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Research Article

A Comparison of Different Multi-Criteria Analyses for Electric Vehicle Charging Station Deployment

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Abstract. Scarcity in near future, and the price fluctuation of fossil fuels lead to many industries change their products that use these resources into more eco-friendly versions. One of the most recent and noticeable example of this situation is the automobile industry. As a result of this, electric vehicles have started to become more popular and their sales increase substantially. Since these electric vehicles have a limited range for transportation before they require charging, the number and the positions of charging units become very important. In this study, we consider a *electric vehicle* (EV) *charging station* (CS) placement problem which aims to maximize users' utility. To deal with these problem, we survey to find the weights of criterion, which are selected as accessibility, traffic convenience and waiting time calculated by AHP method and VIKOR and TOPSIS methods are used to evaluate each alternative. As a main tool for charging station deployment, an integer programming model, which maximizes electric vehicle driver's utility in term of evaluation results, is developed and the effects of different evaluation techniques on deployment procedure is shown and compared.

Keywords. AHP; VIKOR; TOPSIS; Electric vehicles; Integer programming

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1. Introduction

Ever since the Industrial Revolution the fossil fuels have been the best option for means of energy to a majority of individuals and corporates for heating, industry, production of secondary energy resources, transportation and so on. However, their limited reserves and fast consumption rates causes scarcity in near future. For example, according to BP [2], in 2017 total oil reserve in the world is 239 thousand million tons and annual consumption is 4691.9 millions tons. At this rate of usage, the reserves will be depleted in approximately 52 years. Also, volatile prices of the crude oil price per barrel over years (Figure 1(a)) [12] and increasing emission of CO_2 [1] pushes to use alternative energy resources. One of the most recent and noticeable example of this situation is the automobile industry. As a result of this environmental awareness, electric vehicles have started to become more popular and forecast shows that share of EVs will increase dramatically (Figure 2) [11]. This increase in the sale of electric vehicles impose a major issue that must be dealt with. Since these electric vehicles have a limited range for transportation before they require charging, the number and the positions of charging units become very important for the comfort of the EV drivers. The emphasis of this paper is on the placing and sizing of these charging units so that driver comfort is maximized in terms of utility.

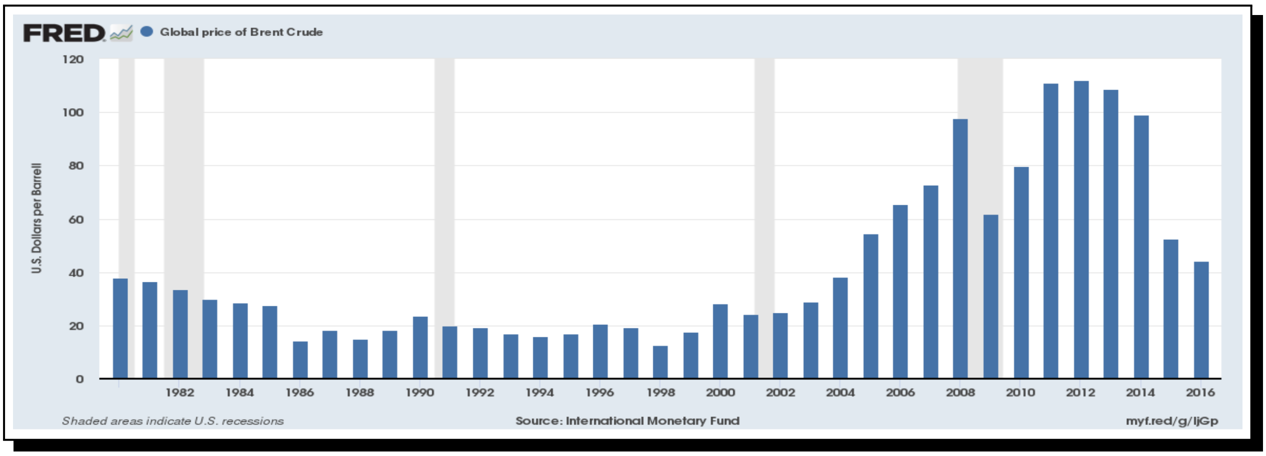

Figure 1. Yearly average crude oil prices

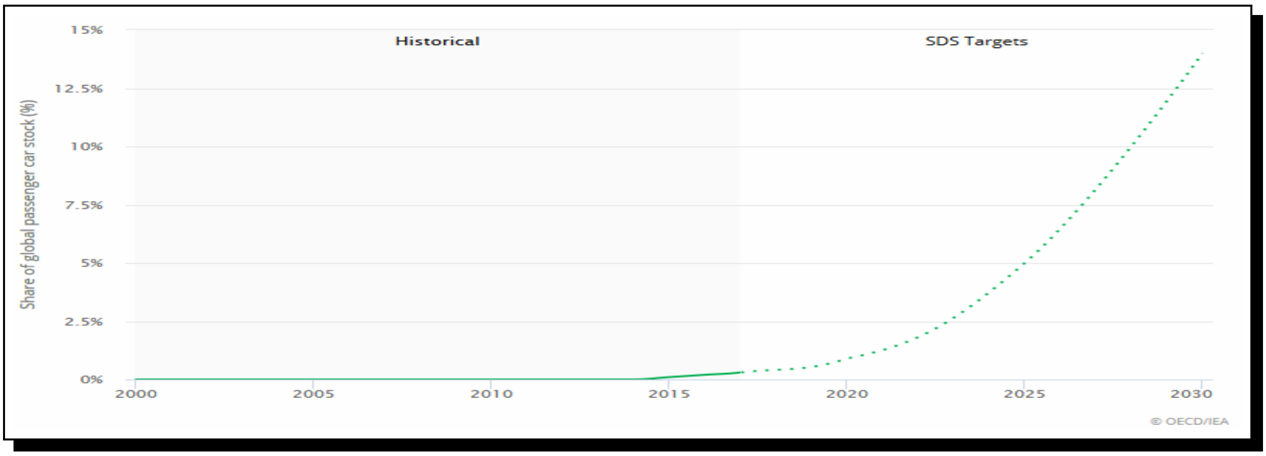

Figure 2. Share of global passenger car stock

In this paper, we conduct a study on electric vehicle charging station placement problem in Ankara, Turkey. We firstly categorized alternatives as housing estate and shopping malls. After that we selected five alternatives for each category for deployment procedure. Then, a survey is used to evaluate criterion and alternatives. These criterion are accessibility, traffic convenience, waiting time. For the evaluation process AHP is used to calculate weights of criterion, TOPSIS and VIKOR are used to find weights of each location. As a main tool for charging station deployment, an integer programming model is developed. Its objective function is to maximize electric vehicle driver's utility in term of evaluation results subject to budget, capacity constraints of locations. Lastly, according to results of deployment and sensitivity analysis we compare effects of VIKOR and TOPSIS methods on CS deployment and we conclude our study with potential future directions. The main contributions of this paper are as follows:

- We develop optimal locations for charging stations by exploiting problem structure for an area in Ankara. We test the performance of each method by comparing results with each other.
- According to cores obtained from VIKOR and TOPSIS our proposed mathematical model yields different optimal solutions
- Finally, the corporations can observe the marginal benefit of an additional budget or station by using our proposed allocating method. By this way, the investment decisions could be more effective.

The rest of the paper is organized as follows. In Section 2, we provide a brief review of the related literature. In Section 3, we present AHP, TOSIS and VIKOR methodologies and the explanation of the mathematical model. Section 4 explains criteria for the charging station location selection are showed and determined. The weights of each criterion are calculated by using each method and result obtained from mathematical model for both VIKOR and TOPSIS are explained alongside with sensitivity analysis. We conclude with a discussion of the results and future research directions in Section 5.

2. Literature Review

Our scopes in this works are the *electric vehicle charging station* (EVCS) deployment in perspective of MCDM and comparison of VIKOR and TOPSIS methodologies for cases such as engine selection and alternative fuel buses. Fan and Yang [6] develops fuzzy AHP-TOPSIS method to select best alternative for EVCS site selection. Tzeng *et al*. [23] compares alternative fuel busses such as electricity, hydrogen, hybrid, ethanol based by using AHP method to calculate weights of criteria and compare alternatives using TOPSIS and VIKOR. In [25], queuing theory and AHP method are integrated and a flexible simulation model is proposed to harging station placement for Yıldız Technical University Davutpaşa Campus. Finally, optimal charging stations in the campus selected with evaluating survey data based on drivers habits around the campus and implemented the offered approach. Ergul *et al*. [5] uses VIKOR and TOPSIS methods to evaluate six different engine system and for this purpose six criteria for each alternative are selected and engines are analyzed and compared. *Feng et al*. [7] proposes using GAHP (*Grey Analytic Hierarchy Process*) and Delphi method to deploy charging 11 stations. Case study of the study shows the effectiveness of the method on a real life problem. In [9] first fuzzy-TOPSIS based multi-criteria decision making technique is proposed and detailed list of economic, social and environmental criterion are evaluated for site selection. The optimal selection for sites was created with expert opinions on the criteria performances of different alternatives and their weights. Alternatives were ranked by fuzzy-TOPSIS method. As a result, site A2 located at Changping district in Beijing has the highest score and remain its top ranking under the possible changes on sub-criteria weights. Genevois and Kockman [8] proposes an AHP based integer programming model for placement for Kadıköy and Ataşehir provinces of İstanbul and criterion weights are used in objective function as utility function multipliers. As final outcome, the integrating methodology presents effective and robust results for the problem. Erbaş *et al*. [4] fuzzy AHP and TOPSIS methodologies are used to determine new potential locations for EVCSs and a case study is applied on Ankara. In [13], a new multi-criteria approach is offered for charging stations. Study proposes greedy heuristics and AHP methodology that minimize walking distance, grid power loss and maximize drive comfort for charging station placement. The approach in this study illustrated on an example. As a result charging stations selected among 10 possible locations. Liu and Wei [15] investigates risk levels of charging station placement for public private projects by using fuzzy TOPSIS. This study chooses projects in China and contains their categorization and risk factor definitions. It concerns ranking of the risk for three alternative projects and detailed suggestions for them. As a result this study provides risk response strategies and clarity on the projects. Raposo *et al*. [18] develops dynamic PROMETHEE method by adding decision memory, versatility and adaptability to design charging network. The aim of the article is apply the offered approach to a Portuguese city and creating effective charging networks. The case study presented in this paper gives flexible work environment under different policies and scenarios.

Author	Methodology	Journal	Year
[23]	TOPSIS-VIKOR	Energy Policy	2005
[7]	GAHP And Delphi Method	Electric Power Automation Equipment	2012
[9]	Fuzzy-TOPSIS	Applied Energy	2015
[18]	Dynamic PROMETHEE	AIP Advances	2015
[25]	Queuing Theory And AHP	Turkish Journal of EE & CS	2016
[6]	Fuzzy-AHP	POMS 27TH Annual Meeting	2016
[5]	VIKOR-TOPSIS	ICENS 2016	2016
[13]	AHP Method	Transportation Research Part C	2017
[24]	PROMETHEE	Energies	2016
[8]	AHP Method	International Journal of Transportation Systems	2018
[15]	Fuzzy-TOPSIS	Journal of Cleaner Production	2018
[14]	MCDM method	IEEE Intelligent Transportation Systems	2018
[4]	Fuzzy AHP-TOPSIS	Energy	2018

Liu *et al.* [14] develops novel integrated MCDM (*multi-criteria decision making*) method with grey decision making trial and evaluation laboratory to find optimal site for charging stations. Also to show the effectiveness of the proposed method this study decide on handling Shanghai, China. The results of the study show that the offered approach is functional for the optimal locationing for charging stations. Wu *et al.* [24] deal with the location problem of electric vehicle charging stations. They develop PROMETHEE and cloud model and applied the model to Beijing to show the validity of the proposed approach.

3. Methodology

In this paper, we used 10 different possible charging location point is determined and to evaluate each alternative three different criterion, which are accessibility,traffic convenience and waiting time, are selected. To determine weights of criterion AHP method is used. Then, TOPSIS and VIKOR methods are used to determine the weights of each candidate location. For the mathematical programming, an integer programming model which aims to maximize driver utility is created and weights of each location are considered as multiplier of the utility function

3.1 Analytical Hierarchy Process (AHP)

AHP is multi-criteria decision making method, which are arrangement of factors in hierarchic structure, presented by Saaty [21]. A generic AHP has four step procedure:

- Defining problem.
- Arranging evaluation matrix.
- Calculation of weights.
- Selection of best alternative.

To arrange evaluation matrix, 1-9 scale of Saaty is used in Table 1 [20]:

Table 1. Saaty's 1-9 evaluation scale [21]

Rating	Definition
1	Equally Important
3	Moderately Important
5	Strongly Important
7	Very Strongly Important
9	Absolutely Important
2, 4, 6, 8	intermediate values

Weight Calculation Algorithm of AHP

- Elements in each column is summed up
- Normalized Evaluation matrix is calculated:

$$b_{ij} = \frac{a_{ij}}{\sum_j a_{ij}} \,. \tag{3.1}$$

- Average values of elements in each row is calculated and weights w_j are found.

Calculation of Consistency Ratio

$$\lambda_{\max} = \frac{\sum_i \sum_j a_{ij} w_j / w_i}{N}. \tag{3.2}$$

After calculating $\lambda_{\max}$, consistency index (CI) is calculated as:

$$CI = \frac{\lambda_{\max} - N}{N-1}. \tag{3.3}$$

Evaluation of decision maker is consistent if consistency ratio (CR) is less than 0.1.

$$CR = \frac{CI}{RI}, \tag{3.4}$$

where RI is random index.

3.2 VIKOR

VIKOR is a multicriteria optimization of complex systems and finds ranking list proposed by Opricovic [16], assuming each alternative is evaluated by a function and L_p-*metric* are used to determine ranking measure. For alternative a_k, rating function of the jth criteria is shown by f_{kj} VIKOR has following steps:

- Determine $f_j^* = \max_k f_{kj}$ and $f_j^- = \min_k f_{kj}$ that are the best and worst values of all criterion functions.

Compute the values S_k and R_k values:

$$S_k = \sum_{j=1}^{m} w_j |f_j^* - f_{kj}| / |f_j^* - f_j^-|, \tag{3.5}$$

$$R_k = \max\{|f_j^* - f_{kj}| / |f_j^* - f_j^-|, j = 1, 2, \dots, m\}, \tag{3.6}$$

where w_j is the weight of criteria j, S_k is group utility of a_k, R_k is the individual regret. For each alternative k, compute Q_k:

$$Q_k = v(S_k - S^*)/(S^- - S^*) + (1-v)(R_k - R^*)/(R^- - R^*) \tag{3.7}$$

where v is the weight of strategy of "the majority of criteria" and taken as 0.5. Rank the alternatives, sorting S, R, Q in decreasing order.

To propose alternative A', which is the best ranked according to Q, as compromise solution two conditions below must be satisfied:

- *Acceptable advantage*: $Q(A'') - Q(A') \geq DQ$ where A'' is the second best solution and $DQ = 1/(J-1)$ where J is the number of alternatives
- *Acceptable stability*: Alternative A' must also be the best alternative according to ranking by S or R

3.3 TOPSIS

This method is developed by Hwang and Yoon [10] and improved by Chen and Hwang [3]. The aim of the method is to choose an alternative that closest to ideal and furthest to worst solution. The procedure is as follows:

- Evaluation matrix consists m alternative and n criteria $(a_{ij})_{m\times n}$ is constructed.

- Normalized evaluation matrix $R = (r_{ij})_{m\times n}$ is calculated as follows:

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^{m} a_{kj}^2}} \quad \forall\ i,j. \tag{3.8}$$

- Calculation of weighted normalized matrix $v_{ij} = r_{ij}w_j$, where

$$w_j = \frac{W_j}{\sum_k W_k}, \quad \sum_i w_j = 1. \tag{3.9}$$

Positive ideal solution A^* and negative ideal solution A^- are calculated as:

$$A^* = \{(\max_i v_{ij} | j \in J), (\min_i v_i j | j \in J)\}, \quad A^* = \{v_1^*, \dots, v_n^*\}, \tag{3.10}$$

$$A^- = \{(\min_i v_{ij} | j \in J), (\max_i v_i j | j \in J)\}, \quad A^- = \{v_1^-, \dots, v_n^-\}. \tag{3.11}$$

Separation values can be found:

$$\delta_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2}\ , \tag{3.12}$$

$$\delta_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}\ . \tag{3.13}$$

The similarities to the positive ideal solution are derived as:

$$C_i^* = \frac{\delta_i^-}{\delta_i^* + \delta_i^-} \quad \text{where } 0 \le C_i^* \le 1. \tag{3.14}$$

3.4 Mathematical Model

Aim of the mathematical model is to maximize EV driver's utility by deploying optimal number of charging stations in eyes of an aggregator. In this model, evaluation scores are considered as utility multiplier and number of EVCS deployed to locations are constrained by available space for EVCS and the budget of aggregator.

Index

l : Index of locations

Decision Variables

x_l : number of charging station type deployed on location l

Parameters

C : cost of building a charging station

B : available budget

M_l : upper limit for charging stations can be deployed l

P_l : evaluation score of location l obtained from VIKOR or TOPSIS

$$\max \sum_l x_l P_l \tag{3.15}$$

subject to

$$\sum_l x_l C \le B \tag{3.16}$$

$$x_l \leq M_l \quad \forall\, l \tag{3.17}$$

$$x_l \in \mathbb{Z}_+ \cup \{0\} \quad \forall\, l \tag{3.18}$$

Eq. (3.15) aims to maximize user utility by using the evaluation score of obtained from VIKOR and TOPSIS. Eq. (3.16) is the budget constraint of aggregator (3.17) ensures that charging stations to be deployed cannot exceed their available limit for each location. Eq. (3.18) is lower bound for number of charging stations deployed.

4. Case Study

For this study we take five housing estates and five shoppings malls. Selected alternatives are located on newer and wealthier areas compared to other regions of Ankara. Also, for now, we do not consider fuzziness and take an expert opinions of 3 EV drivers. Locations of potential deployments are shown in Figure 3.

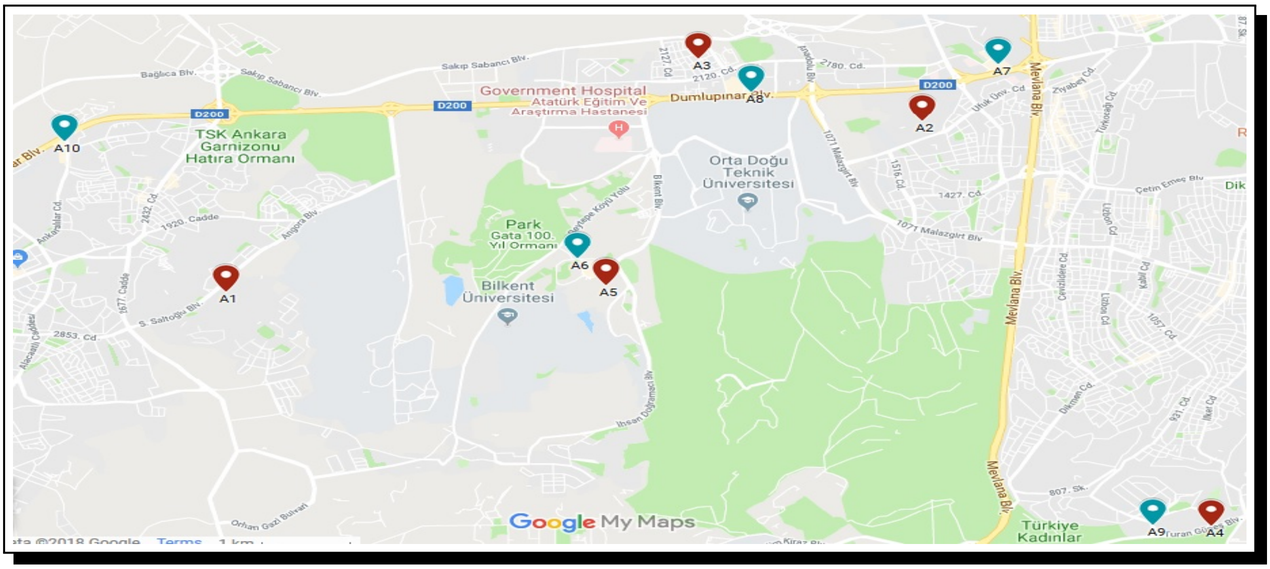

Figure 3. Selected potential deployment sites

In evaluation process, three criterion are selected:

(C1) *Accessibility*: Walking distance between charging station and that location. EV drivers feels more comfortable, if the distance is small.

(C2) *Traffic Convenience*: It means the vehicle flow around the candidate location. Frequency of traffic jam affects comfort of reaching that location and higher jam frequency becomes the utility will decrease.

(C3) *Waiting Time*: Amount of waiting time in charging queue. As the waiting time increases, EV drivers become dissatisfied.

Weights of the criterion are calculated by using AHP with consensus of 3 EV users Pairwise comparison matrix and values of weights are shown in Table 2.

Table 2. Evaluation of criterion and normalized weights

	C1	C2	C3	Normalized weights
C1	1.00	5.2	2.88	0.625
C2	0.20	1.00	0.25	0.092
C3	0.33	4.00	1.00	0.282

The results above show that the most important criteria for the EV drivers is Criteria 1 by 62 % and it is followed by Criteria 3 and Criteria 2 whose weights are 28 % and 9 $, respectively. For the consistency of evaluation, we calculate $\lambda_{\max} = 3.07$, $CI = 0.21$ and $CR = 7.3\%$. CR value is less than 0.1 and it shows that results are consistent.

For VIKOR and TOPSIS methods we ask to rate each alternative with respect to each criteria. Since our aim is to maximize utility, we decide to use the score set $\{1,2,\dots,10\}$ where 10 is the best and 1 is the worst. We decided weight of each EV user is equal and rating are calculated by taking the arithmetic average. Average scores given to each alternative with respect to criterion is shown in Table 3. A1-A5 denotes housing estates and the remaining are for shopping malls. Housing estates and shopping malls are evaluated among each other, in other words alternative categories are not aggregated.

Table 3. Scores given by EV users

Alternatives	Criteria 1	Criteria 2	Criteria 3
A1	6.33	5	7.66
A2	4	5.33	3.33
A3	2.33	6.33	8.33
A4	6	7.66	5.66
A5	7.66	3.33	9
A6	9.33	3	8
A7	8.33	6.66	7
A8	6.66	7	4.33
A9	7.66	7.33	6
A10	5.33	7.66	4.66
Weights	0.625	0.092	0.282

Table 4. Normalized Weights, S, R and Q values obtained from VIKOR

Alternatives	Crit 1.	Crit. 2	Crit. 3	R	S	Q	Ranking	Alternatives	Crit. 1	Crit. 2	Crit. 3	R	S	Q	Ranking
A1	0.15	0.06	0.07	0.15	0.28	0.19	2	A6	0.00	0.10	0.00	0.10	0.10	0.00	1
A2	0.43	0.05	0.28	0.43	0.76	0.81	4	A7	0.15	0.02	0.08	0.15	0.25	0.16	2
A3	0.62	0.03	0.03	0.62	0.68	0.94	5	A8	0.41	0.01	0.28	0.41	0.71	0.70	4
A4	0.19	0.00	0.17	0.19	0.36	0.29	3	A9	0.26	0.01	0.15	0.26	0.42	0.36	3
A5	0.00	0.10	0.00	0.10	0.10	0.00	1	A10	0.62	0.00	0.26	0.62	0.88	1.00	5

Table 5. Weighted normalized matrix, distances and similarity to positive ideal solution obtained from TOPSIS

Alternatives	Crit 1.	Crit. 2	Crit. 3	δ^*	δ^-	C	Ranking	Alternatives	Crit. 1	Crit. 2	Crit. 3	δ^*	δ^-	C	Ranking
A1	0.32	0.04	0.14	0.07	0.21	0.75	2	A6	0.34	0.02	0.16	0.12	0.36	0.75	1
A2	0.20	0.04	0.06	0.21	0.08	0.29	4	A7	0.31	0.04	0.14	0.16	0.32	0.67	2
A3	0.12	0.05	0.15	0.27	0.09	0.25	5	A8	0.25	0.04	0.09	0.23	0.24	0.51	4
A4	0.30	0.06	0.10	0.10	0.19	0.65	3	A9	0.28	0.05	0.12	0.19	0.29	0.61	3
A5	0.38	0.02	0.16	0.03	0.28	0.90	1	A10	0.20	0.05	0.10	0.27	0.20	0.42	5

S, R and Q values are shown in Table 4. Results of these values show that A5 and A6 are the best alternative for housing estate and shopping malls, respectively but ranking orders are different for some alternatives. However, acceptable advantage and acceptable stability is not our main concern in this work. We only use Q values for having a utility multiplier for the mathematical programming model.

After applying TOPSIS procedure, normalized weighted matrix, δ^*, δ^- and C values are shown in Table 5. Just like VIKOR method, $A2$ and A6 are the best alternative for housing estates and shopping malls. Also, for the remaining alternatives ranking lists remain same for both housing estates and shopping malls.

4.1 Results

In this section, we compare the results obtained from mathematical programming with following assumptions:

- Since there is only one type of *charging station* (CS), its unit cost is taken as 1.
- Maximum amount of money can be spent is 8.
- In VIKOR, alternatives are ranked by increasing order of Q, therefore these values cannot be taken as multipliers of a utility function to be maximized. To revert it, Q values are subtracted from 1 and these values are used as multiplier.
- In TOPSIS, C values are taken as utility multiplier since greater C value makes its alternative more preferable.

Table 6 indicates the dataset for available space M for each location, since we do not know how many available space can be given for EVCS, we create available spaces randomly for each location: Both in Table 7(a) and Table 7(b) number of CS deployed is same for VIKOR and TOPSIS. Also, due enough total available space all of the budget is spent to deploy CS but A2, A3 and A5 do not have any CS.

Table 6. Number of available space that CS station can be deployed

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
M(l)	3	1	4	3	3	4	2	3	2	4

Table 7. Results of mathematical model

Alternatives	A1	A2	A3	A4	A5
VIKOR	3	0	0	2	3
TOPSIS	3	0	0	2	3
Alternatives	A6	A7	A8	A9	A10
VIKOR	4	2	0	2	0
TOPSIS	4	2	0	2	0

4.2 Sensitivity Analysis

To understand the effect of budget and available space we multiply these parameters by 2 for both cases to see if changes in budget and available space yields different assignments for the alternatives or not.

Deployment of multiplied budget for are shown in Table 8. Unlike the previous case, all of the alternatives have at least 1 CS to serve customers. Besides, optimal deployment does not differ regardless of the ranking scores obtained from methodologies.

Table 8. Number of CS assigned to locations when budget is multiplied by 2

Alternatives	A1	A2	A3	A4	A5
VIKOR	3	1	4	3	3
TOPSIS	3	1	4	3	3
Alternatives	A6	A7	A8	A9	A10
VIKOR	4	2	3	2	4
TOPSIS	4	2	3	2	4

When the available spaces are doubled for each location, following results are obtained and shown in Table 9. Just like previous cases optimal deployment for each location is same for both VIKOR and TOPSIS in case of household sites. Also, same situation can be observed for the shopping mall alternatives.

Table 9. Number of CS assigned to locations when available spaces are multiplied by 2

Alternatives	A1	A2	A3	A4	A5
VIKOR	2	0	0	0	6
TOPSIS	2	0	0	0	6

(a) Deployment for housing estate

Alternatives	A6	A7	A8	A9	A10
VIKOR	8	0	0	0	0
TOPSIS	8	0	0	0	0

(b) Deployment for shopping malls

Results of the mathematical model show and sensitivity analysis show that regardless of the methodology based on optimal deployment is not changed for both housing estate and shopping malls. Also, it is observed that as available space increases while budget remains same better alternatives gets all or the majority of CS but poor alternatives remains little or none.

5. Conclusion

In this paper, we compare VIKOR and TOPSIS for charging station deployment problem. Since, they follow different steps to rank alternative, we want to test if they assign different number of CS to same location by using a mathematical model. After the alternatives are picked in the selected region of Ankara, we determine 3 criterion which are accessibility, traffic convenience and waiting time. Then, we ask experts to evaluate each criteria among themselves by Saaty's scale and we calculate the weights of criterion by using AHP. Then, by using VIKOR and TOPSIS methods to calculate the weights of the each alternative location according to each criteria and their weights and use these result on the mathematical programming model which maximizes the users' utility function and takes weights of alternatives as function's multiplier. To compare TOPSIS and VIKOR in terms of utility, weights obtained from VIKOR are subtracted from 1. By this way, greater the result of the subtraction, more utility it gives. For the case study, we test the effects of VIKOR and TOPSIS. We firstly observe the same deployment results for both VIKOR and TOPSIS. Sensitivity analysis results yields the same situation. For future studies, we plan to add all 3 levels of CSs and demand satisfaction constraints in order to get more accurate results. Furthermore, in this work we show that scores obtained from VIKOR and TOPSIS does not change optimal deployment in an empirical manner. As number of alternatives or number of EV users who participates survey increases we may observe different optimal deployments. Last, it is expected that the demand on charging stations grow in Ankara due to increasing popularity of the electric car and it will grow the need of electric vehicle chargers among the city, and the benefit of using our model will increase as well to determine the deployment of the chargers.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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