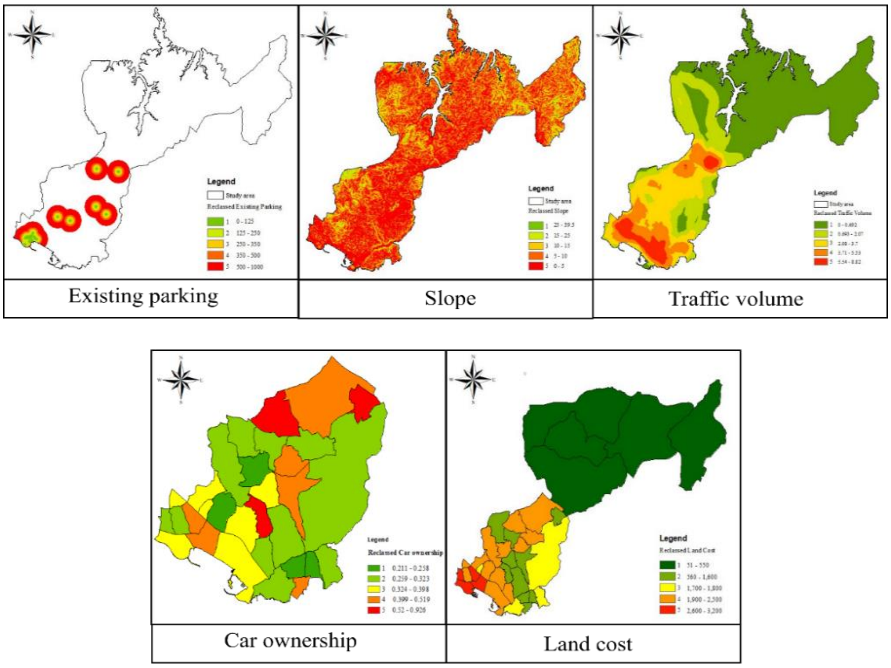

Figure 7. The classified maps of parking criteria.

Producing Parking Suitability Map with AHP

Three main criteria and 18 sub-criteria (Figure 2) were chosen as the most effective factors for developing a parking suitability map. The AHP method was used to calculate the weights of each criterion and their sub-criteria. The values were used to compare the relative importance of each criterion given in Table 1. Afterwards, the classified maps were

DOI: 10.15320/ICONARP.2025.314

integrated through the raster calculator tool in GIS where the maps were multiplied by their weights to obtain the suitable areas.

By integrating AHP with GIS in two phases, the pairwise comparison between each sub-criteria of transportation, parking criteria, and travel absorption centers was performed, and then their weights were calculated. In Tables 4, 5, and 6, the pairwise comparison matrix of sub-criteria for transportation, parking criteria, and travel absorption criteria was presented with their corresponding weights respectively.

Table 4. Pairwise comparison matrix of transportation criteria

Criteria	Arteries	highways	Bus stations	Train stations	Metro stations	Weight of criteria
Arteries	1	9	7	5	5	0.568
Highways	1/9	1	1/3	1/5	1/5	0.035
Bus stations	1/7	3	1	1/4	1/4	0.065
Train stations	1/5	5	4	1	1.00	0.166
Metro stations	1/5	5	4	1.00	1	0.166
$\lambda max = 5.268$, $CI = 0.067$, $RI = 1.12$, $CR = 0.06 < 0.1$						

Table 5. Pairwise comparison matrix of parking criteria

Criteria	Existing parking	Slope	Traffic volume	Car ownership	Land cost	Weight of criteria
Existing parking	1	7	5	1	3	0.347
Slope	1/7	1	1/3	1/7	1/7	0.035
Traffic volume	1/5	3	1	1/7	1/5	0.062
Car ownership	1	7	7	1	3	0.370
Land cost	1/3	7	5	1/3	1	0.186
$\lambda max = 5.273$, $CI = 0.07$, $RI = 1.12$, $CR = 0.061 < 0.1$						

Table 6. Pairwise comparison matrix of travel absorption criteria

Criteria	Residential and workplace	Cultural	Educational	Health	Public Institutional	Sports	Shopping malls	Green space	Weight of Criteria
Residential & Workplace	1	9	9	5	7	9	5	9	0.436
Cultural	1/9	1	1/2	1/7	1/3	1	1/9	3	0.028
Educational	1/9	2	1	1/7	1/5	3	1/7	5	0.042
Health	1/5	7	7	1	3	7	1	9	0.172
Public Institutional	1/7	3	5	1/3	1	5	1/5	5	0.084
Sports	1/9	1	1/3	1/7	1/5	1	1/7	1	0.023
Shopping malls	1/5	9	7	1	5	7	1	9	0.197
Green space	1/9	1/3	1/5	1/9	1/5	1	1/9	1	0.018
$\lambda max = 8.893$, $CI = 0.128$, $RI = 1.41$, $CR = 0.091 < 0.1$									

In Figures 8, 9, and 10, the overlaid maps of sub-criteria for transportation, parking criteria, and travel absorption criteria were illustrated respectively

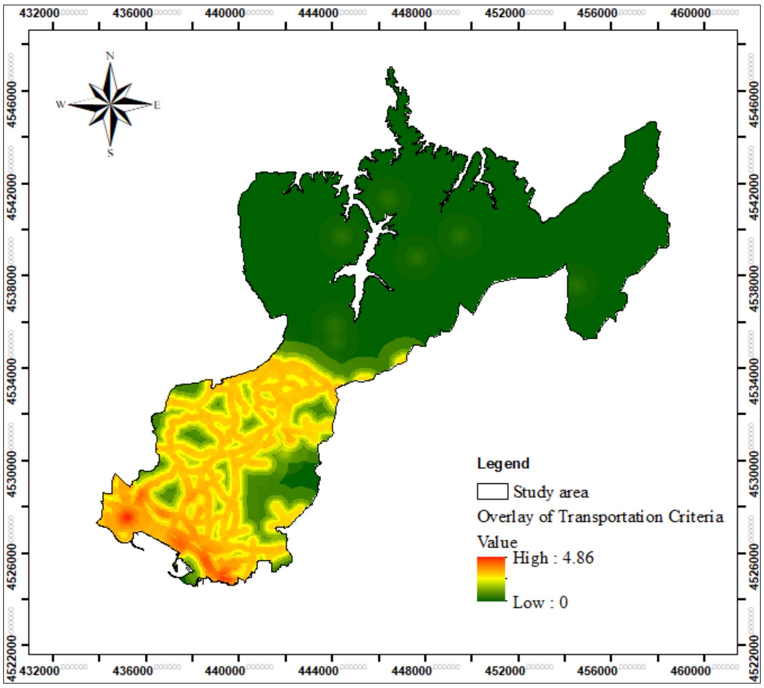

Figure 8. Overlaid map of transportation ctiteria.

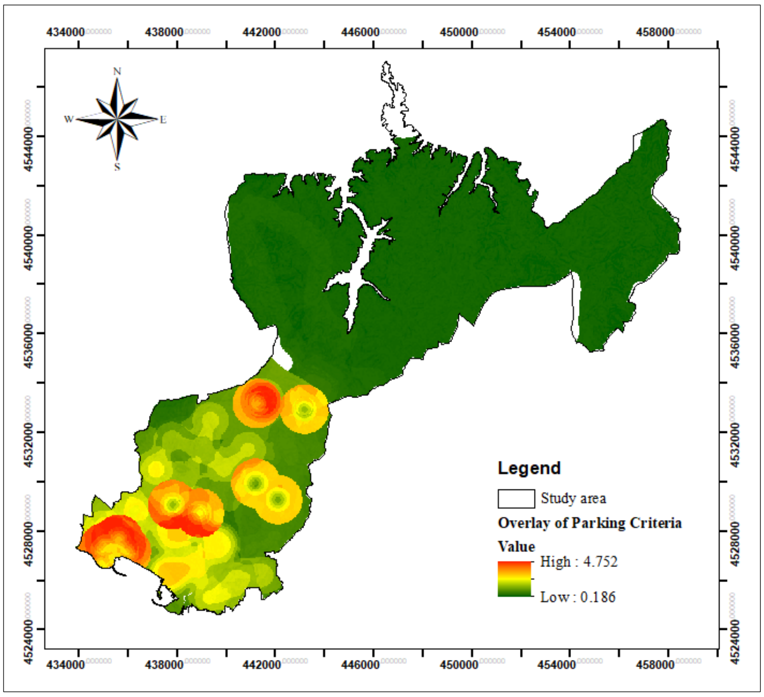

Figure 9. Overlaid map of parking. criteria.

DOI: 10.15320/ICONARP.2025.314

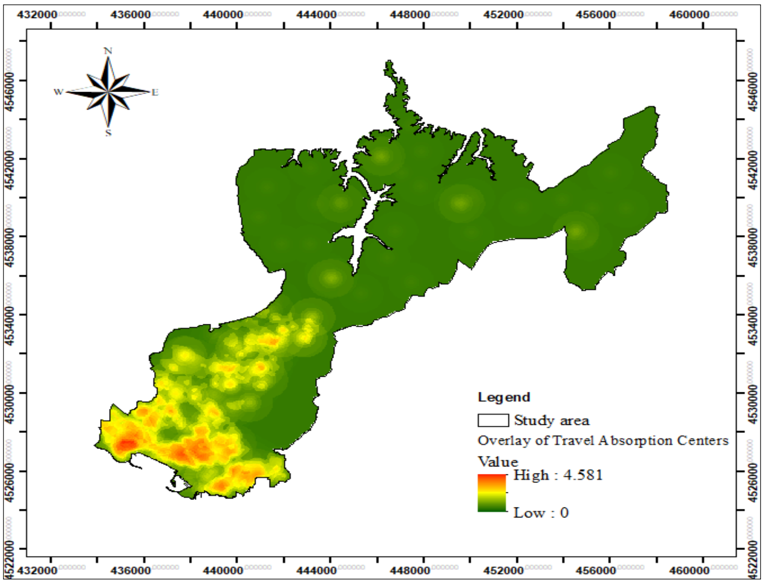

Figure 10. Overlaid map of travel absorption criteria.

To reach the final result, it's necessary to integrate the main criteria as well. The pairwise comparison between the main criteria was performed and their weights were calculated. The pairwise comparison matrix of the main criteria with their corresponding weights is presented in Table 7.

Table 7. Pairwise comparison matrix of main criteria

Criteria	Transportation	Parking criteria	TAC	Weight of Criteria
Transportation	1	5	2	0.559
Parking criteria	1/5	1	1/5	0.089
TAC	1/2	5	1	0.352
$\lambda max = 3.054$, $CI = 0.027$, RI = 0.58, CR = 0.052 < 0.1				

Next, the overlaid maps of transportation, parking criteria, and travel absorption criteria concerning their weights were combined and overlapped. As a result, the parking suitability map was produced as illustrated in Figure 11.

ICONARP – Volume 13, Issue 1 / Published: 30.06.2025

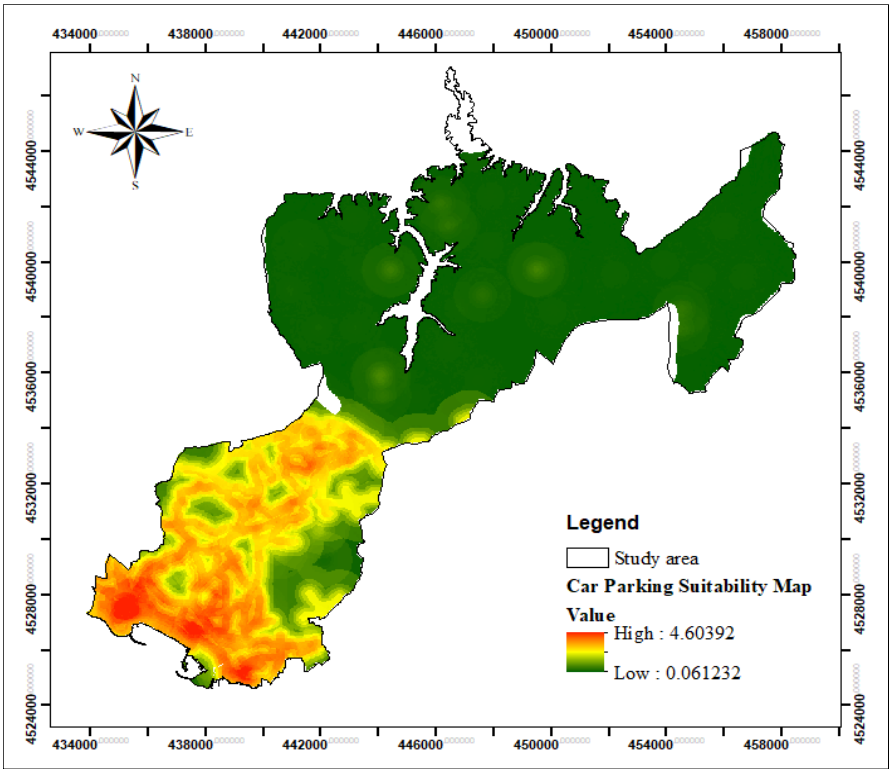

Figure 11. Parking suitability map.

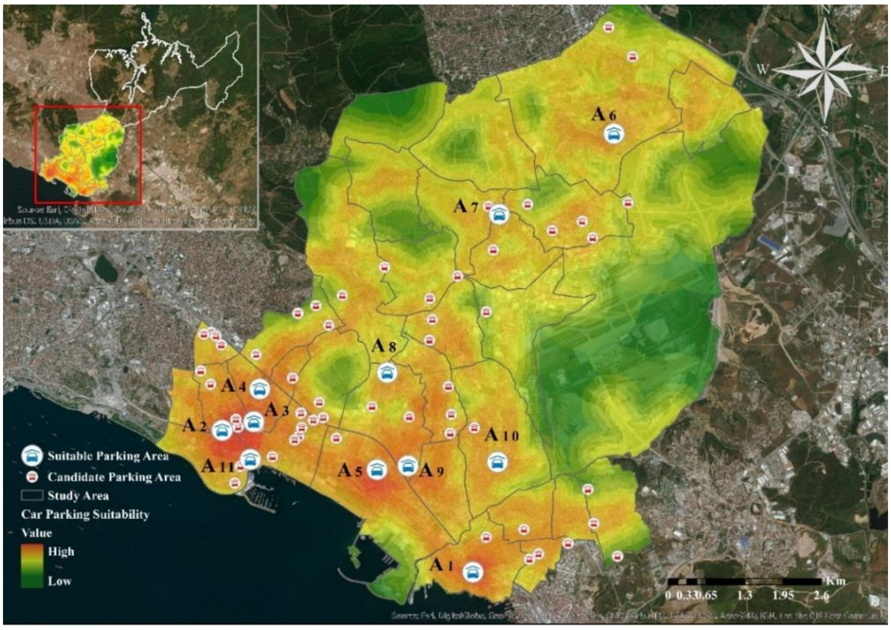

Figure 12. Locations of suitable parking and candidate parking.

The parking suitability map shows that the red-colored areas depict high numbers situated in the southeast of the study area and are the most suitable for building parking areas. Locations of suitable parking areas were determined by taking into account high suitable values in the zoning plans. Thus, 11 parking areas with high parking suitable values were determined in the study area. In Figure 12, suitable parking areas were numbered from 1 to 11 as A1, A2, ... A11.

DOI: 10.15320/ICONARP.2025.314

Parking Area Selection Analysis with TOPSIS and VIKOR

The ranking was made among 11 suitable parking areas determined in the parking suitability map. For this purpose, the ranking analysis was performed by using TOPSIS and VIKOR techniques. Comparative analysis of Criteria and Alternatives is required for both of these techniques. Regarding Alternatives, 11 suitable parking areas were used. Regarding Criteria, 18 sub-criteria determined by the AHP in 3 criteria groups were used. The weights of the sub-criteria were normalized to their main weight. In this context, normalized weight ratios of a total of 18 criteria from Transportation Criteria, Parking Criteria, and Travel Absorption Criteria groups can be seen in Table 8.

Table 8. Normalized weights of sub-criteria

Main Criteria	Sub-Criteria	Criteria Number	AHP Weights	Normalized Weights
Transportation Criteria	Main roads	K1	0.568	0.3175
	Highways	K2	0.035	0.0196
	Bus stations	K3	0.065	0.0363
	Metro stations	K4	0.166	0.0928
	Train stations	K5	0.166	0.0928
Parking Criteria	Existing parking	K6	0.347	0.0309
	Slope	K7	0.035	0.0031
	Traffic volume	K8	0.062	0.0055
	Car ownership	K9	0.370	0.0329
	Land cost	K10	0.186	0.0166
Travel Absorption Criteria	Residential & workplaces	K11	0.436	0.1535
	Cultural facilities	K12	0.028	0.0099
	Educational facilities	K13	0.042	0.0148
	Health facilities	K14	0.172	0.0605
	Public institutions	K15	0.084	0.0296
	Sport facilities	K16	0.023	0.0081
	Shopping malls	K17	0.197	0.0693
	Green space	K18	0.018	0.0063
				∑=1.0000

For a comparative analysis of 11 parking areas that are based on 18 criteria, the data sets developed for each criterion were used. Using GIS analysis, values of each criterion were calculated for alternatives representing suitable parking areas (Table 9). For example; for the K1 criteria (Distance to Main Roads), the A1 alternative is 10m away and the A2 alternative is 30m away; for the K7 (Slope) criteria, the A1 alternative is 3.71°and the A2 alternative is 1.43°.

Table 9. Decision matrix of TOPSIS and VIKOR techniques

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12	K13	K14	K15	K16	K17	K18
A1	10	150	10	408.04	241.87	3615.09	3.71	0.0094	3.75	1804.00	8393.20	127.28	42.43	127.28	108.17	1404.56	692.60	108.17
A2	30	1166.92	150	189.74	212.13	256.32	1.43	0.0033	2.57	2425.49	10267.40	152.97	67.08	108.17	134.16	484.67	323.11	174.93
A3	60	700.36	67.08	375.9	375.9	108.17	1.82	0.0089	2.64	3073.22	6620.85	305.94	60.00	134.16	212.13	912.41	241.87	305.94
A4	30	212.13	120	295.47	849.06	600.75	3.11	0.0081	2.40	3073.22	4817.94	300.00	174.93	108.17	42.43	732.39	674.17	512.64
A5	67.08	308.87	120	488.37	630	1701.56	4.79	0.0037	6.42	2175.86	14703.40	234.31	90.00	30.00	10.00	400.25	800.50	10.00
A6	60	1991.11	60	2249	7549.34	666.11	4.17	0.0031	4.71	2118.28	6091.18	1517.00	582.50	161.56	512.64	690.65	324.50	174.93
A7	42.43	4218.07	94.87	2457.99	5420.79	2018.04	9.01	0.0037	2.51	2079.79	6900.96	930.00	218.40	108.17	458.91	408.04	2713.30	84.85
A8	60	1129.29	180	381.84	2317	480.00	3.93	0.0040	4.73	1995.84	1914.95	729.93	351.14	335.41	920.27	313.21	2093.13	67.08
A9	108.17	127.28	10	966.08	882.33	1934.24	1.39	0.0077	6.04	1995.84	13318.10	108.17	10.00	67.08	67.08	216.33	1266.06	212.13
A10	67.08	1398.46	90	1894.04	1803.25	1867.24	3.05	0.0005	7.04	1513.81	8556.17	603.74	120.00	120.00	84.85	254.56	1332.22	510.00
A11	30	1236.93	94.87	540.83	550.73	67.08	3.77	0.0041	3.06	3224.59	8775.17	174.93	318.90	271.66	94.87	483.74	655.21	212.13

DOI: 10.15320/ICONARP.2025.314

RESULTS

Results of TOPSIS

To prioritize the suitable parking areas with the TOPSIS technique, the working steps described in the method section were implemented. Positive (A+) and negative ideal (A-) solution values created from Equations 7 and 8 are shown in Table 10. It is very important to determine the positive (A+) and negative ideal (A-) solution values appropriately.

For determining the Positive (A+) ideal solution values, it can be stated that 11 suitable parking areas should be close to Main Roads, Highways, Bus stations, Metro stations, Train stations, Residential & Workplace, Cultural facilities, Educational facilities, Health facilities, Public institutions, Sports facilities, Shopping malls, Green space; be far from Existing parking; be high for Traffic volume and Car ownership; and be low for Slope and Land Cost.

Table 10. Determination of positive ideal (A+) and negative ideal (A-) solution values

Criteria	A+	A-	Criteria	A+	A-
K1	0.01671	0.18076	K10	0.00318	0.00677
K2	0.00047	0.01545	K11	0.00993	0.07628
K3	0.00106	0.01905	K12	0.00051	0.00714
K4	0.00430	0.05577	K13	0.00018	0.01048
K5	0.00199	0.07097	K14	0.00331	0.03698
K6	0.02096	0.00039	K15	0.00025	0.02285
K7	0.00031	0.00203	K16	0.00080	0.00518
K8	0.00267	0.00013	K17	0.00402	0.04511
K9	0.01559	0.00533	K18	0.00007	0.00365

From Equations 9 and 10, the distances between the positive and negative ideal points were calculated (Table 11). Using Equation 11, the relative proximity to the ideal solution was calculated. Then, alternative points are listed by using the obtained C_i * values as given in Table 11.

Table 11. Calculation of distances to positive ideal (S+) and negative ideal (S-) points

Alternative	S+	S-	S+ + S-	Ci*	Rank
A1	0.0398	0.1951	0.2349	0.8304	1
A2	0.0627	0.1669	0.2296	0.7270	3
A3	0.0923	0.1340	0.2263	0.5920	5
A4	0.0470	0.1694	0.2164	0.7826	2
A5	0.1180	0.1189	0.2369	0.5020	8
A6	0.1249	0.1040	0.2290	0.4544	10
A7	0.1058	0.1231	0.2289	0.5377	6
A8	0.1098	0.1259	0.2357	0.5341	7
A9	0.1767	0.0891	0.2658	0.3353	11
A10	0.1132	0.1042	0.2174	0.4794	9
A11	0.0688	0.1617	0.2305	0.7016	4

Results of VIKOR

To prioritize the suitable parking areas with the VIKOR technique, we followed the working steps described in the method section. Table 12 presents the best and the worst values of all criteria that were created from Equations 13 and 14.

Table 12. Determining the best and the worst values of all criteria

Criteria	f+ (Best)	f- (Worst)	Criteria	f+ (Best)	f- (Worst)
K1	10.00	108.167	K10	1513.809	3224.593
K2	127.279	4218.070	K11	1914.950	14703.400
K3	10.00	180.0000	K12	108.167	1517.00
K4	189.737	2457.990	K13	10.0000	582.495
K5	212.132	7549.340	K14	30.00	335.410
K6	3615.090	67.082	K15	10.0000	920.272
K7	1.3918	9.0094	K16	216.333	1404.560
K8	0.0094	0.0005	K17	241.868	2713.300
K9	7.0363	2.4046	K18	10.00	512.640

S_j, R_j and Q_j values were calculated for each alternative using Equations 18, 19, and 20. Then, alternative points are listed in Table 13 by using the obtained Q_j values.

Table 13. S_j, R_j and Q_j values

Alternative	Sj	Rj	Qj	Rank (Qj)
A1	0.1597	0.0777	0.0258	1
A2	0.3009	0.1002	0.2456	3
A3	0.3585	0.1617	0.4387	5
A4	0.2557	0.0647	0.1191	2
A5	0.4322	0.1846	0.5755	8
A6	0.5362	0.1617	0.6592	10
A7	0.5321	0.1049	0.5418	6
A8	0.4466	0.1617	0.5480	7
A9	0.5625	0.3175	1.0000	11
A10	0.4625	0.1846	0.6131	9
A11	0.3442	0.0823	0.2639	4
S*, R*	0.1597	0.0647		
S-, R-	0.5625	0.3175		

The S_j, R_j and Q_j values were ranked in ascending order in Table 14. At the end of the calculations, we found that A1 has the smallest value among the Q values compared to other alternatives. For the A1 alternative to be accepted, condition 1 and condition 2 must be satisfied. Considering condition 1, 0.1191- 0.0258 = 0.09 and <0.10 (DQ), therefore condition 1 is not satisfied. According to condition 2, the alternative A1 was the column S_j in Table 13. Therefore, condition 2 is satisfied. Then, the ranking was done according to the minimum value of Q. The results of the ranking are presented in Table 15.

DOI: 10.15320/ICONARP.2025.314

Table 14. The ranking by S_j, R_j, and Q_j values

Alternative	S_j	Alternative	R_j	Alternative	Q_j
A1	0.1597	A4	0.0647	A1	0.0258
A4	0.2557	A1	0.0777	A4	0.1191
A2	0.3009	A11	0.0823	A2	0.2456
A11	0.3442	A2	0.1002	A11	0.2639
A3	0.3585	A7	0.1049	A3	0.4387
A5	0.4322	A3	0.1617	A7	0.5418
A8	0.4466	A6	0.1617	A8	0.548
A10	0.4625	A8	0.1617	A5	0.5755
A7	0.5321	A5	0.1846	A10	0.6131
A6	0.5362	A10	0.1846	A6	0.6592
A9	0.5625	A9	0.3175	A9	1.0000

When the results of the TOPSIS and VIKOR methods are compared, we note that the same results were achieved in both methods as can be seen in Table 15. These methods point to the same alternative as the best option and give the same results in the ranking of the location alternatives. Therefore, it is concluded that the TOPSIS and VIKOR methods can be successfully used for selecting vehicle-parking areas in common.

Table 15. The comparison of TOPSIS and VIKOR results

Rank	1	2	3	4	5	6	7	8	9	10	11
TOPSIS	A1	A4	A2	A11	A3	A7	A8	A5	A10	A6	A9
VIKOR	A1	A4	A2	A11	A3	A7	A8	A5	A10	A6	A9

DISCUSSION AND CONCLUSION

Allocating public services like vehicle parking areas is a complex decision-making problem that should be accomplished accurately to increase the efficiency of parking and avoid extra costs. The allocation of parking areas that have been performed using traditional methods was unsuccessful in considering all the effective parameters and therefore these gave insufficient results. This study adopted a wide range of effective parameters and developed an approach that considers all the parameters simultaneously. GIS integrated with MCDA techniques is effective in solving the complicated problem of locating parking areas. Accordingly, the MCDA methods were applied in two stages. First, the AHP technique was applied to calculate the weight of corresponding criteria and sub-criteria. Afterward, the weights were integrated with GIS to prepare the parking suitability map. Second, the TOPSIS and VIKOR techniques were implemented to prioritize the parking locations amongst suitable parking areas and to determine the best location for establishing parking areas.

Pendik district of Istanbul was selected as the study area in this research given that the district suffers from a lack of parking areas.

Rapid growth of population and urbanization, and development of transportation infrastructure investments in the city signify the need for parking areas. To tackle this complex problem, in this study, a wide range of effective parameters were considered and identified based on three criteria i.e. transportation criteria, parking criteria, and travel absorption criteria. The criteria determined within the scope of this model can also be used for determining suitable parking areas in any district outside the study area.

The integration of the GIS with MCDA techniques appears to be a highly successful method in dealing with geographic data as well as in manipulating criteria importance and in the prioritization process towards defining the optimum locations of parking areas. The AHP method was adopted to provide the weights of each decision criterion that was combined with GIS to prepare the parking suitability map. Consequently, TOPSIS and VIKOR were used to rank the alternatives. We anticipate that this novel integrative approach with its future variations will be instrumental in future works for determining efficient parking areas in highly populated cities and urban regions. In addition, as a decision-making tool, this approach using GIS-based MCDA techniques is proposed to allocate any public service by determining suitable areas and prioritizing these areas according to the criteria weights.

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Resume

Arif Cağdaş AYDINOĞLU, as a geomatics engineer, worked about developing national geographic data models in UGent-Belgium, ITC-the Netherlands, and TUDelft-the Netherlands during his Ph.D. in Turkey. He managed projects about Turkey National GIS and worked as vice-director of GIS Research Center of Istanbul Technical University (ITU). He completed his post-doc research as a part of INSPIRE project in the European Commission Joint Research Center (JRC) in European Union IPA project and as academic coordinator of Turkey National GIS infrastructure projects. His research interests are GIS, Geographic data management, Geospatial analysis, Geospatial Data Infrastructure (SDI), and Urban GIS for planning. http://arifcagdas.com/en/

Ahmad Shekib IQBQL is an Assistant Professor in the Department of Geographical Information Systems and Remote Sensing at Kabul Polytechnic University, Kabul, Afghanistan. He obtained his Bachelor's Degree in Engineering Geodesy Department from Kabul Polytechnic University in 2015. he completed his Master of Science in Geodetic and Geographic Information Technologies at the Faculty of Geomatics Engineering, Gebze Technical University, Turkey, in 2020. His primary research interests encompass Geographical Information Systems (GIS), Remote Sensing, GIS-based Transportation Analysis, and Multi-Criteria Decision Analysis.

Suleyman ŞİŞMAN, currently works at the Department of Geomatics Engineering, Gebze Technical University, Turkey. He, as a geomatics engineer, completed his M.Sc. study on modelling mass real estate valuation by GIS-based machine learning techniques. He continues his PhD study about machine learning techniques, smart cities, spatial data analysis, sustainable land management, and

DOI: 10.15320/ICONARP.2025.314

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ICONARP – Volume 13, Issue 1 / Published: 30.06.2025