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# A fermatean fuzzy SWARA-TOPSIS methodology based on SCOR model for autonomous vehicle parking lot selection

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## HIGHLIGHTS

- Autonomous Vehicle (AV) parking lot selection problem is presented.
- SCOR model is adopted for AV parking lot selection problem.
- A comprehensive list of criteria for AV parking lot site selection is identified.
- A SWARA integrated TOPSIS methodology under fermatean fuzzy environment is proposed.
- The methodology can be applied to other urban planning and site selection problems.

## ARTICLE INFO

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## ABSTRACT

Population growth in crowded cities and the resulting increase in vehicle use have led to the problem of insufficient parking. When public parking lots and urban growth are not in coordination, vehicles park on the street and close the crosswalks. In the coming years, this problem will become more complicated with the addition of autonomous vehicles (AVs) to urban traffic. This study addresses the research question of how to effectively select AV parking lots in urban areas experiencing population growth and increased vehicle usage. For this aim, a hybrid Multi-Criteria Decision Making (MCDM) methodology, combining SWARA (Step-wise Weight Assessment Ratio Analysis) and TOPSIS (Technique for Order Preference by Similarity) approaches in a Fermatean Fuzzy (FF) environment is proposed. The decision hierarchy based on the SCOR model has been developed to determine and construct the evaluation criteria. Then, a case study analysis has been applied to selected districts in Istanbul, which is Turkiye's most populous and developing city. Operating expenses, safety and security, and land costs are determined as the most important factors. As a result of the detailed fuzzy analysis, which districts should primarily be chosen for AV parking lots in Istanbul is determined and finally, the robustness and validity of the results obtained by the sensitivity analysis being questioned. The study contributes by providing insights into AV parking lot selection, demonstrating the efficacy of the proposed methodology, and highlighting the importance of addressing this issue in urban planning.

## 1. Introduction

Population growth in developing cities and the resulting increase in vehicle use cause the problem of insufficient parking spaces. Parking lots are part of the urban transport system and play an important role in reducing the heavy traffic load. At the same time, parking lots are a social issue that seriously limits the development of society and the economy, and also affects the quality of life [1]. With the lack of harmony between urban development and public parking lots, vehicles occupied the crossings by standing on the street, thus disrupting the smooth traffic flow, and causing problems in transportation systems and urban traffic [2]. By determining the parking areas in the right place and

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sufficient size, the areas reserved for the vehicles parked on the roadside will be freed. As a result, it can be considered an effective approach reducing the traffic load in the city centers in terms of increasing the usable areas of the roads and contributing to urban transformation [3].

Traffic is still considered one of the biggest problems of urban transportation. Lack of sufficient parking spaces, especially in big cities, causes a vehicle to stop on the side of the road and areas exposed to traffic turn into parking areas, thus causing traffic problems on the road [10]. Nowadays, finding a parking space is a major problem in many large and medium-sized cities, and this situation is stressful and time-consuming in a congested area [10–12]. Public parking lots, as an essential component of a city, play a significant role in addressing traffic congestion [13]. It is reaffirmed every day that the existing parking lots, especially in crowded metropolises such as Istanbul, are not sufficient for vehicle owners. When the change in basic data regarding parking in Istanbul between 2013 and 2021 is examined, while the amount of cars per thousand people was 152 in 2013, this number increased to 200 in 2021[14]. In addition, due to the increasing rate of private vehicle ownership, the "Hourly Model Approach" has been developed within the scope of Istanbul Metropolitan Municipality to calculate the parking demand on an hourly basis in order to determine the parking supply, the scope of their use and the parking demand in order to provide suitable parking spaces [15]. According to the 2022 Activity Report of the Istanbul Metropolitan Municipality (IMM), as of December 2022, there will be 1 million 143 thousand 907 parking lots throughout the city, excluding residential building car parks. Although there are 7 thousand 195 car parks with a vehicle capacity, the traffic congestion due to the parking problem has a visible effect. As a precaution against this problem, new parking lots are built every year by the municipality and private companies, and an online geographical information system has even been created with an application called Parking Data Sharing Platform for Istanbul [16]. With the introduction of AVs in recent years, it has become necessary to address the parking problem for these vehicles. In particular, some studies [6,17] have argued that autonomous vehicles can take actions that avoid parking costs, such as driving on the street, returning home, or parking on the street instead of parking. Autonomous vehicles driving instead of parking could worsen traffic by increasing the number of vehicles on the streets. Moreover, constant driving of vehicles will increase wear and maintenance costs. All these imply that urban planners should address the problem of effective selection and design of parking spaces for autonomous vehicles as soon as possible.

Parking lots are an important element of the urban transport framework in reducing traffic on street corners. Accessible parking areas play an important role in reducing crowding and traffic density by removing stagnant traffic in urban transportation [4]. The lack of parking in city centers means that drivers spend a lot of time finding a suitable parking spot, and perhaps use more roads for this reason [4]. The traditional method for parking lot planning is based on traffic demand; a certain area is determined as a parking lot, based on the parking demand obtained from the parking space estimation, and taking into account the turnover and utilization rate of the parking spaces [5]. Nonetheless, this approach resulted in the allocation of valuable urban land, and also increased traffic [5]. The lack of accessible parking also affects the quality of life of residents. Providing enough parking spaces for people to park easily and comfortably is one of the main interests of urban administrations [6]. Detailed and systematic analyzes are required to make useful and efficient decisions about the locations for parking lots [7]. Moreover, with the inclusion of autonomous vehicles (AV) in traffic in the coming years, the parking problem will become an even more prominent urban issue. The parking lot selection problem for AVs is an issue that also needs to be urgently addressed by managers and strategists as a preventive approach. As urban populations grow and technology transforms transportation systems, strategic AV parking lot selection becomes crucial for sustainable urban planning. Inadequate parking spaces exacerbate traffic congestion, hinder economic growth, and degrade citizens' quality of life. With the proliferation of AVs, strategically positioned and efficiently managed parking spaces become pivotal.

One of the most important decisions for a public urban place is site selection, which can be based on topographic interest, land availability, land use, and public preference [8]. While building a new parking lot can improve society's convenience, it can also lead to negative effects like increased air and noise pollution and traffic congestion due to ineffective planning techniques [9]. Suitable site alternatives are taken into account in site selection problems, and it is often necessary to consider various dimensions such as economic and environmental parameters [6]. An efficient location selection approach should be applied in order to minimize the economic and environmental costs of the location problems of new car parking lots [9]. Complex multi-criteria analyses incorporating a variety of factors, including economic, social, technical, environmental, and political issues that may result in conflicting objectives are necessary for the site selection process [8]. Addressing the dynamic challenges of urban development and the integration of emerging technologies like AVs requires innovative decision-making methodologies. One prominent challenge is the selection of optimal parking lots for AVs, a subject gaining prominence due to its profound impact on urban mobility, traffic management, and overall quality of life. Multi-criteria decision-making (MCDM) has been used for many years to deal with site selection problems including parking lots. One of the most well-known techniques for solving decision-making problems, MCDM, calls for the attributes to be used to categorize the decision alternatives [6]. The use of MCDM methods can be used to rank alternatives, list a limited number of alternatives for more in-depth analysis, or distinguish between acceptable and unacceptable alternatives [10]. Parking lot selection is also a problem that can be evaluated within the scope of MCDM and reasonable results can be reached through this approach. In the problem of choosing the location for an AV parking lot, uncertainty is involved due to many factors, such as the existence of criteria that cannot be expressed in quantitative terms and the hesitations of decision makers. At this point, the fuzzy logic approach is successfully integrated into MCDM problems and used effectively to handle uncertainty. Fermatean Fuzzy Sets (FFSs) have been proposed as an effective extension of the intuitionistic fuzzy sets (IFS) and Pythagorean fuzzy sets (PFS), the goal of which is to more comprehensively characterize uncertain information [11].

When it comes to handling uncertainty, the FFS is a more effective, adaptable, and comprehensive than other fuzzy extensions [12]. The utilization of FFSs is a noteworthy approach to address the uncertain data that emerges during decision-analysis processes, hence rendering them applicable to a broader spectrum of uses [13–16]. FFSs are very convenient for describing expert opinions, which makes them popular in multi-criteria decision-making processes [13]. Using FFSs in site selection problems makes sense because they provide a more nuanced representation of uncertainty and ambiguity inherent in decision-making scenarios [17]. Site selection involves multiple criteria that may not have clear boundaries, and decision-makers often have hesitations in assigning membership degrees to certain options. FFSs allow for expressing both membership and non-membership degrees, as well as hesitations, which helps capture the complexities of site suitability and trade-offs more accurately. This comprehensive representation can lead to more informed and robust decisions in site selection, especially in cases where traditional fuzzy sets might not adequately capture the uncertainty involved. Based on all these findings, a combination of SWARA and TOPSIS methods under FF environment is proposed to address the complex nature of the AV parking lot location problem in this paper. Firstly, the criteria to evaluate the parking lots for AVs is determined and structured via SCOR model and have been weighted by FF-SWARA. Then, the candidate parking lot alternatives for AV vehicles have been determined and ranked using the FF-TOPSIS method in İstanbul, Turkiye. To the best of our knowledge, this is the first study to apply the hybrid extended fuzzy MCDM approach for parking lot

selection of AVs.

This study introduces a novel integrated MCDM methodology that combines SCOR based on SWARA and TOPSIS within the FF environment. By introducing FFSs, which extend beyond traditional fuzzy sets to model uncertainty and ambiguity more comprehensively, the methodology stands at the forefront of innovative decision-making techniques.

This proposed methodology bridges the critical gap by providing decision-makers with a robust and adaptable tool to address the complex AV parking lot selection problem. By considering a comprehensive range of criteria and incorporating uncertainties inherent in real-world decision-making, this approach empowers urban planners, policymakers, and stakeholders to make informed and optimal decisions. This research advances the field of decision-making methodologies and offers practical solutions to a pressing urban challenge with far-reaching implications.

The following sections of the paper are presented as follows. Section 2 gives the literature review about the application and adopted methodology. Section 3 includes the suggested methodology while Section 4 presents the real case application with a sensitivity analysis. Finally, Section 5 gives the conclusion and future directions.

## 2. Literature review

A systematic and detailed literature search has been conducted to examine the previous studies on parking lot selection, determine the evaluation criteria, and reveal the research that can form a basis for the study. The SCOPUS database has been used to provide access to articles, books and conference papers related to the parking lot selection problem. To guarantee a methodical and systematic progression in the literature search process, the PRISMA methodology which stands for "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" is adopted. PRISMA is a protocol that scholars have increasingly used in recent years to conduct thorough literature reviews. The PRISMA technique, which was developed by Moher et al., consists of five main parts [18]. The establishment of eligibility criteria takes place in the first part, and the analysis and evaluation of resources occur in the second. The third step entails choosing suitable literary works. Data collection and data item selection are the fourth and fifth stages of the PRISMA [19, 20]. Table 1 shows the literature review results for the study.

As a result of the literature search using keywords in the SCOPUS database given in Table 1, a total of 223 studies have been found. Due to their repeated appearance in various searches, some of the findings are redundant. Studies whose full text could not be reached, studies that did not clearly describe the methodology or findings used, and studies written in languages other than English have also been excluded from literature research. The articles that emerged because of the literature research and that can form the basis of the study and their contributions to the literature are summarized in Table 2. In this way, the studies that are closest to this paper and that have been utilized to create a hierarchy of criteria have been revealed and the differences between all these studies from this paper have been presented.

**Table 1**
Literature review results.

| Database | Details of the Search | Number of studies |
|---|---|---|
| SCOPUS | TITLE-ABS-KEY ("parking area" AND location AND selection) | 11 |
| | TITLE-ABS-KEY ("parking lot" AND site AND selection) | 44 |
| | TITLE-ABS-KEY ("parking lot" AND location AND selection) | 43 |
| | TITLE-ABS-KEY (parking AND "location selection") | 20 |
| | TITLE-ABS-KEY ("autonomous vehicle") AND TITLE-ABS-KEY ("location selection") | 3 |
| | TITLE-ABS-KEY ("autonomous vehicle") AND TITLE-ABS-KEY (location) AND TITLE-ABS-KEY (parking)) | 102 |

Table 2 shows a summary of prominent studies in the reviewed literature. Parking lot selection studies as an application area have been mostly carried out in China, Iran, and Turkiye. Generally, the geographic information systems approach has been used to handle the parking lot selection problem, and this approach and MCDM methods have been adopted in a hybrid way. Although there are some studies using fuzzy logic, there is not a remarkable number of studies that include extended fuzzy sets. This gap points to an important deficiency in the literature. In addition, the methods frequently applied in the literature have been applied by repeating, and it is noteworthy that the new and effective MCDM methods have not been used for the problem of parking lot selection. In the light of all these literature inferences, FFSs have been used for parking lot selection for the first time in this paper. A significant contribution of this paper is the extension of TOPSIS with SWARA into an FF environment, marking the first-time application of this approach. This extension enhances the capabilities of TOPSIS to address complex decision-making problems with uncertain and ambiguous information. Additionally, this research pioneers the application of parking lot selection methodologies to address the unique challenges posed by AVs. By integrating SWARA and the extended TOPSIS methodology within the FF context, this paper offers a novel approach to solving the AV parking lot selection problem. The subsequent sections of this paper delve into the detailed methodology employed for implementation and provide a real-life application of the proposed approach.

## 3. Suggested methodology

In the context of selecting a location for an AV parking lot, fuzzy logic may successfully manage the ambiguity and subjectivity inherent in decision-making. Fuzzy logic permits partial truth values and the use of subjective data, such as expert views in the decision-making process. The capacity to handle various criteria and trade-offs between them is one of the primary advantages of utilizing fuzzy logic to identify AV parking lot. Frequently, site selection issues entail several variables that may be in conflict with one another, such as accessibility to transit routes, cost, environmental conditions, safety, and the availability of electricity and internet connection [38]. Fuzzy logic may give a more flexible and realistic method for assessing these criteria by allowing for partial truth values and subjective input, as opposed to only depending on exact mathematical models and clear facts. In addition, fuzzy logic may effectively reflect uncertainty and ambiguity, which are often present in real-world issues, into the decision-making process. In certain regions, the availability of electricity and internet access may be unpredictable, and the cost of maintaining the AV parking lot may fluctuate dependent on a number of variables. This uncertainty may be handled using fuzzy logic, resulting in a more robust decision-making process. In conclusion, fuzzy logic is a valuable tool for the selection of AV parking lots; because it permits the incorporation of multiple conflicting criteria, uncertainty, and subjective information into the decision-making process, resulting in a more thorough and accurate evaluation of potential sites. Therefore, in this study, a combination of the SWARA and TOPSIS methods under FF environment has been proposed to address the complex nature of the AV parking lot selection problem.

In this study, we introduce a novel integrated MCDM methodology, which consists of SWARA and TOPSIS under the FF environment. The steps of the proposed methodology are presented in this section. Firstly, the FF-SWARA proposed by Kersuliene et al. [39] and extended for FFSs by Ayyildiz [16] is employed to determine criteria weights, then FF-TOPSIS introduced to literature by Hwang and Yoon [40] and extended for FFSsby Senapati and Yager [41] is utilized to evaluate and determine best AV parking lot based on experts' opinions. The flowchart of the suggested integrated fuzzy methodology can be shown in Fig. 1.

This study pioneers the integration of SWARA and TOPSIS within the FF environment to tackle the AV parking lot selection problem. The

**Table 2**
The summary of the literature review.

| # | Author(s) | Year | Aim | Fuzzy Set | MCDM Approach | Adopted Methodology | Applied Region |
|---|---|---|---|---|---|---|---|
| 1 | Qin et al. [21] | 2024 | To present a strategy for selecting ideal parking spaces and making driving judgments. | - | - | Behavior Tree Decision Model with a deep Q-learning network, Long and short-term memory model, Constant velocity model | - |
| 2 | Fakhrmoosavi et al. [22] | 2024 | To investigate the service consequences of shared AVs parking in lawful on- or off-street places when idle. | - | - | Dynamic Simulation-Based Parking Assignment Model | - |
| 3 | Sayarshad [23] | 2023 | To give a rent bid for daytime AV parking in order to evaluate parking methods that AV users may choose. | - | - | Lagrangian relaxation algorithm | USA |
| 4 | Kaur and Garg [24] | 2023 | To guarantee that AV parking spaces are properly utilized, and that relevant criteria information is concealed from the target. | √ | √ | Probabilistic neutrosophic hesitant Einstein weighted aggregation operators | - |
| 5 | Tian et. al. [25] | 2023 | To attempt to gather meaningful insights on people's parking spot preferences for self-driving automobiles. | - | - | Survey Analysis | China |
| 6 | Bahk et al. [26] | 2022 | To investigate the effects of private AVs, especially their near-activity location travel patterns, on vehicle miles traveled. | - | - | Mathematical Modeling | - |
| 7 | Penki et al. [27] | 2022 | To suggest a GIS-based MCDM approach in the selection of suitable places for the vehicle parking | - | √ | GIS; AHP | India |
| 8 | Zhang et al. [28] | 2021 | To apply a traffic impact analysis in the selection of the site for the new public parking lot | - | - | Traffic impact analysis | China |
| 9 | Aydinoglu and Iqbal [29] | 2021 | To design an exemplary geoanalytic method for determining parking demand and positioning parking spaces | - | - | GIS | Turkey |
| 10 | Demir et al. [7] | 2021 | To use a GIS-based fuzzy AHP method to determine optimum locations for parking lot supply in four districts of Istanbul. | √ | √ | GIS; AHP | Turkey |
| 11 | Ozturk and Kilic-Gul [30] | 2020 | To apply CBS and OWA method for analyzing the problem of parking place selection in Samsun | √ | √ | GIS; OWA | Turkey |
| 12 | Prasertsri and Sangpradid [31] | 2020 | To provide a multi -criteria decision analysis to solve the selection of parking for light rail stations | √ | √ | AHP; TOPSIS | Thailand |
| 13 | Karimi et al. [4] | 2020 | To provide integration of GIS-based ordinal weighted average used in spatial location selection of parking lots | √ | √ | GIS; OWA | Iran |
| 14 | Shen et al. [32] | 2019 | To present the optimal parking lot selection scheme for green urban road networks to reduce CO2 emissions of traffic flows | - | - | Partheno-Genetic Algorithm | China |
| 15 | Samani et al. [8] | 2018 | To provide a collaborative decision-making approach through a geo-social network to estimate the selection of the site for the public park in Tehran | √ | √ | AHP | Iran |
| 16 | Darani et al. [9] | 2018 | To deal with site selection criteria and uncertainties associated with a decision -making process to find a new public parking lot | √ | √ | AHP; TOPSIS | Iran |
| 17 | Kulinich and Lee [33] | 2016 | To propose a GIS-based, optimal method for choosing parking locations in Khabarovsk City. | - | - | Geographic Information Systems (GIS) | Russia |
| 18 | Jelokhani-Niaraki and Malczewski [34] | 2015 | To provide a web-based GIS-MCDA procedure to address the selection of parking in Tehran | - | √ | GIS; OWA | Iran |
| 19 | He et al. [35] | 2015 | To present a new site selection method for public parking lot | - | √ | Genetic algorithms; Multi-objective modelling; AHP | China |
| 20 | Aliniai et al. [2] | 2015 | To find the most suitable places for public parking lots in one of the most populous cities of Western Iran | √ | √ | GIS; AHP; OWA | Iran |
| 21 | Tang et al. [36] | 2015 | To provide a decision -making approach for the mechanical parking system using GIS, Fuzzy Rough Sets and Attribute Reduction Algorithms methods | √ | √ | GIS; Inductive learning algorithm | China |
| 22 | Farzanmanesh et al. [3] | 2010 | To select of suitable parking space for one of the high traffic regions of Isfahan city | √ | √ | GIS; AHP; OWA | Iran |
| 23 | Tang and Ren [1] | 2009 | To analyse location selection and assessment of shared mechanical parking | - | - | Spatial Analysis; Inductive Learning | China |
| 24 | Tang and Ren [37] | 2009 | To suggest a GA-SVM model in the field selection of mechanical park garage | - | - | Genetic algorithms (GA); SVM | China |

innovative approach and comprehensive analysis spotlight the significance of the research topic. This work is poised to inspire further exploration in this burgeoning field, fostering sustainable urban development through effective decision-making. The proposed FF-based hybrid decision-making methodology includes three main stages. In the first phase, SCOR based site selection criteria hierarchy is constructed based on both the expert opinion and literature review. Then, the experts are evaluated according to their experience and qualifications, unlike in most of group decision-making approaches. In this phase, the expert reputations (weights) are determined, unlike most of the

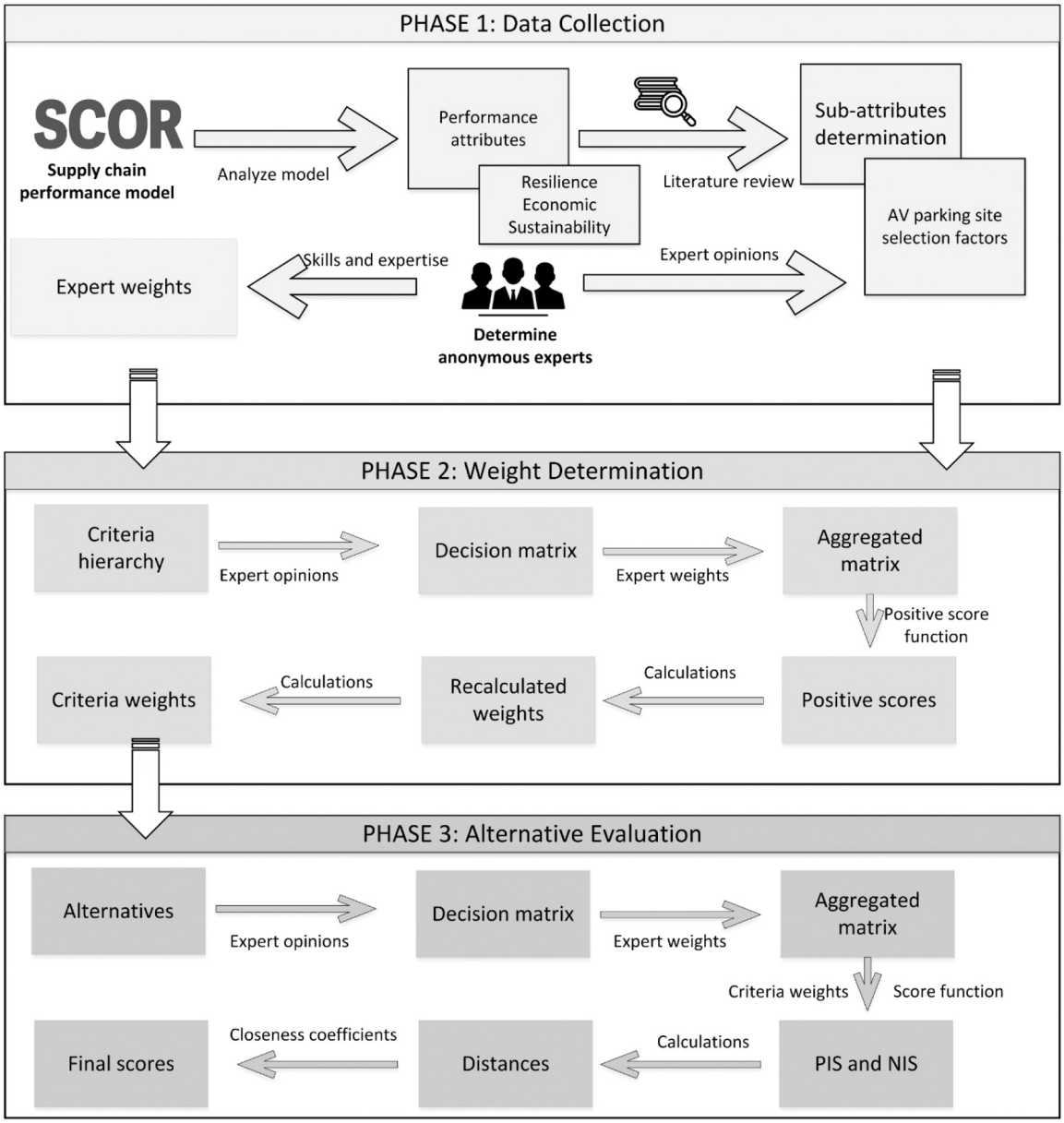


**Fig. 1.** Flowchart of the proposed methodology.

available approaches that use equal expert weights or assume that the expert reputation vector is known. In the second phase, FF-SWARA methodology is employed to determine the weight of the main and sub-criteria based on expert opinions. In the last stage, FF-TOPSIS is used to evaluate the alternative sites and determine the best one. The proposed methodology is explained in detail in the following sub-sections.

The superiority of the proposed methodology is evident through its innovative integration of SWARA with TOPSIS approach within the FF framework. This unique combination facilitates a comprehensive evaluation of alternative AV parking lot locations by systematically considering qualitative and quantitative factors. This adaptation enhances the method's capability to effectively manage uncertainties and ambiguities inherent in AV parking lot selection. Through the utilization of FFSs alongside TOPSIS, the decision-making process gains enhanced precision and flexibility, ensuring more dependable outcomes even within intricate decision contexts.

The FF-SWARA method was preferred in this study for several reasons. Firstly, the SWARA method offers decision-makers the flexibility to prioritize criteria according to their preferences, making it suitable for subjective criterion weighting [42,43]. SWARA stands out among existing subjective methods due to its simplicity and ease of use, involving a low number of comparisons and allowing decision-makers to choose their priorities based on current conditions [44]. Compared to other methods like FUCOM, BWM, LBWA, and OPA, SWARA is computationally simpler and involves fewer pairwise comparisons, resulting in less complexity and greater ease of understanding [45]. In the SWARA approach, which places greater emphasis on the decision-makers' roles, it enables them to determine their own priorities while considering the present circumstances [46]. Moreover, SWARA does not require decision-makers to adhere to a specific scale, allowing for more unrestricted expression of opinions. In the context of this study, the FF-SWARA approach enhances the reliability of criteria weighting by efficiently handling uncertain expert judgments and determining weights that can be seamlessly integrated into any MCDM algorithm operating with FF evaluation information [47].

The FF- TOPSIS method emerges as a favorable choice for this study due to its versatility and effectiveness as a complementary approach [48]. Unlike some methods, TOPSIS doesn't impose restrictions on

sample size. It avoids subjectivity in data interpretation, and doesn't necessitate the formulation of an objective function, thereby offering a flexible and objective evaluation approach [48]. This method relies on assessing the distance between the optimal and worst solutions in a multi-objective decision-making scenario [49]. By considering the distance from the positive ideal solution (PIS) and the negative ideal solution (NIS), TOPSIS identifies the most suitable alternatives [49]. In real-world scenarios where human preferences and judgments are often uncertain, classical sets may fall short [50]. The fuzzy TOPSIS method addresses this challenge by modeling problems under uncertainty within the framework of MCDM [46]. The method prioritizes alternatives based on their closeness coefficients, where a larger coefficient indicates proximity to the PIS, signifying an advantageous alternative. Conversely, a smaller coefficient suggests proximity to the NIS, indicating suboptimal solutions [51]. Adhering to a fundamental principle, TOPSIS positions superior alternatives closer to the PIS and farther from the NIS [52].

The methodology's strength lies in its tailored approach to address AV-specific challenges. Incorporating AV-specific criteria and utilizing a sophisticated decision-making framework, the approach offers a targeted solution that accommodates the unique requirements of AV parking lots. This customized perspective ensures that the selected parking lot aligns with diverse objectives and requirements, ultimately leading to more optimal and informed decisions. Additionally, the comprehensive evaluation of parking lot alternatives contributes to the method's superiority. By considering a broad spectrum of criteria, such as local weather conditions, incident response, proximity to transportation hubs, and more, the methodology guarantees alignment with multiple objectives and demands. Furthermore, the practical application of this methodology in a real-life case study centered on Istanbul, Turkey, demonstrates its adaptability and effectiveness in addressing authentic AV parking lot selection challenges. This practical implementation adds credibility and showcases the method's applicability in the context of urban transportation and AVs.

### 3.1. Fermatean Fuzzy Sets

Fuzzy logic is a powerful mathematical framework for handling uncertainty and vagueness in decision-making problems [53]. Unlike classical binary logic, which operates on the basis of absolute truths and falsehoods, fuzzy logic incorporates degrees of membership to express the ambiguity of a statement. This makes fuzzy logic a valuable tool for modeling real-world, complex systems where precision is often lacking. The logic is particularly useful in controlling processes where the information is complex, nonlinear, and challenging to model, and the nature of the information is uncertain or unclear [54]. Fuzzy logic adopts an approach of approximate reasoning instead of relying solely on exact values, allowing for qualitative assessments and subjective judgment to be incorporated into the evaluation of complex decision-making problems [16]. In fuzzy logic, information is represented through linguistic expressions such as "important," "small," "very little," etc., which can be defined through different fuzzy sets to handle the fuzziness and uncertainty of the information [55].

Traditional fuzzy sets rely solely on the membership function ($\mu$) to determine the degree of an element's membership to the set and the non-membership degree can be computed as $1-\mu$. However, this approach may not be adequate in certain situations to fully capture the fuzziness of the set. In response, Atanassov proposed the intuitionistic fuzzy sets (IFSs) theory, which extends the traditional fuzzy set theory [56]. In addition to the membership function, the IFSs theory also uses a non-membership function ($v$) to define an element in the set. Both functions can take on values in the range of [0,1]. To complete the representation, Atanassov added a third function called hesitancy ($\pi$) which is the sum of the membership and non-membership degrees and equals 1.

### 3.2. Preliminaries of Fermatean Fuzzy Sets

The idea of FF sets was advanced by Senapati and Yager as a broadening of both intuitionistic IFSs and Pythagorean fuzzy sets [41, 57,58]. This type of fuzzy set is considered an innovative way to express unreliable, imprecise, and uncertain information in a fuzzy environment [59–62].

**Definition 1.** : A fermatean fuzzy number (FFN) in a fixed set X is represented as $\widetilde{F}$ [57]:

$$\widetilde{\mathrm{F}} \cong \left\{x, \quad \mu_{\widetilde{F}}(x), \quad v_{\widetilde{F}}(x); x \in X\right\} \tag{1}$$

$\mu_{\widetilde{F}}(x): X \mapsto [0,1]$ and $v_{\widetilde{F}}(x): X \mapsto [0,1]$ represent the degree of membership and non-membership of element $x \in X$ to FFN $\widetilde{F}$.

where;

$0 \le \mu_{\widetilde{F}}(x)^3 + v_{\widetilde{F}}(x)^3 \le 1(2)$

The hesitancy degree is determined by calculation which is given in Eq. 3.

$$\pi_{\widetilde{F}}(x) = \sqrt[3]{1-(\mu_{\widetilde{F}}(x))^3 + (v_{\widetilde{F}}(x)^3)} \tag{3}$$

**Definition 2.** The operation of multiplying an FFN $\widetilde{\alpha} = (\mu_{\widetilde{\alpha}}, \quad v_{\widetilde{\alpha}})$ by a positive scalar [60]:

$$\lambda\widetilde{\alpha} = \left(\sqrt[3]{1-\left(1-\mu_{\widetilde{\alpha}}^3\right)^{\lambda}}, v_{\widetilde{\alpha}}^{\lambda}\right) \tag{4}$$

**Definition 3.** The operation of the positive power of an FFN $\widetilde{\alpha} = (\mu_{\widetilde{\alpha}}, \quad v_{\widetilde{\alpha}})$ [60]:

$$\widetilde{\alpha}^{\lambda} = \left(\mu_{\widetilde{\alpha}}^{\lambda}, \sqrt[3]{1-\left(1-v_{\widetilde{\alpha}}^3\right)^{\lambda}}\right) \tag{5}$$

**Definition 4.** The score value of FFN $\widetilde{\alpha} = (\mu_{\widetilde{\alpha}}, \quad v_{\widetilde{\alpha}})$ can be calculated [57].

$$\mathrm{S}(\widetilde{\alpha}) = \mu_{\widetilde{\alpha}}^3 - v_{\widetilde{\alpha}}^3 \tag{6}$$

**Definition 5.** The positive score value of FFN $\widetilde{\alpha} = (\mu_{\widetilde{\alpha}}, \quad v_{\widetilde{\alpha}})$ can be calculated [63].

$$\mathrm{S}^{+}(\widetilde{\alpha}) = 1 + \mathrm{S}(\widetilde{\alpha}) = 1 + \mu_{\widetilde{\alpha}}^3 - v_{\widetilde{\alpha}}^3 \tag{7}$$

**Definition 6.** The Euclidean distances between two FFNs $\widetilde{\alpha} = (\mu_{\widetilde{\alpha}}, v_{\widetilde{\alpha}})$ and $\widetilde{\beta} = (\mu_{\widetilde{\beta}}, \quad v_{\widetilde{\beta}})$ is given [41].

$$d\left(\widetilde{\alpha}, \widetilde{\beta}\right) = \sqrt{\frac{1}{2}\left[\left(\mu_{\widetilde{\alpha}}^3 - \mu_{\widetilde{\beta}}^3\right)^2 + \left(v_{\widetilde{\alpha}}^3 - v_{\widetilde{\beta}}^3\right)^2 + \left(\pi_{\widetilde{\alpha}}^3 - \pi_{\widetilde{\beta}}^3\right)^2\right]} \tag{8}$$

**Definition 7.** This study introduced the following equation to the literature to calculate the Manhattan distance between two FFNs $\widetilde{\alpha} = (\mu_{\widetilde{\alpha}}, \quad v_{\widetilde{\alpha}})$ and $\widetilde{\beta} = (\mu_{\widetilde{\beta}}, \quad v_{\widetilde{\beta}})$

$$d\left(\widetilde{\alpha}, \widetilde{\beta}\right) = 0.5\left[\left|\mu_{\widetilde{\alpha}}^3 - \mu_{\widetilde{\beta}}^3\right| + \left|v_{\widetilde{\alpha}}^3 - v_{\widetilde{\beta}}^3\right| + \left|\pi_{\widetilde{\alpha}}^3 - \pi_{\widetilde{\beta}}^3\right|\right] \tag{9}$$

### 3.3. Fermatean Fuzzy SWARA

SWARA is an MCDM technique designed to solve decision-making issues involving many criteria. It is a methodical and iterative procedure that combines quantitative and qualitative techniques to assign weights to criteria and assess alternatives [62,64]. This method was introduced by Keršulienė et al. [42] and focuses on giving decision-makers the agency to choose their own priorities in light of current conditions. The method places a strong emphasis on the role of experts, who are also considered decision-makers, in determining the criteria weights. This is due to the fact that the primary feature of SWARA is the use of expert opinions in weighting the criteria [46].

When compared to other weighting strategies, SWARA offers various benefits. SWARA is easy to understand and implement [65]. Because it employs just elementary-level mathematical operations and language, SWARA can be understood and implemented by non-experts with no training in the decision-making field. Mathematical models are used to assign relative importance to each criterion in SWARA, making it an objective process. The step-wise approach of SWARA makes it feasible to analyze the interdependence of criteria and to adjust the weighing process as additional information becomes available [42]. It's easy to adapt SWARA to fit a wide variety of challenges, making it a versatile decision-making tool. SWARA's weighing technique ensures that the final weights appropriately represent the significance of each criterion because of its high accuracy.

In this paper, the FF-SWARA method is employed to assess the significance of the main and sub-criteria for selecting a parking lot for AVs. The hierarchical structure of the criteria is constructed, and the FF-SWARA method is utilized to determine the importance weight of each criterion at each level of the hierarchy. This approach is useful for identifying the priorities of the criteria, considering the opinions of experts and taking into account the current conditions. The steps of FF-SWARA are as follows [16]:

**Step 1:** First, the evaluation of experts is carried out and the weight or reputation of each expert is determined. Table 3 is used to distinguish experts based on their experience and qualifications.

The weight of each expert is then calculated using the following equation: The number of experts (d) is given and $E_t = (\mu_t, \nu_t)$ is the corresponding FFN to determine the weight of expert $t$ based on their skill and expertise. During this step, each expert is evaluated individually, and their weight is calculated.

$$\psi_t = \frac{S^+(E_t)}{\sum_{t=1}^{d} S^+(E_t)} = \frac{1+\mu_t^3-\nu_t^3}{\sum_{t=1}^{d}\left(1+\mu_t^3-\nu_t^3\right)} \tag{10}$$

**Step 2:** In this step, the opinions of the experts are collected and transformed into a decision matrix by utilizing linguistic terms provided in Table 3. Each expert is asked to evaluate each criterion using the terms in Table 4. The evaluation of criterion $j$ by expert $t$ is then represented by the FFN $A_{it} = (\mu_{jt}, \nu_{jt})$. The scale in Table 4 is used to convert the linguistic terms into FFNs.

**Step 3:** The next step in FF-SWARA is to aggregate the experts' opinions about the criteria to form an FF decision matrix. This is done by taking into account the weight $(\psi_t)$ of each expert, so that the opinions of more highly weighted experts have a greater impact on the final result. The aggregation process is used to combine the individual evaluations from each expert into a single overall evaluation of each criterion.

**Table 3**
Linguistic terms to evaluate experts.

| Linguistic Term | μ | ν |
|---|---|---|
| Absolutely Skilled-AS | 0.95 | 0.10 |
| Very Skilled-VS | 0.75 | 0.30 |
| More Skilled-MS | 0.55 | 0.50 |
| Skilled-S | 0.30 | 0.75 |
| Less Skilled-LS | 0.10 | 0.95 |

**Table 4**
Linguistic terms to evaluate criteria.

| Linguistic Term | μ | ν |
|---|---|---|
| Extremely Important-E | 0.975 | 0.10 |
| Very Important-V | 0.85 | 0.20 |
| Important-I | 0.70 | 0.35 |
| Moderately Important-M | 0.55 | 0.50 |
| Slightly Important-S | 0.35 | 0.70 |
| Not Important-N | 0.20 | 0.85 |
| Extremely Unimportant-U | 0.10 | 0.975 |

$$z_j = Y\left(\mu_j, \nu_j\right) = \left(\prod_{t=1}^{d}\left(\mu_{jt}\right)^{\psi_t}, \sqrt[3]{1-\prod_{t=1}^{d}\left(1-\left(\nu_{jt}\right)^3\right)^{\psi_t}}\right), j = 1, \ldots, n \tag{11}$$

$z_j$ is the aggregated value for criterion $j$ and $n$ is the number of criteria.

**Step 4:** The positive score $S^+(j)$ of each criterion is determined.

$$S^+(j) = 1 + \mu_j^3 - \nu_j^3 \tag{12}$$

**Step 5:** In the next step of FF-SWARA, the criteria are ranked based on their calculated positive scores. The ranking of criteria is done in descending order, so the criterion with the highest score appears at the top of the list, and the one with the lowest score appears at the bottom.

**Step 6:** The comparative significance $(c_j)$ of each criterion is calculated by taking the difference between the positive score values $S^+(j)$ of criterion $(j)$ and the positive score value of the second preferred criterion $(j-1)$.

**Step 7:** The comparative coefficients are calculated.

$$k_j = \begin{cases} 1, & j = 1 \\ c_j + 1, & j > 1 \end{cases} \tag{13}$$

**Step 8:** Recalculated weights are determined.

$$q_j = \begin{cases} 1, & j = 1 \\ \dfrac{q(j-1)}{k_j}, & j > 1 \end{cases} \tag{14}$$

**Step 9:** The final criteria weights are determined by normalizing the recalculated weights.

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_j} \tag{15}$$

### 3.4. Fermatean Fuzzy TOPSIS

TOPSIS is a well-established method in MCDM that was developed by Hwang & Yoon in 1981 [66,67]. It is widely used in various fields, such as manufacturing, engineering, marketing, and management [68–73] due to its user-friendliness, reliability, and robustness [74]. The method aims to find the best alternative by maximizing its distance from the negative ideal solution and minimizing its distance from the positive ideal solution [75]. The positive ideal solution tends to promote the beneficial criteria and limit the cost criteria [76]. The method uses Euclidean distance to evaluate the distances from the positive and negative ideal solutions for each alternative [74]. One of the strengths of TOPSIS is that it can handle a large number of alternatives and criteria without affecting its calculation time [77]. However, it is criticized for its inability to handle imprecision and uncertainty [15]. To address this issue, the authors in this research used the FF-TOPSIS method to evaluate alternative locations in Istanbul for selecting autonomous vehicle parking lots. The steps of FF-TOPSIS are as follows [15]:

**Step 1:** A decision matrix is created by gathering opinions from

experts regarding each criterion. The evaluations of alternative $i$ with respect to criterion $j$ by expert $t$ is represented by $A_{ij}^{t} = \left(\mu_{ij}^{t}, \nu_{ij}^{t}\right)$. The process involves using linguistic terms from Table 5 [78] to obtain the evaluations. $m$ represents the number of alternatives, while $n$ represents the number of criteria.

**Step 2:** Aggregate the opinions of experts to form FF decision matrix.

$$Z = \begin{bmatrix} (\mu_{11}, \nu_{11}) & (\mu_{12}, \nu_{12}) & \cdots & (\mu_{1n}, \nu_{1n}) \\ (\mu_{21}, \nu_{21}) & \ddots & \ddots & (\mu_{2n}, \nu_{2n}) \\ \vdots & \ddots & \ddots & \vdots \\ (\mu_{m1}, \nu_{m1}) & \cdots & \cdots & (\mu_{mn}, \nu_{mn}) \end{bmatrix} \tag{16}$$

$$z_{ij} = Z\left(\mu_{ij}, \nu_{ij}\right) = \left(\sqrt[3]{1 - \prod_{t=1}^{d}\left(1 - \left(\mu_{ij}^{t}\right)^{3}\right)^{\psi^{t}}}, \quad \prod_{t=1}^{d}\left(\nu_{ij}^{t}\right)^{\psi^{t}}\right) \tag{17}$$

**Step 3:** FF Positive Ideal Solution (FF-PIS) and FF Negative Ideal Solution (FF-NIS) are calculated for the aggregated decision matrix (Z) using a score function.

$$S^{+}\& = \begin{cases} \max\limits_{i}\langle score\left(z_{ij}\right)\rangle | j = 1, 2, \ldots, n; \text{for beneficial criterion} \\ \min\limits_{i}\langle score\left(z_{ij}\right)\rangle | j = 1, 2, \ldots, n; \text{ for cost criterion} \end{cases} \tag{18}$$

$$\& = \left\{\left(\mu_1^{+}, \nu_1^{+}\right), \left(\mu_2^{+}, \nu_2^{+}\right), \ldots, \left(\mu_n^{+}, \nu_n^{+}\right)\right\}$$

$$S^{-}\& = \begin{cases} \min\limits_{i}\langle score\left(z_{ij}\right)\rangle | j = 1, 2, \ldots, n; \text{for beneficial criterion} \\ \max\limits_{i}\langle score\left(z_{ij}\right)\rangle | j = 1, 2, \ldots, n; \text{ for cost criterion} \end{cases} \tag{19}$$

$$\& = \left\{\left(\mu_1^{-}, \nu_1^{-}\right), \left(\mu_2^{-}, \nu_2^{-}\right), \ldots, \left(\mu_n^{-}, \nu_n^{-}\right)\right\}$$

**Step 4:** Calculate the weighted Euclidean distances from FF-PIS and FF-NIS for each alternative. At this step, criteria weights determined by FF-SWARA is used.

$$\& D(S_i, S^{+}) = \sum_{j=1}^{n} w_j \sqrt{0.5\left[\left(\mu_{ij}^{3} - \left(\mu_j^{+}\right)^{3}\right)^{2} + \left(\nu_{ij}^{3} - \left(\nu_j^{+}\right)^{3}\right)^{2} + \left(\pi_{ij}^{3} - \left(\pi_j^{+}\right)^{3}\right)^{2}\right]} \tag{20}$$

$$\& D(S_i, S^{-}) = \sum_{j=1}^{n} w_j \sqrt{0.5\left[\left(\mu_{ij}^{3} - \left(\mu_j^{-}\right)^{3}\right)^{2} + \left(\nu_{ij}^{3} - \left(\nu_j^{-}\right)^{3}\right)^{2} + \left(\pi_{ij}^{3} - \left(\pi_j^{-}\right)^{3}\right)^{2}\right]} \tag{21}$$

**Step 5:** The closeness coefficient for each alternative is determined.

$$\phi_j = \frac{D(S_i, S^{-})}{D(S_i, S^{-}) + D(S_i, S^{+})} \tag{22}$$

**Step 6:** Finally, in step 6, the alternatives are ranked from the highest to the lowest based on their closeness coefficients. The alternative with the highest coefficient is determined as the best option.

**Table 5**
Linguistic terms to evaluate alternatives.

| Linguistic Term | $\mu$ | $\nu$ |
|---|---|---|
| Extreme High-EH | 0.9 | 0.1 |
| Very High-VH | 0.8 | 0.2 |
| High-H | 0.7 | 0.2 |
| Moderate High-MH | 0.6 | 0.3 |
| Moderate-M | 0.5 | 0.4 |
| Moderate Low-ML | 0.4 | 0.6 |
| Low-L | 0.3 | 0.7 |
| Very Low-VL | 0.2 | 0.8 |
| Extreme Low-EL | 0.1 | 0.9 |

## 4. Real case analysis in Istanbul, Turkiye

AVs are transforming the transportation business and generating demand for supporting infrastructure. Among the essential components is AV parking lots, which enable secure and easy parking for AVs while they are not in use. Selecting the best location for an AV parking lot is a complex task that involves considering various factors. One of the key issues in selecting a site for an AV parking lot is the requirement to balance numerous variables. These aspects could include accessibility to public transit, availability of sustainable energy supplies, community support, influence on the local ecology, and the possibility of resale value [79]. Each of these main criteria can be further broken down into specific sub-criteria, each with its own weight or level of importance. To build a thorough hierarchy of criteria, the performance measurements of the SCOR model have been employed and enhanced with technological performance metrics. This model allows for the analysis of aspects that may influence the efficiency and efficacy of the AV parking lot and the selection of the most appropriate site. Another problem in selecting an AV parking lot is the necessity to handle uncertainty and ambiguity. Availability of energy and internet connectivity, for example, might vary by location, and the cost of maintaining an AV parking lot can fluctuate depending on a number of variables. Fuzzy decision-making approaches that include partial truth values and subjective data are proposed way of handling the difficulties mentioned.

The proposed FF decision-making method provides a complete and systematic framework for evaluating suitable park sites by considering multiple criteria. The combination of SWARA and TOPSIS enables the consideration of both subjective and objective criteria, as well as the handling of uncertainty and ambiguity in decision-making. In the first step of the methodology, the criteria hierarchy for identifying the ideal location for an AV parking lot is established. The SCOR based criterion hierarchy is built based on a review of the literature and feedback from experts. Using the SWARA method, the second step entails determining the weight of each criterion. Using the opinions of several experts, the SWARA approach is utilized to determine the significance of each criterion. The third step involves evaluating candidate locations based on the defined criteria. The evaluation is performed using the TOPSIS approach, which calculates the relative closeness of each location to the ideal solution. Overall, the methodology employed in this study is a complete and systematic approach to identifying the ideal location for an AV parking lot, taking many variables and uncertainties into account.

### 4.1. Site selection criteria hierarchy

The SCOR model is a widely used tool for managing and optimizing supply chain performance [80]. The model, developed in the 1990s by the Supply Chain Council, provides a framework for understanding and controlling the processes and activities that comprise a supply chain [81]. It is utilized by organizations from a variety of sectors to enhance their supply chain processes and achieve operational excellence. Numerous industries, including manufacturing, healthcare, and retail,

have widely accepted and implemented the SCOR concept. It has been demonstrated that its application significantly improves supply chain performance.

The SCOR model is founded on a hierarchical framework with four levels that breaks down the supply chain into its constituent processes. Plan, source, make, deliver, and return processes comprise the first level of process types [82]. The second level, process categories, gives a more comprehensive breakdown of each process type. The third level, process components, breaks down the process categories into particular actions, while the fourth level, performance indicators, describes the metrics that may be used to evaluate the performance of each process element [83]. The SCOR model provides a common language and structure for analyzing and controlling supply chain activities. It assists firms in identifying supply chain improvement opportunities and benchmarking their performance against industry standards. By utilizing the model, businesses may find best practices and optimize their supply chain performance to achieve cost savings, higher efficiency, and enhanced customer service.

The SCOR model has three main performance metrics: resilience, economic, and sustainability [84]. The first performance metric, resilience, is essential for ensuring that the supply chain can swiftly recover from interruptions. There are three Level-2 metrics: reliability, responsiveness, and agility [85]. Reliability is the ability of the supply chain to continuously provide products or services in accordance with customer requirements. The responsiveness of the supply chain is its quickness and adaptability in responding to changing customer demands or market conditions. Agility in the supply chain is defined as the capacity to respond quickly and effectively to changing conditions and disturbances, such as those caused by weather events or epidemics [86].

The second performance metric is economic, and Level-2 economic performance metrics include cost, assets, and profit. Cost refers to the expenditures incurred by the supply chain in the course of its operations. Asset management is the effective utilization of assets, such as inventories, buildings, and equipment, to support supply chain activities. Profit relates to the supply chain's financial performance, including revenue, profit margins, and return on investment.

Sustainability is the third performance metric, which includes environmental and social metrics. Environmental sustainability refers to the effect of supply chain activities on the natural environment, including carbon emissions, water consumption, and waste production. Social sustainability refers to the effects of supply chain activities on society, such as worker health and safety, human rights, and community relations. The technological sustainability metric examines the influence of the parking lot for AVs on the technological ecosystem. This may include internet connectivity and charging infrastructure, the utilization of advanced technology such as artificial intelligence and machine learning, and the incorporation of AV parking lots into broader smart city ecosystems. By including technological factors into the sustainability index, the SCOR model can give a more complete analysis of the possible impact of AV parking lots on the environment, society, and technology. This can help decision-makers to make better-informed decisions on the location of AV parking lots, taking into account not just traditional sustainability factors but also technology variables that might affect the long-term profitability and success of the AV parking lot.

In order to further assess the candidate AV parking lots using the SCOR model, a criterion hierarchy has been developed based on a literature review and conversations with industry experts. The criterion hierarchy adds specificity and details to the evaluation procedure. The addition of technical aspects in the sustainability metric emphasizes the need for supply chain operations to include current technologies. There are three levels in the hierarchy, with five level-3 performance measures assigned to each level-2 metric. The level-3 performance metrics have been established based on the opinions of industry professionals and current research. The SCOR model can be applied to assess and improve the supply chain operations for the AV parking lot, including the transportation and logistics of AVs inside the parking lot. By evaluating possible AV parking lots using the SCOR model, decision-makers may gain insight into the potential transportation expenses, inventory carrying costs, delivery dependability, and order fulfillment cycle time associated with each location. This data may be utilized to make an educated selection about the ideal placement for the AV parking lot, taking into consideration the most crucial success elements. The SCOR model is a valuable tool for analyzing and improving the AV parking lot's supply chain activities. Using the SCOR model's defined performance measures, decision-makers may determine the ideal placement for the parking lot and constantly enhance the supply chain processes for maximum efficiency. Overall, the methodology employed in this study is a complete and systematic approach to identifying the ideal location for an AV parking lot, taking many variables and uncertainties into account. The SCOR technique provides a balanced and complete way to assess suitable locations for AV parking lots by using resilience, economic, and sustainability performance metrics. In Table 6, the performance metrics (main criteria and sub-criteria) used in this study are presented.

### 4.2. Determination of criteria weights using FF-SWARA

After constructing the criteria hierarchy, the first step in the proposed model is to evaluate the experts who will provide opinions on the highlighted problem. This is a critical point since the views of the experts will be utilized to define the final weights for each of the model's performance metrics. Education, experience, and professional affiliations issues of experts are considered in the evaluation process. The experts have been rated according to their degree of competence in each hierarchy criterion. The rankings have been used to assess the reputations of the experts, which are then included in the final calculations for the criterion as weights. In the computations, the experts with the best reputations have been assigned the highest weights, while those with lesser reputations have been assigned the lowest weights. This procedure insured that the most qualified and experienced experts had the most impact on the final results. Overall, the examination and determination of the reputations of experts are the important steps in the implementation of the proposed model. The model is able to offer a more accurate evaluation of the organization's performance by including the insights of decision-makers with the most expertise and experience in the relevant measures. In the evaluation of the experts, a total of 5 experts have been involved in the study. One expert has been deemed Absolutely Skilled (AS), one has been deemed Very Skilled (VS), two have been deemed More Skilled (MS), and one has been deemed Skilled (S). Eq. 17 has been applied to determine the reputations or weights of the experts, taking into consideration their individual evaluations. As a consequence of the computation, the expert with the greatest reputation or weight has been graded as AS with the weight of 0.312. With a weight of 0.233, the expert with the second-highest weight has been graded as VS. The two MS-evaluated experts have had identical weights of 0.175, but the S-evaluated expert has had a weight of 0.102. Using these weights, the final scores for the performance measures at each level have been calculated, including the expert views and assessments into the overall study.

Step 2 of the proposed methodology is gathering the views of the experts and translating them into a decision matrix using the linguistic terms listed in Table 4. To do this, each expert is required to assess the criteria and sub-criteria based on their knowledge and experience, with the offered linguistic terms serving as a guide. Firstly, experts' evaluations for the main criteria is given in Table 7.

Linguistic terms are then converted to FFNs using Table 3. Evaluations from experts have been aggregated by Eq. 18 as shown in Table 8.

Score values of the main criteria have been calculated by Eq. 19 using aggregated criteria evaluations given in Table 8. Main criteria has been ordered according to their score values in descending order. Steps 5–9 of FF-SWARA are then applied to determine the weight of each main criterion as given in Table 9.

**Table 6**
The criteria hierarchy to evaluate the locations of AV parking lots.

| Main Criteria | Level-2 Sub-Criteria | Source | Level-3 Sub-Criteria |
|---|---|---|---|
| Resilience | R1. Reliability | [87,88] | R11. Location safety and security<br>R12. Infrastructure reliability<br>R13. Local weather conditions<br>R14. Equipment and technology reliability<br>R15. Incident response and management |
| | R2. Responsiveness | [7,89] | R21. Distance to the nearest main road<br>R22. Proximity to public transportation<br>R23. Availability of amenities<br>R24. Ease of use and accessibility<br>R25. Traffic congestion |
| | R3. Agility | [89,90] | R31. Space utilization and optimization<br>R32. Flexibility of operations<br>R33. Automation and robotics<br>R34. Scalability and modularity<br>R35. Speed and efficiency of operations |
| Economic | E1. Cost | [90–92] | E11. Land cost<br>E12. Operating expenses<br>E13. Maintenance and repair costs<br>E14. Construction and infrastructure costs<br>E15. Labor costs |
| | E2. Profit | [7,89,90,93,94] | E21. Parking gaining<br>E22. Market demand<br>E23. Potential revenue from extra services<br>E24. Return on investment<br>E25. Competition from existing parking options |
| | E3. Assets | [7,95] | E31. Physical infrastructure and facilities<br>E32. Equipment<br>E33. Resale value<br>E34. Space availability<br>E35. Human capital and expertise |
| Sustainability | S1. Environmental | [90,96,97] | S11. Impact on the local ecosystem<br>S12. Sustainable energy resources<br>S13. Waste management and disposal<br>S14. Water usage and conservation<br>S15. Air quality and pollution control |
| | S2. Social | [90,98] | S21. Community support<br>S22. Employment and job creation<br>S23. Demographics<br>S24. Quality of life for local residents<br>S25. Local economy |
| | S3. Technological | [7,99] | S31. Available technology and infrastructure<br>S32. Proximity to technology hubs<br>S33. Integration with existing systems<br>S34. Access to technical support<br>S35. Adoption of new technologies |

**Table 7**
Main criteria evaluations by each expert.

| Main Criteria | E-1 | E-2 | E-3 | E-4 | E-5 |
|---|---|---|---|---|---|
| **Resilience** | V | M | I | M | V |
| **Economic** | E | I | V | I | E |
| **Sustainability** | E | I | M | S | M |

**Table 8**
Aggregated main criteria evaluations.

| Main Criteria | $\mu$ | $\nu$ |
|---|---|---|
| **Resilience** | 0.751 | 0.399 |
| **Economic** | 0.859 | 0.270 |
| **Sustainability** | 0.774 | 0.485 |

**Table 9**
Results of FF-SWARA application for the main criteria.

| Main Criteria | Score | $c_j$ | $k_j$ | $q_j$ | Weight |
|---|---|---|---|---|---|
| **Economic** | 1.615 | | 1 | 1 | 0.387 |
| **Resilience** | 1.361 | 0.254 | 1.254 | 0.797 | 0.308 |
| **Sustainability** | 1.349 | 0.012 | 1.012 | 0.788 | 0.305 |

The same experts are consulted to construct the evaluation matrices of Level-2 criteria. The expert evaluations and weights for each Level-2 criterion are given in Table 10. Criteria weights have been obtained by re-applying the steps of FF-SWARA. To determine the global weights of the Level-2 criteria, the weights of each Level-2 criterion have been multiplied by the corresponding weight of the main criterion to which it belongs. These weights have been calculated by re-applying the steps FF-SWARA, as described previously. Table 10 gives the local and global weights of Level-2 criteria.

After determining the weights of Level-1 and Level-2 criteria, the same weight determination procedure is repeated to determine the weights of Level-3 criteria. The expert evaluations for the Level-3 criteria are presented in Table 11. The local weight of each criterion has been calculated using FF-SWARA, and the global weights for Level-3 criteria have been determined by multiplying the local weights of related Level-2 and main criteria weights. Table 11 also presents the weights of each criterion.

This phase is essential for ensuring the accuracy and fairness of the alternative evaluation. The weights of the criteria are the basis of the decision-making process, thus they must be meticulously calculated. Expert participation in the approach for determining weight gives significant insight and ensures that all relevant factors are addressed. The FF-SWARA method provides a reliable and systematic way for determining the weights of the criteria transparently. The process for determining weights can also be employed to update the weights of the criteria if the decision-making environment changes. By reapplying the FF-SWARA stages, the weights of the criteria may be modified in accordance with the most recent expert judgments and current priorities. In general, the FF-SWARA technique offers a strong and adaptable method for determining the weights of criteria in the MCDM problems. The strategy may be used in a variety of decision-making circumstances and can assist decision-makers in reaching objective and well-informed conclusions.

### 4.3. Evaluation of AV parking lots using FF-TOPSIS

The number of vehicles in Turkey has been steadily increasing over the years, reflecting the growth in the country's population and economy as presented in Fig. 2 [100]. In 2005, there were 11,145,826 vehicles registered in Turkey, and by 2023, this number had risen significantly to 28,740,492 vehicles. Istanbul, as the most populous city

**Table 10**
Level-2 criteria evaluation by the experts and criteria weights.

| Main Criteria | Level-2 Criteria | E-1 | E-2 | E-3 | E-4 | E-5 | Local Weight | Global Weight |
|---|---|---|---|---|---|---|---|---|
| **Resilience** | Reliability | I | V | V | V | E | 0.401 | 0.124 |
| | Responsiveness | V | M | I | S | M | 0.297 | 0.092 |
| | Agility | M | I | M | M | I | 0.301 | 0.093 |
| **Economic** | Cost | V | E | E | M | E | 0.377 | 0.146 |
| | Profit | E | V | M | S | V | 0.322 | 0.124 |
| | Assets | M | I | I | E | S | 0.301 | 0.116 |
| **Sustainability** | Environmental | I | M | I | M | E | 0.314 | 0.096 |
| | Social | M | S | S | S | N | 0.224 | 0.068 |
| | Technological | V | V | V | E | V | 0.462 | 0.141 |

**Table 11**
Level-3 criteria evaluation by the experts and criteria weights.

| | E-1 | E-2 | E-3 | E-4 | E-5 | Local Weight | Final Weight | Ranking |
|---|---|---|---|---|---|---|---|---|
| **R11** | V | V | I | I | I | 0.265 | 0.0328 | 2 |
| **R12** | E | M | V | E | E | 0.262 | 0.0324 | 4 |
| **R13** | S | S | M | N | M | 0.124 | 0.0153 | 39 |
| **R14** | M | M | S | I | I | 0.185 | 0.0229 | 21 |
| **R15** | M | M | M | S | M | 0.164 | 0.0203 | 27 |
| **R21** | I | S | M | M | I | 0.189 | 0.0173 | 36 |
| **R22** | V | M | S | E | N | 0.228 | 0.0209 | 24 |
| **R23** | S | N | N | S | S | 0.159 | 0.0146 | 41 |
| **R24** | E | M | M | M | M | 0.217 | 0.0199 | 30 |
| **R25** | I | I | E | M | I | 0.207 | 0.0190 | 32 |
| **R31** | I | E | I | I | M | 0.221 | 0.0205 | 26 |
| **R32** | M | M | S | M | I | 0.187 | 0.0174 | 35 |
| **R33** | M | I | M | I | M | 0.198 | 0.0184 | 34 |
| **R34** | M | M | I | S | N | 0.179 | 0.0166 | 38 |
| **R35** | I | V | I | I | E | 0.215 | 0.0200 | 29 |
| **E11** | V | S | M | V | E | 0.223 | 0.0325 | 3 |
| **E12** | I | M | S | I | M | 0.225 | 0.0329 | 1 |
| **E13** | S | M | M | M | M | 0.191 | 0.0278 | 10 |
| **E14** | M | S | M | M | I | 0.196 | 0.0285 | 8 |
| **E15** | S | N | N | N | N | 0.166 | 0.0242 | 15 |
| **E21** | V | N | N | I | V | 0.201 | 0.0250 | 14 |
| **E22** | E | M | S | I | V | 0.230 | 0.0286 | 7 |
| **E23** | M | M | M | S | M | 0.189 | 0.0235 | 19 |
| **E24** | I | N | N | M | S | 0.189 | 0.0236 | 18 |
| **E25** | M | M | I | S | N | 0.191 | 0.0237 | 17 |
| **E31** | M | I | V | E | E | 0.222 | 0.0258 | 12 |
| **E32** | S | M | M | E | I | 0.196 | 0.0228 | 22 |
| **E33** | I | S | M | M | M | 0.199 | 0.0231 | 20 |
| **E34** | M | M | I | I | I | 0.206 | 0.0240 | 16 |
| **E35** | S | M | M | S | M | 0.178 | 0.0207 | 25 |
| **S11** | E | N | N | V | E | 0.220 | 0.0210 | 23 |
| **S12** | S | M | M | I | I | 0.195 | 0.0186 | 33 |
| **S13** | M | I | I | M | S | 0.212 | 0.0203 | 28 |
| **S14** | N | M | S | M | M | 0.175 | 0.0168 | 37 |
| **S15** | S | I | I | I | M | 0.198 | 0.0190 | 31 |
| **S21** | I | I | V | M | I | 0.215 | 0.0147 | 40 |
| **S22** | S | M | I | I | S | 0.186 | 0.0127 | 45 |
| **S23** | M | I | M | S | N | 0.198 | 0.0135 | 43 |
| **S24** | S | V | I | M | U | 0.194 | 0.0133 | 44 |
| **S25** | M | I | M | M | N | 0.207 | 0.0141 | 42 |
| **S31** | I | M | I | V | M | 0.207 | 0.0292 | 6 |
| **S32** | M | M | M | M | M | 0.188 | 0.0265 | 11 |
| **S33** | E | V | V | M | I | 0.228 | 0.0322 | 5 |
| **S34** | M | I | I | I | E | 0.199 | 0.0280 | 9 |
| **S35** | S | I | M | M | S | 0.178 | 0.0251 | 13 |

in Turkey, has experienced a particularly notable surge in vehicle numbers. In 2023 alone, the number of vehicles in Istanbul reached 5406,820. This upward trend in vehicle ownership has created a pressing need for adequate parking facilities, especially in densely populated urban areas like Istanbul.

With more vehicles on the roads, the demand for parking spaces has intensified, leading to challenges such as congestion, limited parking availability, and increased traffic. As a result, urban planners and policymakers are faced with the task of implementing effective strategies to address the growing demand for car parking and alleviate the associated urban mobility issues.

The Istanbul Metropolitan Municipality (IMM) and its subsidiary, the Istanbul Parking Authority (ISPARK), are responsible for the planning, provision, and oversight of parking facilities throughout Istanbul. Fig. 3 illustrates the capacities of both on-street and off-street parking lots managed with public resources. Additionally, private enterprises and facilities contribute to the parking capacity, with capacities of 146,528 and 526,925, respectively, in 2015 [101]. It is worth noting the significant increase in the number of cars compared to the expansion of parking lot capacity over the same period [7].

The demand for autonomous vehicles is anticipated to steadily rise in the coming years [102]. However, this surge in demand poses potential challenges, particularly in cities lacking adequate parking infrastructure for AVs. Istanbul serves as a pertinent real-world case study in this regard, as it currently lacks designated parking spaces for AVs. With the anticipated increase in the adoption of AVs, the absence of dedicated parking facilities could exacerbate urban congestion and accessibility issues. As such, the need to address the parking lot selection problem for AVs becomes increasingly pressing, underscoring the relevance and urgency of research in this area.

This research aims to determine the ideal locations for an AV parking lot in Istanbul, Turkiye. Selecting the best locations of AV parking lots in Istanbul is vital for various reasons. The first reason is to accommodate the rising demand for AV parking lots throughout the city. With the development and application of AV technology, it is anticipated that the number of AVs on the roads will rise in the future years. These cars will require specialized parking facilities with charging stations and other essential infrastructure, such as internet connection and safety precautions. Secondly, situating AV parking lots in the correct places can assist minimize traffic congestion and promote road safety. By offering suitable parking spots for AVs, it can encourage more people to use AVs, lowering the number of traditional automobiles on the roads. This reduction can assist alleviate traffic congestion and reduce the number of accidents resulting from human error. Finally, determining the location of parking lots for AVs might have economic advantages for the city. AV parking lots can create new employment possibilities and improve the local economy through the increased demand for local services. In addition, the construction of AV parking lots can attract new enterprises and investments to the city, therefore contributing to the region's growth and development. Lastly, locating parking facilities for AVs in Istanbul can contribute to the city's sustainability goals. AV parking spaces can be equipped with sustainable energy resources, such as solar panels, to decrease energy usage and carbon emissions. In addition, by promoting the use of AVs, which are generally electric or hybrid cars, the city may minimize its carbon footprint and contribute to a cleaner and more sustainable environment. In conclusion, determining the locations of AV parking lots in Istanbul is essential for satisfying the needs of AV technology, decreasing traffic congestion and enhancing road safety, encouraging the local economy, and contributing to the city's sustainability goals. Hence, a comprehensive and systematic strategy is needed to analyze and select the most ideal locations for AV parking lots in Istanbul. The proposed FF-SWARA integrated FF-TOPSIS framework is applied in the city of Istanbul as a real-case analysis to illustrate the

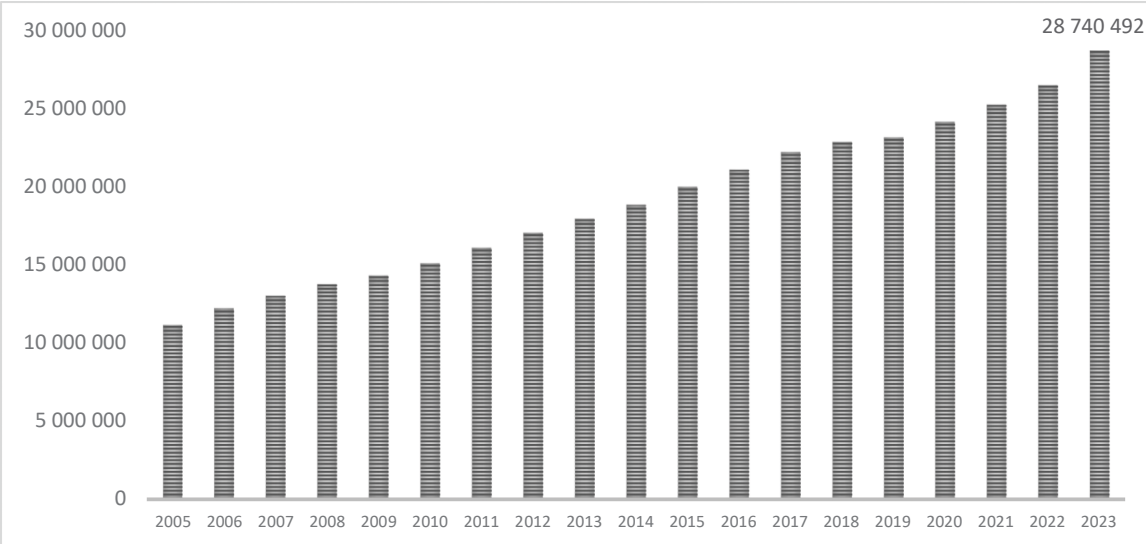


**Fig. 2.** Number of vehicles in Turkiye.

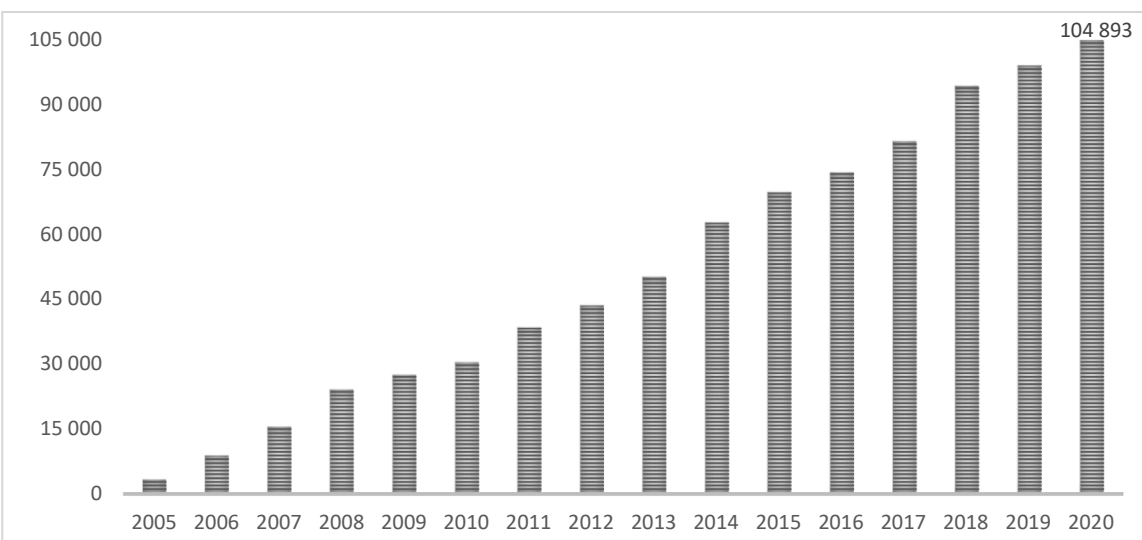


**Fig. 3.** Parking capacity in İstanbul, Türkiye.

applicability of proposed methodology. The proposed methodology evaluates nine alternative locations in Turkiye, which are depicted in Fig. 4.

The case study region, Istanbul, holds particular significance in the context of parking lot selection. As the most populous and developed city in Turkey, Istanbul grapples with a multitude of urban transportation challenges. As Turkey's most populous city, Istanbul is home to over 15 million residents [103] and experiences a daily influx of commuters and tourists. Rapid population growth and increasing vehicle usage have exacerbated the demand for efficient parking solutions [104]. The city's extensive road network spans approximately 5000 kilometers, contributing to its ranking as one of the most congested cities globally [105]. The city's geographical expanse and diverse neighborhoods further complicate the allocation of suitable parking areas. Istanbul's unique urban landscape, characterized by historical sites, commercial districts, and residential zones, necessitates a nuanced approach to parking lot selection. Furthermore, Istanbul is characterized by its rapid urbanization and economic significance. It contributes around 30 % [106] of Turkey's GDP (Gross Domestic Product), serving as the country's primary economic hub. The city's economic prowess attracts a diverse demographic, with a variety of transportation needs ranging from work-related commutes to leisure activities. This dynamic environment necessitates innovative approaches to alleviate traffic congestion and improve urban mobility. Moreover, Istanbul is a critical hub for technological innovation and economic activities, attracting both local and international attention. The city has made strides in embracing technology, with a rising number of tech startups and investments in smart city initiatives. This dynamic environment calls for a forward-looking perspective on AV integration, making it an ideal case study region for AV parking lot selection. The complex network of roads, public transportation options, and traffic patterns necessitates a comprehensive evaluation of potential parking locations. The city's diverse demographic composition and varying economic dynamics further highlight the need for a well-informed and strategic approach to parking lot selection.

In this study, the assessment of alternative locations for the AV parking lot is performed by considering the relative weights of the predefined criteria. The first step in the evaluation process is to construct

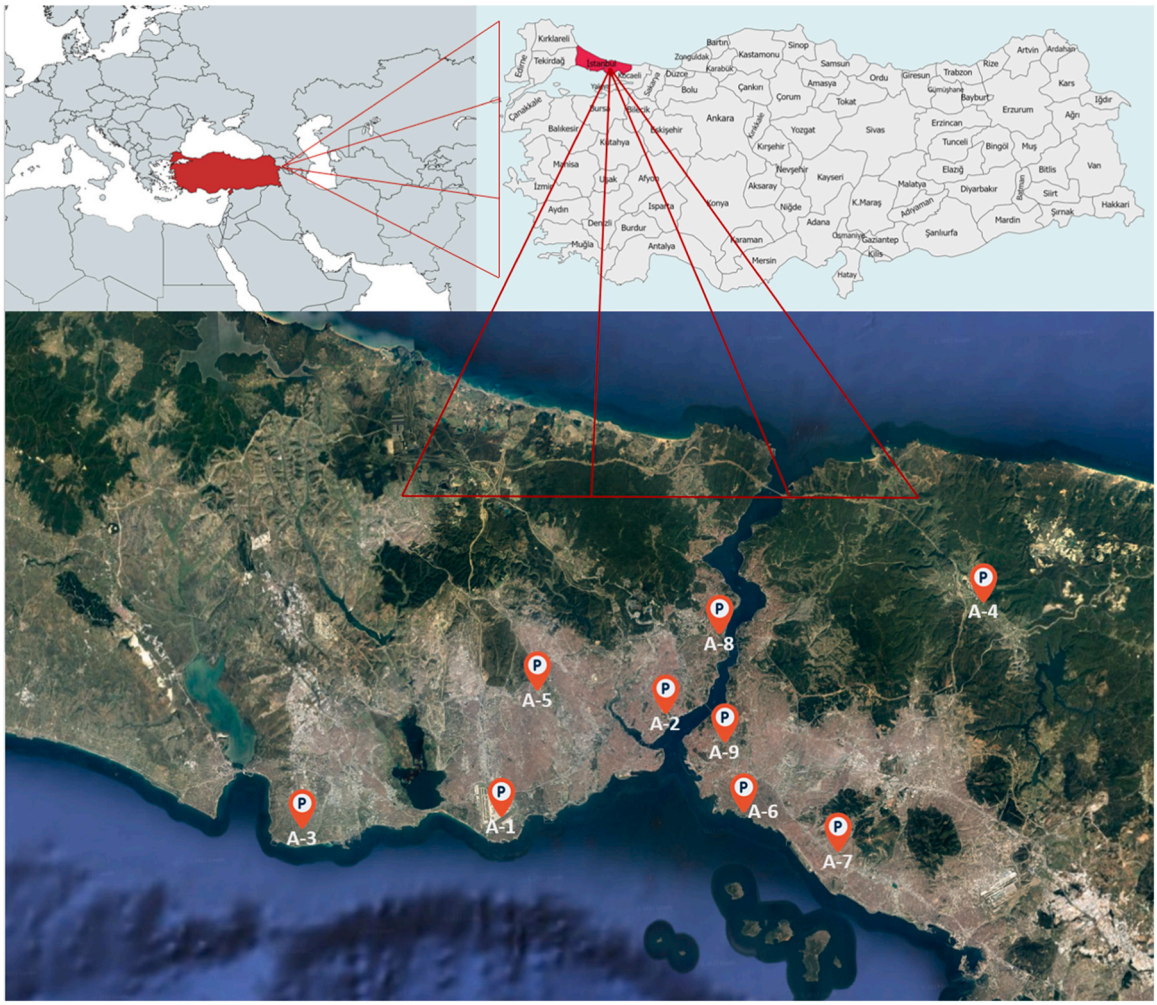


**Fig. 4.** Alternative locations in Istanbul.

a decision matrix, which is used to evaluate the options based on the linguistic terms provided in Table 5. This approach allows for a more comprehensive and accurate assessment of the alternative locations by taking into account multiple criteria and their relative importance. The decision matrix helps to standardize the evaluation process by providing a common framework for experts to evaluate alternative AV parking lots. Table 12 presents criteria - alternative evaluations by Expert-1 as an example. The other alternative evaluation matrices for other experts are excluded from this study due to space limitations (see Supplementary Materials for the remaining parts of the criteria - alternative evaluation matrix).

In the context of selecting a suitable location for a parking lot, the evaluation matrix for different alternatives is transformed into FFNs. The ideal solutions for each criterion are then determined using Eq.s25 and 26. Tables 13 and 14 provide the FF-PIS and FF-NIS, respectively. At this step R25, E11, E12, E13, E14, E15 and E25 are considered as cost criteria, while the other criteria are considered as benefit criteria.

In the AV parking lot selection problem, the distances of each location from the ideal solutions are calculated using the criteria weights obtained by the FF-SWARA method. These ideal solutions have been determined in the previous step for each criterion using Eq. 25 and Eq. 26. Table 15 presents the positive and negative distances of each location from the ideal solutions. These distances provide a clear understanding of the relative strengths and weaknesses of each location in terms of the evaluation criteria.

Following the calculation of the distances from the ideal solutions for each location using the weights determined by FF-SWARA, the final scores of the locations for AV parking lot are determined with Eq. 29, as shown in Fig. 5. The results of the final score calculation are then used to rank the alternative locations, with A-2: Besiktas being identified as the most suitable AV parking lot location in Istanbul, Turkiye. Therefore, based on the selected criteria and expert opinions, it can be concluded that Besiktas offers the most favorable conditions for the development of an AV parking lot.

The examination of alternative AV parking lots is based on a number of criteria, each with its weighting. Following a comprehensive analysis of the alternatives using FF-SWARA and FF-TOPSIS, it is concluded that A-6 in Besiktas is found as the best choice for the AV parking lot. This is owing to its advantageous location in relation to several factors, including:

- Proximity to public transportation: Metro, bus, and ferry services are readily available in Besiktas. This is essential for an AV parking lot since it would facilitate consumer accessibility.
- Availability of amenities: Besiktas has a range of facilities, including retail complexes, restaurants, and entertainment venues. This would give clients a nice experience while their automobiles are being serviced.
- Return on investment: Besiktas's population density and local economy are rather robust. This would give the AV parking lot a huge client base and the possibility for a strong return on investment.
- Local weather conditions: The climate in Besiktas is moderate, with mild winters and pleasant summers, which is conducive to the operation of an AV parking lot.

**Table 12**
Alternative evaluation matrix for Expert-1.

| | A-1 | A-2 | A-3 | A-4 | A-5 | A-6 | A-7 | A-8 | A-9 |
|---|---|---|---|---|---|---|---|---|---|
| **R11** | MH | H | M | ML | L | MH | L | VH | H |
| **R12** | H | VH | MH | L | L | H | ML | MH | H |
| **R13** | M | H | M | L | M | H | L | H | H |
| **R14** | H | VH | MH | M | L | MH | M | VH | MH |
| **R15** | H | VH | MH | M | L | H | ML | H | MH |
| **R21** | MH | ML | MH | L | VH | MH | M | ML | MH |
| **R22** | H | VH | L | VL | L | VH | M | L | MH |
| **R23** | H | VH | MH | L | VL | VH | M | MH | H |
| **R24** | H | VH | MH | L | L | H | M | MH | H |
| **R25** | M | MH | ML | VL | L | H | L | VL | H |
| **R31** | MH | VL | ML | L | M | MH | L | MH | MH |
| **R32** | H | VH | MH | L | M | H | ML | M | MH |
| **R33** | M | H | MH | L | ML | M | L | VL | MH |
| **R34** | H | VH | M | L | L | M | ML | H | MH |
| **R35** | VH | EH | H | L | VL | H | L | MH | MH |
| **E11** | M | VH | ML | VL | L | H | L | EH | H |
| **E12** | M | H | L | VL | ML | MH | VL | L | MH |
| **E13** | M | H | MH | ML | L | MH | M | VL | MH |
| **E14** | M | VH | MH | ML | L | H | M | VH | H |
| **E15** | M | H | ML | L | L | H | L | VH | H |
| **E21** | H | VH | MH | M | L | H | M | VH | H |
| **E22** | M | VH | MH | ML | L | H | M | H | MH |
| **E23** | M | H | L | VL | ML | MH | L | H | M |
| **E24** | H | VH | MH | M | L | H | MH | M | MH |
| **E25** | EH | VH | M | ML | L | VH | M | H | H |
| **E31** | MH | VH | M | L | ML | H | M | H | H |
| **E32** | MH | MH | M | M | ML | M | M | MH | M |
| **E33** | M | MH | M | L | ML | MH | L | VH | H |
| **E34** | MH | M | H | ML | M | H | ML | H | H |
| **E35** | H | VH | M | L | L | VH | M | H | H |
| **S11** | M | M | L | VL | L | M | L | H | M |
| **S12** | M | M | MH | ML | VL | MH | MH | H | MH |
| **S13** | ML | ML | MH | M | ML | ML | MH | M | ML |
| **S14** | M | ML | MH | MH | M | ML | MH | M | ML |
| **S15** | M | ML | M | MH | ML | ML | MH | MH | ML |
| **S21** | MH | H | ML | M | L | H | M | VH | MH |
| **S22** | M | ML | MH | H | M | ML | MH | ML | ML |
| **S23** | M | H | M | L | VL | H | M | M | H |
| **S24** | H | VH | ML | L | L | H | M | VH | MH |
| **S25** | MH | H | ML | L | L | H | M | VH | MH |
| **S31** | MH | VH | ML | ML | L | VH | M | MH | MH |
| **S32** | MH | EH | ML | VL | MH | H | L | VH | MH |
| **S33** | H | VH | MH | ML | M | EH | M | ML | VH |
| **S34** | MH | VH | L | VL | MH | H | ML | VH | MH |
| **S35** | MH | H | MH | M | ML | H | MH | MH | M |

- Distance to the nearest main road: Besiktas is located close to a major road, which would make it easily accessible for customers.
- Scalability and modularity: Besiktas has the potential for scalability and modularity, allowing the AV parking lot to expand and adapt to changing demands over time.
- Demographics: Besiktas's diversified population would offer a large client base for the AV parking lot.

Besiktas is the best solution for the AV parking lot owing to its advantageous position, robust economy, accessibility, and extension potential.

### 4.4. Sensitivity analysis

The sensitivity analysis is a crucial aspect in determining the ideal location for an AV parking lot in Istanbul, as it assesses the effect of minor changes in the weights of the criteria on the final selection. Little variations in the relative weights may have a substantial effect on the final rankings of alternative locations. As relative weights are frequently based on subjective expert opinions, it is vital to evaluate the ranking's stability when the weights of the criteria change. Sensitivity analysis may be carried out using hypothetical scenarios that represent prospective future occurrences or various viewpoints on the relative significance of the criteria. By slightly modifying the weights and watching their effect on the selection, it could be feasible to obtain insight into the robustness of the decision-making process, especially when uncertainties exist. The sensitivity analysis can highlight the ranking's reliability, and if the ranking is particularly sensitive to slight changes in the weights given to the criteria, it is strongly advised that the weights be extensively evaluated.

In this study, sensitivity analysis is performed to examine the impact of criterion weights on the selection of the ideal location of AV parking lot in Istanbul. Therefore this analysis provides decision-makers with vital information to make informed decisions and construct a more sustainable transportation system. It is essential to notice that the weights of the other criteria reflect the relative nature of the weights; that is, the sum of all weights must equal 100 %. To do this, weight of each main criterion has been changed individually. Thus, the weight of each sub-criterion has been modified. Table 16 presents the modified main criteria weights.

Sensitivity analyses are necessary when adjusting the relative importance of criteria, as changes in significance may require adjustments to the weighting of each criterion to ensure that strategy selection is based on the predetermined criteria. The sensitivity analysis of the AV parking lot selection problem is performed by altering the weights of the three main (Level-1) criteria (Resilience, Economic, and Sustainability) by 10–30 % each. FF-TOPSIS recalculates the final ratings for each alternative. The results of the sensitivity analysis are consistent with the current findings. Table 17 presents the first three alternatives for each scenario.

According to the sensitivity analysis performed on the AV parking lot selection problem, Besiktas is the optimal alternative under all scenarios with different final scores. This finding shows that the ideal placement for a parking lot for AV depends on the scenario or set of criteria being evaluated. The fact that alternatives have different score values in different scenarios highlights the need to carefully analyze the weights allocated to each criterion and the decision-makers' individual requirements and objectives. By conducting sensitivity analysis, decision-makers may acquire useful insights into the robustness of the decision-making process and create more sustainable transportation system decisions.

Besiktas district has a high degree of resilience, which means it can resist and recover from interruptions or shocks, such as natural catastrophes or unanticipated occurrences. This is a crucial aspect of an AV parking lot since it guarantees that the facility can continue to operate

**Table 13**
Positive ideal solutions.

| | μ | ν | | μ | ν | | μ | ν | | μ | ν | | μ | ν |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **R11** | 0.764 | 0.144 | **R25** | 0.673 | 0.288 | **E14** | 0.547 | 0.337 | **E33** | 0.756 | 0.120 | **S22** | 0.686 | 0.191 |
| **R12** | 0.709 | 0.185 | **R31** | 0.585 | 0.342 | **E15** | 0.509 | 0.377 | **E34** | 0.729 | 0.144 | **S23** | 0.750 | 0.144 |
| **R13** | 0.680 | 0.186 | **R32** | 0.709 | 0.164 | **E21** | 0.758 | 0.118 | **E35** | 0.777 | 0.102 | **S24** | 0.748 | 0.134 |
| **R14** | 0.771 | 0.136 | **R33** | 0.700 | 0.169 | **E22** | 0.802 | 0.095 | **S11** | 0.617 | 0.265 | **S25** | 0.755 | 0.139 |
| **R15** | 0.780 | 0.116 | **R34** | 0.744 | 0.131 | **E23** | 0.704 | 0.191 | **S12** | 0.633 | 0.238 | **S31** | 0.741 | 0.133 |
| **R21** | 0.671 | 0.211 | **R35** | 0.782 | 0.181 | **E24** | 0.744 | 0.150 | **S13** | 0.663 | 0.202 | **S32** | 0.792 | 0.139 |
| **R22** | 0.855 | 0.084 | **E11** | 0.656 | 0.255 | **E25** | 0.537 | 0.339 | **S14** | 0.610 | 0.261 | **S33** | 0.826 | 0.099 |
| **R23** | 0.803 | 0.120 | **E12** | 0.530 | 0.365 | **E31** | 0.770 | 0.126 | **S15** | 0.679 | 0.192 | **S34** | 0.756 | 0.120 |
| **R24** | 0.755 | 0.139 | **E13** | 0.539 | 0.332 | **E32** | 0.710 | 0.184 | **S21** | 0.786 | 0.139 | **S35** | 0.664 | 0.200 |

**Table 14**
Negative ideal solutions.

| | μ | ν | | μ | ν | | μ | ν | | μ | ν | | μ | ν |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **R11** | 0.395 | 0.530 | **R25** | 0.825 | 0.105 | **E14** | 0.802 | 0.095 | **E33** | 0.523 | 0.380 | **S22** | 0.559 | 0.337 |
| **R12** | 0.439 | 0.457 | **R31** | 0.413 | 0.486 | **E15** | 0.784 | 0.134 | **E34** | 0.426 | 0.463 | **S23** | 0.518 | 0.407 |
| **R13** | 0.552 | 0.351 | **R32** | 0.496 | 0.390 | **E21** | 0.528 | 0.350 | **E35** | 0.523 | 0.380 | **S24** | 0.487 | 0.408 |
| **R14** | 0.562 | 0.345 | **R33** | 0.489 | 0.382 | **E22** | 0.468 | 0.392 | **S11** | 0.428 | 0.460 | **S25** | 0.528 | 0.383 |
| **R15** | 0.557 | 0.324 | **R34** | 0.572 | 0.332 | **E23** | 0.559 | 0.341 | **S12** | 0.545 | 0.356 | **S31** | 0.487 | 0.408 |
| **R21** | 0.549 | 0.334 | **R35** | 0.593 | 0.303 | **E24** | 0.560 | 0.316 | **S13** | 0.499 | 0.358 | **S32** | 0.552 | 0.339 |
| **R22** | 0.568 | 0.343 | **E11** | 0.876 | 0.084 | **E25** | 0.810 | 0.112 | **S14** | 0.472 | 0.394 | **S33** | 0.567 | 0.327 |
| **R23** | 0.517 | 0.385 | **E12** | 0.712 | 0.181 | **E31** | 0.593 | 0.296 | **S15** | 0.554 | 0.306 | **S34** | 0.563 | 0.339 |
| **R24** | 0.454 | 0.421 | **E13** | 0.664 | 0.203 | **E32** | 0.540 | 0.346 | **S21** | 0.655 | 0.268 | **S35** | 0.548 | 0.350 |

**Table 15**
The distances from ideal solutions.

| Alternative | $D(S_i, S^+)$ | $D(S_i, S^-)$ |
|---|---|---|
| A−1: Bakirkoy | 0.106 | 0.141 |
| A−2: Besiktas | 0.031 | 0.215 |
| A−3: Beylikduzu | 0.155 | 0.093 |
| A−4: Cekmekoy | 0.211 | 0.036 |
| A−5: Esenler | 0.217 | 0.029 |
| A−6: Kadikoy | 0.067 | 0.180 |
| A−7: Kartal | 0.197 | 0.052 |
| A−8: Sariyer | 0.093 | 0.154 |
| A−9: Uskudar | 0.106 | 0.141 |

successfully despite unforeseen obstacles. Second, Besiktas is also extremely sustainable, a factor that is becoming more significant for transportation networks across the globe. Besiktas's viability may be ascribed to its closeness to public transit, the availability of facilities, and its placement in a technological cluster. These elements make Besiktas a desirable alternative for people wishing to lower their carbon footprint or make ecologically responsible decisions. In the sensitivity analysis, the higher weighting of resilience and sustainability variables seems to have benefitted Besiktas. This finding underscores the importance of carefully weighing the relevant criteria and conducting sensitivity analyses when selecting a site for an AV parking lot. This decision involves multiple factors and can significantly impact transportation and infrastructure development.

Besiktas, Kadikoy and Sariyer consistently emerge as the top three alternatives in the AV parking lot selection problem. This suggests that they are reliable selections, with high overall performance across a variety of weighing conditions. Besiktas, Kadikoy and Sariyer excel in several areas, which may explain their persistent position at the top of the rankings. For example, Kadikoy does highly in terms of accessibility

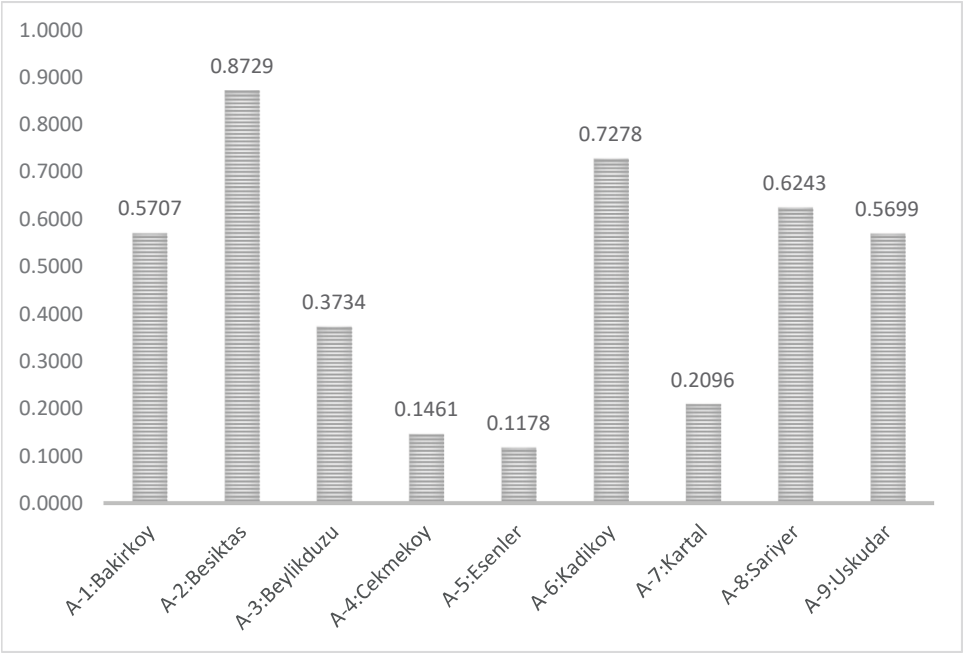


**Fig. 5.** Final scores of alternative locations.

**Table 16**
Modified main criteria weights for sensitivity analysis.

| Increasing | | **Resilience** | | | **Economic** | | | **Sustainability** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **10 %** | **20 %** | **30 %** | **10 %** | **20 %** | **30 %** | **10 %** | **20 %** | **30 %** |
| **Scenario Number** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| Resilience | 0.308 | 0.339 | 0.370 | 0.401 | 0.289 | 0.269 | 0.250 | 0.295 | 0.281 | 0.268 |
| Economic | 0.387 | 0.370 | 0.352 | 0.335 | 0.425 | 0.464 | 0.503 | 0.370 | 0.353 | 0.336 |
| Sustainability | 0.305 | 0.291 | 0.278 | 0.264 | 0.286 | 0.267 | 0.247 | 0.335 | 0.366 | 0.397 |

**Table 17**
The results of sensitivity analysis.

| | 1st Alternative | | 2nd Alternative | | 3rd Alternative | |
|---|---|---|---|---|---|---|
| Scenario | Score | Site | Score | Site | Score | Site |
| 0 | 0.8729 | Besiktas | 0.7278 | Kadikoy | 0.6243 | Sariyer |
| 1 | 0.8717 | Besiktas | 0.7260 | Kadikoy | 0.6199 | Sariyer |
| 2 | 0.8705 | Besiktas | 0.7241 | Kadikoy | 0.6152 | Sariyer |
| 3 | 0.8693 | Besiktas | 0.7222 | Kadikoy | 0.6107 | Sariyer |
| 4 | 0.8738 | Besiktas | 0.7298 | Kadikoy | 0.6319 | Sariyer |
| 5 | 0.8747 | Besiktas | 0.7319 | Kadikoy | 0.6396 | Sariyer |
| 6 | 0.8756 | Besiktas | 0.7338 | Kadikoy | 0.6472 | Sariyer |
| 7 | 0.8733 | Besiktas | 0.7279 | Kadikoy | 0.6221 | Sariyer |
| 8 | 0.8738 | Besiktas | 0.7281 | Kadikoy | 0.6198 | Sariyer |
| 9 | 0.8742 | Besiktas | 0.7281 | Kadikoy | 0.6174 | Sariyer |

to public transit, amenity availability, and proximity to the closest major road. Besiktas, on the other hand, is more suited for sustainable transportation systems due to its higher resilience and sustainability ratings. It is also crucial to highlight that both options are situated in the heart of Istanbul, close to technological centers and with strong levels of human capital and experience. These aspects add to their overall desirability as the locations of AV parking lots. Overall, the persistent placing of Kadikoy and Besiktas at the top of the rankings indicates that they are viable possibilities for the AV parking lot in Istanbul. The selection of one site over the other will rely on how decision-makers and stakeholders weigh the different factors.

In the second stage of the sensitivity analysis of the study, a single modification is applied to the FF-TOPSIS method. The change consisted of the replacement of a traditionally used distance metric to an alternative metric: instead of the Euclidean distance, the FF-TOPSIS technique is used with the Manhattan distance. This change allowed for testing the sensibility of the FF-TOPSIS results to a different distance measure for assessing the results. The Manhattan distance, known as the taxicab distance or city block distance, measures the difference between two points based on their coordinates. In the study, the Manhattan distance for ranking calculation is obtained by summing the absolute difference between two identical pairs of data points. This approach to the distance calculations attributed it to integral coordinate vectors creating sensitivity still to the FF-TOPSIS-type calculations. Thus, by comparing the outcomes of the FF-TOPSIS procedure with the Manhattan distances used for the calculation of final scores, updated rankings are obtained. Fig. 6 shows the final scores of alternatives.

Following the adjustment, the final scores of the alternatives were recalculated to determine any notable differences or fluctuations in the rankings of the parking lot locations under consideration. Besides, rankings of alternatives are compared and presented in Fig. 7. Fig. 7 shows the rankings for bot Euclidean distance and Manhattan distance.

The comparison between the two distance measures used in the proposed methodology, the Euclidean distance and the Manhattan distance, provide evidence of the sensitivity and consistency of the results. Despite the small changes observed in the ranking of specific alternatives, the overall patterns remained consistent between the two methodologies. In particular, the alternative ranked third in the proposed methodology dropped to fourth when the Manhattan distance was used. Conversely, the alternative ranked fourth in the proposed methodology rose to third when the Manhattan distance metric was used. This small change underlines the robustness of the decision process and shows that the results are both sensitive to changes in methodology and consistent across different distance metrics.

### 4.5. Comparative analysis

To further enhance the robustness and comprehensiveness of the proposed approach for AV parking lot site selection, a comparative analysis is performed involving different uncertainty measurement methods. This analysis addresses the inherent uncertainty in decision-making processes and provides valuable insights into the suitability of the chosen FF measurement approach. The proposed approach is extended to incorporate TOPSIS method within both spherical fuzzy (SF-TOPSIS) and pythagorean fuzzy (PF-TOPSIS) environments. This comparative analysis aims to offer an in-depth assessment of the effectiveness and consistency of the proposed methodology in different uncertain environments. By integrating the TOPSIS method across distinct fuzzy frameworks, the objective is to verify the reliability and stability of

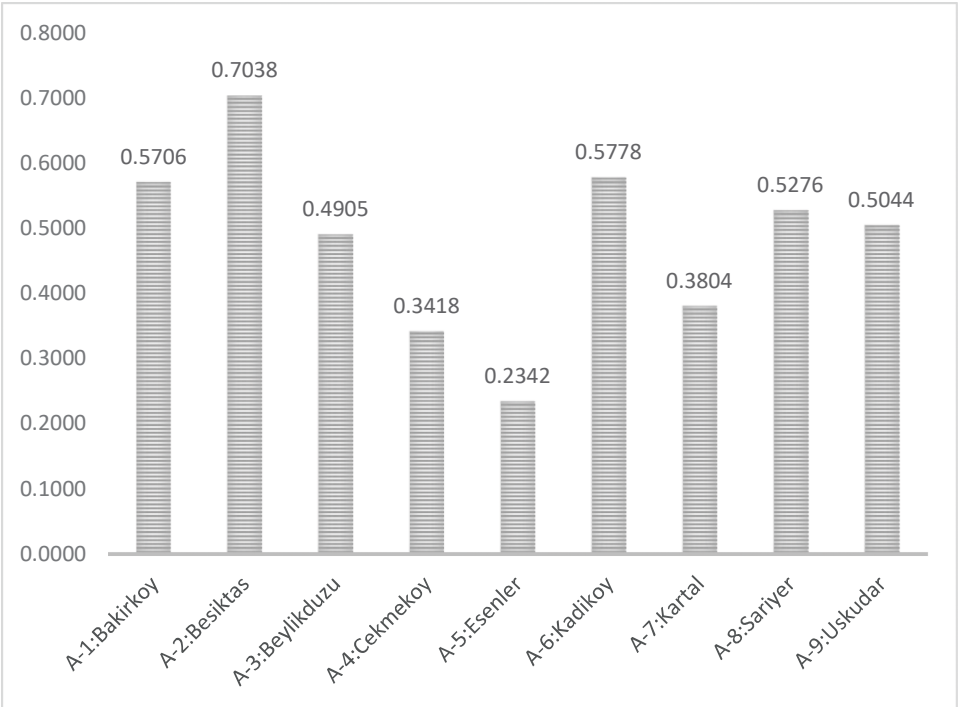


**Fig. 6.** Final scores of alternative locations for Manhattan distance.

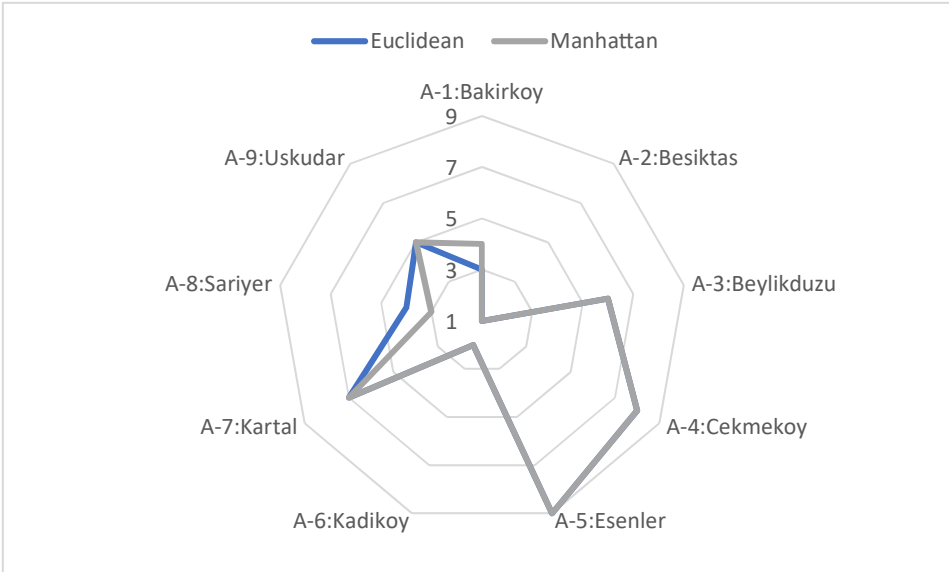


**Fig. 7.** Rankings of alternatives for different distance metrics.

**Table 18**
Final scores of alternative locations by PF-TOPSIS.

| | A-1 | A-2 | A-3 | A-4 | A-5 | A-6 | A-7 | A-8 | A-9 |
|---|---|---|---|---|---|---|---|---|---|
| **Final Score** | 0.4965 | 0.6004 | 0.4601 | 0.3768 | 0.3215 | 0.5250 | 0.4016 | 0.4735 | 0.4801 |
| **Ranking** | 3 | 1 | 6 | 8 | 9 | 2 | 7 | 5 | 4 |

the FF technique and its compatibility with established methodologies. The outcomes of this analysis contribute to a comprehensive understanding of the strengths and limitations associated with various uncertainty measurement techniques.

Pythagorean fuzzy sets are selected due to their ability to represent both the extent of belonging and the extent of non-belonging of an element within a set. This characteristic enhances their capacity to effectively manage the uncertainties and ambiguities inherent in decision-making scenarios. The PF-TOPSIS technique is employed to rank the available alternatives, utilizing the defined location selection criteria. A comparative analysis is conducted between the outcomes yielded by PF-TOPSIS and those achieved through the proposed integrated methodology. The prescribed application steps (see reference [107] for detailed information) of PF-TOPSIS are executed to yield the results, which are subsequently presented in Table 18 to show the location rankings obtained by PF-TOPSIS.

As shown in Table 18, the order of alternatives remains consistent across both methodologies, confirming that alternative A-2: Besiktas obtained as the best location.

Then, spherical fuzzy sets are chosen for their ability to encompass both the membership and non-membership degrees of elements within a set, providing a robust means to navigate uncertainties and ambiguities in decision-making contexts. SF-TOPSIS is employed to establish the rankings of alternatives, employing the predetermined location selection criteria. A comparative examination is conducted between the outcomes generated by SF-TOPSIS and those resulting from the proposed methodology. The application procedures as outlined (refer to [108] for comprehensive details) for SF-TOPSIS are performed, yielding the results detailed in Table 19, presenting the alternative rankings determined by SF-TOPSIS.

Based on the SF-TOPSIS results, the optimal alternative retained its position, while the second and third alternatives exchanged ranks. Notably, the fourth alternative dropped to fifth in the SF-TOPSIS rankings, and conversely, the fifth alternative moved up to fourth. Among the remaining five alternatives, their rankings remained unchanged.

The objective of the comparative analysis is to assess the effectiveness of the integrated FF-based MCDM approach proposed for selecting AV parking lot locations. This analysis involved a comparison between two distinct methods: PF-TOPSIS and SF-TOPSIS. Rankings are generated for the same alternatives and location selection criteria using both methods, as illustrated in Fig. 8.

Remarkably, nearly same rankings emerged across all methods, with only minor differences in final scores. This highlights the prowess and resilience of the integrated approach in effectively addressing MCDM challenges associated with selecting AV parking lot sites. The comparative analysis shows the methodology's potential to guide decision-makers toward informed and optimal choices within fuzzy and uncertain contexts. The results demonstrate the effectiveness and adaptability of the proposed methodology, which can be applied to a wide range of MCDM problems.

## 5. Conclusion and future directions

The selection of location for the parking lot is a social issue that severely restricts the development of society and the economy and has an impact on the quality of life. Parking lots are a component of the

**Table 19**
Final scores of alternative locations by SF-TOPSIS.

| | A-1 | A-2 | A-3 | A-4 | A-5 | A-6 | A-7 | A-8 | A-9 |
|---|---|---|---|---|---|---|---|---|---|
| **Final Score** | 0.6677 | 0.7210 | 0.5431 | 0.3579 | 0.1790 | 0.6535 | 0.4346 | 0.5954 | 0.5903 |
| **Ranking** | 2 | 1 | 6 | 8 | 9 | 3 | 7 | 4 | 5 |

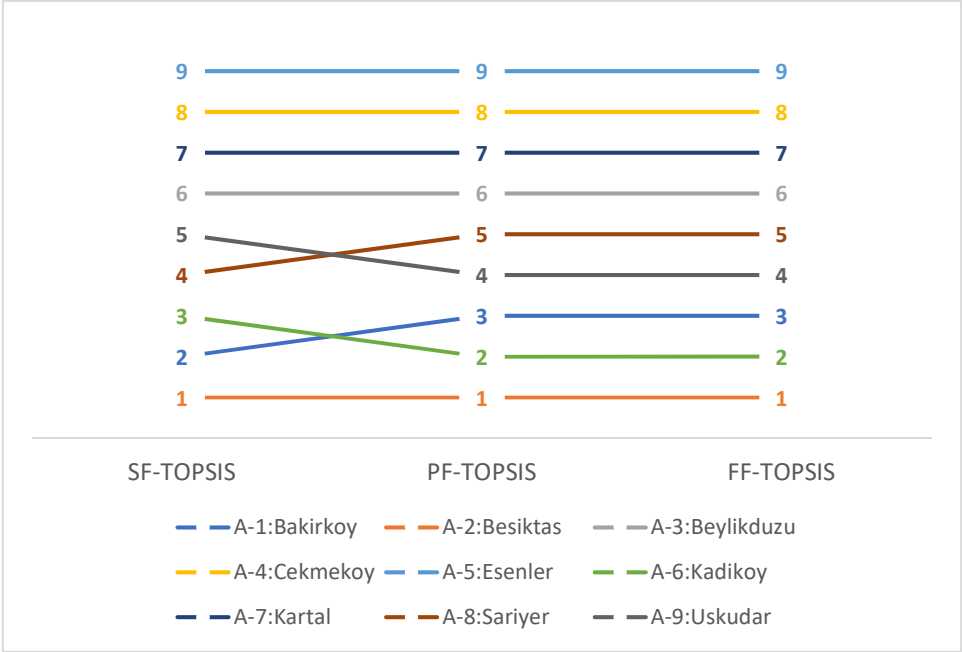


**Fig. 8.** The results of comparative analysis.

urban transportation system and are crucial in reducing the heavy traffic burden. With the inability to choose the parking areas correctly, vehicles occupy the pedestrian crossings by stopping on the street, thus disrupting the smooth traffic flow, and causing problems in transportation systems and urban traffic. Drivers need to spend a lot of time searching for a suitable parking spot in city centers, which may require them to use more roads. Making choices about new parking lots effectively and efficiently necessitates conducting thorough and methodical analyses. Additionally, as autonomous vehicles (AVs) are integrated into traffic in the upcoming years, the parking issue will become an even bigger urban concern. In this study, the parking lot selection problem for AVs is handled and SWARA and TOPSIS methods are used under FF environment to cope with the uncertain and complicated features of the problem. The SCOR-based hierarchy of location selection factors has been initially developed based on both professional judgment and literature analysis. Based on the views of experts, the main and sub-criteria weights have been determined using the FF-SWARA methodology, and in the final stage, the FF-TOPSIS method has been used to compare potential parking locations. Bakirkoy, Besiktas, Beylikduzu, Cekmekoy, Esenler, Kadikoy, Kartal, Sariyer and Uskudar districts have been determined as alternative regions in the case study for Istanbul which is the most populated and developed city of Turkiye. As a result of the detailed analysis, Kadıköy with its advantageous location, solid economy, accessibility, and expansion potential has been identified as the best solution for the AV parking lot. Sensitivity analysis has been then applied to help decision-makers gain useful insights into the robustness of the decision-making process and create more sustainable transport system decisions. The sensitivity analysis for AV parking lot selection challenges revealed that Kadikoy and Besiktas are the best options in a number of different situations. Both options have strong human capital and experience levels, are located in the center of Istanbul, and they are placed near to technological hubs. As a result, it increases their general appeal as AV parking lots. Overall, Kadikoy and Besiktas are feasible options for AV parking lots in Istanbul.

The managerial insights from this study provide insights into the best selection of AV car parks, focusing on two key criteria: cost and technological considerations. Cost and technology criteria are critical to the selection of AV car parks for several reasons. Firstly, cost considerations have a direct impact on the viability and sustainability of car parks. AV car parks require significant investment. Therefore, assessing the cost implications helps decision makers to allocate resources efficiently and ensure the economic viability of the project. Secondly, technological criteria are crucial as AVs rely heavily on advanced technologies for navigation, communication and automation. The selected car parks should be equipped with the necessary infrastructure to support the operation of AVs, such as charging stations, connectivity systems and automatic entry/exit mechanisms. The decision-makers evaluating the sub-criteria made a comprehensive assessment of the factors influencing site selection. Operating costs, safety and security measures and land costs were identified as the most important sub-criteria. This holistic approach enables them to make informed decisions aimed at minimizing costs, increasing security measures and optimizing land use. By prioritizing these aspects, urban planners and policy makers can strategically allocate resources, improve urban infrastructure, and contribute to the development of smarter, more efficient transport systems.

Identifying suitable parking spaces for AVs can increase the incentive for users to use AVs, which will lead to a noticeable reduction in all air and environmental pollutants from conventional vehicles. As mentioned in the previous sections, it would help to eliminate the alternative of having autonomous vehicles constantly cruising instead of parking, reducing wear and maintenance costs as well as congestion due to autonomous vehicles cruising in traffic when they are not actually needed. Because of these contributions to traffic management, this paper handles the problem of "optimal parking location for autonomous vehicles" is a unique guideline for urban planners to use in determining the appropriate location.

Although this study provides valuable information on the selection of AV car parks using hybrid fuzzy MCDM methodology, it also has some limitations. The evaluation criteria used in our study are based on expert opinion and literature review. However, the complexity of real-world decision scenarios may not be fully reflected by these criteria. Future research could explore more comprehensive criteria that cover a wider range of factors influencing AV parking choice. The results of our study are based on a case study analysis conducted in Istanbul, Turkiye. While the methodology is applicable to other urban areas facing similar challenges, the specific findings and conclusions may not be directly generalizable to different geographical contexts. Replication of the study in different locations may provide more robust and widely applicable

information. The selection of AV car parks is influenced by various external factors and uncertainties, such as legislative changes, technological developments and socio-economic trends. While this study accounts for some of these factors, the dynamic nature of external influences adds uncertainty to the decision making process. To address these challenges more effectively, future work could explore methods for combining uncertainty analysis and scenario planning.

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## CRediT authorship contribution statement

**Melike Erdogan:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Ertugrul Ayyildiz:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.asoc.2024.112198.

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