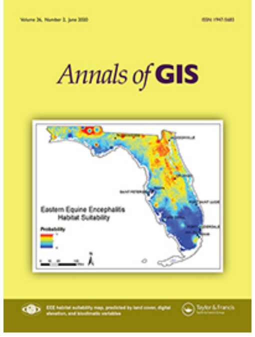

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Suitable location selection for the electric vehicle fast charging station with AHP and fuzzy AHP methods using GIS

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ABSTRACT

Electric vehicles arouse interest since they not only contribute economies of countries in the context of dependency to oil but also support to more livable and sustainable urban areas. The location selection of electric vehicle charging stations is one of the most vital topics in order to enhance the use of electric vehicles. In this sense, the aim of this paper is to propose an approach that integrates Geographic Information System (GIS) techniques and Multi-Criteria Decision Making (MCDM) methods for finding suitable locations of the electric vehicle charging stations. In this regard, the Analytic Hierarchy Process (AHP) and the Fuzzy Analytic Hierarchy Process (FAHP) methods are used to calculate the weights of criteria. While the two different weights for each criterion are obtained by means of AHP in terms of environmental impact and accessibility, another weight for each criterion is obtained as a means of applying the FAHP. The intersection of three different suitability indexes is determined so as to achieve a holistic, credible result. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is used to rank the alternative locations. The results show that the proposed approach offers a notable solution to be selected suitable charging station locations. Moreover, policymakers and administrators could benefit from these results in order to make efficient decisions for forward planning and strategies.

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Geographic Information Systems (GIS); Multi-Criteria Decision Making (MCDM); Analytic Hierarchy Process (AHP); Fuzzy Analytic Hierarchy Process (FAHP); electric vehicle charging station; location selection

1. Introduction

Citizens often benefit from transportation services to continue their daily life routine properly. These services comprise of land transportation, water transportation, and air transportation. As a commonly used transportation option, fuel-powered vehicles affect the environment and people's health negatively because they generate some harmful gases such as carbon dioxide, nitrogen oxides, ozone, and microscopic particles. According to the World Resource Institute (WRI) report that includes worldwide energy usage ratios and is published in 2006, while carbon dioxide composes 65% of this ratio, transportation services that use fossil fuels compose 21% of it (You and Hsieh 2014).

Since mobility is a vital necessity for actualizing of many economic and private activities, the requirement for mobility is generally provided with road traffic in urban areas of many industrialized countries (Helms et al. 2010). Energy efficiency is an important factor for the economic model of the countries because sustainability needs more energy than it consumes. Nowadays, there are concerns regarding the energy crisis since natural energy sources, including oil, gas, and coal are finite (Villacreses et al. 2017). The demand for fossil fuel energy can diminish because of the current financial and economic crisis in the world, but the general opinion states that this situation is temporary (Charabi and Gastli 2011).

Public administrations of many cities seek to enhance the use of electric-powered vehicles as urban transportation service in order to protect the environmental and economic sustainability since these vehicles produce much less pollution in comparison with the traditional fuel-powered vehicles. Moreover, electric vehicles are named as partial zero-emission vehicles despite the fact that they release some contaminants (You and Hsieh 2014). In light of this information, electric vehicles are acknowledged as one of the proper solutions to be markedly decreased traffic emissions and petroleum dependency (He et al. 2013).

The development of the electric vehicles accelerates thanks to researchers and experts who currently try to explore the new ways that promote the transmission of energy and power systems. Hence, the energy transmission stage has begun for the global auto industry. Charging stations are one of the main contributive factors to be enabled the more widespread use of electric vehicles (Ge, Feng, and Liu 2011); therefore, suitable location planning of electric vehicle charging stations is a significant problem. If the charging stations are built in

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inappropriate places, drivers and traffic networks can be negatively influenced (Liu, Wen, and Ledwich 2013). Regarding this, fast charging stations located in appropriate locations can provide more effective use of electric vehicles that citizens have (Nansai et al. 2001; Fox 2013). In this sense, this paper investigates how suitable locations of electric vehicle charging stations can be determined efficaciously. Also, the study addresses the research questions in follows:

- Which methodology can enable the selection of suitable locations of electric vehicle charging stations in a more applicable way?
- How can the holistic approach result that takes various objectives into account be obtained?

There are several studies that aim to find suitable locations for electric vehicle charging stations. These efforts mostly comprise of optimization and multiple criteria techniques. While some of these efforts take electric and transport networks into consideration, some studies utilize point-based and flow-based models in terms of demand for charging stations. Cai et al. (2014) carried out a comprehensive analysis by using taxi route data to determine the best locations of public electric vehicle charging stations in Beijing. According to the results of this study, they identified the suitable hot spots for possible locations of charging stations in the city. Also, they found that the charging stations located in proper locations have a positive effect on the model of travel. They mentioned that the use of charging stations reached the highest point at noon and summer. Lam, Leung, and Chu (2014) utilized different methods to overcome the problem of locating electric vehicle charging stations, but their methodology only allows them to select suitable territories rather precise locations for siting charging stations. Differently, in the presented study, a spatial analysis based approach is performed to find suitable locations in more detail. In other words, candidate locations are pixels, not regions. Guo and Zhao (2015) used the fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) approach that is one of the popular Multi-Criteria Decision Making (MCDM) methods to select the suitable locations of electric vehicle charging stations. They took different factors such as the environment, economy, society, electric power system, and transportation system into consideration. In this study, it is first determined four alternative charging station locations, and then the best one is selected. This approach can cause the elimination of the various suitable locations for charging stations. Furthermore, the authors did not use any spatial analysis to evaluate alternative locations. With the aim of eliminating these shortcomings, the present paper applies an approach that integrates Geographic Information Systems (GIS) and MCDM to select and assess candidate charging station locations. Song, Wang, and Yang (2015) benefitted from Voronoi diagrams to come through the electric vehicle charging station placement problems with the objective of minimizing social cost. He, Kuo, and Wu (2016) proposed a methodology that involves the comparison of different factors such as local constraints, demand for electric vehicle charging stations, and plant location models to be determined the appropriate positions of public electric vehicle charging stations. The authors did not mention how the weights of criteria were calculated in demand analysis. To remove this ambiguity, the present study uses MCDM methods that enable to check the consistency of decisions. Andrenacci, Ragona, and Valenti (2016) generated a model based on an analysis of driving samples to find ideal places of electric vehicle charging stations in urban areas of Rome. They mentioned that the generated model can be applied to different placement problems. Philipsen et al. (2016) conducted a study that investigates the effective usage potential of electric vehicles charging stations located in citizen's working areas. The criteria used in this study were obtained from previous studies that aimed to find suitable charging station locations. Their study results showed that motorway service stations, shopping centres, and traditional petrol stations can be evaluated as potential fast-charging station locations. However, the exact locations of alternative charging stations were not examined in detail. For this reason, the present study performs an evaluation analysis by using the TOPSIS method to assess determined charging station locations. Wu et al. (2016) used the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) method based on decision-making for detecting the suitable locations of electric vehicle charging stations. Analytical Network Process (ANP) method is applied to measure the correlation of parameters. In this study, the optimal site is selected among predetermined alternative locations. With the aim of realizing a detailed analysis, the present paper endeavours to select suitable locations by assuming that all pixels in the study area are alternatives. Zhao and Li (2016) accomplished research that includes selecting the proper one out of five different potential electric vehicle charging station sites. They remarked that environment sub-criteria have the highest effect according to their study results. The authors determined suitable districts rather than precise locations. That is why the present study aims to propose an approach that enables to obtain the elaborative results by using spatial data and analyses. Zhu et al. (2016) proposed a model that uses the genetic-algorithm method to solve the charging station location problem of electric vehicles with the aim of minimizing the total cost. It was underlined that the expanded model can provide a more effective location structure according to the results of this study. Yet the authors did not take land-use features into consideration and they also assumed that the demand for charging stations is homogenous in the study area. The present paper attempts to find suitable locations by taking both different objectives and built environment into account. Awasthi et al. (2017) carried out a study that contains the integration of genetic and improved swarm optimization methods in order to find optimal electric vehicle charging station structures in terms of placement and sizing. Wu et al. (2017) developed an index system that bases on different factors such as economic, social environment, planning, and settlements by using the Triangular Intuitionistic Fuzzy Numbers (TIFNs) method so as to solve the problem of electric vehicle charging station positioning. The authors made a selection for districts. As mentioned before, a detailed analysis is performed in the presented study. Wei et al. (2018) introduced a method that provides the optimal placement of electric bus system batteries by taking the spatio-temporal characteristics of buses into consideration. He et al. (2018) generated charging station best location selection model based on driving ranges of electric vehicles by applying the bi-level programming method. According to the results of this study, they observed that the driving rages dominantly affect the selection process of appropriate charging station locations. Erbaş et al. (2018) proposed an approach that combines GIS techniques and MCDM methods to determine optimal locations of electric vehicle charging stations in Ankara, Turkey. The authors applied different scenarios relating to obtaining weights of criteria, but they did not analyse the intersection of suitable location suitability indexes that are gained from these scenarios. To contribute to the literature, the present paper takes the objectives of environmental impact and accessibility into account and creates the intersection suitability result by benefiting from these objectives. Csiszár et al. (2019) proposed a technique that integrates weighted multi-criteria methods and hexagon-based approach to locate the new electric vehicle charging stations. The authors did not mention the consistencies of criteria that are used and they also did not clarify the value ranges of supplementary sub-criteria, namely slope and charging price. In the presented study, the consistencies of all decisions are calculated. Dong et al. (2019) proposed a methodology that benefits from maximal coverage location models and also spatial statistics to determine the optimal charging station locations. This study is utilized by using low pixel resolution as 1 km. In this respect, the present study performs the spatial analysis by using relatively high resolution (30 m x 30 m).

The main aim of this paper is to offer an efficient and viable approach that allows being found the suitable locations of electric vehicle charging stations. The other aim of the study is to show and enable location selection by taking different objectives into consideration. By doing this, it will be provided more participatory and convincing outcomes for location selection. Researchers generally select the optimal locations of charging stations from among predetermined, alternative ones. This can regrettably limit the effectiveness of location selection. Moreover, the ranking of alternative locations is realized by using MCDM without applying any spatial analysis. This is because Spatial Decision Support Systems (SDSS) are used to overcome this shortcoming since each pixel can be recognized as an alternative location for the electric vehicle charging station. The location selection problem is affected by various factors. In this context, this paper presents an approach that integrates GIS techniques and MCDM in order to be effectively selected the optimal locations for electric vehicle charging stations. This research can contribute to the existing literature in the following ways:

- While the two different criteria weights are obtained by using the Analytic Hierarchy Process (AHP) in terms of both environmental impact and accessibility, other weights of criteria are calculated by means of the Fuzzy Analytic Hierarchy Process (FAHP). By doing so, it will be enabled overarching location selection as well as providing trustworthy results.
- By utilizing GIS techniques, the suitable charging station locations are determined not only using semantic information but also benefiting from the integration of spatial and semantic information. First, the spatial layers related to criteria are created, and then the suitability index is calculated by assigning criteria weights to relevant spatial layers with the help of the Weighted Linear Combination (WLC). GIS techniques provide to be spatially represented the criteria as well as allowing the realization of various spatial analyses such as *slope* and *kernel density*.
- The final charging station location suitability index is found as a means of intersecting three different suitability index; therefore, the shortcomings that stem from negative features of different methods could be removed.

- The alternative charging station locations are ranked by using the TOPSIS method; besides, this ranking is compared with the ranking that is obtained by using suitability index pixel values of locations. Thus, this will give a helpful viewpoint to researchers for future studies.

The proposed approach is illustrated as a case study in three neighbour districts, including Atasehir, Uskudar, and Kadikoy within Istanbul, Turkey (Figure 1). Istanbul is located in the northwest Marmara region of Turkey. Their boundaries are represented with the coordinates of 28°10′ and 29°40′ East longitude and 40°50′ and 41°30′ North latitude. According to the 2017 Turkish Statistical Institute (TurkStat) data (TurkStat 2017), Istanbul has a population of 15,029,231 and is the most populous city across the nation. It is also the greatest compact city of Turkey in terms of economics, culture, and global interest. Istanbul notably grew in the context of the environment, economy, and socialization because of rapid industrialization and urbanization that occurred in the second half of the 20th century. In the study area, there are transportation transfer centres, main roads, connection roads, and meeting points that are commonly visited by society. Moreover, green and urban areas are the dominant land use classes.

In Turkey, the government tries to determine policies in order to efficiently encourage and enhance the use of electric vehicles since only 1% of cars that are registered to the traffic use electric-hybrid fuel type as can be seen in Figure 2 (TurkStat 2019). This is why the determination of suitable charging station locations is of vital importance.

The first section gives a brief overview of the importance of electric vehicles and surveys the relevant literature and provides the contributions and aims of the research. The remainder of the paper is organized as follows. Section 2 outlines the methodology that is used in this research. Section 3 presents the case study results and discusses them. Finally, Section 4 concludes the paper and conveys the suggestions.

2. Methodology

This paper investigates how to use the integration of GIS techniques and MCDM for finding suitable locations of electric vehicle charging stations. In this regard, the workflow of the study is composed to enable the repeatability of the proposed approach in different regions (Figure 3). First, the study area is determined in order to exemplify the methodology, and then the relevant literature is reviewed in detail to be decided on the

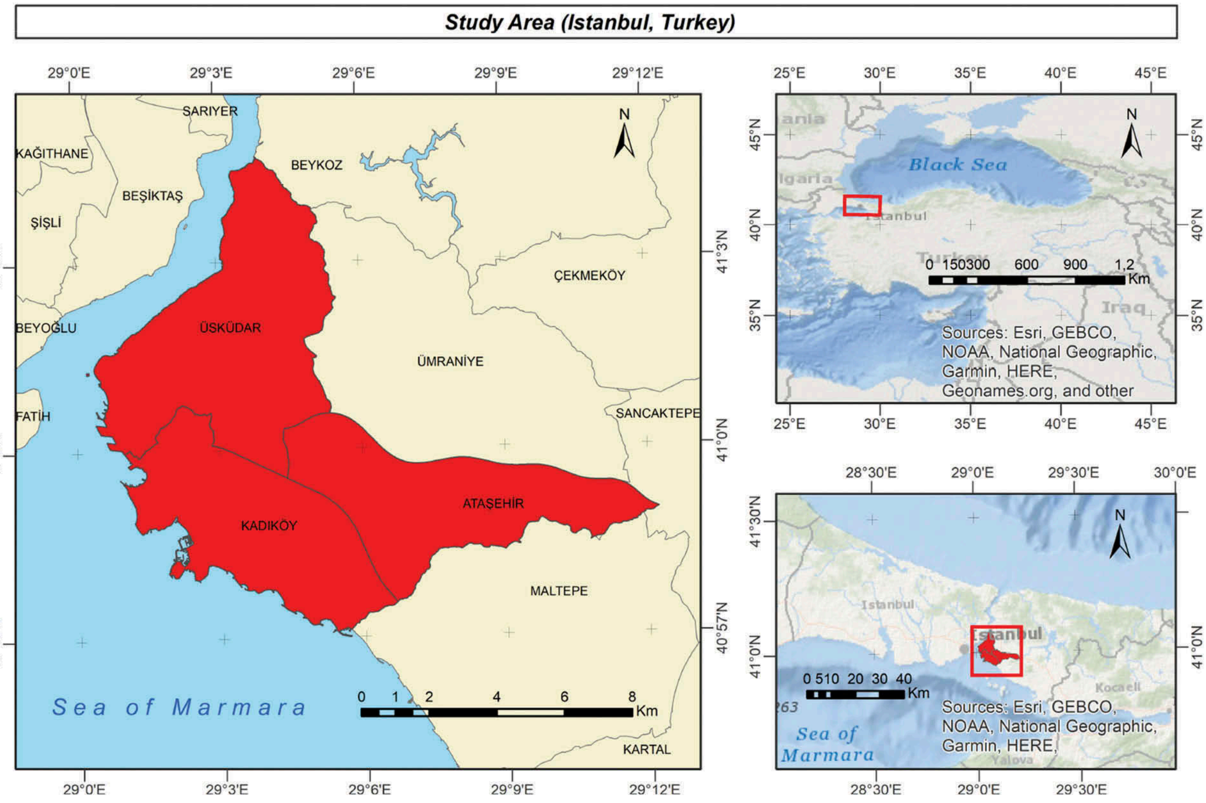
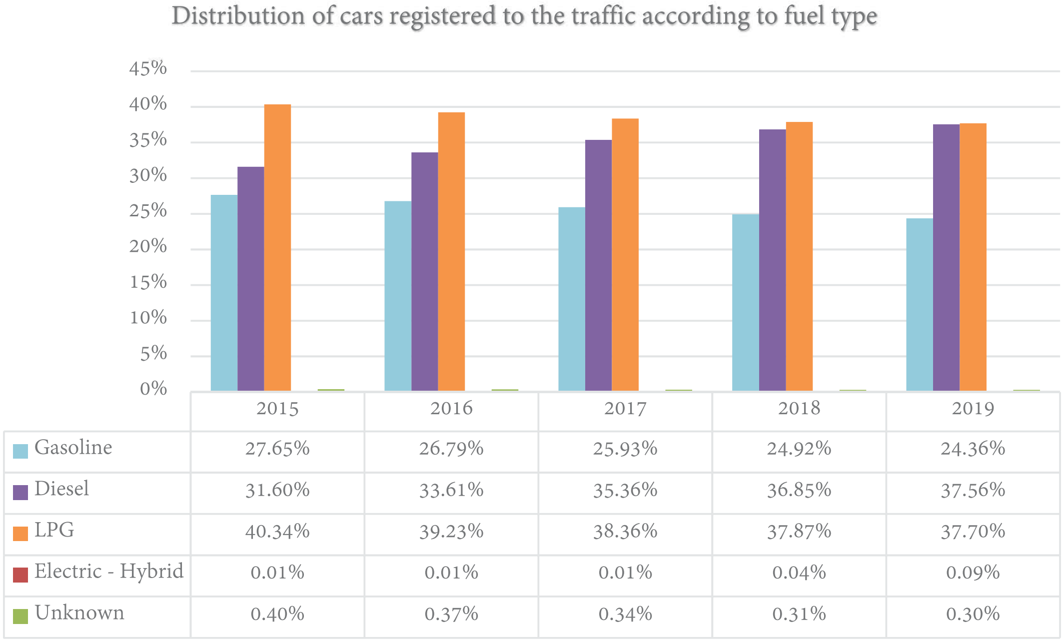


Figure 1. The map of the study area.



	2015	2016	2017	2018	2019
Gasoline	27.65%	26.79%	25.93%	24.92%	24.36%
Diesel	31.60%	33.61%	35.36%	36.85%	37.56%
LPG	40.34%	39.23%	38.36%	37.87%	37.70%
Electric - Hybrid	0.01%	0.01%	0.01%	0.04%	0.09%
Unknown	0.40%	0.37%	0.34%	0.31%	0.30%

Figure 2. Distribution of cars registered to the traffic according to fuel type in Turkey (TurkStat 2019).

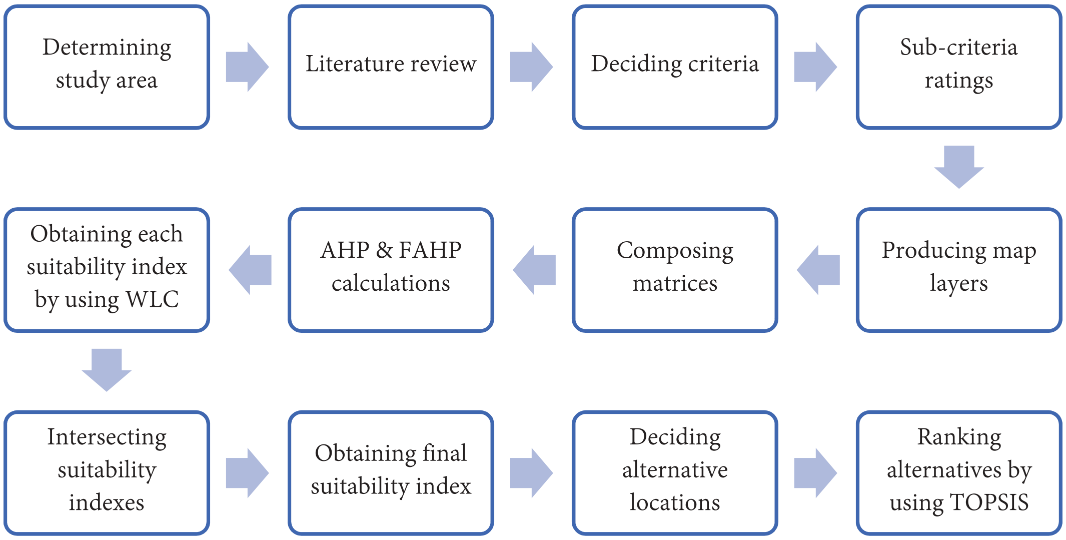


Figure 3. The workflow of the study.

criteria that affect the suitable locations of charging stations. The spatial features of the study area are considered when selecting the criteria; thereafter, the sub-criteria values that show the location suitability are determined between zero and five. While zero is used to represent not suitable areas, five is used to represent the most suitable areas. The next section detailedly clarifies which criteria are used and how sub-criteria values are assigned in this research. In order to execute spatial analyses, map layers that represent each criterion are produced in the GIS environment. The ArcGIS software package is used to realize spatial analyses, projection transformations, and visualizations. All layers have the same projection system as WGS84. Also, all raster-based spatial analyses are carried out by using 30 m x 30 m cell resolution. This resolution is determined according to both previous works and large scale study extent (Güler and Yomralıoğlu 2017). The next step in the workflow is to compose the pairwise comparison matrices of AHP and FAHP in order to get the weight of each criterion. If the weights of criteria are obtained by taking multiple objectives into consideration, this will provide a holistic solution for finding suitable locations. To do this, two different comparison matrices for AHP are composed in terms of environmental impact and accessibility. On the other hand, the weights of criteria are not exactly acquired all the time since each MCDM method has some typical disadvantages. Researchers generally assume that there is no specific best method in MCDM studies. In this regard, if one method can be integrated with other MCDM methods, this method has an advantage in the sense of reliability. Accordingly, AHP and FAHP methods are used together in this study. In order to eliminate the disadvantages to some extent, another comparison matrix for FAHP is composed additionally. After this, the procedure steps in the methodologies of AHP and FAHP have applied and hence three different weights for each criterion could be calculated by using constituted comparison matrices. In the next step, each suitability index is obtained by applying WLC that can associate each criterion layer to its weight and combine all of them. The common areas associated with each suitability class are found as a means of intersecting each suitability index layer so that the dependableness of the results is enhanced. This process is conducted by means of map algebra and also provides the final suitability index. The alternative locations of charging stations are determined according to the high suitable class of the final suitability index. Finally, these locations are ranked by using the TOPSIS.

In this study, a GIS-based MCDM approach is applied to determine suitable locations of electric vehicle charging stations. Since GIS techniques can manipulate both spatial data and semantic data, researchers benefit from them in order to tackle the different complex problems that require spatial data and analyses. GIS techniques enable to be used the different criteria, including land values and population density with their spatial information for location selection applications because they realize the spatial analyses by using both vector and raster data formats. The same spatial analyses are repeated in MCDM applications that include a large number of different criteria. For example, various, resulting maps are obtained by using three different weights of criteria in this research. With the aims of preventing repetitive operations and providing automation in the GIS environment, the location selection model is created by means of a *model builder* tool in ArcMap (Figure 4). The criterion map layers are entered into this model in the first step. These layers are used as input and they can be seen as blue in the figure. After, spatial analyses are executed by using the *Euclidean distance* method for criteria that need to distance analysis. Other criteria such as income rates and land values that exist in a vector data format are transformed to raster data by applying the *feature to raster* spatial analysis tool. In the next step, *reclassification* analysis is applied to all criterion data layers by using attribute class intervals in Table 1. These interval values are selected by taking previous studies into account. The location selection resulting map is obtained by using the *weighted sum* spatial analysis tool in the final phase.

2.1. Description of the criteria

In this paper, ten criteria are used to select suitable locations of the electric vehicle charging stations. The existing researches are taken into consideration in order to select the criteria that affect the charging station location. These criteria are population density, shopping malls, roads, income rates, transportation stations, petrol stations, park areas, green areas, slope, and land values. This section presents the comprehensive explanations of each criterion and its sub-criteria. Also, the maps that represent the spatial suitability distribution of each criterion were produced. Table 1 lists the scores of sub-criteria. The sub-criterion scores of distance-based criteria are determined by taking walking distance that is between station and demand point into account. It is accepted that this distance is optimally less than 250 m.

2.1.1. Population density

The necessity for charging stations is greater in areas where electric vehicles are frequently used. For this reason, population density can be used as a factor to determine these regions. In this study, the up-to-date population data of TurkStat is used. Population density is calculated for each neighbourhood, and then they are classified according to the Natural Breaks (Jenks) method. If the location has a high population density, it will be more suitable.

2.1.2. Shopping malls

Shopping malls can be considered as an evaluable option to find suitable locations of electric vehicle charging stations because charging stations located close to shopping malls will be more beneficial. Google Maps is used to create a map layer of the shopping malls criterion. The coordinates of shopping malls are obtained and then the coordinate system transformation is applied. If the location is close to shopping malls, it will be more suitable.

2.1.3. Roads

The roads that are often used by electric vehicles are critical in order to determine suitable locations of electric vehicle charging stations. To create the roads map layer, roads that have two or more lanes are first determined, and then the new map layer is formed by using these data. The road map layer is created as a vector data format. If the location is close to the roads, it will be more suitable.

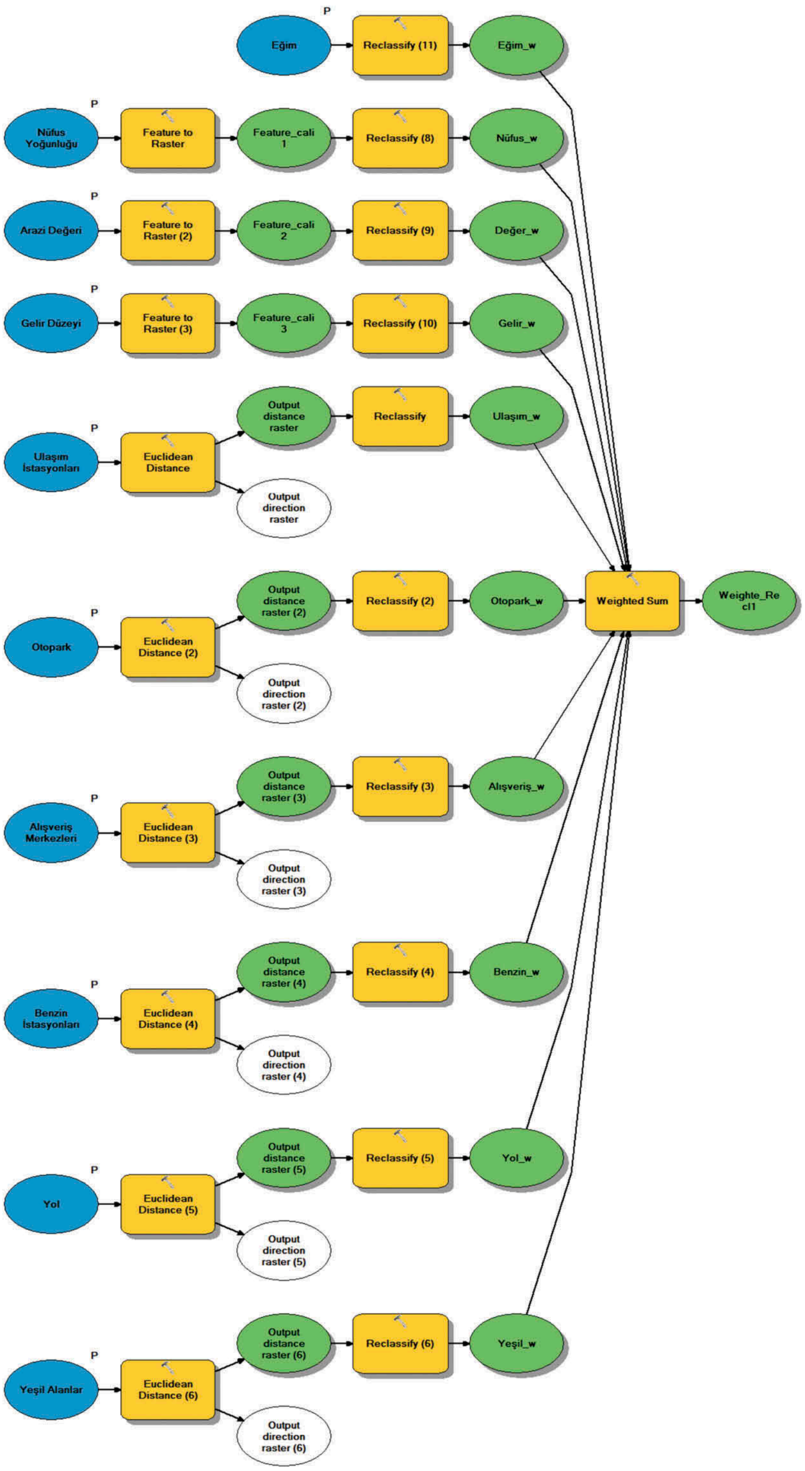


Figure 4. Electric vehicle charging station location selection model.

2.1.4. *Income rates*

Income rates can be evaluated in the location selection of the electric vehicle charging station. The map layer is created by using income rates statistics of districts that are shared with the public. This new map layer is classified into three ranges. If the location has a high-income rate, it will be more suitable.

2.1.5. *Transportation stations*

The study area includes many public transportation stations since it connects significant parts of the city. Electric vehicle owners can benefit from electric vehicle charging stations located close to transportation stations because they can park their vehicles for charging and use public transportation services. The transportation map layer is

Table 1. Criterion scores.

Criterion	Sub-Criterion	Score
Population density (C1)	33<	5
	23–32	4
	17–22	3
	10–16	2
	<9	1
Shopping malls (C2) (m)	<250	5
	250–500	4
	500–750	3
	750–1000	2
	1000<	1
Roads (C3) (m)	<250	5
	250–500	4
	500–750	3
	750–1000	2
	1000<	1
Income rates (C4) (TL)	9025	5
	6987	3
	6577	1
Transportation stations (C5) (m)	<250	5
	250–500	4
	500–750	3
	750–1000	2
	1000<	1
Petrol stations (C6) (m)	<250	5
	250–500	4
	500–750	3
	750–1000	2
	1000<	1
Park areas (C7) (m)	<250	5
	250–500	4
	500–750	3
	750–1000	2
	1000<	1
Green areas (C8) (m)	300<	5
	250–300	4
	200–250	3
	150–200	2
	100–150	1
	<100	0
Slope (C9) (°)	<5	5
	5–10	4
	10–15	3
	15–20	2
	20–25	1
	25<	0
Land values (C10) (TL)	<677	5
	678–1068	4
	1069–1450	3
	1451–2907	2
	2908<	1

composed of metro and metrobus stations that are used by an average of three million passengers each day. If the location is close to transportation stations, it will be more suitable.

2.1.6. Petrol stations

The petrol stations are one of the first locations that come to mind for electric vehicle charging stations. Yet the station requirements are different for internal combustion vehicles as compared to electric vehicles. Nevertheless, the existing petrol stations can be considered as suitable locations for electric vehicle charging stations because these areas are located according to the current traffic network. If the location is close to petrol stations, it will be more suitable.

2.1.7. Park areas

The park areas are another criterion that is taken into account for electric vehicle charging stations. Spatial and attribute information of the car parks is obtained from ISPARK that is the official corporation in Istanbul, Turkey. The park areas map layer is prepared by using this data. The parked cars can be efficiently charged. If the location is close to park areas, it will be more suitable.

2.1.8. Green areas

Green areas are used as an environmental factor in this study when finding suitable locations of electric vehicle charging stations. Since the study area only contains green areas in terms of environmental impact, there is no other criterion. The map layer is created by using a remotely sensed image. The maximum likelihood supervised classification method is applied to the Sentinel-2A satellite image that is freely distributed by the European Space Agency (ESA). If the location is far from green areas, it will be more suitable.

2.1.9. Slope

The slopes of locations can affect the location selection process of electric vehicle charging stations in terms of both construction cost and feasibility. The study area includes the regions that have a nonstable and high slope. For these reasons, the slope map layer is created by executing the *slope* spatial analysis tool of ArcMap. ASTER GDEM digital elevation model that is generously distributed with the world is used as a source data. If the location has a low slope, it will be more suitable.

2.1.10. Land values

Land values are taken into consideration as an economic factor for suitable location selection of electric vehicle charging stations since the study area includes the regions that have very variable land values. In this perspective, the land values map layer is prepared by using street-scaled statistics that are in the Turkish Lira (TL) unit and are shared by the Revenue Administration of Turkey. First, the average land values of each neighbourhood are calculated, and then these data are associated with the relevant spatial criterion layer. If the location has a low land value, it will be more suitable.

2.2. Multi-criteria decision making (MCDM) methods

The suitable location selection for the electric vehicle charging station is an MCDM problem because it is affected by a lot of criteria. This process can be realized by taking several criteria into consideration. MCDM methods are an analytical tool that provides making efficient decisions when different considerations get involved in the process. These methods are generally categorized as Multi-Objective Decision Making (MODM) and Multi-Attribute Decision Making (MADM). In this study, it is benefitted from AHP, FAHP, and TOPSIS methods.

2.2.1. *The analytic hierarchy process (AHP)*

AHP is a method that assists to deal with complicated problems. It was developed by Saaty (Saaty 1990) in the 1970s and has significantly progressed over the years. AHP uses the criteria that are essential for the decision-making process. It forms a hierarchical structure by providing the uninterrupted steps. Starting from the general purpose, the rankings of criteria and sub-criteria are obtained, and then the alternatives are determined. Decision-makers decide how important one criterion is in comparison with another criterion when creating the pairwise comparison matrices.

The aim of creating matrices is to convert the preferences of the decision-makers into a calculable scale. This conversion is realized by using the scales that are shown in Table 2 (Ma et al. 2005). Furthermore, this scaling approach provides that the weights of the criteria can be homogeneously determined. Pairwise comparison matrices are formed by using all criteria. To calculate the weights of criteria quantitatively, the eigenvalue vector method is applied (Eskandari 2017). A detailed methodology of AHP can be found in (Höfer et al. 2016).

The AHP also provides a mathematical determination of the inconsistencies in the decision-makers' judgements. The consistency ratio (CR) can be calculated based on the properties of the comparison matrices. If the (CR) is less than 0.1, pairwise comparisons are accepted. Otherwise, the matrices should be recreated, and then the new (CR) value should be also checked for consistency (Ma et al. 2005).

In this research, the AHP hierarchy is composed of three main criteria, namely accessibility, environmental, and economic. These main criteria also have different sub-criteria. Figure 5 shows the AHP hierarchy of this study. Pairwise comparison matrices are created by taking relevant researches in the literature into consideration (Guo and Zhao 2015; Wu et al. 2016; Zhao and Li 2016; Wu et al. 2017). Two different weights for each criterion are obtained in terms of environmental impact and accessibility. In this sense, pairwise comparison matrices are separately generated, and then the normalized weights of criteria are calculated by means of AHP methodology (Tables 3–8). Figure 6 presents the ratios of weights of criteria in the context of environmental impact and accessibility. The CR value is calculated as acceptable for all pairwise comparison matrices.

Table 2. Fundamental scale for pairwise comparisons in AHP.

Verbal scale	Numerical values
Equally important, likely or preferred	1
Moderately more important, likely or preferred	3
Strongly more important, likely or preferred	5
Very strongly more important, likely or preferred	7
Extremely more important, likely or preferred	9
Intermediate values to reflect compromise	2, 4, 6, 8

2.2.2. *Fuzzy analytic hierarchy process (FAHP)*

The determination of the exact values of the data according to the measurements is very problematic for human judgement. Decision-makers and policymakers prefer natural language representations rather than crisp numbers. The fuzzy set theory is used in ambiguous or uncertain situations. The concept of the fuzzy theory was first presented by Zadeh (1965). The FAHP method was developed as an extension of the AHP method. Although AHP uses the crisp numbers to express the expert's knowledge in decision making, FAHP can reflect human thoughts more realistic than AHP since it uses the interval values of simple crisp numbers. Therefore, the FAHP method is frequently applied in MCDM problems that are hierarchical and complex. In this study, it is used the extent analysis method that is proposed by Chang (1996).

Table 9 presents the scale values that are used to create the pairwise comparison matrix in the context of fuzzy scaling (Lee, Mogi, and Hui 2013). The detailed methodology of Chang's extent analysis method can be found in (Dağdeviren, Yüksel, and Kurt 2008).

Figure 7 shows the FAHP hierarchy of this study. Pairwise comparison matrices are established by benefiting from research in the literature (Guo and Zhao 2015; Wu et al. 2016; Zhao and Li 2016; Wu et al. 2017). Table 10 shows the FAHP pairwise comparison matrix in this study. The weights of criteria are calculated by using this matrix. The CR is not normally calculated in Chang's method because if one of the weights of the criteria is zero, this creates mathematical uncertainty. In this study, the consistency ratio is calculated since the weights of all criteria are different from zero. In addition, the pairwise comparison is accepted because the CR is lower than 0.1. All FAHP calculations are executed by using MATLAB software. The code can be costlessly downloaded from the sharing platform (Guler 2020). Figure 8 details the ratios of weights of criteria.

2.2.3. *Technique for order preference by similarity to ideal solution (TOPSIS)*

TOPSIS is used to rank the alternatives in decision making studies. If the most preferred alternative has the shortest distance from the positive ideal solution and it has the longest distance from the negative ideal solution, this situation provides a reliable ranking solution. TOPSIS is

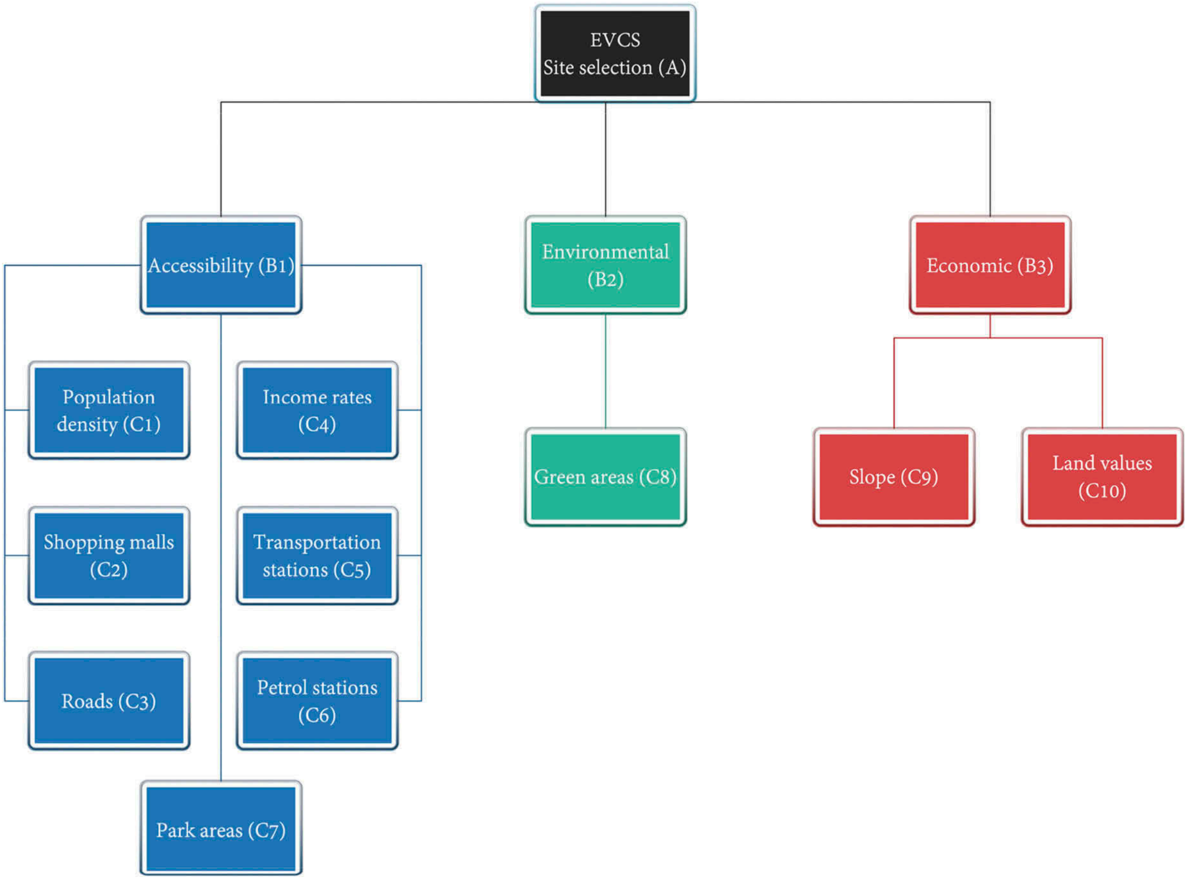


Figure 5. AHP hierarchy of this study.

Table 3. The pairwise comparison matrix of environmental impact scenario.

A	B_1	B_2	B_3	W
B_1	1	1/2	3	0,3196
B_2	2	1	4	0,5584
B_3	1/3	1/4	1	0,1220

CR = 0.019, B_1: Accessibility, B_2: Environmental, B_3: Economic

Table 4. The pairwise comparison matrix of accessibility sub-criteria.

B_1	C_1	C_2	C_3	C_4	C_5	C_6	C_7	W
C_1	1	1/2	1/2	1/2	2	1/2	1/2	0,0875
C_2	2	1	1/3	2	2	1/2	2	0,1520
C_3	2	3	1	2	3	2	2	0,2656
C_4	2	1/2	1/2	1	2	1/2	1/2	0,1067
C_5	1/2	1/2	1/3	1/2	1	1/2	1/2	0,0665
C_6	2	2	1/2	2	2	1	2	0,1917
C_7	2	1/2	1/2	2	2	1/2	1	0,1300

CR = 0.044, C_1: Population density, C_2: Shopping malls, C_3: Roads, C_4: Income rates,
C_5: Transportation stations, C_6: Petrol stations, C_7: Park areas

Table 5. The pairwise comparisons matrix of economic sub-criteria.

B_3	C_9	C_{10}	W
C_9	1	1/3	0,25
C_{10}	3	1	0,75

CR = 0, C_9: Slope, C_{10}: Land values

Table 6. The pairwise comparisons matrix of accessibility scenario.

A	B_1	B_2	B_3	W
B_1	1	6	4	0,6910
B_2	1/6	1	1/3	0,0914
B_3	1/4	3	1	0,2176

CR = 0.056, B_1: Accessibility, B_2: Environmental, B_3: Economic

Table 7. The weights of environmental impact scenario.

Goal A	Hierarchy B	Hierarchy C	W
A	B_1	C_1	0,0280
		C_2	0,0486
		C_3	0,0848
		C_4	0,0341
		C_5	0,0213
		C_6	0,0613
		C_7	0,0416
	B_2	C_8	0,5583
	B_3	C_9	0,0305
		C_{10}	0,0915

C_1: Population density, C_2: Shopping malls, C_3: Roads, C_4: Income rates, C_5: Transportation stations, C_6: Petrol stations, C_7: Park areas, C_8: Green areas, C_9: Slope, C_{10}: Land values

based on this mentioned approach. The detail formulation of the TOPSIS method can be found in (Hwang, Lai, and Liu 1993). In this study, TOPSIS is used to rank the alternative locations of electric vehicle charging stations.

Table 8. The weights of accessibility scenario.

Goal A	Hierarchy B	Hierarchy C	W
A	B_1	C_1	0,0605
		C_2	0,1050
		C_3	0,1835
		C_4	0,0737
		C_5	0,0459
		C_6	0,1325
		C_7	0,0898
	B_2	C_8	0,0915
	B_3	C_9	0,0544
		C_{10}	0,1632

Table 9. Fuzzy scale.

Linguistic scale for importance	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	(1, 1, 1)	(1, 1, 1)
Equally important	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly more important	(1, 3/2, 2)	(1/2, 2/3, 1)
Strongly more important	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strongly more important	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more important	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

3. Results and Discussion

3.1. *Identification of suitable locations*

To determine suitable locations for electric vehicle charging stations, a GIS-based MCDM approach is used by applying the model that is explained in the methodology section. In the model, while all spatial analysis processes can be seen as yellow, all output data can be seen as green. Suitability maps of all criteria that are obtained after from *reclassification* phase are shown in Figures 9 and 10. It can be seen from these figures that while some criteria, including C3 and C9 have more suitability, some of them such as C2, C5, C6, C7, and C8 have less suitability. This shows that suitability for charging stations differs depending on different criteria. Thus, sub-criterion scores in Table 1 have importance for the final suitability index because of their impacts on each criterion. All spatial layers have pixel values between zero and five. This means that the standardization process is completed before WLC. By utilizing the mentioned model, three different suitability indexes are obtained in this research (Figures 11–13). As can be seen from figures, the weights of criteria highly affect the suitability index. The same pixel value classification is used to create an electric vehicle charging station location suitability index; otherwise, the trustworthy suitability results could not be achieved. Figure 14 details the percentage area values of all suitability classes in suitability indexes. The figure shows that suitability classes have different area values in the study area. From the figure, it can be seen that while the environmental objective resulting map has the most *high suitable* area class percentage, accessibility objective resulting map has the greatest *suitable* area class percentage. Furthermore, the environmental objective resulting map has a maximum *unsuitable* area class percentage. This can be stemmed from the C8 having more than 50% weight in the environmental impact scenario. Also, the FAHP resulting map has the most *low suitable* area class percentage. The change analysis is realized by means of the *raster calculator* tool in ArcMap in order to show this mentioned differences in suitability class percentage. Figure 15 presents the map that shows the changes from accessibility

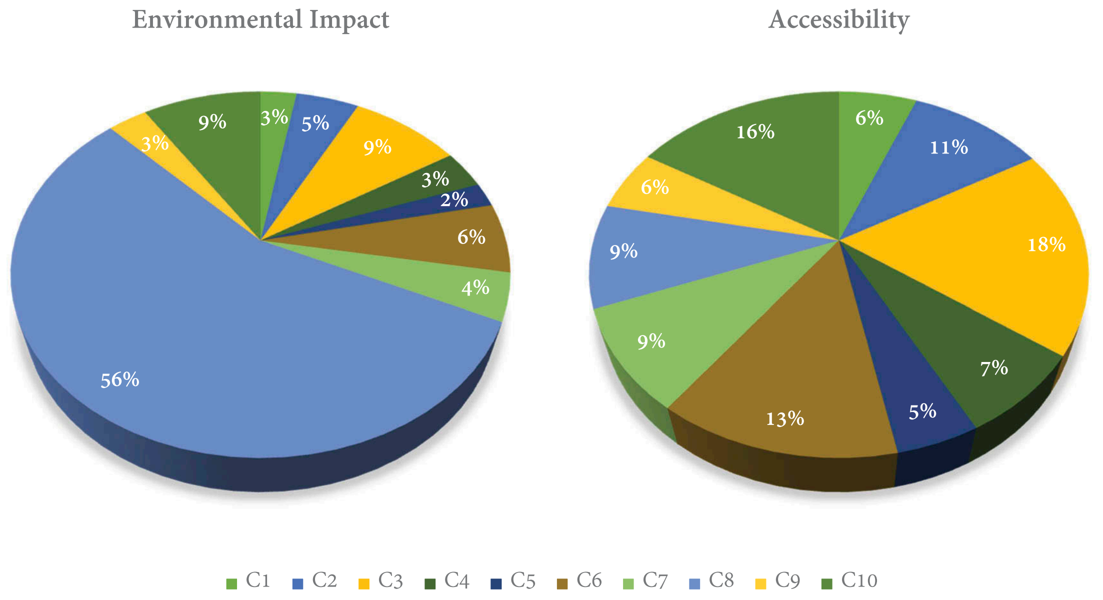


Figure 6. AHP weights according to scenarios, C_1: Population density, C_2: Shopping malls,C_3: Roads, C_4: Income rates, C_5: Transportation stations, C_6: Petrol stations, C_7: Park areas, C_8: Green areas, C_9: Slope, C_{10}: Land values.

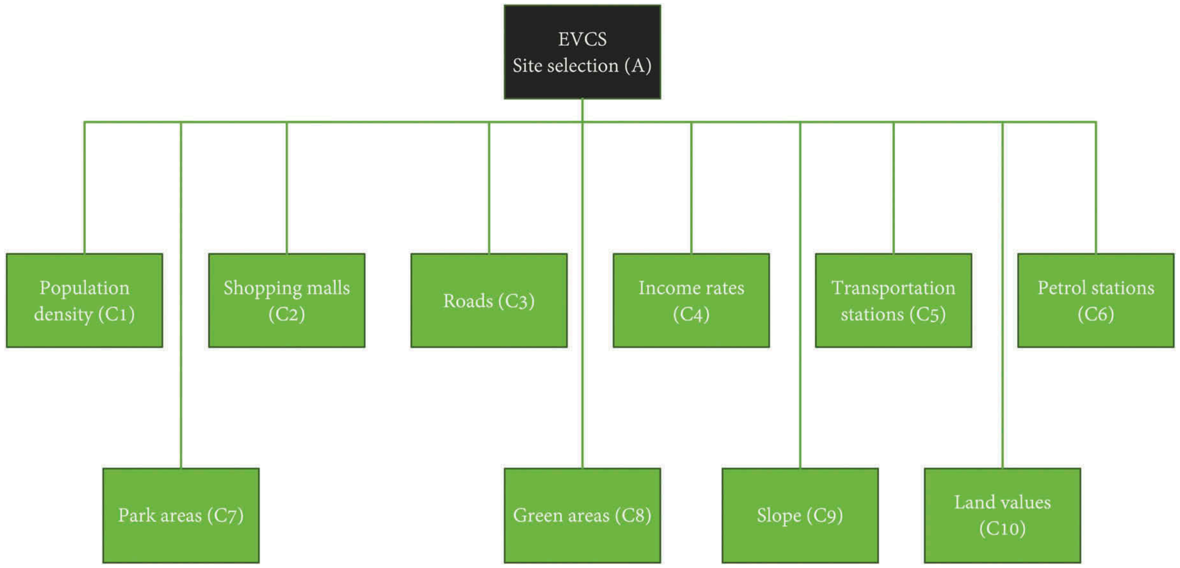


Figure 7. FAHP hierarchy of this study.

Table 10. The pairwise comparison matrix for FAHP.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	W
C1	(1, 1, 1)	(2/3, 1, 2)	(2/3, 1, 2)	(2/3, 1, 2)	(1/2, 1, 3/2)	(2/3, 1, 2)	(2/3, 1, 2)	(2/5, 1/2, 2/3)	(2/3, 1, 2)	(1/2, 2/3, 1)	0,0951
C2	(1/2, 1, 3/2)	(1, 1, 1)	(1/2, 2/3, 1)	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(2/3, 1, 2)	(1/2, 1, 3/2)	(2/5, 1/2, 2/3)	(2/3, 1, 2)	(2/3, 1, 2)	0,0887
C3	(1/2, 1, 3/2)	(1, 3/2, 2)	(1, 1, 1)	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(1, 3/2, 2)	(1/2, 1, 3/2)	(2/5, 1/2, 2/3)	(1/2, 2/3, 1)	(2/3, 1, 2)	0,0929
C4	(1/2, 1, 3/2)	(2/3, 1, 2)	(2/3, 1, 2)	(1, 1, 1)	(1/2, 1, 3/2)	(2/3, 1, 2)	(2/3, 1, 2)	(2/5, 1/2, 2/3)	(2/3, 1, 2)	(2/3, 1, 2)	0,0983
C5	(2/3, 1, 2)	(2/3, 1, 2)	(2/3, 1, 2)	(2/3, 1, 2)	(1, 1, 1)	(2/3, 1, 2)	(2/3, 1, 2)	(2/5, 1/2, 2/3)	(2/3, 1, 2)	(1/2, 2/3, 1)	0,0970
C6	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(1/2, 2/3, 1)	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(1, 1, 1)	(1/2, 1, 3/2)	(2/5, 1/2, 2/3)	(2/3, 1, 2)	(2/3, 1, 2)	0,0862
C7	(1/2, 1, 3/2)	(2/3, 1, 2)	(2/3, 1, 2)	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(2/3, 1, 2)	(1, 1, 1)	(2/5, 1/2, 2/3)	(2/3, 1, 2)	(2/3, 1, 2)	0,0964
C8	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(1, 1, 1)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	0,1590
C9	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(1, 3/2, 2)	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(2/5, 1/2, 2/3)	(1, 1, 1)	(2/3, 1, 2)	0,0921
C10	(1, 3/2, 2)	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(1, 3/2, 2)	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(2/5, 1/2, 2/3)	(1/2, 1, 3/2)	(1, 1, 1)	0,0943

CR = 0.036, C_1: Population density, C_2: Shopping malls, C_3: Roads, C_4: Income rates, C_5: Transportation stations, C_6: Petrol stations, C_7: Park areas, C_8: Green areas, C_9: Slope, C_{10}: Land values

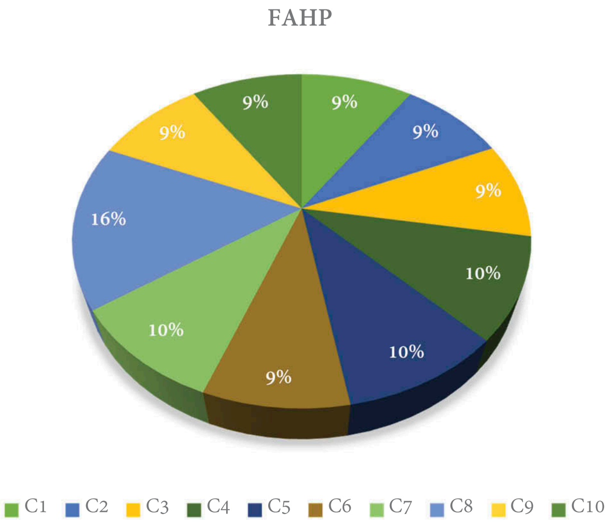


Figure 8. FAHP weight ratios of criteria, C_1: Population density, C_2: Shopping malls, C_3: Roads, C_4: Income rates, C_5: Transportation stations, C_6: Petrol stations, C_7: Park areas, C_8: Green areas, C_9: Slope, C_{10}: Land values.

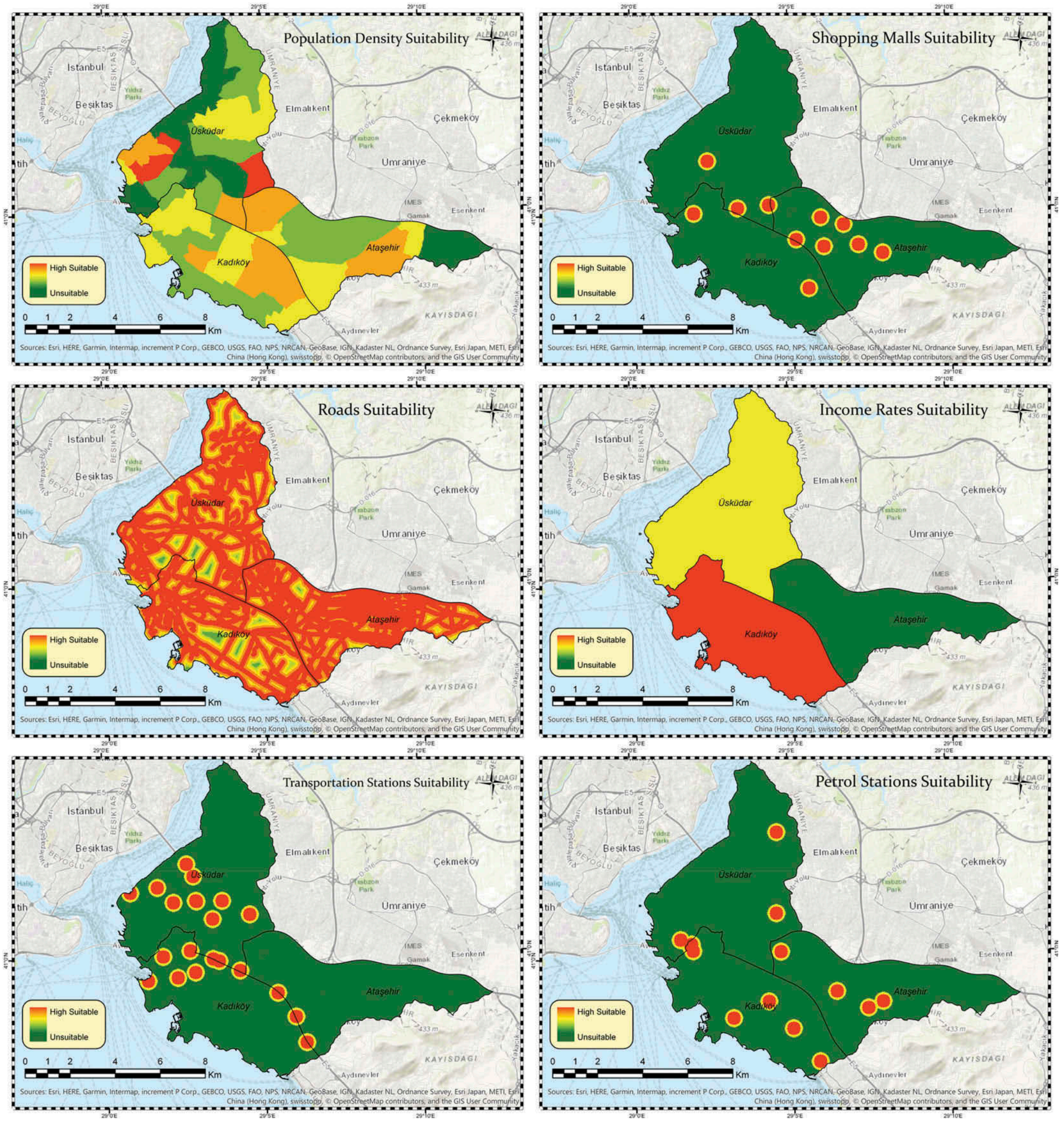


Figure 9. Criterion suitability maps of C_{1-6}.

objective result to FAHP result. The figure clearly shows that Kadikoy has more suitability than other counties in terms of accessibility objective. The change detection analysis can contribute to understanding how to differentiate the suitabilities depending on different objectives. Figure 16 demonstrates the map that includes the intersection of all results. In so doing, the high detailed suitability index is obtained. The *map algebra* is used when finding the intersection of different suitabilities. Specifically, the *con* tool in ArcGIS is exploited in the spatial analyses. The figure shows that the resulting map is mostly composed of *no intersection* areas. That is to say, three suitability maps jointly include *no intersection* areas at most. Additionally, it can be seen from the figure, Kadikoy county has *high suitable* areas remarkably. Figure 16 also illustrates that *high suitable* and *suitable* classes have more areas than *low suitable* and *unsuitable* classes. This means that *low suitable* and *unsuitable* classes do not appear in different suitability results commonly. Moreover, it can be seen from figures between 11 and 13 that *high suitable* classes dominantly located in all of the suitability indexes.

3.2. *Examination of alternative ranking*

Alternative locations or points are determined in the MCDM-based location selection studies. These alternatives are ranked according to their final suitability index values, i.e. their pixel values. In the TOPSIS method, the

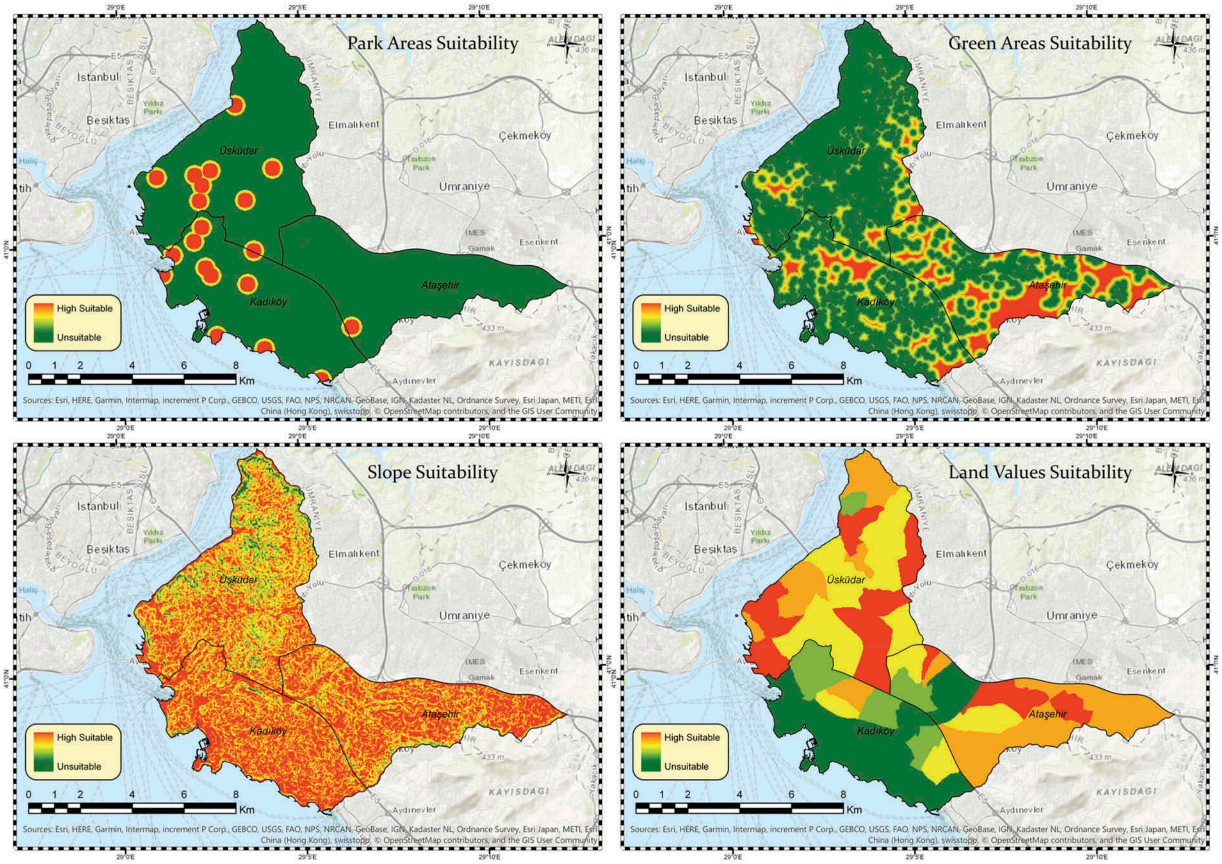


Figure 10. Criterion suitability maps of C_{7-10}.

criterion values of alternatives are obtained from their pixel values in the relevant criterion map layer when applying a GIS-based approach. In this regard, the ranking of alternatives that is obtained by using the TOPSIS method is compared with the ranking that is got according to pixel values in the suitability index. Accessibility objective resulting map is used to realize this comparison. Figure 17 shows the locations of alternative electric vehicle charging stations. The alternative locations are determined by taking resulting suitability pixel values into account. Additionally, when deciding these locations, it is considered that alternative stations should locate in proper distribution.

Table 11 lists the values of alternative stations in the TOPSIS method. First, TOPSIS methodology is applied as criterion weights are equal. Table 12 details the ranking of alternative stations according to this consideration. Second, the ranking of alternatives is obtained by using criteria weights regard to accessibility objectives in Table 7. Table 13 shows the ranking of alternatives that is attained according to the mentioned assessment from TOPSIS calculation. Lastly, the ranking of alternative stations is determined by using their pixel values in the suitability index.

From the chart, we can see that the ranking of alternatives changes in relation to different approaches (Figure 18). However, the four alternative stations have a matching rank in accessibility objective weighted TOPSIS and pixel values approaches. Also, the five alternative stations have equal ranking for both weighed TOPSIS and pixel value approaches.

The results of this study match up with a previous study (Zhang et al. 2019) because both studies selected suitable locations by taking accessibility into account. So, it can be underlined that selected perspectives influence the suitability results significantly. For this reason, holistic approaches that take different aspects into consideration are important to actualize more functional solutions for the dissemination of electric vehicles. Furthermore, the present paper provides a high-resolution solution to location selection of electric vehicle charging stations as suggested in the previous study

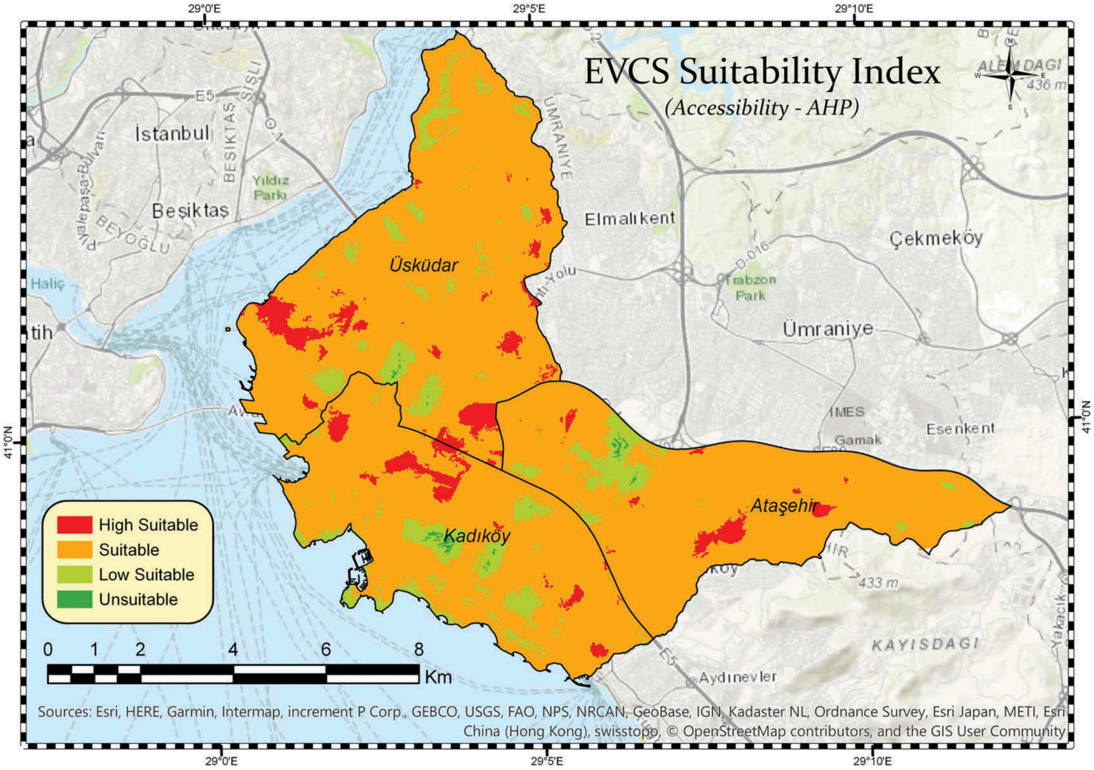


Figure 11. Suitability map for accessibility.

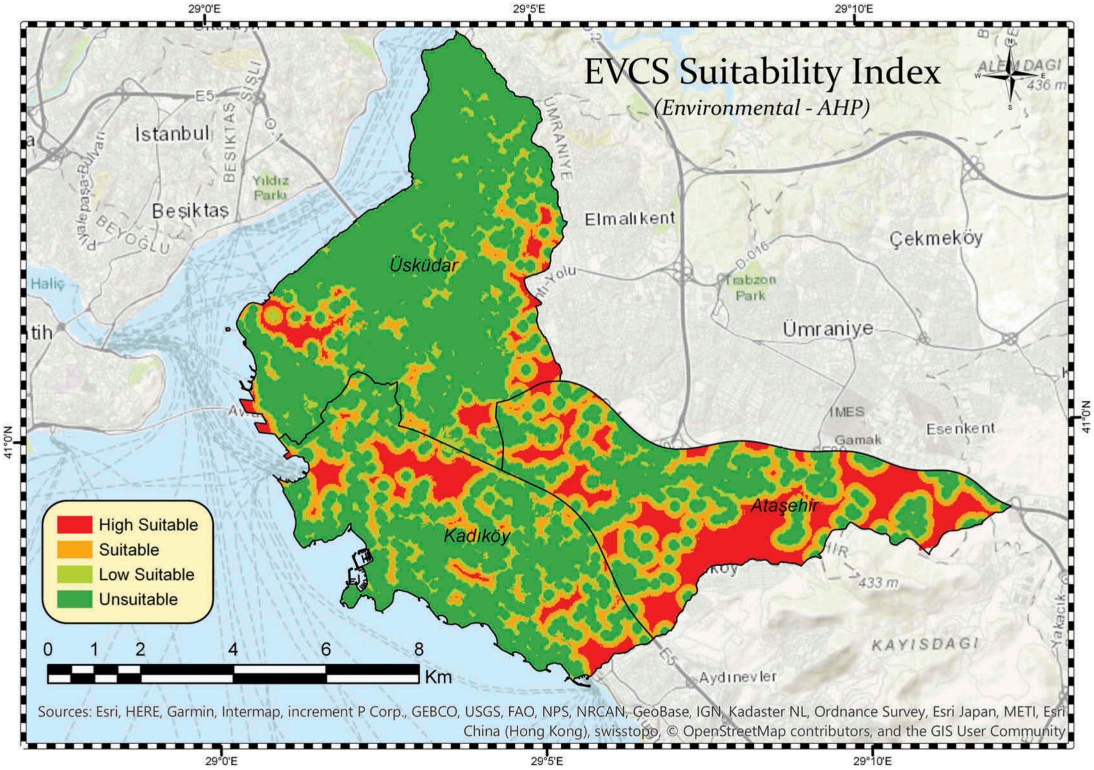
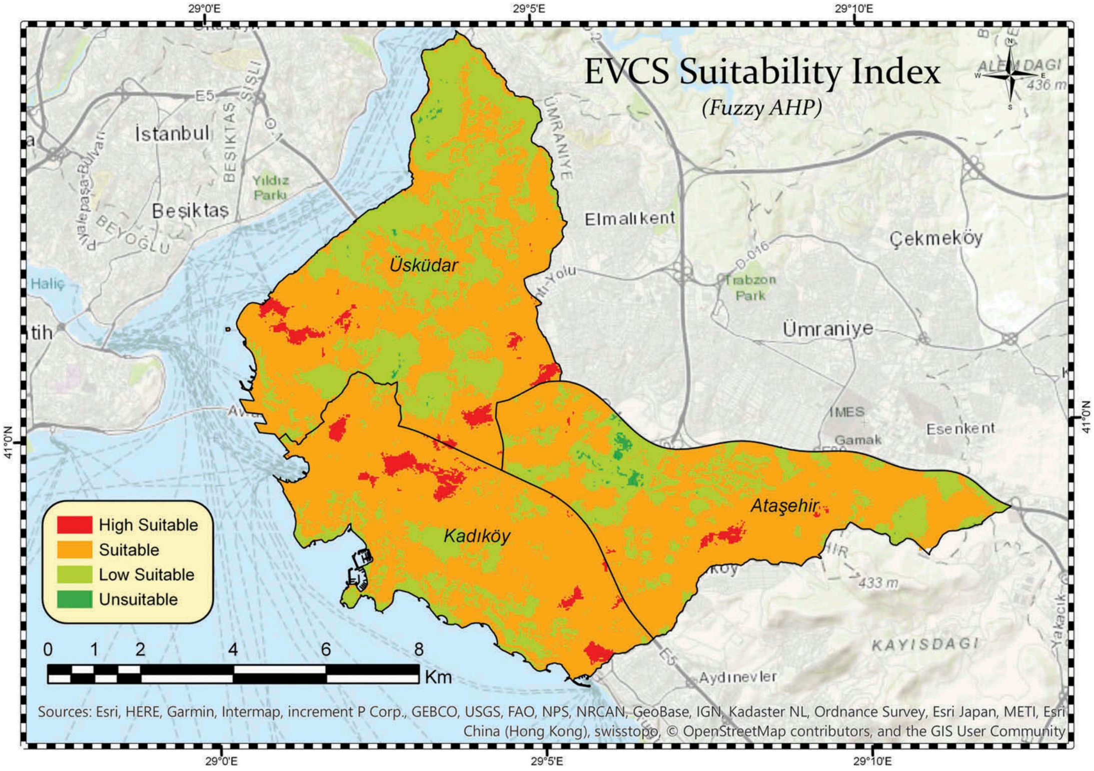


Figure 12. Suitability map for environmental impact.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 13. Suitability map for FAHP.

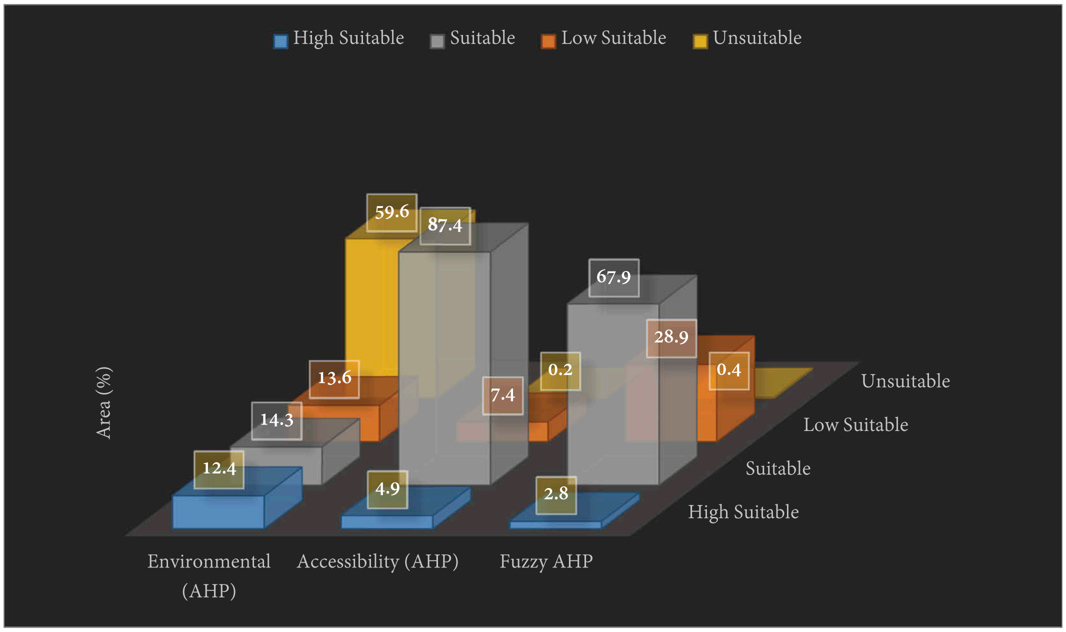


Figure 14. Percentage area values of all suitability classes.

(Dong et al. 2019). By applying the higher analysis resolution, more detailed suitability results are obtained. Thus, the proposed approach could efficiently aid decision-makers for prospective spatial plannings since it enables the comprehensive assessment of location suitability of the application area. Nowadays, metropolises can have unstable land uses; therefore, it is needed for more elaborative location analysis results to make feasible decisions. Moreover, the results presented here are in line with former research (Erbaş et al. 2018)

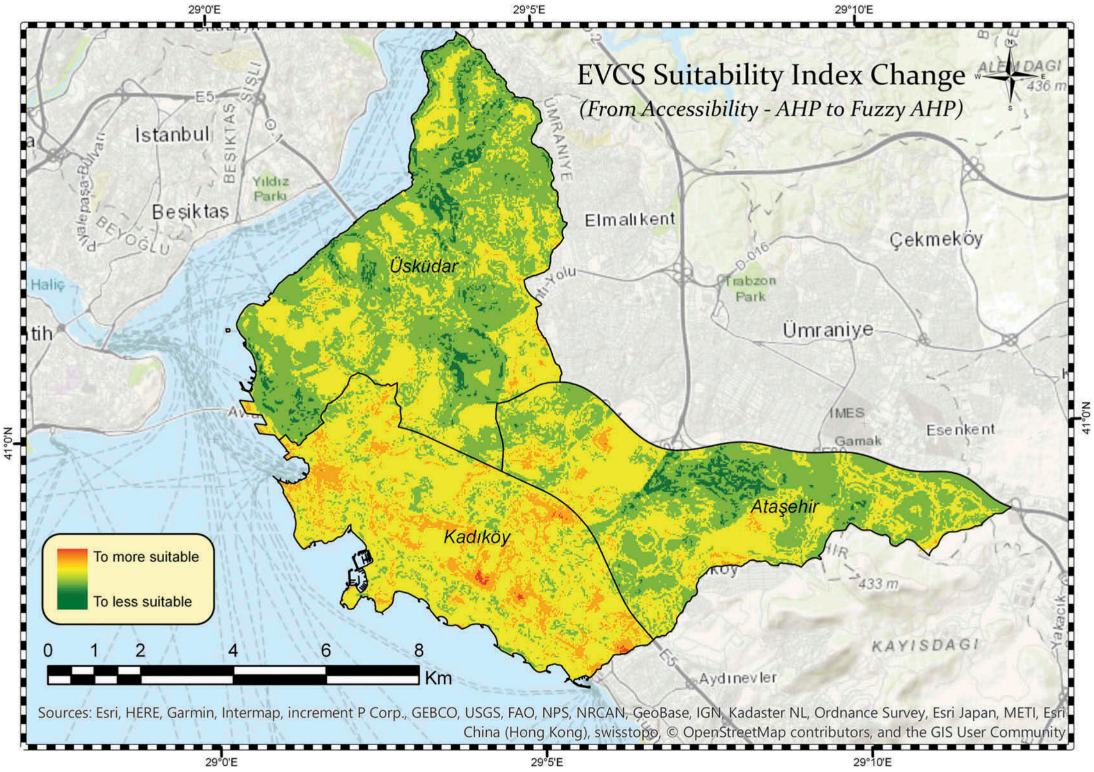


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Figure 15. Suitability change map.

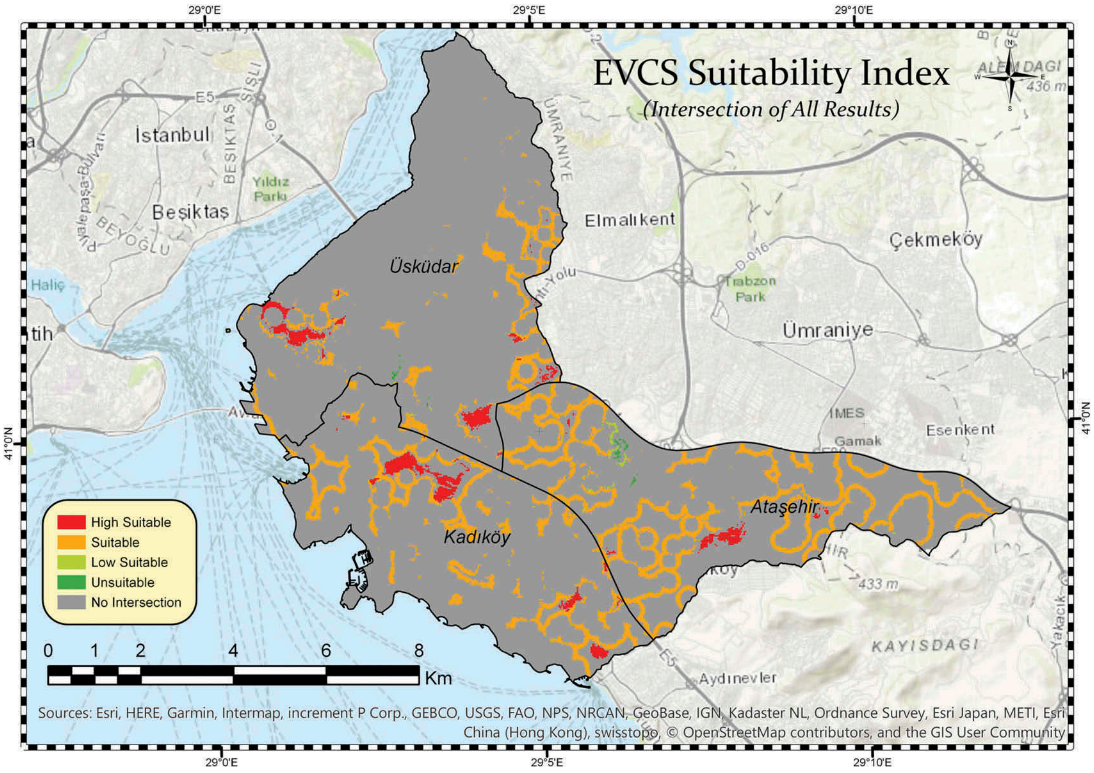

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Figure 16. Suitability intersection map.

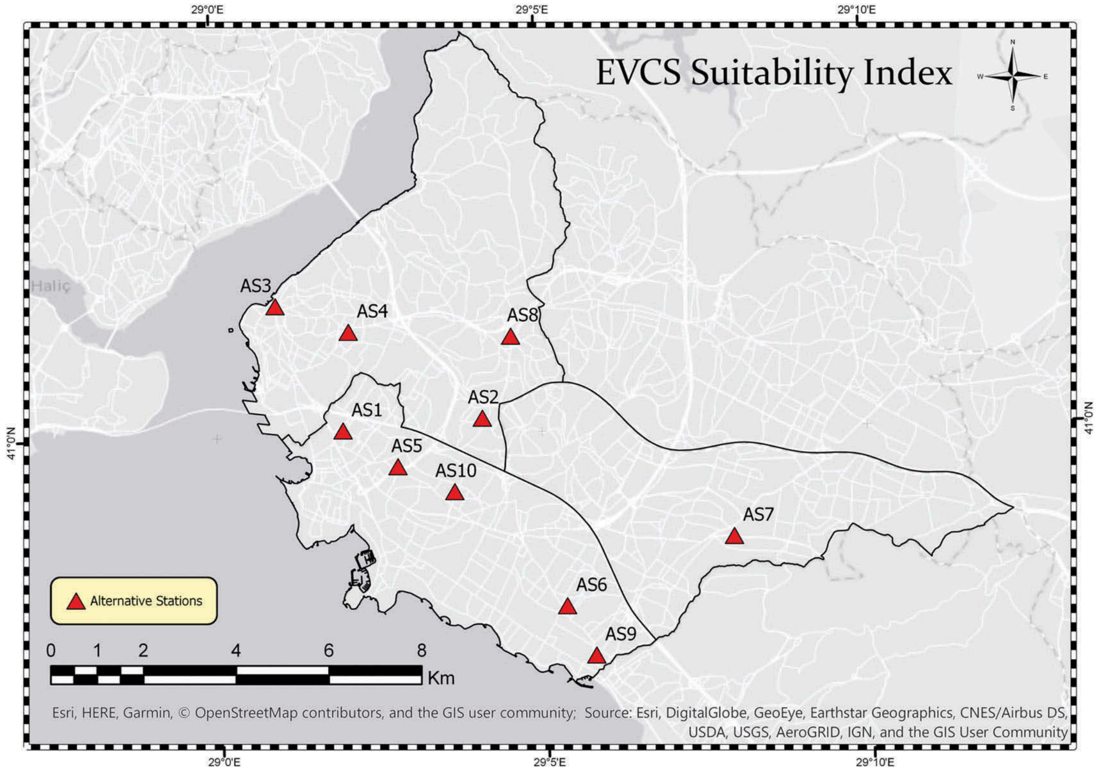

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Figure 17. Alternative stations map.

Table 11. Alternatives' values in respect to criteria on TOPSIS.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
AS1	3	5	5	5	5	5	5	2	5	2
AS2	4	4	5	3	2	2	2	5	5	5
AS3	5	4	5	3	5	1	4	1	4	5
AS4	4	4	5	5	1	3	1	5	5	3
AS5	4	4	5	1	1	5	1	5	4	4
AS6	2	3	5	5	4	1	4	4	5	4
AS7	4	1	5	3	4	1	5	4	5	5
AS8	3	1	5	5	1	5	3	5	5	1
AS9	5	1	5	3	5	5	1	3	5	3
AS10	2	3	5	1	1	5	1	1	4	5

AS: Alternative Station

because the results of both studies show that suitable locations can be found by using a GIS-based approach and the weights of criteria alternate the final suitability.

4. Conclusions

In this paper, the approach that integrates GIS techniques and MCDM method is presented to overcome the location selection problem of the electric vehicle charging station. MDCM methods are used since the location selection of the electric vehicle charging station depends on different factors. Three different weights related to determined criteria are calculated in order to show that the weight of criterion affects to location selection suitability. In this context, this paper has underlined the importance of determining the weights of criteria because location selection suitability varies regarding different weights. Moreover, the strong point of our contribution lies in the intersecting of all different location selection suitability indexes, unlike previous studies. However, the area percentages of suitability classes can be changed according to the study region. Another significance of our work is related to the determination method of alternative stations' ranking. It is critical to note that the ranking of alternative stations can change according to pixel values and TOPSIS method. We have demonstrated that GIS techniques are powerful tools for suitable location selection of electric vehicle charging stations. Besides, we have obtained

Table 12. Ranking of alternative stations according to equal weights.

	AS1	AS3	AS6	AS7	AS2	AS4	AS9	AS5	AS8	AS10
Si+	0,0385	0,0524	0,0496	0,0557	0,0527	0,0609	0,0624	0,0666	0,0676	0,0794
Si-	0,0837	0,0713	0,0667	0,0683	0,0618	0,0628	0,0635	0,0625	0,0625	0,0503
Ci	0,6852	0,5762	0,5735	0,5507	0,5395	0,5074	0,5045	0,4841	0,4803	0,3878
Rank	1	2	3	4	5	6	7	8	9	10

Table 13. Ranking of alternative stations according to accessibility weights.

	AS1	AS2	AS5	AS3	AS10	AS6	AS7	AS4	AS9	AS8
Si+	0,0465	0,0480	0,0504	0,0571	0,0615	0,0544	0,0621	0,0539	0,0631	0,0712
Si-	0,0780	0,0711	0,0739	0,0712	0,0717	0,0633	0,0707	0,0612	0,0601	0,0624
Ci	0,6265	0,5972	0,5945	0,5551	0,5382	0,5377	0,5326	0,5316	0,4877	0,4670
Rank	1	2	3	4	5	6	7	8	9	10

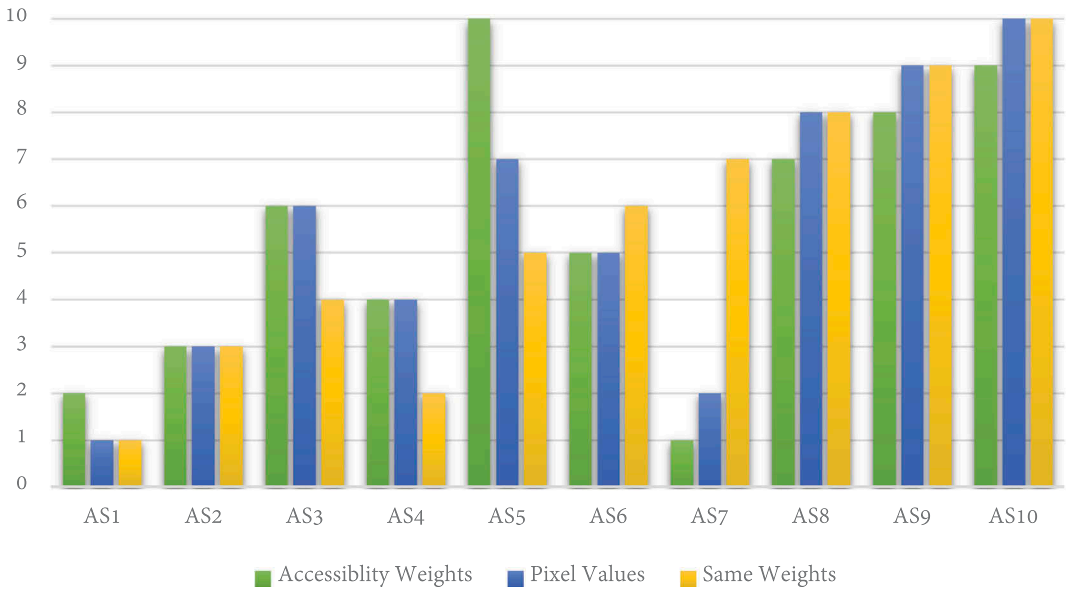

Figure 18. Ranking of alternative stations according to different approaches.

satisfactory results showing that GIS techniques are effective decision support tools in order to solve different urban planning problems. Furthermore, our procedure can be applied to different study areas readily.

Finally, a number of potential limitations need to be considered. First, the suitability that is found by using the proposed approach can be tested with real, reliable station location data in future studies. Second, the weights of criteria can be determined by benefitting from surveys or experts. Last, the electrical requirement context is not considered in this study. Further studies could investigate the use of an open-source web GIS approach in order to enhance the presented solution in this paper (Mete, Guler, and Yomralioglu 2018).

Disclosure Statement

No potential conflict of interest was reported by the authors.

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References

Andrenacci, N., R. Ragona, and G. Valenti. 2016. “A Demand-Side Approach to the Optimal Deployment of Electric Vehicle Charging Stations in Metropolitan Areas.” *Applied Energy* 182: 39–46. doi:10.1016/j.apenergy.2016.07.137.

Awasthi, A., K. Venkitusamy, S. Padmanaban, R. Selvamuthukumaran, F. Blaabjerg, and A. K. Singh. 2017. “Optimal Planning of Electric Vehicle Charging Station at the Distribution System Using Hybrid Optimization Algorithm.” *Energy* 133: 70–78. doi:10.1016/j.energy.2017.05.094.

Cai, H., X. Jia, A. S. F. Chiu, X. Hu, and M. Xu. 2014. “Siting Public Electric Vehicle Charging Stations in Beijing Using Big-Data Informed Travel Patterns of the Taxi Fleet.” *Transportation Research Part D: Transport and Environment* 33: 39–46. doi:10.1016/j.trd.2014.09.003.

Chang, D.-Y. 1996. “Applications of the Extent Analysis Method on Fuzzy AHP.” *European Journal of Operational Research* 95 (3) North-Holland: 649–655. doi:10.1016/0377-2217(95)00300-2.

Charabi, Y., and A. Gastli. 2011. “PV Site Suitability Analysis Using GIS-Based Spatial Fuzzy Multi-Criteria Evaluation.” *Renewable Energy* 36 (9): 2554–2561. doi:10.1016/j.renene.2010.10.037.

Csiszár, C., B. Csonka, D. Földes, E. Wirth, and T. Lovas. 2019. “Urban Public Charging Station Locating Method for Electric

Vehicles Based on Land Use Approach." *Journal of Transport Geography* 74 (January) Pergamon: 173–180. doi:10.1016/J.JTRANGEO.2018.11.016.

Dağdeviren, M., I. Yüksel, and M. Kurt. 2008. "A Fuzzy Analytic Network Process (ANP) Model to Identify Faulty Behavior Risk (FBR) in Work System." *Safety Science* 46 (5): 771–783. doi:10.1016/j.ssci.2007.02.002.

Dong, G., J. Ma, R. Wei, and J. Haycox. 2019. "Electric Vehicle Charging Point Placement Optimisation by Exploiting Spatial Statistics and Maximal Coverage Location Models." *Transportation Research Part D: Transport and Environment* 67 (February) Elsevier Ltd: 77–88. doi:10.1016/j.trd.2018.11.005.

Erbaş, M., M. Kabak, E. Özceylan, and C. Çetinkaya. 2018. "Optimal Siting of Electric Vehicle Charging Stations: A GIS-Based Fuzzy Multi-Criteria Decision Analysis." *Energy* 163 (November) Pergamon: 1017–1031. doi:10.1016/J.ENERGY.2018.08.140.

Eskandari, S. 2017. "A New Approach for Forest Fire Risk Modeling Using Fuzzy AHP and GIS in Hyrcanian Forests of Iran." *Arabian Journal of Geosciences* 10 (8): 190. doi:10.1007/s12517-017-2976-2.

Fox, G. H. 2013. "Electric Vehicle Charging Stations: Are We Prepared?" *IEEE Industry Applications Magazine* 19 (4): 32–38. doi:10.1109/MIAS.2012.2215652.

Ge, S., L. Feng, and H. Liu. 2011. "The Planning of Electric Vehicle Charging Station Based on Grid Partition Method." In *International Conference on Electrical and Control Engineering*, 2726–2730. doi:10.1109/ICECENG.2011.6057636.

Guler, D. 2020. "Fuzzy AHP (Chang) (Liou, Wang)." *MATLAB Central File Exchange*. https://www.mathworks.com/matlabcentral/fileexchange/66688-fuzzy-ahp-chang-liou-wang

Güler, D., and T. Yomralıoğlu. 2017. "Alternative Suitable Landfill Site Selection Using Analytic Hierarchy Process and Geographic Information Systems: A Case Study in Istanbul." *Environmental Earth Sciences* 76 (20) Springer Berlin Heidelberg: 678. doi:10.1007/s12665-017-7039-1.

Guo, S., and H. Zhao. 2015. "Optimal Site Selection of Electric Vehicle Charging Station by Using Fuzzy TOPSIS Based on Sustainability Perspective." *Applied Energy* 158 (Supplement C): 390–402. doi:10.1016/j.apenergy.2015.08.082.

He, F., D. Wu, Y. Yin, and Y. Guan. 2013. "Optimal Deployment of Public Charging Stations for Plug-in Hybrid Electric Vehicles." *Transportation Research Part B: Methodological* 47 (Supplement C): 87–101. doi:10.1016/j.trb.2012.09.007.

He, J., H. Yang, T.-Q. Tang, and H.-J. Huang. 2018. "An Optimal Charging Station Location Model with the Consideration of Electric Vehicle's Driving Range." *Transportation Research Part C: Emerging Technologies* 86: 641–654. doi:10.1016/j.trc.2017.11.026.

He, S. Y., Y.-H. Kuo, and D. Wu. 2016. "Incorporating Institutional and Spatial Factors in the Selection of the Optimal Locations of Public Electric Vehicle Charging Facilities: A Case Study of Beijing, China." *Transportation Research Part C: Emerging Technologies* 67: 131–148. doi:10.1016/j.trc.2016.02.003.

Helms, H., M. Pehnt, U. Lambrecht, and A. Liebich. 2010. "Electric Vehicle and Plug-in Hybrid Energy Efficiency and Life Cycle Emissions." In *18th International Symposium Transport and Air Pollution*, 5 vol, 113–124. Citeseer.

Höfer, T., Y. Sunak, H. Siddique, and R. Madlener. 2016. "Wind Farm Siting Using A Spatial Analytic Hierarchy Process Approach: A Case Study of the Städteregion Aachen." *Applied Energy* 163 (February) Elsevier: 222–243. doi:10.1016/J.APENERGY.2015.10.138.

Hwang, C.-L., Y.-J. Lai, and T.-Y. Liu. 1993. "A New Approach for Multiple Objective Decision Making." *Computers & Operations Research* 20 (8) Pergamon: 889–899. doi:10.1016/0305-0548(93)90109-V.

Lam, A. Y. S., Y. W. Leung, and X. Chu. 2014. "Electric Vehicle Charging Station Placement: Formulation, Complexity, and Solutions." *IEEE Transactions on Smart Grid* 5 (6): 2846–2856. doi:10.1109/TSG.2014.2344684.

Lee, S. K., G. Mogi, and K. S. Hui. 2013. "A Fuzzy Analytic Hierarchy Process (Ahp)/data Envelopment Analysis (DEA) Hybrid Model for Efficiently Allocating Energy R&D Resources: In the Case of Energy Technologies against High Oil Prices." *Renewable and Sustainable Energy Reviews* 21: 347–355. doi:10.1016/j.rser.2012.12.067.

Liu, Z., F. Wen, and G. Ledwich. 2013. "Optimal Planning of Electric-Vehicle Charging Stations in Distribution Systems." *IEEE Transactions on Power Delivery* 28 (1): 102–110. doi:10.1109/TPWRD.2012.2223489.

Ma, J., N. R. Scott, S. D. DeGloria, and A. J. Lembo. 2005. "Siting Analysis of Farm-Based Centralized Anaerobic Digester Systems for Distributed Generation Using GIS." *Biomass and Bioenergy* 28 (6): 591–600. doi:10.1016/j.biombioe.2004.12.003.

Mete, M. O., D. Guler, and T. Yomralioglu. 2018. "Development of 3D Web GIS Application with Open Source Library." *Selcuk University Journal of Engineering, Science, and Technology* 6 (Special): 818–824. doi:10.15317/Scitech.2018.171.

Nansai, K., S. Tohno, M. Kono, M. Kasahara, and Y. Moriguchi. 2001. "Life-Cycle Analysis of Charging Infrastructure for Electric Vehicles." *Applied Energy* 70 (3): 251–265. doi:10.1016/S0306-2619(01)00032-0.

Philipsen, R., T. Schmidt, J. van Heek, and M. Ziefle. 2016. "Fast-Charging Station Here, Please! User Criteria for Electric Vehicle Fast-Charging Locations." *Transportation Research Part F: Traffic Psychology and Behaviour* 40: 119–129. doi:10.1016/j.trf.2016.04.013.

Saaty, T. L. 1990. "How to Make a Decision: The Analytic Hierarchy Process." *European Journal of Operational Research* 48 (1): 9–26. doi:10.1016/0377-2217(90)90057-I.

Song, L., J. Wang, and D. Yang. 2015. "Optimal Placement of Electric Vehicle Charging Stations Based on Voronoi Diagram." In *IEEE International Conference on Information and Automation*, 2807–2812. doi:10.1109/ICInfA.2015.7279764.

TurkStat. 2017. "Address Based Population Registration System." http://www.turkstat.gov.tr/PreTablo.do?alt_id=1059

TurkStat. 2019. "Transportation Statistics." http://www.turkstat.gov.tr/PreTablo.do?alt_id=1051

Villacreses, G., G. Gaona, J. Martínez-Gómez, and D. J. Jijón. 2017. "Wind Farms Suitability Location Using Geographical Information System (GIS), Based on Multi-Criteria Decision Making (MCDM) Methods: The Case of Continental Ecuador." *Renewable Energy* 109: 275–286. doi:10.1016/j.renene.2017.03.041.

Wei, R., X. Liu, Y. Ou, and S. Kiavash Fayyaz. 2018. "Optimizing the Spatio-Temporal Deployment of Battery Electric Bus System." *Journal of Transport Geography* 68 (April) Pergamon: 160–168. doi:10.1016/J.JTRANGEO.2018.03.013.

Wu, Y., C. Xie, C. Xu, and F. Li. 2017. "A Decision Framework for Electric Vehicle Charging Station Site Selection for

Residential Communities under an Intuitionistic Fuzzy Environment: A Case of Beijing." *Energies* 10: 9. doi:10.3390/en10091270.

Wu, Y., M. Yang, H. Zhang, K. Chen, and Y. Wang. 2016. "Optimal Site Selection of Electric Vehicle Charging Stations Based on a Cloud Model and the PROMETHEE Method." *Energies* 9 (3): 157. doi:10.3390/en9030157.

You, P.-S., and Y.-C. Hsieh. 2014. "A Hybrid Heuristic Approach to the Problem of the Location of Vehicle Charging Stations." *Computers & Industrial Engineering* 70 (Supplement C): 195–204. doi:10.1016/j.cie.2014.02.001.

Zadeh, L. A. 1965. "Fuzzy Sets." *Information and Control* 8 (3) Academic Press: 338–353. doi:10.1016/S0019-9958(65)90241-X.

Zhang, Y., Q. Zhang, A. Farnoosh, S. Chen, and Y. Li. 2019. "GIS-Based Multi-Objective Particle Swarm Optimization of Charging Stations for Electric Vehicles." *Energy* 169 (February) Elsevier Ltd: 844–853. doi:10.1016/j.energy.2018.12.062.

Zhao, H., and N. Li. 2016. "Optimal Siting of Charging Stations for Electric Vehicles Based on Fuzzy Delphi and Hybrid Multi-Criteria Decision Making Approaches from an Extended Sustainability Perspective." *Energies* 9 (4): 270. doi:10.3390/en9040270.

Zhu, Z.-H., Z.-Y. Gao, J.-F. Zheng, and H.-M. Du. 2016. "Charging Station Location Problem of Plug-in Electric Vehicles." *Journal of Transport Geography* 52 (April) Pergamon: 11–22. doi:10.1016/J.JTRANGEO.2016.02.002.