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Fuzzy-based GIS approach with new MCDM method for bike-sharing station site selection according to land-use types

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A R T I C L E I N F O

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A B S T R A C T

Bike-Sharing Systems (BSSs) support urban mobility by strengthening the scope of public transport networks, which may be insufficient in smart cities. This paper aims to present a hybrid approach that includes a Fuzzy Logic (FL)-based Geographic Information System (GIS), the Analytic Hierarchy Process (AHP), the VIse Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method, and the Psychometric-VIKOR method for the problem of the selection of BSS station sites depending on transportation and recreational land uses. The FL approach was included in the GIS analysis in order to characterize the uncertainty of a potential passenger's tendency to start a trip at a station within an accessible distance from the urban facilities. By combining fuzzy-based GIS analysis with the AHP method, a spatial analysis was performed for the deployment of BSS stations. The VIKOR and Psychometric-VIKOR methods were used to evaluate the performance of current and alternative locations of BSS station. This study is the first known application of the Psychometric-VIKOR method for the problem of the selection of BSS locations. The innovative hybrid approach can be used by authorities as a useful tool in solving decision-making problems that involve uncertainty in future urban investments.

1. Introduction

A BSS is an intelligent bike-rental system that allows urbanites to rent bicycles for short-term and short-distance journeys for a fee. A BSS is a system that aims to prevent climate change and traffic congestion and to increase physical activity (Guo et al., 2020b; Ma et al., 2020; Nikitas, 2018). Thanks to BSSs, urbanites can have the opportunity to use bikes, which are a healthier and greener transportation alternative (Midgley, 2009).

BSSs, which are smarter, cleaner, and healthier transportation models, can be utilized not only as an alternative in urban transportation, but also as a part of public transportation by bridging the gaps between different urban transportation modes (Eren and Uz, 2020; Guo et al., 2020a; Midgley, 2009, 2011; Shaheen et al., 2012). There are two types of bike-sharing models: the free-floating and station-based models (Ji et al., 2020; Pal et al., 2017). Unlike a free-floating BSS (Orvin et al., 2021), a station-based BSS can be defined as a type of public transport that provides bikes that can be rented from stations for short-term use (Gleason and Miskimins, 2012; Lu et al., 2019). In addition, due to the first- and last-mile solution, BSSs are transportation alternatives that support public transport networks (Chevalier et al., 2019). The first- and last-mile solution is intended to bridge the gap between transit hubs, shift individuals from motor vehicles to a healthier and more environmentally friendly mode of transportation, and increase the number of transit passengers (Shaheen and Chan, 2016). However, this replacement can occur in cities with strong BSS networks.

The success of station-based BSSs is based on the establishment of strong systems that can maximize users' demands and support or replace public transport (Eren, 2020; Scott et al., 2019; Sun et al., 2018). One of the most important strategic problems in planning and configuring systems for the success of a BSS is the determination of the optimal station locations by considering the spatial information (the built environment, land use, transportation infrastructure, natural environment, etc.) that can affect the travel demands (Zhang et al., 2017; Zhao et al., 2020). To overcome this problem, researchers have used GISs as tools for helping to manage spatially distributed data; they have also utilized GIS-based multi-criteria decision-making (MCDM) techniques that transform multiple spatial and non-spatial data into knowledge in order to decide on the best locations for BSS stations and to improve the efficiency of the BSS stations (Kabak et al., 2018; Unal et al., 2020; Yang et al., 2020).

Moreover, Faghih-Imani et al. (2017) stated that different travel

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demand patterns can be observed at stations that are deployed in areas with different types of land uses. Hence, to establish a successful station network, Shu et al. (2019) argued that it should be considered that the different land-use types and the intensity of their use can affect the station selection behavior of passengers. In addition, in their study, they determined the optimum distance and tolerable distance between the station and building entrance/exit by considering different land-use types and the intensity of their use. Therefore, in this paper, the land-use types are divided into two classes: transportation and recreation. In addition, the optimal distance and tolerable distances determined by Shu et al. (2019) are included in this study. The objectives of this research can be listed as follows:

- To present a fuzzy-based GIS approach with the AHP, VIKOR, and new Psychometric-VIKOR (Arslan, 2020) methods in order to determine suitable BSS station locations according to different land-use types.
- To evaluate the changes in the weights of the effectiveness of the spatial criteria in the deployment of BSS stations by using the AHP method according to the type of land use.
- To utilize the fuzzy approach to characterize the uncertainty of a potential passenger's tendency to start a trip at stations within optimal or tolerable distances from facilities.
- To assess the performance of existing and potential station locations for different types of land uses based on the final evaluation results obtained using innovative GIS-based multi-criteria-decision-making techniques: VIKOR and the new Psychometric-VIKOR.

2. Related work

Many methods have been developed for site selection problems by researchers working in different fields. However, this section focuses on studies on BSS station site selection that use the many different GIS-based optimization methods found in the literature.

The selection of suitable station locations to increase the effectiveness of BSSs is a popular topic in the literature. A few researchers have attempted to solve the problem of finding the most suitable locations by using hybrid approaches, including GISs, fuzzy methods, VIKOR, and other MCDM methods. Leigh et al. (2009) proposed a general GIS-based model for the BSS station site selection problem on the campus of Monash University in Australia. However, Luo-ke (2010) presented a comprehensive assessment that was not based on GIS, but included AHP and fuzzy methods for the problem of BSS station location selection in the Desheng Community and used various influencing factors. Wuerzer et al. (2012) defined a GIS-based optimization model to determine the optimal number of BSS stations and the station capacity in Boise. In this GIS-based model, buffer distances of 250 and 500 m—a walkable distance—were defined for very few decision criteria in order to limit the concept of proximity. Lin et al. (2013) developed a hub location inventory model for the design of a bike-sharing system. In their studies, the locations and capacities of the BSS stations were determined according to the costs of establishing the facilities, the user travel costs, and the service levels, but spatial features were not considered. Ghandehari et al. (2013) identified a hybrid model with mathematical programming and the AHP method in order to find the best locations for bicycle stations. In this study, a case study was conducted by weighting four main decision criteria: bicycle paths, transport and road networks, attraction areas that were in demand, and types of use. Similarly, in their study, to ensure the maximum efficiency in the use of public bicycles, Deng et al. (2015) determined that areas that were close to commercial and residential areas were suitable for stations by weighting effective criteria with the AHP method. Similarly to our work, in another study on the evaluation and repositioning of existing BSS station locations in Mashhad, seven decision criteria were weighted with the AHP. The fuzzy approach to the GIS was used to characterize notions of proximity, but not decisions to begin travel (Jahanshahi et al. (2019)). However, the study was carried out in a very limited framework due to the use of the concept of proximity, and the defined distances were not sufficiently supported by the literature. In addition, the suitability of the locations of nine existing stations belonging to a BSS was evaluated by Kabak et al. (2018). At the same time, they recommended the most suitable alternative BSS station locations in İzmir, Turkey, which were determined using the GIS-based AHP and MULTIMOORA methods with a maximum-coverage and minimum-impedance approach.

Moreover, the GIS-based location allocation model presented by Lopez Gonzalez (2016) maximized the coverage area to determine the optimal BSS station locations while minimizing the number of facilities. Frade and Ribeiro (2015) considered the optimal locations of alternative BSS stations, the size of the bicycle fleet, and the capacities of the stations under budget constraints with the maximum coverage model. Unlike this study, Conrow et al. (2018) investigated the best alternative BSS station locations in Arizona according to the GIS-based maximum-coverage and minimum-impedance approach while considering low-income regions for social equity. Likewise, a coverage model was proposed in order to determine the best station locations under a limited budget while considering multimodal accessibility of the BSS and public transport in order to minimize the inequalities between different groups in a population (Caggiani et al. (2020)). In addition, García-Palomares et al. (2012) introduced a GIS-based maximum-coverage and minimum-impedance model to determine the optimal station locations and capacities for a BSS while taking into account the spatial characteristics of the system's demand. Moreover, factors affecting bike-sharing system demand, such as transportation, built environment, and socioeconomic characteristics, were used in a GIS-based direct-demand model in order to determine the best BSS station locations in the catchment area of Divvy (G. Zhang et al. (2019)). Furthermore, studies using GIS and retail location theory for the determination of the most suitable locations for the establishment of new BSS stations and for the identification of hot spots that lacked bikes or bike racks were also encountered in the literature (J. Wang et al. (2016), Wuerzer and Mason (2016)). In addition to all of these studies, there were studies in the literature that performed BSS network optimization based on machine learning in order to perform balanced pick-and-drop activities in BSS networks (Liu et al. (2015)). The state of the art in bike-sharing site selection is shown in Table 1.

In previous studies that focused on the subject of bike-sharing station site selection, many methodologies that used various sub-criteria related to the built environment, land-use characteristics, transportation infrastructure, natural environment, and weather conditions were proposed. However, there are very few studies that have defined the access distances of all sub-criteria or assigned a buffer distance to the BSS stations. In addition, this paper advocates the necessity of using the fuzzy approach in order to characterize the tendencies of users to start trips at the stations within the access distances.

Moreover, the contributions of this paper to the literature are listed as follows:

- This is a new and comprehensive study that determines alternative BSS station locations by considering distances that that could affect a potential passenger's tendency to start a trip according to different land-use types. In addition, in this study, the spatial criteria were weighted according to different land-use types.
- This study is the first known application of the new Psychometric-VIKOR model proposed by Arslan (2020) for the site selection problem, which a multi-criteria-decision-making problem.
- In previous studies on the solution of alternative station location selection problems for BSSs (see Section 2), the complex and uncertain relationship between the distance to the nearest station from a facility and the decision to start trip was ignored. On the other hand, the studies contained proximity expressions for urban facilities or station buffer distances (Kabak et al., 2018). Unlike in previous studies (see Section 2), in this study, the optimal and tolerable access

Table 1
Studies on bike-sharing station site selection.

References	Scope of study	Methods	Key points
Leigh et al. (2009)	BSS station site selection on the Monash University campus in Australia was made using the constraints set by the Australian Standards for bicycle parking facilities.	GIS-based general model	The speed limit on the roadway which can be found near the stations to ensure passenger traffic safety is important.
Luo-ke (2010)	A solution method for the Desheng Community BSS in Hangzhou, China, station location selection problem using various influencing factors is proposed.	Fuzzy comprehensive assessment, AHP	The fuzzy comprehensive approach is useful for the BSS station site selection.
Wuerzer et al. (2012)	It is aimed to determine the optimum number of BSS stations and station capacity according to different station access distances (250 and 500 m) in an area of a 2.25-mile radius in Boise city center. Consequently, the optimum number of bicycle stations was determined as 14 stations and station capacities as 140 docks.	GIS optimization	In the created GIS model, the weight given to the criteria related to the university area and the transportation network is taken twice the weight of the criteria such as the park, restaurant, and ATM.
García-Palomares et al. (2012)	A model considering characteristics of transport infrastructure such as metro and suburban stations to determine the optimum station location and station capacity for a BSS, as well as the spatial characteristics of the system's demand, is proposed.	GIS-based maximum coverage and minimum impedance	An additional station accessibility analysis was also conducted to identify stations with low demand.
Lin et al. (2013)	In order to determine the number and location of bicycle stations, a model is created that takes into account the creation of bicycle lanes between stations and the bicycle inventory levels at the stations.	A hub location inventory model	Establishment costs of the facilities included in the system design, user travel costs, and service levels are taken into consideration.
Ghandehari et al. (2013)	A case study was conducted for BSS station site selection in Iran on criteria for four main groups of bicycle path, transport and road networks, demand attraction areas and type of use.	AHP and GIS	Determining the optimal bike rental station location would increase the use of bicycles in urban transportation.
Deng et al. (2015)	For layout optimizing of public bicycle stations, the decision criteria determined to increase the trip generation at the Wuhan BSS stations is weighted according to the land use type using the AHP method, and the type of land use increasing trip generation is indicated.	AHP	The station area proximity to commercial areas and residential communities should be preferred for maximum trip demand in BSS station site selection studies.
Liu et al. (2015)	A bike sharing network optimization study is carried out to achieve balanced pick-up and drop off activities in the BSS station network.	Voronoi-based grid method	The study is conducted using attractor points (shopping centers, entertainment centers, administrative areas, restaurants) and features related to the transportation network.
Frade and Ribeiro (2015)	Optimum location of alternative BSS stations, the size of the bicycle fleet and the capacity of the stations under budget constraints is determined.	Maximum coverage model	The study area is divided into 61 traffic zones for small enough to allow walking between two points, or a maximum of 500 m.
Lopez Gonzalez (2016)	The optimum BSS station locations is determined with a GIS-based location allocation model that maximizes coverage and minimizes the number of facilities.	GIS-based location allocation	Identifying optimal BSS station locations is an important parameter for a successful system.
Wang et al. (2016)	It was aimed to determine the most suitable location for the new stations that could be established and, the lacking-bike and/or lacking-bike rack hot spots in Taiwan.	GIS, Retail location theory, Anselin Local Moran's I	In cases where the Euclidean distance between any two stations is less than 600 m, the user demand should be analyzed accordingly.
Wuerzer and Mason (2016)	It is aimed to determine the optimum station location for a new BSS in the USA.	GIS-based retail gravity	In the model, a radius of 800 m is defined to industrial-commercial areas.
Kabak et al. (2018)	The most suitable alternative BSS station locations in İzmir, Turkey are determined. Also, the location suitability of nine existing stations belonging to a BSS is evaluated. Existing and alternative station locations are sorted.	GIS, AHP- and MULTIMOORA	Optimum station locations is assigned under the condition of proximity to sub-criteria.
Conrow et al. (2018)	The best alternative BSS station locations in Arizona are investigated considering low-income regions for social equity.	GIS-based coverage optimization	Different access distances have been defined such as 0.5 miles to the bike path, 0.25 miles to the bus stop, 0.5 miles to the low-middle income region, 0.5 miles to the population density.
Zhang et al. (2019)	The most suitable station location for Divvy BSS in Chicago is determined using independent variables related to transportation, built environment, and socio-economic characteristics that affect bike sharing demand.	GIS- direct demand model	The relationship between the independent variables and the monthly rental numbers in the station was investigated by defining the access distance of BSS stations between 200-800 m.
Jahanshahi et al. (2019)	For the evaluation and repositioning of existing Mashhad BSS station locations, seven decision criteria are weighted by AHP. The fuzzy approach in GIS is used to characterize the concepts of proximity. From the suitability maps, 22 alternative station locations are determined. The 128 available stations are sorted with VIKOR.	Fuzzy, GIS, AHP, VIKOR and JENKS	The study is carried out in a very limited framework since the concept of proximity is usually used, the defined access distances are not sufficiently supported by the literature.
Caggiani et al. (2020)	In this study, a model is proposed to determine the best station location under a limited budget, considering the multimodal BSS-public transport accessibility in order to minimize the inequalities between different groups of the population.	Theil index	it is argued that the users 'having less walking distance to the public transportation system would increase the users' tendency to use the system.
Proposed Paper	Optimum locations for the bike-sharing station are determined using the fuzzy-based GIS approach with innovative MCDM technique according to twenty-one sub-criteria for two land-use types.	Fuzzy-GIS-AHP-VIKOR-Psychometric-VIKOR	This study is the first known application of Psychometric-VIKOR for the site-selection problem. Also, the access distances of each facility to the BSS station are conceptualized with a fuzzy methodology.

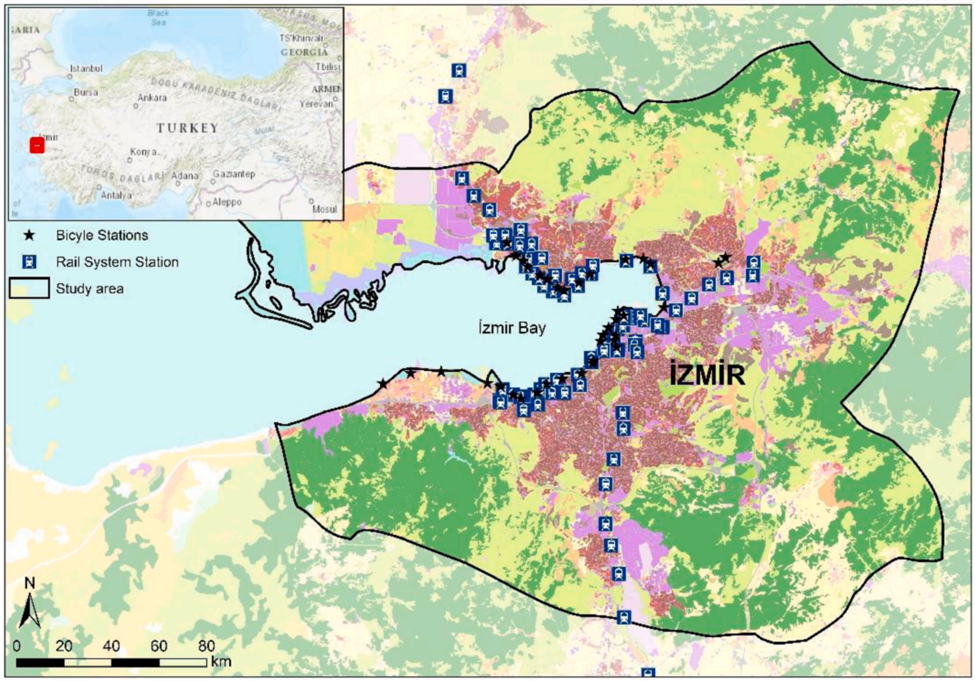

Fig. 1. Study area.

distances of each facility with respect to the BSS stations were conceptualized with a fuzzy methodology. Therefore, this study fills an important gap in the literature regarding alternative station site selection problems, especially for BSSs.

3. Materials and Methods

3.1. Study area

İzmir is one of Turkey's most important metropolises with regards to the intensity of transportation and economic and cultural mobility. Bisim is a BSS operating in the province of İzmir. The system contains 40 stations and 550 bicycle fleets. Almost all existing stations are located on scenic roads on the seaside and close to recreation areas. The fact that the station network of the system is located only in seaside areas and the unbalanced distribution of distances between existing bicycle-sharing stations are expressed as important problems that negatively affect the sustainability of the system (Kabak et al., 2018). Therefore, this study is intended to eliminate station-level problems that affect the sustainability of the existing system in order to have a more homogeneously distributed station network. Thus, eight central districts of the İzmir province were selected as the study area (Fig. 1).

3.2. Determination of criteria and access distances

The determination of the criteria that are effective in establishing or configuring a BSS network is the most important part of the achievement of smooth operation and profit from the system. In this study, three main factors, nine main criteria, and twenty-one sub-criteria for the selection of the optimal BSS station locations according to different land uses in İzmir were determined by using previous studies and expert opinions. The hierarchical structure established is shown in Fig. 2.

The expert panel consisted of a group of thirteen decision makers. The expert panel included a chief of the İzmir Transportation Planning Directorate and five, three, and four academics concerned with transportation planning, location selection, and sustainability, respectively. Regarding the decision criteria, the brief descriptions, optimum and tolerable access distances, analysis types, and data sources are presented in Table 2.

The access distances given in Table 2 are the key findings of a study by Shu et al. (2019). Shu et al. (2019) defined two distances for the access distances from the facilities to the BSS stations. They were the optimal distance and the tolerable distance. The optimal distance refers to the distance of a BSS station from their location for which 85% of the passengers are likely to continue or start their travel by renting a bike. These locations include facilities such as railway system stations, bus stops, hospitals, etc. On the other hand, a tolerable distance is the distance between the station and facility for which only 15% of users are willing to choose to start their trip. In addition, in their statistics-based studies, Hyndman RJ et al. revealed similar results regarding the appropriateness of using these given probability values. Moreover, almost no passengers prefer to rent bicycles at stations that are located at locations that are more remote than the tolerable distance. Furthermore, the access distance from a facility to the nearest station can vary according to facility. This is due to the fact that potential passengers' travel purposes are different, and individuals tend to change their walking distances according to their travel purposes.

Meanwhile, previous studies that have included the BSS station location selection criteria used in this paper are brought together and shown in Table 3. The BSS station site selection criteria that were frequently used in previous studies were taken into consideration in this study, and a comprehensive study was carried out by including new additional criteria from decision makers. According to Table 3, the population density, parks, rail system stations, and bicycle paths stand out as the most frequently used criteria in previous studies.

3.3. Proposed Fuzzy-based GIS approach to the BSS Site selection problem

The fuzzy logic approach was first introduced by Zadeh (1965) in order to identify complex systems and solve ambiguous real-life problems. In this study, the fuzzy approach was utilized to characterize the uncertainty of a potential passenger's tendency to start a trip at stations within the optimal and tolerable distances from the facilities. The decision to start a trip at the BSS station closest to the facility at which a potential passenger is located may vary depending on the distance

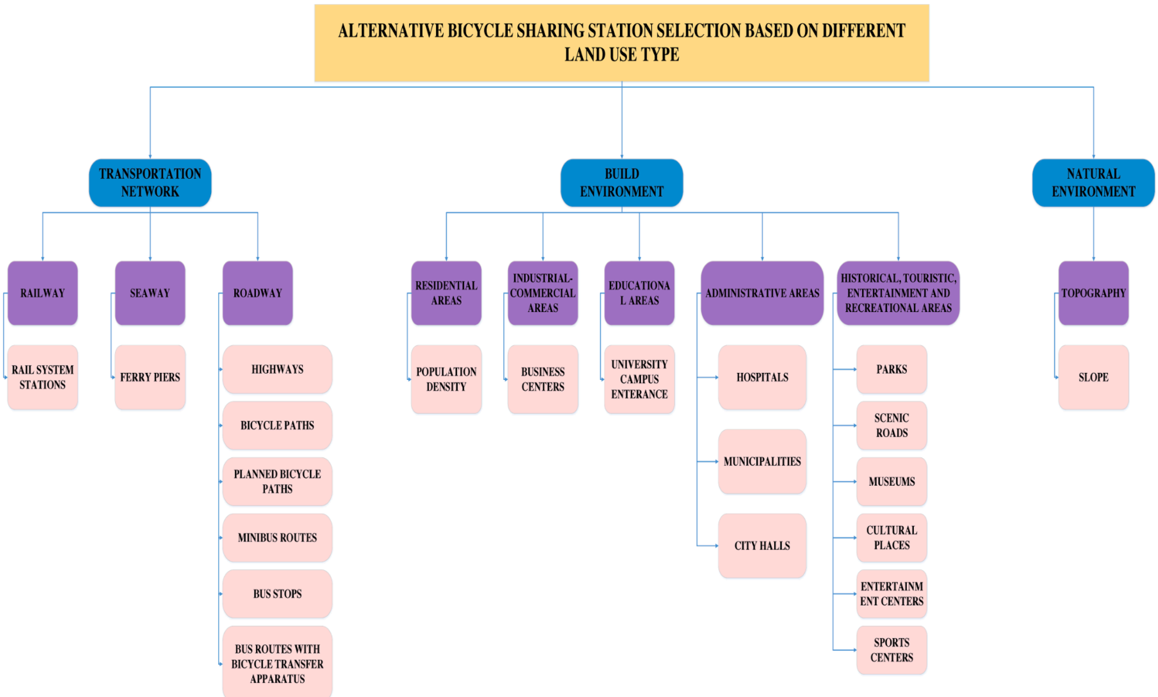

Fig. 2. Main factors, main criteria, and sub-criteria in hierarchical structure.

between the facility and the BSS station. In addition, the walking distances of individuals can be short or long relative to each other depending on their travel purposes (Caggiani et al., 2020). This uncertainty in the decision to start a trip at a BSS station can be expressed as a fuzzy problem. On the other hand, the reason for this can be explained by the fact that passengers sometimes tend not to want to rent bicycles despite the proximity of the BSS station, or they can walk long distances regardless of how far they are from the station from which they want to rent. This gives an innovative perspective to the literature in terms of the incorporation of ambiguity in passengers' decisions to start a trip into research within a scientific framework by using a fuzzy approach and determining the exact points of the appropriate locations of alternative stations within the optimal and tolerable distances, rather than by using a relative expression, such as proximity (Fig. 3).

Fig. 3 shows the working principles of the fuzzy-based GIS approach. The fuzzy membership tool in the GIS environment not only defines a value of "1" for "each blue location within the blue circle with the optimal distance radius", but also assigns a value between 1 and 0 to "each green location within the green circle with the tolerable distance radius". Moreover, the tendency to start a trip at a station located further from a point on the periphery of the green circle is considered as a value of "0" by the fuzzy membership tool. For example, the linear membership function is selected with the fuzzy membership tool in GIS for the bus stop criterion. Then, the fuzzy membership tool is utilized to assign the value of 1 as a fuzzy number for the range of 0–30 m (optimal distance) and a linearly decreasing fuzzy number from 1 to 0 for the range of 30–120 m (tolerable distance). The fuzzy membership tool includes different types of membership functions: S-shaped, J-shaped, linear, etc. (Unal et al., 2020). In this regard, the types and control points of the membership functions can be determined by researchers depending on the nature of the problem under consideration (Katanalp and Eren, 2020).

GIS allows the visualization of 3D scenes, the editing of different types of data, and spatial analyses of information layers. However, in the pre-analysis step in GIS, depending on the purpose of the analysis, the collected data may have many differences in terms of their form, size, coordinate system, and scale (Katanalp and Eren, 2021; Rahimi et al., 2020). Therefore, data should be standardized before the main analysis steps in GIS. However, because the fuzzy-based GIS approach provides standardized maps, there is no need for an additional standardization process. Thus, this approach provides suitability maps by displaying more than one standardized information layer on a single map. In the main analysis step, the weights obtained with the AHP method according to the land-use types are multiplied with the standardized maps. Finally, two suitability maps are obtained with the fuzzy-based GIS approach by combining weighted and standardized maps.

The framework of this study is presented in Fig. 4. As shown in Fig. 4, the first stage includes the review of the literature related to the purpose of this study, the formation of the decision-making group, the determination of the decision criteria, and the identification of the access distances of sub-criteria. In the second stage, spatial analyses are performed in GIS by creating maps of the determined sub-criteria. Then, the fuzzy approach is integrated with the GIS analysis in order to characterize the uncertainty in a potential passenger's tendency to start a trip at stations that are within accessible distances from facilities. In the next stage, the AHP method is utilized to evaluate the criteria that are effective in deploying BSS stations in areas with different land-use types and to evaluate the changes in the weights of the criteria according to the land-use types. In the fifth stage, by overlaying the weighted and fuzzified maps, suitability maps for transportation and recreation are obtained. Finally, the performance of the alternative and existing station locations is evaluated by using the VIKOR method and the new Psychometric-VIKOR method.

3.4. Analytic hierarchy process (AHP)

The Analytic Hierarchy Process (AHP) was recommended by Saaty not only for identifying and prioritizing indicators that can serve particular purposes, but also for ranking alternatives from the best to the worst (Saaty, 1980). On the other hand, the AHP is an MCDM method that is frequently used in the literature for the linear weighting of decision criteria that were determined by decision makers to solve site selection problems (Ali et al., 2020). In the AHP method, the knowledge of decision makers is used to estimate the relative size of criteria through

Table 2
Definition of each criterion.

Factors	Main-Criteria	Sub-criteria	Definition	Access Distance		Analysis Type	Data Source
				Optimum	Tolerable		
Transportation Network (F1)	Railway (C1)	Rail System Stations (C1.1)	Associated with higher station use.	55 m	165 m	Euclidean Distance	Izmir Metropolitan Municipality
	Seaway (C2)	Ferry Piers (C2.1)	Increases not only the number of transit passengers between different modes but also the demand for maritime transport.	65 m	165 m	Euclidean Distance	Open Street Map Data
	Roadway (C3)	Highways (C3.1)	May facilitate access to urban transport alternatives.	10 m	30 m	Euclidean Distance	Izmir Metropolitan Municipality
		Bicycle Paths (C3.2)	BPS stations built on roads equipped with bicycle facilities are more preferred by users.	20 m			
	80 m Euclidean Distance	Izmir Metropolitan Municipality					
		Planned Bicycle Paths (C3.3)				Euclidean Distance	Izmir Metropolitan Municipality
		Minibus Routes (C3.4)	Provides support for public transportation.	30 m	130 m	Euclidean Distance	Izmir Metropolitan Municipality
		Bus Stops (C3.5.)	Increases the number of transit passengers between different modes.	30 m	130 m	Euclidean Distance	ESHOT General Directorate
		Routes of Bus Lines with Bicycle Transfer Apparatus (C3.6)				Euclidean Distance	ESHOT General Directorate
Build Environment (F2)	Residential Areas (C4)	Population Density (C4.1)	High population density is associated with more station use.	45 m	140 m	Density	https://www.nufusu.com/ilceleri/izmir-ilceleri-nufusu
	Industrial-Commercial Areas (C5)	Business Centers (C5.1)	Cycling to work is important for the relief of traffic.	45 m	140 m	Euclidean Distance	Open Street Map Data
	Educational Areas (C6)	University Campus Entrance (C6.1)	Young and highly educated individuals tend to use bicycles.	50 m	120 m	Euclidean Distance	Open Street Map Data
	Administrative Areas (C7)	Hospitals (C7.1)	Facilitating access to important public institutions and urban administrative areas with BPS stations increases the demand for bicycle sharing at stations.	40 m	105 m	Euclidean Distance	Open Street Map Data
		Municipalities (C7.2)				Euclidean Distance	Open Street Map Data
		City Hall (C7.3)				Euclidean Distance	Open Street Map Data
	Historical / Touristic, Entertainment and Recreation Areas (C8)	Parks (C8.1)	High trip generation in the stations located close to Historical / Tourist, Entertainment and Recreation Areas	65 m	125 m	Euclidean Distance	Open Street Map Data
		Scenic roads (C8.2)		75 m	190 m	Euclidean Distance	Open Street Map Data
		Museums (C8.3)		45 m	150 m	Euclidean Distance	Open Street Map Data
		Cultural places (C8.4)				Euclidean Distance	Open Street Map Data
		Entertainment Centers (C8.5)				Euclidean Distance	Open Street Map Data
		Sports Centers (C8.6)				Euclidean Distance	Open Street Map Data
Natural Environment (F3)	Topography (C9)	Slope (C9.1.)	Slope levels between 0 and 8 degrees are acceptable for cycling. 0-2 is very good, 2-4 is good, 4-6 is moderate, 6-8 is bad. Bicycle use is generally not preferred in areas with slopes over 8 degrees.	0-4%	4-8%	Slope	Open Street Map Data

binary comparisons (Rahimi et al., 2020). Firstly, a decision problem must be defined, and the main criteria and sub-criteria related to the problem are determined by consulting the literature and expert opinions. Then, according to the nature of the problem, a multi-level hierarchical structure is created, which includes the main criteria and sub-criteria. Based on the hierarchical structure that is created, pairwise comparisons are performed by experts according to the Saaty scale (Saaty, 1980). Thereby, the weights of the evaluation criteria are obtained.

3.5. The VIse Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR)

VIKOR is an MDCM technique for revealing the preferences of decision makers that has become widespread in recent years. VIKOR was presented by Opricovic (1998), and its use (alone or modified with another model) in the field of transportation engineering has spread over various topics, such as road material maintenance (Babashamsi et al., 2016; Zheng et al., 2019), route planning (Deveci et al., 2017; Kosijer et al., 2012), optimal station site selection (Hsu et al., 2018; Xu et al., 2017), and logistic activities (Kabir, 2015; Soner et al., 2017). In addition, the VIKOR method is a method that is frequently preferred in all other fields in the literature that utilize site selection or rank alternatives (Kannan et al., 2020). In this study, while sorting the alternative BSS station locations with VIKOR, the problem is addressed in the form of a matrix (Eq. 1).

Table 3
The BSS station location selection criteria in previous studies.

Sub-Criteria	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
Rail System Stations (C1.1)			▼		▼			▼	▼		▼	▼
Ferry Piers (C2.1)									▼			▼
Highways (C3.1)	▼				▼							▼
Bicycle Paths (C3.2)				▼		▼		▼	▼	▼	▼	▼
Planned Bicycle Paths (C3.3)						▼						▼
Minibus Routes (C3.4)								▼				▼
Bus Stops (C3.5.)		▼		▼	▼			▼		▼		▼
Routes of Bus Lines with Bicycle Transfer Apparatus (C3.6)												▼
Population Density (C4.1)		▼	▼	▼		▼		▼	▼	▼	▼	▼
Business Centers (C5.1)			▼	▼			▼	▼			▼	▼
University Campus Entrance (C6.1)		▼			▼							▼
Hospitals (C7.1)							▼					▼
Municipalities (C7.2)				▼			▼					▼
City Hall (C7.3)				▼			▼					▼
Parks (C8.1)		▼	▼	▼			▼	▼	▼			▼
Scenic roads (C8.2)									▼			▼
Museums (C8.3)					▼		▼					▼
Cultural places (C8.4)				▼	▼			▼	▼			▼
Entertainment Centers (C8.5)					▼		▼	▼	▼		▼	▼
Sports Centers (C8.6)			▼						▼			▼
Slope (C9.1.)	▼					▼					▼	▼

▼: Source: [1] Leigh et al. (2009), [2] Wuerzer et al. (2012), [3] García-Palomares et al. (2012), [4] Ghandehari et al. (2013), [5] Croci and Rossi (2014), [6] Lopez Gonzalez (2016), [7] Wuerzer and Mason (2016), [8] Cetinkaya (2017), [9] Kabak et al. (2018), [10] Conrow et al. (2018), [11] Jahanshahi et al. (2019), [12] Proposed paper.

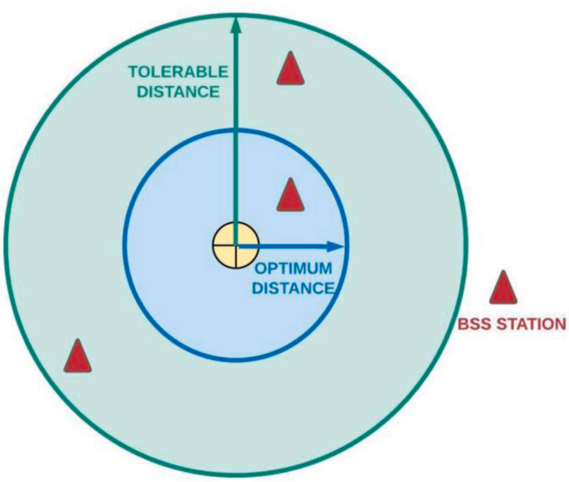

Fig. 3. Optimum and tolerable distances from urban facilities.

$$MCD = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \\ \vdots \\ A_i \end{array} \left[\begin{array}{cccccc} & criteria\,(c_1 \ldots c_j) & & & & \\ f_{11} & f_{12} & f_{13} & f_{14} & \cdots & f_1j \\ f_{21} & f_{22} & f_{23} & f_{24} & \cdots & f_2j \\ f_{31} & f_{32} & f_{32} & f_{34} & \cdots & f_3j \\ f_{41} & f_{42} & f_{43} & f_{44} & \cdots & f_4j \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ f_{i1} & f_{i2} & f_{i3} & f_{i4} & \cdots & f_ij \end{array} \right] \tag{1}$$

where MCD is the multi-criteria decision matrix, A_i represents the alternative BSS station locations, c_j represents the criteria for each alternative, and f_{ij} denotes the rating values of the BSS station locations A_i with respect to each criterion c_j. After obtaining the necessary data for the building of the multi-criteria decision matrix from GIS, application of VIKOR for the ordering of the BSS station locations is performed by using the following algorithm.

1. The best and worst values that the criteria get are determined.
while f_j^* is the best and f_j^- is the worst value
if criterion j is the benefit criterion

$$f_j^* = max_i\left(f_{ij}\right), f_j^- = min_i\left(f_{ij}\right) \tag{2}$$

if criterion j is the cost criterion

$$f_j^* = min_i\left(f_{ij}\right), f_j^- = max_i\left(f_{ij}\right) \tag{3}$$

2. Calculation of S_i and R_i

$$S_i = \sum w_j\left(f_j^* - f_{ij}\right) \Big/ \left(f_j^* - f_j^-\right) \tag{4}$$

$$R_i = max_i\left[w_j\left(f_j^* - f_{ij}\right) \Big/ \left(f_j^* - f_j^-\right)\right] \tag{5}$$

3. Calculation of Q_i**while** $S^* = min_i S_i$, $S^- = max_i S_i$, $R^* = min_i R_i$, $R^- = max_i R_i$

$$Q_i = (\vartheta(S_i - S^*) / (S^- - S^*) + (1 - \vartheta)(R_i - R^*) / (R^- - R^*)) \tag{6}$$

where ϑ is the weight strategy with the maximum benefit. Note that ϑ is generally accepted to be 0.5 (Kim and Ahn, 2019).

4. The values of S, R, and Q are sorted and the ranking results of the BSS station locations are obtained. Note that after listing the BSS station locations A_i, the conditions of acceptable advantage and acceptable stability must be met.

3.6. *The Psychometric-VIKOR Method*

The Psychometric-VIKOR approach is a modification of the traditional VIKOR method with the Weber–Fechner psycho-physical law from behavioral psychology. The Psychometric-VIKOR method reflects perceptual discrimination by assessing the alternatives according to a given set of criteria in an MCDM problem in which decision makers' preferences and subjective judgments are fully unidentified (Arslan, 2020). MCDM methods such as TOPSIS, ELECTRE, and PROMETHEE are not skilled enough to reveal the cognitive aspects of human behavioral psychology (Arslan, 2020). However, the Psychometric-VIKOR approach is a useful tool for characterizing the non-linearity of subjective assessment scales in the perceptions of decision makers. This skill comes from the "just-noticeable differences" (jnds) idea in the Weber–Fechner psycho-physical law (Stevens, 1957; Weber, 1834). Moreover, this idea refers to the Psychometric scale that is used to measure the distances from the best or worst solution.

$$Q\Delta f_0 = \in f \ or \ \in = \Delta f_0 / f \tag{7}$$

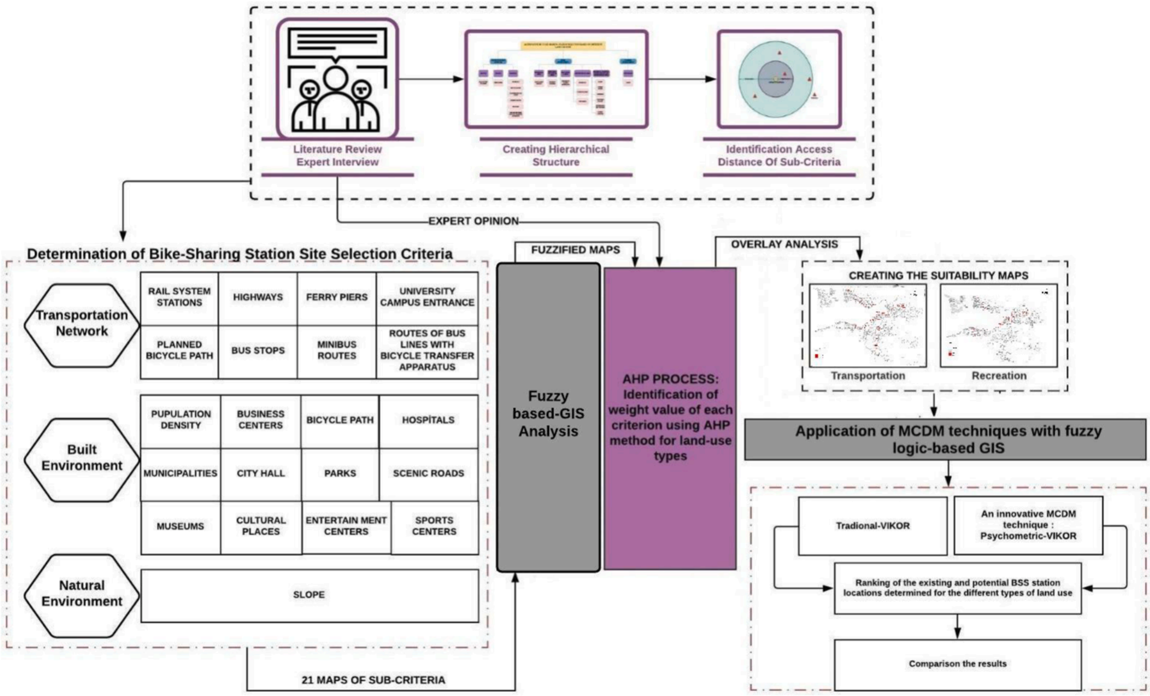

Fig. 4. The framework of the study.

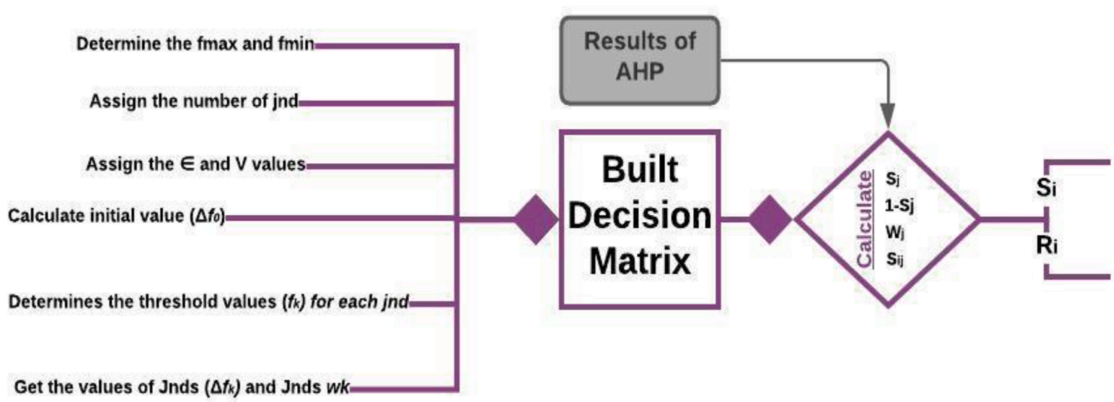

Fig. 5. The flowchart for Psychometric-VIKOR method.

where Δf represents the jnd, f represents the initial stimulus intensity, and $\in$ is a ratio called the Weber fraction. Moreover, the relationship between the intensities of two real stimuli in a given range creates a geometric sequence (for more details, please refer to (Arslan, 2020)), and here, the first value can be defined as follows:

$$\Delta f_0 = \frac{fmax - fmin}{(1 + \in)^{v}} \tag{8}$$

$$\Delta_{f_1} = \Delta_{f_0} + \in \Delta_{f_0} \tag{9}$$

where $(1 + \in)$ is the progression factor in a geometric sequence, and v is an integer representing the value of the number of jnds – 1, which is determined in the range of $fmax - fmin$. In the Weber–Fechner law, when the two alternatives are compared over $fmax - fmin$, the effects of the unit distances between the alternatives to *fmin* and *fmax* are different from each other and change nonlinearly. As a result, the Psychometric-VIKOR method, which was created by adapting the f_j^- and f_j^* values in VIKOR to $fmax - fmin$ in the Weber–Fechner law, eliminates the shortcomings of the VIKOR method in characterizing the nonlinearity of subjective evaluation scales in the perceptions of decision makers.

According to Fig. 5, the Psychometric-VIKOR method includes an eight-step preliminary stage.

- Determine *fmax* and *fmin* based on criteria related to the benefit or cost.
- Assign the number of jnds, $\in$, and v depending on the nature of the decision problem.
- Calculate the initial value (Δf_0) by using Equation 12.
- Determine the threshold values (f_k) for each jnd.
- Get the values of the jnds for (Δf_k) and the jnd w_k.
- Build the decision matrix.
- Calculate S_j, (1-Sj), W_j, S_{ij}, S_i, and R_i with the use of the results of the AHP.
- Rank by ascending value of S_i and check the values of R_i.

In the Psychometric-VIKOR method, a standardized decision matrix is created first, as in the VIKOR method. To define the weight for criterion j, first, Sj is calculated (Equation 14).

while f_j denotes the rating value of criterion j,

Table 4
Identification of weight of each criterion.

Criteria / Land-use Type		Transportation	Recreation
F1-Transportation Network		0.6407	0.3495
C1	C1.1	0.2520	0.0912
C2	C2.1	0.1637	0.1011
C3	C3.1	0.0416	0.0227
	C3.2	0.0535	0.0440
	C3.3	0.0311	0.0231
	C3.4	0.0207	0.0147
	C3.5	0.0334	0.0234
	C3.6	0.0448	0.0293
F2- Build Environment		**0.1782**	**0.4645**
C4	C4.1	0.0558	0.1432
C5	C5.1	0.0271	0.0577
C6	C6.1	0.0501	0.0791
C7	C7.1	0.0117	0.0212
	C7.2	0.0098	0.0195
	C7.3	0.0060	0.0111
C8	C8.1	0.0041	0.0251
	C8.2	0.0033	0.0192
	C8.3	0.0015	0.0131
	C8.4	0.0020	0.0174
	C8.5	0.0031	0.0357
	C8.6	0.0038	0.0225
F3-Natural Environment		**0.1811**	**0.1860**
C9	C9.1	0.1811	0.1860

if $f_k \le f_j < f_{k+1}$

$$S_j = \frac{(fmax - f_j) * (jnd\ w_k)}{\sum_{k=1}^{Number\ of\ jnd} (jnd\ w_k) * (jnd\ \Delta f_k)} \tag{10}$$

In addition, f_j is the standardized form of the weight obtained by the AHP for criterion j, and $jnd\ w_k$ is the weight value assigned to each jnd. Then, the values of Sj are subtracted from 1 (1 – Sj) and normalized. Thereby, a weight value (W_j) is obtained for each criterion in the range of 0–1. Moreover, the performance value S_{ij} of each alternative is calculated according to the following steps:

while f_{ij} denotes the rating values of alternative i with respect to each criterion j,

if $f_k \le f_{ij} < f_{k+1}$

$$S_{ij} = \frac{(jnd\ w_{k+1}) * (f_k - f_{ij}) + \sum_{k=0}^{k} (jnd\ w_k) * (jnd\ \Delta f_k)}{\sum_{k=1}^{Number\ of\ jnd} (jnd\ w_k) * (jnd\ \Delta f_k)} \tag{11}$$

Furthermore, the values of S_i and R_i are calculated by using Eqs. 12 and 13.

$$S_i = \sum_{j=1}^{n} W_j * S_{ij} \tag{12}$$

$$R_i = max_i [W_j * S_{ij}] \tag{13}$$

Finally, the values of S_i and R_i obtained for each alternative are listed in ascending order.

4. Results and discussion

4.1. Analysis of the AHP

Not every independent criterion given in the hierarchical structure will have the same importance, impact, or weight when deploying stations in areas with different land uses. The AHP method was used to determine the weights of each independent criterion at station locations in areas with different land uses. A thirteen-person group of decision makers was established for the weighting of each independent criterion in the AHP method; the evaluators were highly prestigious academics and experts on issues related to transport planning, site selection, sustainability, and accessibility. As a result of the evaluation, the final scores were obtained by taking the geometric means of the scores in the pairwise comparison matrices created by the thirteen decision makers using the Saaty scale. Then, it was necessary to compare whether the consistency ratio (CR) values of the pairwise comparison matrices were within the range of 0 to 0.10. In the pairwise comparisons that were conducted according to different land uses, the CR value of each matrix was calculated, and it was determined that it did not exceed 0.10. In addition, the CR values of each matrix were controlled by using the "Super decision" program. After checking if the consistency test was passed, the pairwise comparison matrices were normalized. Thus, the weights of the decision criteria were obtained according to the different land-use types and are given in Table 4.

According to the results of the AHP, the order of importance of the factors was determined to be "F1, F3, F2" and "F2, F1, F3" for the transportation and recreation land-use types, respectively. In addition, while the most important criterion for the transportation type was C1 (railway transportation), the most important criterion for the recreational type was C9 (topography). In addition, the order of the criteria from the most important to the least significant was C1-C3-C9-C2-C4-C6-C7-C5-C8 for the transportation land-use type. However, the order for the recreational land-use type was C9-C3-C4-C8-C2-C1-C6-C5-C7. As a result, the levels of importance of the factors, main criteria, and sub-criteria could vary depending on the type of land use, and the resulting weights were assigned to the layers so that they could be superimposed in the spatial analysis performed in the GIS.

4.2. Analysis of the fuzzy-based GIS approach

The most substantial part of this study was the implementation of the fuzzy-based GIS process. In the implementation of this process, the most important issues to consider were the data source reliability and data accuracy. In this study, a dataset of twenty-one sub-criteria was created while paying attention to these issues. The types of spatial analyses (Euclidean distance, kernel density, and slope) that would be applied after the gathering and transfer of the data to the GIS were determined by consulting the literature and according to the authors' experiences; they are given in Table 1. Consequently, in this study, the creation of suitability maps was carried out in six stages: data collection and transfer, GIS analysis, fuzzification, weighting, reclassification, and overlay. Fuzzified maps of the 21 criteria are presented in Fig. 6. In the map layers of each criterion given in Fig. 6, the suitable areas are represented by a pure white color [1], while unsuitable areas [0] are represented by the black color. Moreover, the optimal and tolerable ranges of access for each criterion in Fig. 6 were fuzzified by using the linear function or sigmoidal function in the fuzzy membership tool in the ArcGIS software. The use of the fuzzification process for each criterion enabled the data to become standardized in order to ensure the measurement integrity.

The fuzzification process for each criterion allowed the data to become standardized in order to ensure the measurement integrity. After the fuzzy standardization process, the weights obtained from the AHP were multiplied by the values of each pixel in the layers of the twenty-one sub-criteria whose access distances were fuzzified. Thus, by assigning the weights obtained with the AHP to the maps of the criteria, suitability maps related to different travel purposes were obtained. The suitability maps of the BSS station locations based on the land-use types are given in Fig. 7 and Fig. 8.

The orange and brown areas indicate the most suitable BSS station locations. Although the most suitable locations were found to be mostly in the seaside areas in both maps, additional locations were ascertained close to the rail system stations for the transportation land-use type. Thus, the deployment of stations in suitable locations was considered at a distance of at least 250 m from existing Bisim stations. Although the most appropriate distance between the stations was not clearly stated in the literature (Wang et al., 2018; Zhou, 2015), some studies have maintained that a minimum of 250 m should be used (Faghih-Imani

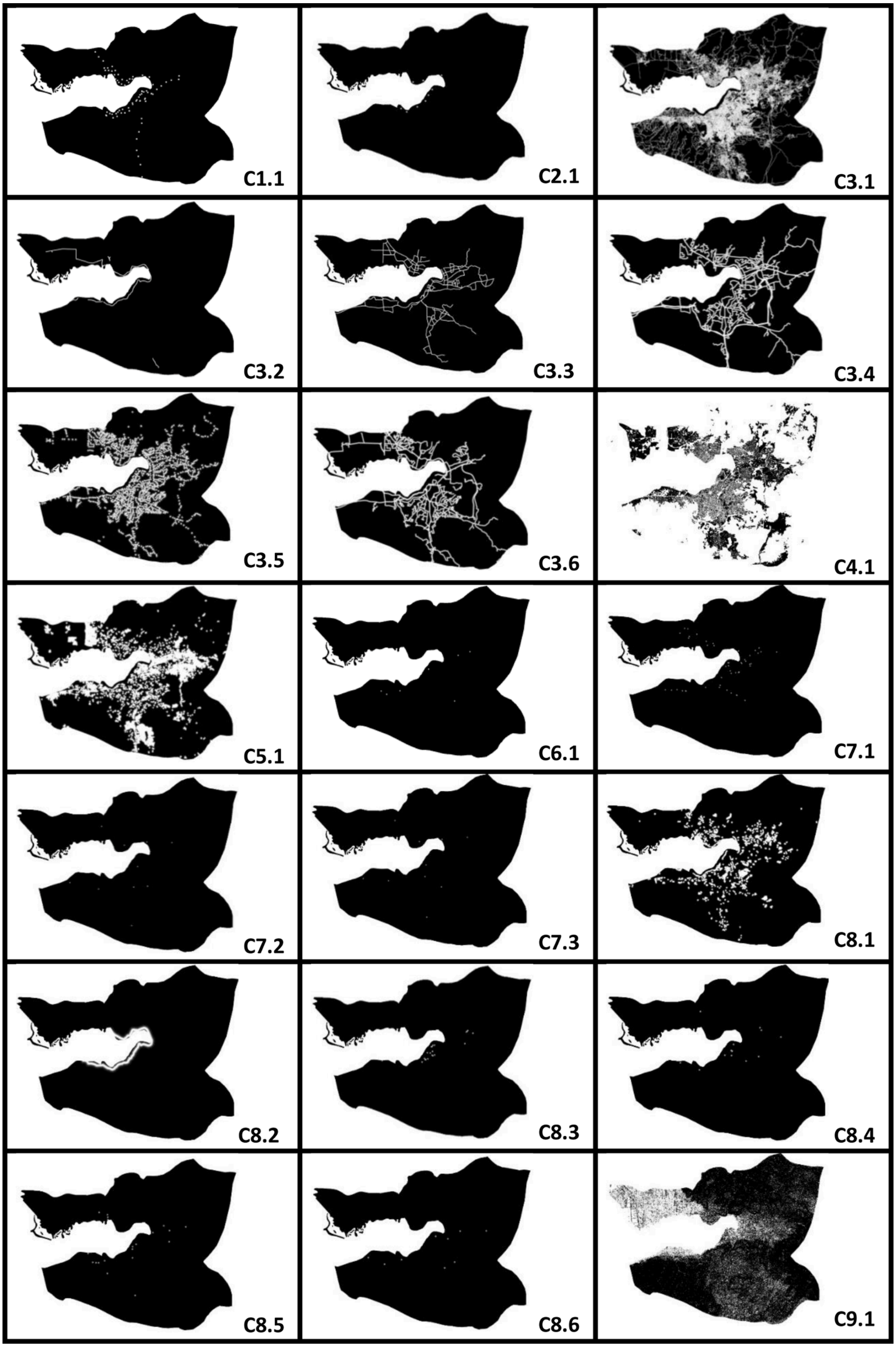

Fig. 6. Fuzzified maps of the evaluation criteria.

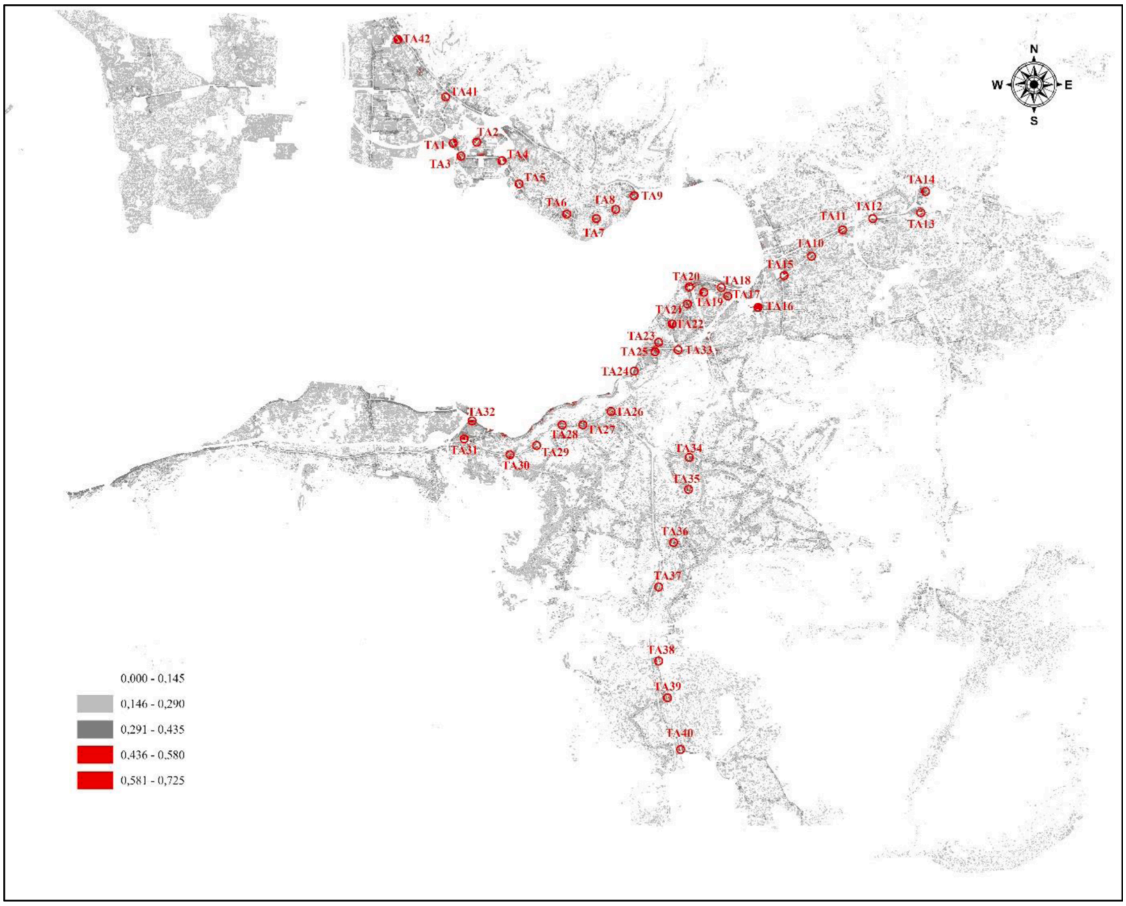

Fig. 7. The suitability map for transportation land use.

et al., 2014; Kabak et al., 2018). For this reason, a minimum distance of 250 m between the stations was adopted in this study. In addition, consideration was given to the presence of other facilities in the alternative station locations that could present obstacles in the construction of the bike-sharing stations. In the light of this information, the number of potential BSS station locations was determined to be 42 the for transportation-related land-use type or 28 for recreational land-use type.

4.3. Application of MCDM techniques

In this section, the VIKOR and Psychometric-VIKOR methods, which are MCDM techniques, were utilized to evaluate the performance of the existing and potential BSS stations in terms of the land-use types. Therefore, a total of four decision matrices were created for MCDM techniques by using the performance values of the alternative and existing station locations obtained for each land-use type as a result of the fuzzy-based GIS analysis.

4.3.1. Analysis with the VIKOR method

In the first step, the best and worst values for each criterion were determined in order to take into account the fact that all of the criteria were benefit-oriented. After this step, the weight values of the criteria obtained from the AHP for each land-use type were assigned as weights of criteria that were known in equations 5 and 6 in order to calculate the values of S_i and R_i. The S_i and R_i values are calculated to obtain the rank measure that is Q_i value. S_i value is the distance rate of the i_{th} alternative to the positive ideal solution for maximum group utility. And, R_i value is the distance rate of the i_{th} alternative to the negative ideal solution individual regret of the opponent (Wei and Zhang, 2014; Wei and Lin, 2008). In the third step, the values of Qi were calculated by using the values of Si and R_i, and the value of ϑ was set to 0.5. In the fourth step, the values of Q_i for the alternative station locations and the existing station locations were ranked from lowest to highest for the two land-use types. Table 5 shows the rankings of the ten best positions of both the existing and alternative stations according to their Q_i values. The details of the values of S_i, R_i, and Q_i in the results of the VIKOR method for all stations are provided in Appendix A. Based on the results of the VIKOR method shown in Table 5, it was concluded that the potential BSS station locations with the best performance values were "Transportation Alternative—TA32" for transportation and “Recreation Alternative—RA21". In addition, Table 5 indicates that station 1105 is in the location with the best performance among the existing stations for the two land-use types.

4.3.2. Analysis with the Psychometric-VIKOR method

In the Psychometric-VIKOR method, the Z-score normalization process was performed on both the decision matrix and the weights obtained with the AHP for the two types of land uses. Thus, normalized decision matrices and weight vectors consisting of values in the range of 0–100 required were obtained. This requirement was based on the ratings of alternatives and criteria in the range of 0–100, which represents $fmax = 100$ and $fmin = 0$ according to the Weber–Fechner law. In other words, since all of the criteria were benefit-oriented, fj* = 100 and fj- = 0 were used in this study. It was possible to divide the interval between fj* and fj- into separate and equal parts using the number of jnds and the threshold values. However, in this study, the number of jnds was set to five because decision makers have a cognitive limit when comparing things, and these threshold values facilitate applicability. Additionally, the detailed threshold values for each jnd are illustrated in Fig. 9.

The graph in Fig. 9 shows the coordinates of the jnds and the threshold values of the jnds. Here, $\Delta f0 = 6.25$ was found by using (1 +

Fig. 8. The suitability map for recreation land use.

Table 5
Ranking of the best ten locations of both existing and alternative stations according to the Qi values.

VIKOR METHOD	Ranking Alternative Station Locations	Transportation	Rank	1	2	3	4	5	6	7	8	9	10
			Station Number	TA32	TA23	TA30	TA31	TA36	TA7	TA40	TA27	TA5	TA42
			Q_i	0.000	0.178	0.195	0.234	0.240	0.254	0.256	0.262	0.263	0.276
		Recreation	**Rank**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
			Station Number	RA21	RA3	RA4	RA5	RA16	RA22	RA15	RA7	RA20	RA1
			Q_i	0.000	0.149	0.175	0.416	0.451	0.476	0.497	0.513	0.522	0.526
	Ranking Existing Station Locations	**Transportation**	**Rank**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
			Station Number	1105	1110	1122	111001	1120	1125	1130	1116	1104	1107
			Q_i	0.000	0.177	0.337	0.360	0.384	0.387	0.389	0.409	0.452	0.462
		Recreation	**Rank**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
			Station Number	1105	1110	111001	1114	1104	1125	1130	1127	1118	111603
			Q_i	0.000	0.005	0.084	0.127	0.182	0.223	0.238	0.244	0.282	0.290

ϵ) = 2 and v = 4 (number of jnds – 1) according to Eq. 12. In addition, the ordinate axis in the graph indicates the changes in sensation according to the Weber–Fechner law. These sensation changes are expressed in linguistic terms—namely, from much more desirable (MMD) to much less desirable (MLD). Moreover, since the value of wk used to represent the weight of each jnd can be compatible with the Saaty scale used in the AHP method, the weight of the MLD value was adapted to be 1.0. In the light of all of this information, the values of Sij, Si, and Ri were determined by using Equations 14–17. Consequently, the values of Si are listed in ascending order for the evaluation of both the existing and potential station locations for the two land-use types and are presented in Table 6.

As a result of the analysis with the Psychometric-VIKOR method, "TA32" and "RA21" were determined to be the best potential station deployment areas. At the same time, the suitability of the station locations in the current system was evaluated according to the land-use types by using the Psychometric-VIKOR method. It was determined that station 1105 was the best available station location for the two land-use types. In addition, the details of the values of S_i and R_i for the results of the Psychometric-VIKOR method for all stations are provided in Appendix A.

The final step of the proposed study involved comparing the results

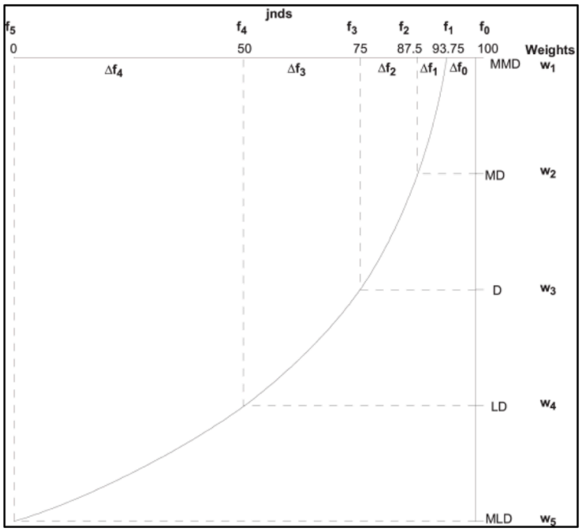

Fig. 9. Representative the threshold values and weights (Arslan, 2020).

of the best five stations obtained with the P-VIKOR and VIKOR methods according to the land uses and determining if these results support each other, as shown in Table 7. The existing station location, station 1105, was close to all transportation alternatives in the city center, on a bicycle path, very close to recreation areas, and in a densely populated place. In addition, the alternative station location TA32 represented an important site that was very close to a transfer center where the metro and tram stations, ferry pier, and bus stops were located. Moreover, the alternative station location RA21 was very close to recreation and entertainment centers with a strong transportation infrastructure.

According to Table 7, it can be said that the VIKOR and Psychometric-VIKOR methods gave similar results. The selection of the thresholds in the Psychometric-VIKOR method may have increased this similarity. However, in addition to the acceptable similarity of the results, the influence of thresholds that represented noticeable changes in the Psychometric-VIKOR method should be considered, and it is believed that more jnd variations should be investigated in future studies. In this context, in this study, the applicability of this new method in which the subjective preferences of decision makers were considered was demonstrated for a location selection problem.

5. Conclusion

A BSS is a shared intelligent transportation model that is expected to be integrated into urban transportation systems and is not ownership-based. The most critical problem in terms of the sustainability of such a system is the complex decision process involved in determining the locations of the stations in the network. This study aims to provide a scientific framework for solving the problem of BSS station site selection with different land-use types by using a fuzzy-based GIS approach combined with MCDM methods. The study consisted of three basic stages. The first stage was the determination of 21 decision criteria by consulting opinions from the literature and experts, as well as the weighting of the criteria according to the land-use types by using the AHP method. The second stage involved performing spatial analyses of twenty-one criteria by using the fuzzy GIS approach, thus characterizing the tendency to start a trip at a station within the optimal and tolerable distances. The last part of this stage was the superposition of maps that were weighted for recreation and transportation land-use types and, thus, the creation of suitability maps. Finally, the third stage included an evaluation of the suitability of both the existing and alternative station locations for the two different land-use types according to the performance values obtained in the GIS environment by using the VIKOR and Psychometric-VIKOR methods.

Regarding the evidence obtained as a result of AHP in the first stage, it can be said that the decision criteria used when determining alternative BSS station locations may have different significance levels (or weights) depending on the land-use types. The order of importance in a transportation network for all types of land uses is as follows: railway transportation, roadway transportation, and seaway transportation. Based on experts' opinions, it can be said that systems should primarily support the use of subways, suburban trains, trams, and trains belonging

Table 7
Comparison of VIKOR and Psychometric-VIKOR.

Rank	ALTERNATIVE STATIONS Transportation		Recreation	
	VIKOR	Psychometric-VIKOR	VIKOR	Psychometric-VIKOR
1	TA32	TA32	RA21	RA21
2	TA23	TA23	RA3	RA4
3	TA30	TA19	RA4	RA3
4	TA31	TA25	RA5	RA27
5	TA36	TA31	RA16	RA23
Rank	**EXISTING STATIONS** **Transportation**		**Recreation**	
	VIKOR	Psychometric-VIKOR	VIKOR	Psychometric-VIKOR
1	1105	1105	1105	1105
2	1110	1122	1110	1110
3	1122	1110	111001	1118
4	111001	1117	1114	1104
5	1120	1118	1104	1114

Table 6
Ranking of the best ten locations of both existing and alternative stations according to the Si values.

PSYCHOMETRIC VIKOR METHOD	Ranking Alternative Station Locations	Transportation	Rank	1	2	3	4	5	6	7	8	9	10
			Station Number	TA32	TA23	TA19	TA25	TA31	TA7	TA12	TA24	TA11	TA36
			S_i	0.589	0.658	0.665	0.672	0.672	0.678	0.688	0.689	0.692	0.692
		Recreation	**Rank**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
			Station Number	RA21	RA4	RA3	RA27	RA23	RA16	RA28	RA19	RA22	RA25
			S_i	0.566	0.658	0.685	0.707	0.713	0.714	0.719	0.730	0.734	0.742
	Ranking Existing Station Locations	**Transportation**	**Rank**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
			Station Number	1105	1122	1110	1117	1118	1120	1130	1116	111001	1125
			S_i	0.506	0.517	0.527	0.558	0.558	0.601	0.601	0.605	0.608	0.612
		Recreation	**Rank**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
			Station Number	1105	1110	1118	1104	1114	1120	1107	1130	1125	111001
			S_i	0.581	0.603	0.642	0.647	0.647	0.649	0.654	0.659	0.663	0.668

to the railway network.

In addition, the conclusions obtained in the second stage can be explained as follows: In studies on the selection of alternative BSS station sites, it is recommended to use a fuzzy-based GIS approach to perform spatial analyses by characterizing ambiguous or unclear real-life problems. In this study, as a consequence of the fuzzy-based GIS approach, the numbers of alternative BSS station locations were determined to be 42 for transportation-related land uses and 28 for recreational land uses. Moreover, these alternative station locations highlighted places that could be integrated into the urban transport system, provide easier access to educational areas, and support entertainment activities.

Finally, the main findings at the third stage showed that with the Psychometric-VIKOR method, a better characterization of the decision makers' nonlinear judgment capabilities could be achieved. Based on the fact that the performance ranking results from the VIKOR method supported those obtained with the Psychometric-VIKOR method, it is suggested that the Psychometric-VIKOR method can be used in site selection studies. The most suitable alternative BSS station locations were determined with both methods to be "TA32" and "RA21".

In future BSS site selection studies, it is suggested that the fuzzy AHP method be utilized while weighting the criteria, and the performance of the PROMETHEE, ELEKTRE, and TOPSIS methods, among others, can be compared with that of Psychometric-VIKOR. In addition, other factors that affect travel demands at existing stations can be investigated, and the determination of the capacities of alternative stations can be included in such studies.

Declaration of Competing Interest

None.

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We gratefully thank the Izmir Metropolitan Municipality and ESHOT General Directorate for sharing GIS data belonging to the urban transportation infrastructure such as rail system stations, ferry piers, highways, bicycle paths, planned bicycle paths, minibus route, bus stops, routes of bus Lines with bicycle transfer apparatus.

Appendix A

Table 5a. Land-use type transportation: ranking alternative station locations according to Qi

Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Station Number	TA32	TA23	TA30	TA31	TA36	TA7	TA40	TA27	TA5	TA42	TA29	TA4	TA8	TA9
S_i	0.346	0.396	0.394	0.408	0.390	0.471	0.403	0.446	0.411	0.420	0.438	0.429	0.487	0.441
R_i	0.111	0.144	0.150	0.156	0.164	0.140	0.164	0.151	0.163	0.164	0.158	0.163	0.145	0.161
Q_i	0.000	0.178	0.195	0.234	0.240	0.254	0.256	0.262	0.263	0.276	0.279	0.287	0.292	0.293
Rank	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Station Number	TA25	TA28	TA11	TA20	TA19	TA38	TA2	TA3	TA6	TA39	TA15	TA10	TA18	TA26
S_i	0.444	0.465	0.438	0.457	0.453	0.454	0.454	0.461	0.478	0.465	0.468	0.476	0.481	0.490
R_i	0.161	0.154	0.164	0.158	0.164	0.164	0.164	0.164	0.159	0.164	0.164	0.164	0.163	0.160
Q_i	0.294	0.297	0.297	0.299	0.315	0.317	0.317	0.325	0.330	0.331	0.333	0.342	0.346	0.348
Rank	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Station Number	TA1	TA35	TA37	TA24	TA33	TA16	TA14	TA12	TA41	TA13	TA17	TA22	TA21	TA34
S_i	0.480	0.489	0.491	0.512	0.541	0.541	0.544	0.556	0.575	0.581	0.600	0.587	0.763	0.634
R_i	0.164	0.164	0.164	0.157	0.163	0.163	0.164	0.164	0.164	0.164	0.163	0.171	0.181	0.252
Q_i	0.349	0.359	0.362	0.362	0.419	0.421	0.425	0.440	0.462	0.470	0.491	0.501	0.749	0.846

Table 5b. Land-use type recreation: ranking alternative station locations according to Qi

Rank	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Station Number	RA21	RA3	RA4	RA5	RA16	RA22	RA15	RA7	RA20	RA1	RA27	RA18	RA6	RA13
S_i	0.483	0.540	0.559	0.643	0.601	0.618	0.633	0.644	0.651	0.684	0.654	0.655	0.659	0.668
R_i	0.088	0.101	0.101	0.125	0.143	0.143	0.143	0.143	0.143	0.135	0.143	0.143	0.143	0.143
Q_i	0.000	0.149	0.175	0.416	0.451	0.476	0.497	0.513	0.522	0.526	0.527	0.528	0.535	0.548
Rank	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Station Number	RA11	RA23	RA19	RA8	RA17	RA28	RA25	RA10	RA24	RA14	RA2	RA9	RA12	RA26
S_i	0.669	0.673	0.675	0.678	0.679	0.680	0.681	0.688	0.697	0.700	0.711	0.722	0.765	0.832
R_i	0.143	0.143	0.143	0.143	0.143	0.143	0.143	0.143	0.143	0.143	0.143	0.144	0.143	0.186
Q_i	0.548	0.554	0.557	0.562	0.563	0.564	0.565	0.575	0.588	0.593	0.609	0.628	0.686	1.000

Table 5c. Land-use type transportation: ranking existing station locations according to Qi

Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Station Number	1105	1110	1122	111001	1120	1125	1130	1116	1104	1107	1117	1118	1121	111603	1123	1124	1109	1103	1127	111604
S_i	0.212	0.361	0.371	0.365	0.363	0.415	0.371	0.403	0.473	0.480	0.466	0.466	0.565	0.590	0.601	0.601	0.633	0.546	0.598	0.748
R_i	0.049	0.080	0.143	0.154	0.164	0.151	0.164	0.163	0.161	0.163	0.190	0.190	0.163	0.163	0.181	0.181	0.201	0.227	0.220	0.182
Q_i	0.000	0.177	0.337	0.360	0.384	0.387	0.389	0.409	0.452	0.462	0.518	0.519	0.519	0.536	0.587	0.587	0.657	0.664	0.681	0.689
Rank	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Station Number	111605	1108	1126	1119	1106	1114	1112	1102	1115	1129	1131	1132	1110101	1111	1110102	1128	1113	1101	111702	111701
S_i	0.666	0.611	0.625	0.602	0.775	0.685	0.690	0.707	0.733	0.761	0.782	0.815	0.817	0.831	0.830	0.849	0.857	0.869	0.931	0.953
R_i	0.213	0.241	0.240	0.250	0.223	0.250	0.251	0.252	0.250	0.251	0.252	0.252	0.252	0.250	0.252	0.248	0.250	0.252	0.252	0.252
Q_i	0.711	0.743	0.749	0.759	0.808	0.815	0.820	0.833	0.845	0.868	0.884	0.907	0.908	0.913	0.917	0.919	0.930	0.943	0.984	0.999

Table 5d. Land-use type recreation: ranking existing station locations according to Qi

Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Station Number	1105	1110	111001	1114	1104	1125	1130	1127	1118	111603	111605	1126	1115	1106	1128	1129	1112	1107	1120	1103
Si	0.451	0.452	0.457	0.513	0.527	0.561	0.573	0.578	0.583	0.622	0.635	0.676	0.678	0.652	0.707	0.719	0.596	0.596	0.592	0.620
Ri	0.078	0.079	0.095	0.091	0.100	0.101	0.101	0.101	0.108	0.101	0.101	0.101	0.103	0.110	0.101	0.101	0.140	0.141	0.143	0.143
Qi	0.000	0.005	0.084	0.127	0.182	0.223	0.238	0.244	0.282	0.290	0.304	0.347	0.360	0.366	0.382	0.395	0.443	0.445	0.453	0.483
Rank	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Station Number	1131	1110102	1119	1108	1117	1102	1113	1121	1122	1109	1116	1124	111604	1123	1101	1111	111702	111701	1110101	1132
S_i	0.807	0.674	0.686	0.680	0.730	0.749	0.804	0.769	0.675	0.845	0.718	0.732	0.744	0.749	0.751	0.838	0.876	0.884	0.889	0.917
R_i	0.101	0.142	0.139	0.143	0.143	0.143	0.153	0.163	0.186	0.153	0.186	0.186	0.186	0.186	0.186	0.186	0.186	0.186	0.186	0.186
Q_i	0.489	0.536	0.537	0.545	0.601	0.621	0.726	0.733	0.740	0.769	0.787	0.801	0.814	0.820	0.822	0.915	0.956	0.964	0.970	1.000

Table 6a. Land use type transportation: ranking alternative station locations according to Si

Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Station Number	TA32	TA23	TA19	TA25	TA31	TA7	TA12	TA24	TA11	TA36	TA20	TA15	TA5	TA38
Si	0.589	0.658	0.665	0.672	0.672	0.678	0.688	0.689	0.692	0.692	0.694	0.695	0.701	0.701
Ri	0.082	0.082	0.103	0.101	0.098	0.077	0.103	0.096	0.103	0.103	0.099	0.103	0.103	0.103
Rank	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Station Number	TA30	TA14	TA40	TA4	TA29	TA41	TA34	TA22	TA3	TA42	TA10	TA21	TA33	TA17
Si	0.709	0.716	0.720	0.721	0.722	0.722	0.724	0.730	0.732	0.734	0.737	0.737	0.738	0.738
Ri	0.094	0.103	0.103	0.103	0.100	0.103	0.103	0.095	0.103	0.103	0.103	0.110	0.103	0.103
Rank	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Station Number	TA27	TA8	TA26	TA9	TA13	TA35	TA37	TA18	TA28	TA16	TA6	TA39	TA1	TA2
Si	0.739	0.740	0.742	0.743	0.749	0.754	0.754	0.755	0.755	0.757	0.758	0.759	0.763	0.763
Ri	0.095	0.085	0.101	0.101	0.108	0.103	0.103	0.102	0.097	0.103	0.100	0.103	0.103	0.103

Table 6b. Land-use type recreation: ranking alternative station locations according to Si

Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Station Number	RA21	RA4	RA3	RA27	RA23	RA16	RA28	RA19	RA22	RA25	RA5	RA20	RA18	RA7
S_i	0.566	0.658	0.685	0.707	0.713	0.714	0.719	0.730	0.734	0.742	0.744	0.748	0.748	0.753
R_i	0.077	0.077	0.077	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.103	0.113	0.113	0.113
Rank	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Station Number	RA24	RA11	RA9	RA26	RA6	RA13	RA10	RA12	RA17	RA8	RA15	RA1	RA2	RA14
S_i	0.758	0.762	0.769	0.776	0.779	0.783	0.788	0.790	0.796	0.799	0.803	0.804	0.810	0.812
R_i	0.113	0.113	0.113	0.115	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.109	0.113	0.113

Table 6c. Land-use type transportation: ranking existing station locations according to Qi

Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Station Number	1105	1122	1110	1117	1118	1120	1130	1116	111001	1125	1107	1103	1104	111609	111605	1127	1109	1108	1121	1124
S_i	0.506	0.517	0.527	0.558	0.558	0.601	0.601	0.605	0.608	0.612	0.621	0.626	0.629	0.637	0.693	0.699	0.700	0.702	0.704	0.717
R_i	0.043	0.043	0.050	0.049	0.049	0.100	0.100	0.100	0.097	0.096	0.100	0.098	0.099	0.100	0.100	0.100	0.100	0.109	0.100	0.107
Rank	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Station Number	1119	1126	1123	1112	1114	1115	1102	111604	1129	1131	1132	1106	1111	1101	1110101	1110102	1128	1113	111702	111701
S_i	0.719	0.728	0.730	0.741	0.744	0.753	0.753	0.755	0.762	0.764	0.764	0.816	0.818	0.835	0.837	0.838	0.847	0.856	0.869	0.876
R_i	0.113	0.109	0.107	0.113	0.113	0.113	0.114	0.107	0.114	0.114	0.114	0.107	0.113	0.114	0.114	0.114	0.112	0.113	0.114	0.114

Table 6d. Land-use type recreation: ranking existing station locations according to Qi

Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Station Number	1105	1110	1118	1104	1114	1120	1107	1130	1125	111001	1103	1108	1127	1112	1110102	1128	111609	1106	1126	1119
Si	0.581	0.603	0.642	0.647	0.647	0.649	0.654	0.659	0.663	0.668	0.669	0.687	0.708	0.718	0.719	0.719	0.719	0.725	0.725	0.726
Ri	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111
Rank	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Station Number	1115	1129	1122	111605	1117	1121	1102	1131	1116	1124	1109	1123	1113	1111	1110101	111604	1101	111702	1132	111701
S_i	0.726	0.729	0.729	0.741	0.748	0.754	0.757	0.768	0.774	0.793	0.797	0.799	0.813	0.829	0.840	0.842	0.842	0.869	0.878	0.879
R_i	0.111	0.111	0.117	0.111	0.111	0.111	0.111	0.111	0.117	0.117	0.111	0.117	0.111	0.117	0.117	0.117	0.117	0.117	0.117	0.117

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