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ACHIEVING SUSTAINABLE URBAN MOBILITY WITH A MODIFIED VIKOR METHOD TO IMPROVE THE SELECTION OF A PARK AND RIDE SYSTEM

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Abstract. In many European cities, municipal authorities have placed restrictions on private transport in city centres to comply with national and European regulations aimed at reducing traffic congestion, air pollution levels, polluting gases emission from transport and the consequences on climate change that have affected the quality of life of the inhabitants. Park and ride (P&R) facilities are key elements to introduce restrictions on private transport in city centres to reduce congestion. In this paper, a methodology is proposed, through multi-criteria decision methods, to determine a sustainable P&R rating and classification. The optimal solution or set of solutions, for P&R facilities is determined by taking into account sustainability criteria: environmental, economic, functional and social. A modified VIKOR multi-criteria decision method was developed and applied by using the Mahalanobis distance by taking into account the correlation between variables. The proposed methodology provides the most sustainable alternatives of P&R and allows local authorities to prioritize necessary actions to achieve more sustainable urban mobility. The method developed was applied to study the P&R system designed for the city of Madrid.

Keywords: urban mobility, park and ride, multicriteria decision making, sustainable selection criteria, Entropy method, Mahalanobis distance.

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1. Introduction

All major cities in the world record high rates of air pollution, due to greenhouse gas (GHG) emissions that occur during activities related to housing (heating and air conditioning) and urban road transport. This requires establishing measures to plan more efficiently land use and achieve sustainable urban mobility. The World Health Organization [WHO] warns of the significant environmental risk to health by air pollution. Environmental pollution is responsible for 7 million premature deaths worldwide per year and causes lung, heart and cancer diseases (data for 2018) (WHO, 2023). According to the World Bank Group database, developed countries emit large amounts of CO_2 per capita income (The World Bank, 2014). These amounts fell between 1990 and 2014, but pollution levels remained very high. In large cities, a high percentage of these emissions are due to transport, and by way of example, in Copenhagen they account for 20% of emissions, in Helsinki 34%, and in Madrid 41% (Siemens plc, 2017).

The 2015 Paris Agreement established commitments to reduce polluting gas emissions to fight climate change (United Nations Climate Change, 2015). The United Nations refers to the need to make cities and human settlements inclusive, safe, resilient and sustainable in the Sustainable Development Goals (SDG 11) (United Nations, 2015). Bearing in mind that transport is one of the activities that most affects the environment, not only through the emission of polluting gases and noise, but also through the use of natural resources and energy, the European Commission promotes sustainable urban mobility planning to ensure accessibility, create high-quality and efficient transport systems, reduce traffic jams, air pollution and accidents, and to improve the quality of life of people living in cities (European Commission, 2017).

City growth and expansion has mainly been due to: development of residential areas in the peripheral crowns of metropolitan areas; growth of industrial areas and depopulation from large city centres; and the growth of vehicles has increased the number of trips per person. As a consequence this has made it necessary to establish joint policy planning for mobility, urban development, and environment needs (Stead & Meijers, 2004; Namdeo et al., 2019). In 2002, the European Parliament Transport Committee in its report on sustainable urban mobility in the European Union (EU) countries and the Organisation for Economic Co-operation and Development (OECD) highlight this fact, but also indicate that this can be reversed with appropriate measures. This report indicates that sustainable mobility is achieved with a strategy that maximises the use of public transport, manages private vehicle use in urban areas through integrated traffic and mobility management, and minimises expansion through land use and transport planning. These initiatives will lead to better air quality, reduce fuel consumption, diminish CO_2 emissions and lower noise levels (European Conference of Ministers of Transport [ECMT], 2002). The European Conference of Ministers of Transport report also establishes sustainable mobility indicators from the different countries that were consulted: greenhouse gas emissions, noise, accidents (traffic safety), congestion and perception of air quality (ECMT, 2002).

The emission of polluting gases due to transport have forced municipal authorities in many European cities to place restrictions on private transport in city centres. Governments in different countries have established strategies for sustainable mobility with the creation of low-emission urban areas (Ministry of Development, 2009). More than 200 European cities have established low-emission zones in city centres, by allowing access only to residents or less polluting vehicles and/or setting entry tolls, known as congestion rates (Afandizadeh et al., 2016). The establishment of these restrictions requires planning and measures to offer people alternative accessibility and mobility opportunities, such as strengthening public transport, intermodality and park and ride facilities in the main corridors of entry to the centre of large cities.

Park and ride (P&R) facilities are very effective tools to implement private transport restrictions in city centres and thus, reduce congestion. In a simple and colloquial way, a P&R facility allows a user to park their vehicle, usually a car, and then use public transport to get around the city centre (Parkhurst & Meek, 2014). Boyce et al. (1972) have indicated that in the early days the development of P&R facilities was considered one of the major innovations in urban public transport at the time. The first facilities were developed in the United States, the United Kingdom and the Netherlands (Noel, 2008; Bullard & Christiansen, 1983; RPS Group, 2009; Parkhurst & Meek, 2014). Different types of P&R facilities can be distinguished by taking into account criteria such as distance from the transport intermodal point to the final destination (Chu et al., 2001); type of public transport for connection; whether there is only one type of public transport or several; types of users; fares, location or motivation for using the P&R services (Parkhurst & Meek, 2014; Mingardo, 2013; American Association of State Highway and Transportation Officials [AASHTO], 2004).

P&R facilities are often taken into account in urban mobility plans to achieve a sustainable transport system. For these facilities to be efficient and effective, however, they have to be located next to a public transport node such as a subway station, railway station or bus terminal, and close to the main entrance roads to the large cities. In addition, the public transport system must be dimensioned and with frequencies to avoid long waiting times for users, otherwise P&R facilities will cease to be useful. Other aspects that users will value for the use of P&R facilities are safety, cleanliness and accessibility to the facilities, among others. They also need to have a low fee or free parking, linked to using public transport. When P&R facilities are properly planned and integrated with other modes of transport, they reduce traffic congestion and GHG emissions and increase public transport travel compared to private transport travel (Özen et al., 2016). In this context, it should be noted that the environmental effects of park and ride policies, emission reductions and energy consumption are determined by the reduction in the number of trips in private vehicles (Dijk et al., 2013; Annisa et al., 2019; Ortega et al., 2020). The effect on traffic reduction has been widely discussed and several studies have indicated that, in some cases, a P&R policy may produce "undesirable" effects (Mingardo, 2013). Among these undesirable effects that can lead to an increase in traffic are, for example, that once the park-and-ride facility is in place, users are attracted to use public transport for part of their journey, whereas previously they used public transport for the whole journey. Regarding the latter effect, one way to avoid this is to regulate the fare conditional on the use of public transport. In any case, P&R facilities, in addition to encouraging and increasing the use of public transport, have additional objectives such as: reducing traffic congestion on entry roads to large cities and, consequently, uncertainty in travel time duration, reduction in city centre traffic; reduction of travel time duration, resulting in lower costs; energy savings; less air pollution; reduction of illegal parking in cities; and fewer parking areas in city centres (EU Technical Committee on Transport, 2005).

Previous researchers tried to determine the best P&R location, optimal fare prices or intermodal mode of transportation (Lakusic, 2018; Holguín-Veras et al., 2012; Khakbaz et al., 2013; Wang et al., 2004). In most cases, the location was determined by the location of the intermodal transport hub and land availability. However, it is important to determine the willingness of commuters to use the facilities before finding a location for a P&R facility. To do this, the behaviour of users is determined by the cost of using the P&R (Holguín-Veras et al., 2012; Lakusic, 2018), or whether the optimal location is determined through the maximisation of a utility function (Sharma et al., 2019; Shen et al., 2017). In most cases, the variables linked to each location and type of P&R, which determine their sustainable mobility performance, are correlated with each other, e.g., GHG emissions reduction in city centres is correlated with demand and the distance of the parking location from the city centre. The correlation between variables is an aspect to consider in selecting P&R facilities alternatives. This aspect was not considered in previous research.

Multicriteria decision-making (MCDM) methods are tools used regularly to select infrastructure alternatives (Zhu et al., 2021). The main advantage of MCDM is the simplicity of application and the versatility it offers to solve any problem where there is a known limited number of alternatives. These methods can be used to select the best alternatives when there are several conflicting criteria in a context of uncertainty (Chen et al., 2008; Du et al., 2021). The methodology also has to establish a systematic procedure in the decision-making process. Finally, the solutions obtained must remain unchanged with changes in preferences of decision makers or variation in the weight of criteria, i.e., provide robust solutions (Medeiros et al., 2017; Simanaviciene & Ustinovichius, 2010; Song & Chung, 2016; Azzini et al., 2020). Therefore, the usefulness of any method depends on the accuracy and reliability of its results. Implying that it is highly desirable to develop decision methods less sensitive to the influence of subjective assumptions made through determining the relative importance of criteria (weighting) or to build strategies that help assess the sensitivity of the model and the uncertainty of the outcome (Maliene et al., 2018). On the other hand, infrastructure projects involve large investments of money and the time horizon is very long. This entails an added risk and uncertainty in the process (Huang et al., 2008). In addition, a P&R project involves different actors (stakeholders): public administration, private sector, users, and people in general (Camargo Pérez et al., 2014). These stakeholders might have different interests and many times conflicting interests that have to be taken into account. Factors such as economic, social, environmental, and functional criteria, including political perspectives, are all involved, but MCDMs can help public policy makers determine the best options (Huang et al., 2008). Decision support tools have been used by different authors for P&R analysis in the context of demand analysis (Zhang et al., 2018; He et al., 2012).

Within the outranking methods, models based on the principle of priority (Pohekar & Ramachandran, 2004), are based on the distance principle, such as TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) and VIKOR (*VIekriterijumsko KOmpromisno Rangiranje*, a Serbian term meaning multi-criteria optimization and compromise solution) (Shumaiza et al., 2019; Opricovic & Tzeng, 2004). Both methods are based on the concept of mathematical distance. In the first case, the TOPSIS method uses the Euclidean distance to determine the ranking of alternatives in the decision problem. In the case of the VIKOR method, the ranking of alternatives is determined from the Manhattan and Chebyshev distances. For this method, the mathematical distance is determined for each alternative to the ideal solution. The ideal solution is a hypothetical solution obtained from the combination of the different alternatives, choosing the variables that best "behave" regarding each criterion. The VIKOR method is more suitable for selecting alternatives for infrastructure projects by being able to apply when there are conflicting criteria and with different units of measurement (Opricovic & Tzeng, 2007). This method has been applied on many occasions for infrastructure projects (Belošević et al., 2018; Sennaroglu & Varlik Celebi, 2018; Ramezanianpour et al., 2016; Awasthi et al., 2018; Mardani et al., 2016). Sometimes the VIKOR method was modified according to the requirements of the problem or applied in combination with other decision methods (İç et al., 2022; Qi et al., 2021; Shumaiza et al., 2019).

Another aspect to consider in the application or design of MCDM methods is the correlation between the input variables (Saaty, 1996), due to the huge influence they can have on the resulting solution. However, most of the existing multi-criteria decision methods do not take into account the correlation between variables. Hence, the solutions obtained by applying these models may not be optimal (Liu et al., 2016; Vega et al., 2014). Therefore, before determining the decision method to be used, it is highly recommended to check the correlation between variables. So, if there is a correlation between variables, it is necessary to apply a decision method that considers this correlation between variables. The TOPSIS and VIKOR methods have the disadvantage that they do not consider the correlation between variables. This is due to the mathematical distance used to determine the distance to the ideal solution for each alternative. Some proposals have been made to modify the traditional methods to consider the correlation between variables, but not in the VIKOR method (Antuchevičienė et al., 2010; Wang et al., 2018; Yorulmaz et al., 2021). For this purpose, a new modified VIKOR method has been developed, using the Mahalanobis distance to determine the distance of the different alternatives to the ideal and anti-ideal solution. Using Mahalanobis distance enables taking into the correlation between variables (Mahalanobis, 1936). Therefore, when this new methodology was applied to the selection of P&R alternatives by achieving sustainable urban mobility, a ranking was obtained in which the correlation between the selection criteria was taken into account. This last issue was the first objective of the present research carried out. The objective was to determine, through multicriteria decision methods, by taking into account the correlation between the selection criteria, a sustainable rating and classification for P&R already built and/or in the design phase to help those responsible for developing urban mobility plans. To this end, the following criteria were taken into account: sustainability, environmental, economic, functional and social criteria, and the correlation among variables (selection criteria). Thus, the proposed methodology was applied, as a case study, to the selection of P&R alternatives in the city of Madrid.

The present study has 4 secondary objectives: 1) developing a new decision methodology by modifying the VIKOR method with the application of the Mahalanobis distance to account for the correlation between variables which will allow public authorities to prioritise investments in infrastructures; 2) identifying characteristics and selection criteria of P&R facilities to achieve sustainable urban mobility; 3) testing the validation of the proposed model through a case study of P&R facilities in the city of Madrid; 4) verifying the stability of the solution to changes in the preferences of decision-makers, through sensitivity analysis. Each of these objectives will be further discussed throughout the following sections.

2. Methodology

2.1. Sustainability criteria selection

To achieve sustainable infrastructures includes: planning, design, construction, operation during their life cycle and then dismantling after their life cycle. All these factors have to conform to a broad sustainability criteria in an ecological-environmental, economic and social setting. Indeed, there is a broad compilation of sustainability criteria in the bibliography to consider (Sierra et al., 2018). If we focus specifically on urban mobility, the main sustainability criteria presented in different studies (Gillis et al., 2016; Perra et al., 2017). It can be concluded that planning for urban mobility properly and to make it sustainable, it is necessary to consider all actors involved: public authorities, users and residents. In addition, the criteria to be included in the decision-making process can be divided into large groups: economic, social/cultural and environmental (De Carvalho et al., 2019a, 2019b). In the case of P&R facilities, the variables that measure sustainability criteria, are considered in most guides for planning, design and implementation of P&R infrastructures (Chu et al., 2001; Colin Buchanan Consultores, 2010; Bullard & Christiansen, 1983). In this way, selection criteria can be grouped into four categories or groups: functional, economic, environmental and social (Table 1).

2.2. New modified VIKOR method

The sustainability criteria involved in the selection of alternative P&R facilities are often correlated. A case in point is that a decrease in emissions of polluting gases (CO_2 case) in a city centre is directly related to an increased demand for P&R. Therefore, we consider the selection or classification of sustainable P&R alternatives by following the VIKOR method as being unsuitable. It would have to be modified to consider correlations between variables. For this reason, a new modified VIKOR method was developed, using the Mahalanobis distance to determine the distance of the different alternatives to the ideal and anti-ideal solution. Mahalanobis distance measures the distance from a set of points to a common point, it is a value without units (Mahalanobis, 1936). Moreover, as the distance Mahalanobis is invariant to scale, normalization of variables would not be necessary. The Mahalanobis distance is a statistical distance characterized by an independence of measurement scale, free from the influence of dimensions between coordinates and capable of eliminating the disturbance of correlation between variables (Wang et al., 2018). However, should the Mahalanobis distance be used to calculate the value of S or even R of the traditional VIKOR method? (Opricovic & Tzeng, 2004, 2007). Considering that in the VIKOR method the S_i value of alternative i is given as the sum of the "j-distances" to the ideal solution of the value of alternative i for each criterion j, i.e., the Manhattan distance (Shahrasbi et al., 2017; Cárdenas-Montes, 2017). The R_i value is the maximum of these "j-distances", i.e., the Chebyshev distance (Shahrasbi et al., 2017; Cárdenas-Montes, 2017), and can be interpreted as an S value involving all criteria, which we call "majority utility". For an R

Table 1. Sustainability criteria selection for P&R facilities

Category or Group	Criteria
Functional	Demand capture based on socioeconomic conditions, Location and origin-destination relations between different points of the corridor, Reduction in vehicle-km travelled by car as a direct consequence of the implementation of P&R, Accessibility to intermodal transport systems, Difficulty parking at destination, Limitations or restrictions on access by private vehicles to city centre, and so on.
Economic	Construction costs, Operating costs, Potential cost-benefit ratio of the system compared to other competitive options, Public financing, private financing or public-private participation, and so on.
Environmental	Fuel savings after implementation of P&R, Reduction of greenhouse gas emissions as a result of reduced traffic congestion on access roads, Reduction of noise pollution and/or air quality, Landscape integration of P&R, Land occupancy, and so on.
Social	Improved quality of life of users, Political or social acceptance of this type of measure by the community, Reduction of road accidents in affected corridors, and so on.

value only that criterion for which an alternative i is closer to the ideal solution is considered regardless of the behaviour (value) of an alternative i for other selection criteria.

In the present paper the P&R is selected with sustainability criteria using the VIKOR method modified by Mahalanobis distance to calculate alternately the value of S or R and then compare the results. For this purpose, we applied the Mahalanobis distance instead of the Manhattan distance to calculate S; that is, to determine the distance of each alternative from the ideal solution, once the values were normalized, while R was calculated according to the Chebyshev distance, traditional VIKOR method. Thus:

$$S_i = \sqrt{\left[\left(\left(\overrightarrow{f_p^*} - \overrightarrow{A_{ip}}\right)\right)^T * \Sigma^{-1} * \left(\left(\overrightarrow{f_p^*} - \overrightarrow{A_{ip}}\right)\right)\right]}, \quad (1)$$

where Σ is the covariance matrix of the alternative's matrix, $\left[a_{ij}\right]$, where a_{ij}, is the evaluation of the alternative A_i with respect to criterion C_j; $f_p^* = \left\{w_1 * f_1^*, w_2 * f_2^*, \ldots, w_j * f_j^*, \ldots w_n * f_n^*\right\}$ is weighted ideal solution vector, where $f_j^* = \max_i a_{ij}$, if criterion j represents a benefit; $f_j^* = \min_i a_{ij}$, if criterion j represents a cost. $A_{ip} = \left\{w_1 * a_{i1,} w_2 * a_{i2,} \ldots, w_j * a_{ij}, \ldots, w_n * a_{in}\right\}$, is weighted vector of the evaluation of the alternative A_i, for each selection criterion, $w = \left\{w_1, w_2, \ldots w_n\right\}$. vector of weights, n, number of criteria.

For the weighting of the criteria, the entropy method is used to determine these weightings in an objective information theory (Shannon, 1948). Objective methods, such as the Shannon Entropy method, have the advantage that they do not depend on expert opinion (Saaty, 1990; Liao et al., 2019; Qin et al., 2019) and increase objectivity (Lee & Chang, 2018). In the objective methods, the weighting of each criterion is obtained from observable data and actual values of the behaviour of the different alternatives according to that criterion (Ye, 2010; Su et al., 2020).

Subsequently, the Mahalanobis distance was applied to calculate the R values, and to calculate S, the Manhattan distance was applied as in the traditional VIKOR method:

$$R_i = \sqrt{\left[\left(\left(\overrightarrow{f_p^*} - \overrightarrow{A_{ip}}\right)\right)^T * \Sigma^{-1} * \left(\left(\overrightarrow{f_p^*} - \overrightarrow{A_{ip}}\right)\right)\right]}. \quad (2)$$

Finally, the results were compared for a consensus situation, i.e., for $\vartheta = 0.5$ (Opricovic & Tzeng, 2004).

To perform the sensitivity analysis of the developed methodology, the weight of each criterion was modified – increasing and decreasing – by a small percentage, e.g., 5%, equally modified – increasing and decreasing – by a large percentage (50%), and finally by 95% (very large change), keeping the weight of the rest of the criteria constant. For the remaining criteria, the weights are increased or decreased as appropriate, and by the same amount, to keep the sum of the weights of all the criteria equal to 1. Hence, the relative sensitivity coefficients of each criterion can be calculated as the number of changes in the ranking of alternatives due to the change (small, large percentage or very large change) in the criteria weights (Maliene et al., 2018). In addition, this method allows for monitoring how the rankings of the solutions change for each case, and not just determining the criterion with the highest sensitivity; this is easily programmable in any programming software. For the present paper, Matlab™ was used to program the sensitivity analysis. It is important to note that not only the total number of changes in the ranking of alternatives should be analysed, but also whether there is any change in the compromise solution or set of solutions provided by the methodology.

3. Case study

Madrid is the capital of Spain with 3.4 million inhabitants (data at 2024) and is the most populous city in the country (Madrid City Council, 2024). The city is also one of the most populated capitals in Europe which receives more than two million visitors daily (Madrid City Council, 2018a). The population of the capital represents 7% of the total population of the country, however, with an area of 606 km^2 it covers less than 1% of the national territory (Siemens plc, 2017). To be a benchmark of sustainable growth for Spain and the rest of Europe the city authorities approved and established a series of measures to reduce pollution (Madrid City Council, 2014, 2017, 2021a, 2021b). According to data from the Madrid City Council Inventory of Pollutant Emissions into the Atmosphere report, in 2021 road transport accounted for almost 50% of greenhouse gas emissions in Madrid (Madrid City Council, 2021c). By polluting gases: 41.1% of NOx emissions came from road traffic, as well as 50% of PM2.5 emissions and 35.4% of carbon monoxide (CO) emissions (Madrid City Council, 2021c). In Spain, Madrid also has the highest number of lost hours per year for private vehicle use due to congestion, which works out at an average of 14 minutes per day or 57.4 hours per year. Compared to other ratios, we observe that this time is very high and only slightly less than the time lost due to absenteeism per worker in Spain which adds up to 67 hours per year (RACC, 2009).

The high levels of polluting emissions in Madrid are produced by transport and are largely due to private transport. Passenger cars account for 81.2% of the journeys that occur in the municipality, and in the downtown area this accounts for 72.6% (Madrid City Council, 2017). The Royal Decree Act 102/2011 of 28 January 2011 on the improvement of air quality (Government of Spain, 2011) sets the alert threshold value for nitrogen dioxide at 400 $\mu g/m^3$ for three consecutive hours in places representative of air quality, in an area of at least 100 km^2 or an entire area or agglomeration if the latter area is less. The decree also sets an annual limit value of 40 g/m^3 and for health purposes sets a time limit value of nitrogen dioxide at 200 $\mu g/m^3$ that should not exceed more than 18 hours per year at any of the stations in the network. However, these threshold values have been repeatedly exceeded since 2010 (Madrid City Council, 2018b). In recent years there have been several pollution episodes with high levels of nitrogen dioxide that have in some cases led to the activation of the Protocol of measures during episodes of high nitrogen dioxide pollution. In the protocol the use of public transport is recommended; apply various restrictions such as decrease the maximum speed limit to 70 km/h on the M-30, the highway outside the city; and the prohibition of parking in the blue areas of the Regulated Parking Zone As a consequence, an action plan had to be established to address the problem generally (Madrid City Council, 2017) including prompt measures to curb emission of polluting gases. One of these measures that stood out especially due to public opinion was the creation of the "Central Madrid" low emission zone, which was judicially repealed on formal grounds and replaced by the "Madrid 360" programme (Madrid City Council, 2021a). Private vehicles were limited or prohibited from accessing this central zone depending on the fuel used or the age of the vehicle. For this measure to be effective it had to be included in other plans that promoted the use of public transport and established a P&R network. Measure 8 of the City of Madrid Air Quality and Climate Change Plan (Madrid City Council, 2017) establishes the development of an intermodal network of car parks in the metropolitan area.

3.1. Alternatives and selection criteria

Table 2 lists the main characteristics of the 12 P&R facilities that were analyzed to obtain a sustainable classification to apply to the decision methodology described above. The following data are included for each P&R facility: the district of the location, typology, entrance corridor, intermodality with public transport and number of planned parking places. Figure 1 shows the geographical location each alternative.

A total of 18 criteria were defined for assessing the sustainability of the set of alternatives. These selection criteria were determined based on the analysis of the literature on sustainability criteria in infrastructure and the P&R design and planning guidelines included in Section 3. Table 3 includes the definition of each criterion, unit of measure, and objectives, maximize if it is a benefit index, or minimize if it is a cost index.

3.2. Evaluation of alternatives according to criteria

Each alternative is valued according to the selected sustainability criteria. For this purpose, different databases and calculation formulas were used for each case and criterion. Thus, the values of each alternative for the environmental criteria for GHG emissions, C1 and C2, was carried out according to the characteristics of the vehicles circulating in the city of Madrid and routes made (vehicles* kilometre) and differentiating by vehicle typology, fuel consumed and emission reduction technology installed in them. From the vehicle circulation-parking data, the fuel savings (in tons), C3, can be calculated and evaluated for each alternative energy efficiency criterion. The GHG emissions of CO_2 per annual tonnes for the operation of each P&R, C4, are due to electricity consumption. For this estimation, the type of parking-surface area, structure or underground structure was taken into consideration. Consumption can then be calculated from the power installed and the hours when the lights are on. In the first case, the electricity consumption is only for night-time lighting and in the other two cases, for lighting during the 24-hour period and ventilation, pumping of wastewater and other ancillary equipment. The costs for each P&R (C9), includes maintenance and operating costs. The maintenance costs of a P&R facility include the cost of routine and periodic maintenance, such as small repairs or pavement repairs (potholes), painting, cleaning of drainage elements, replacement of the pavement and traffic control elements, and barriers; these costs are estimated to be about 54 Euros space per year (Chu et al., 2001). Operating costs include utility costs

Table 2. Planned P&R facilities in municipality of Madrid (Madrid City Council, 2017)

Alternative	District	Typology	Number places	Entrance Corridor	Intermodality		
					Bus	Commuter Train	Subway
Pitis	Fuencarral – El Pardo	Surface Parking	400	M-40	YES	YES	YES
Paco de Lucía	Fuencarral – El Pardo	Surface Parking	185	M-40	YES	YES	YES
Fuente de la Mora	Hortaleza	Surface Parking	330	M-40	YES	YES	YES
Valdebebas	Barajas	Surface Parking	600	M-11	YES	YES	NO
Canillejas	Hortaleza	Structured + Underground	537	A-2	YES	NO	YES
Estadio Olímpico	San Blas	Surface Parking	1510	A-2	NO	NO	YES
Santa Eugenia	Vallecas Villa	Surface Parking	307	A-3	YES	YES	NO
San Cristóbal	Villaverde	Surface Parking	500	A-4	YES	NO	YES
Villaverde Alto	Villaverde	Surface Parking	375	A-42	YES	YES	YES
Villaverde Bajo Cruce	Villaverde	Underground	648	A-4	YES	NO	YES
Aviación Española	Latina	Surface Parking	750	A-5	YES	YES	YES
Colonia Jardín	Latina	Underground	1000	M-502 M-511	YES	NO	YES

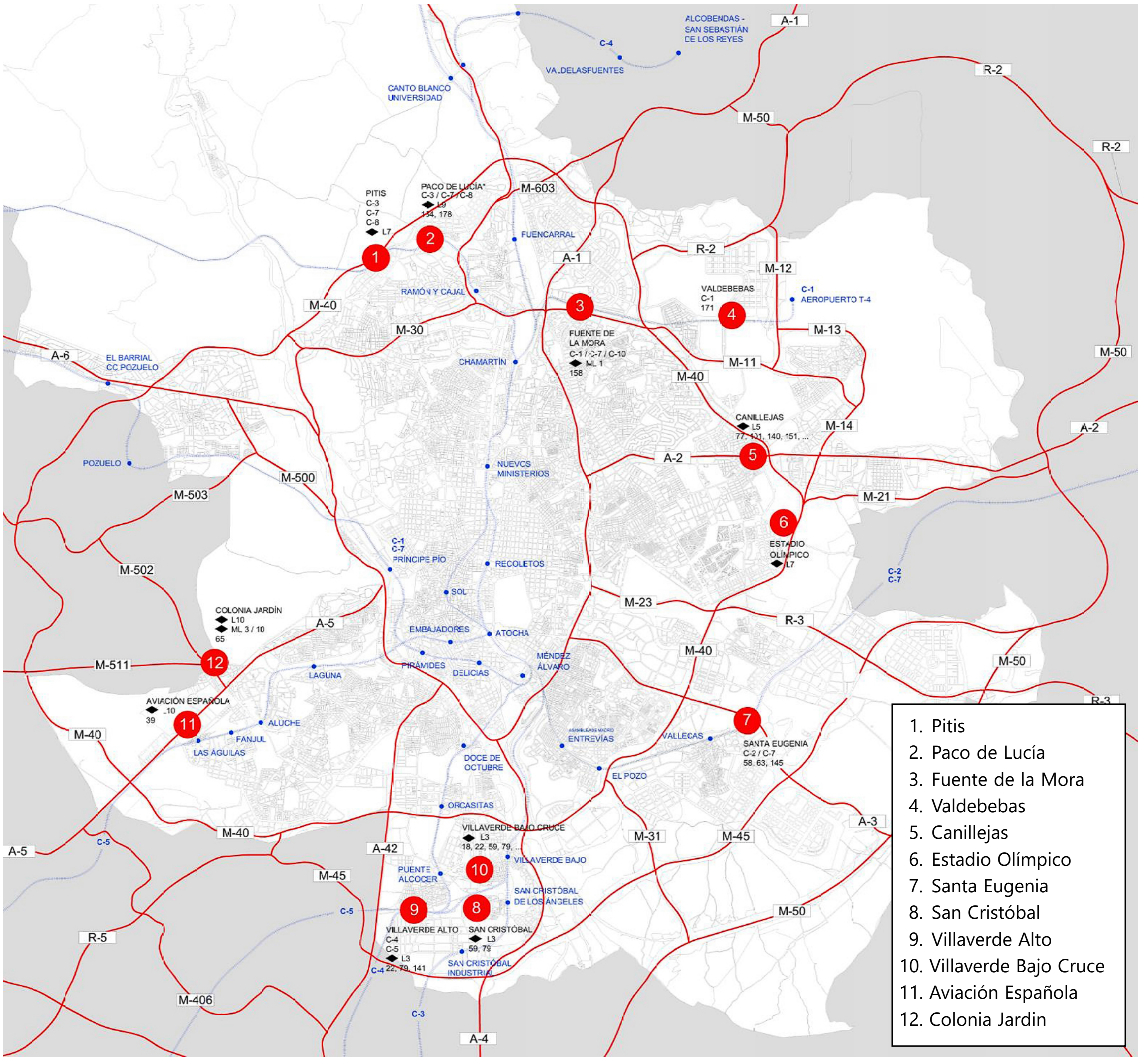

Figure 1. Localization of planned P&R facilities in the municipality of Madrid (Madrid City Council, 2017)

for water and sanitation, electricity, waste management and surveillance. The expected demand for each P&R facility, criterion C12, was the most difficult to determine because it was difficult to rely directly on user behaviour. Several authors argue that an approximate form of calculation is through the adjacent population, intermodality and by the observation of the informal parking available in the area near the transport transfer hub (Bullard & Christiansen, 1983; Chu et al., 2001). The demand for parking, where no previous parking data was available, was first estimated by studying informal parking areas near P&R. The traffic intensity in the entrance corridor, criterion C13, was determined from traffic studies carried out by the regional road administration. Congestion on the road on which P&R facilities, criterion C14, was measured as the average time lost in minutes per day by users of private vehicles due to traffic congestion in that entrance corridor. For our case study, we used the congestion values in each entry corridor that was made by the RACC Foundation in 2009 (RACC, 2009). Considering that the implementation of a P&R in the entry corridor would reduce congestion because corridor users would use more public transport and fewer private vehicles, the P&R alternative located in a corridor with higher congestion will be the best or priority alternative if the objective is to achieve sustainable urban mobility.

For the sustainability analysis of the planned P&Rs, we considered two social criteria, accidents in the entrance corridor and the perception of users through the improvement of the quality of life. Accident reduction (C17) was determined from the "Hazard Index" (HI) of the main road near each P&R alternative. This HI index is calculated from the number of accidents with victims that occurred on a certain stretch of road during a year and is based on the traffic recorded on that road (Ministry of Development, 2016). To achieve sustainable mobility, it is necessary to reduce accidents and the social costs associated with them. The commissioning of a P&R on an entry corridor will reduce private vehicle traffic and reduce accident rates. Therefore, those P&Rs located in corridors with high HI index will be the priority alternatives to reduce the social costs associated with accidents. The assessment of alternatives according to the criterion of improvement of quality of life, such as perception of users, criterion C18, was established as the saving of travel time from P&R to the centre by using public transport compared to using a private vehicle during peak traffic expressed in Euros. Through the Google Maps app, we measured the time spent making the journey from each P&R alternative to the centre by public transport and the time spent doing so by private vehicle. To assess time in economic terms we took into account that users do not value the same time when the trip is done for work or done for leisure reasons (Ministry of Development, 2014). The data for the remaining evaluation of alternatives concerning the other selection criteria were obtained from the City of Madrid Air Quality and Climate Change Plan. Table 4 includes the methodology of evaluation of alternatives according to different criteria.

Table 5 includes the assessment of the different alternatives for the criteria and criteria discussed.

Table 3. Sustainable criteria for selecting P&R facilities in case of study (Madrid)

Category	Criteria	Description	Measurement Unit	Index type
Enviromental	CO_2 emission reduction (C1)	Reduction of CO_2 greenhouse gas emissions in the centre due to private vehicles that as P&R users no longer access the centre	Kg	Maximize
	NO_x emission reduction (C2)	Reduction of NO_x greenhouse gas emissions in the centre due to private vehicles that as P&R users no longer access the centre	Kg	Maximize
	Energy efficiency (C3)	Decrease in fuel consumption, savings in oil equivalent tons for km not travelled by P&R user vehicles	Metric Tonnes	Maximize
	CO_2 emission by exploitation P&R (C4)	Tons per year of CO_2 greenhouse gas emissions during P&R operation due to energy consumption, lighting, and ventilation in the case of underground P&R	Metric Tonnes	Minimize
	Land occupation of P&R (C5)	P&R plot area	m^2	Minimize
	Land not occupied for parking in the centre (C6)	Area of public parking that ceases to be occupied in the centre by the use of P&R	m^2	Maximize
Economic	Construction costs (C7)	Estimating P&R construction costs	€	Minimize
	Plot costs (C8)	Estimation of the cost of the land on which P&R is built, from the average market price of the land in the vicinity of P&R	€	Minimize
	Operating costs (annual) (C9)	Estimation of the annual operating costs of P&R, including current costs of water, electricity and personnel.	€	Minimize
Functional	Dimensions (C10)	Number of parking places in P&R	Number of places	Maximize
	Population (C11)	Number of inhabitants in adjacent residential area and nearby municipalities in P&R entrance corridor	Number of inhabitants	Maximize
	Demand (C12)	Estimate of expected demand for P&R occupancy	Number of occupied places	Maximize
	Traffic (C13)	Traffic intensity in the entrance corridor where P&R is located, measured in ADT – Average Daily Traffic – number of vehicles driving on average in a day in the entrance corridor	Number of vehicles	Maximize
	Congestion (C14)	Average loss of time per day from traffic congestion in the entrance corridor where P&R is located	Minutes	Maximize
	Intermodality (C15)	Index established from the number of commuter train lines, subway lines and possible connecting bus lines for P&R users	Dimensionless	Maximize
	Bike-lane proximity (C16)	Distance to the network of bike lanes in the City of Madrid	Meter	Minimize
Social	Accident reduction (C17)	Hazard Rate that measures accidentality in the entrance corridor where P&R is located based on the number of accidents and ADT.	Dimensionless	Maximize
	Quality of life (C18)	P&R users' perception of quality-of-life improvements as a time-saving journey expressed in monetary terms	€	Maximize

Table 4. Methodology for evaluation of alternatives according to sustainability criteria

Criteria	Methodology for evaluation of alternatives according to each criterion	Source
CO_2 emission reduction (C1)	The value of each alternative for GHG emissions, CO_2 was carried out according to: ▪ the characteristics of the vehicles circulating in the city; ▪ routes made (vehicles* kilometre) and differentiating by vehicle typology, fuel consumed and emission reduction technology installed in them.	European Environment Agency (2012), Madrid City Council (2018a)
NO_x emission reduction (C2)	The value of each alternative for GHG emissions, CO_2 was carried out according to: ▪ the characteristics of the vehicles circulating in the city; ▪ routes made (vehicles* kilometre) and differentiating by vehicle typology, fuel consumed and emission reduction technology installed in them.	European Environment Agency (2012), Madrid City Council (2018a)
Energy efficiency (C3)	The fuel savings (in tons) were been calculated from the vehicles circulating in the city data and non-travelled routes.	Madrid City Council (2018a), Seville City Council (2019)
CO_2 emission by exploitation P&R (C4)	The GHG emissions of CO_2 per annual tonnes for the operation of each P&R, are due to electricity consumption. Surface area parking: electricity consumption is only for night-time lighting Structure and underground structure parking: electricity consumption is due to lighting during the 24-hour period and ventilation, pumping of wastewater and other ancillary equipment.	Ministry of Industry (2008)
Land occupation of P&R (C5)	Land occupation was obtained from the P&R Facilities Program of the municipality of Madrid.	Madrid City Council (2017)
Land not occupied for parking in the centre (C6)	Area of public parking was obtained taking into account the minimum dimensions of a parking space on public roads and the expected demand.	Madrid City Council (2017)
Construction costs (C7)	Construction costs were obtained from the P&R Facilities Program of the municipality of Madrid.	Madrid City Council (2017)
Plot costs (C8)	For land costs, the market price of the land where the P&R is located was analyzed through real estate web portals.	Idealista (2021)
Operating costs (annual) (C9)	Maintenance and operating costs are included. The maintenance costs of a P&R facility include the cost of routine and periodic maintenance, such as small repairs or pavement repairs (potholes), painting, cleaning of drainage elements, replacement of the pavement and traffic control elements, and barriers. Operating costs include utility costs for water and sanitation, electricity, waste management and surveillance.	Chu et al. (2001)
Dimensions (C10)	The number of parking places was obtained from the P&R Facilities Program of the municipality of Madrid.	Madrid City Council (2017)
Population (C11)	The adjacent population was determined as a result of the sum of the population of the districts of the city of Madrid near the P&R and the population municipalities located in the entrance corridor of each P&R.	National Statistics Institute (2019)
Demand (C12)	For several P&R installations, the expected demand was obtained from the P&R Facilities Program of the municipality of Madrid. For the other cases, the expected demand was estimated by studying informal parking areas near P&R.	Madrid City Council (2017), Bullard and Christiansen (1983), Chu et al. (2001)
Traffic (C13)	The intensity of traffic in the entrance corridor was determined from the Average Daily Traffic (ADT) which is the number of vehicles that travel on average in a day on the road, and whose data are published annually by the regional road administration.	Madrid Autonomous Community (2018)
Congestion reduction (C14)	Congestion values in each entry corridor was measured as the average time lost in minutes per day by users of private vehicles due to traffic congestion in that entrance corridor. The P&R alternative located in a corridor with higher congestion will be the best or priority alternative if the objective is to achieve sustainable urban mobility.	RACC (2009), Madrid City Council (2014)
Intermodality (C15)	The intermodality of each P&R facility was determined according to the existence of a subway station (Metro), commuter trains and the number of intercity and urban bus lines.	Authors' own research
Bike-lane proximity (C16)	The proximity to the Madrid cycling network was assessed using the Cycling Infrastructure Map of the city of Madrid.	Madrid City Council (2022)
Accident reduction (C17)	Accidentality were determined from the "Hazard Index" (HI) of the main road near each P&R alternative. This HI index is calculated from the number of accidents with victims that occurred on a certain stretch of road during a year and is based on the traffic recorded on that road: $$HI = \frac{\text{Number of accidents with victims} * 10^8}{ADT * 365 * \text{lenght in km}}.$$	Ministry of Development (2016)
Quality of life (C18)	Through the Google Maps app, the time spent making the journey from each P&R alternative to the centre was measured by public transport and the time spent doing so by private vehicle. To assess time in economic terms, it was taken into account that users do not value the same way when the trip is done for work or leisure reasons.	Ministry of Development (2014)

Table 5. Evaluation of alternatives according to sustainable criteria

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
Pitis (1)	1,317,906.82	1,535.04	0.3733	17.748	8,500	1,012.50	1,540,000	10,710,000	21,806.25	400	494,903	400	123,840	18.07	21	200	9.10	5.1372
Paco de Lucía (2)	358,881.44	418.01	0.1017	10.7803	5,163	1,030.22	647,500	6,505,380	10,219.61	185	490,545	102	123,840	18.07	22	400	9.10	6.7178
Fuente de la Mora (3)	1,254,545.92	1,461.24	0.3554	13.7808	6,600	1,837.69	1,755,000	8,910,000	17,945.20	330	448,160	330	99,584	8.93	32	800	11.40	7.9033
Valdebebas (4)	662,121.46	771.21	0.1876	42.804	20,500	1,518.75	2,100,000	27,675,000	33,553.89	600	103,883	150	52,302	8.93	11	30	4.20	6.3227
Canillejas (5)	1,565,141.07	1,823.01	0.4433	389.614	3,150	4,349.70	8,383,500	2,992,500	196,868.97	537	203,985	537	105,269	11.78	33	210	14.90	5.5323
Estadio Olímpico (6)	446,483.18	520.04	0.1265	44.892	21,500	3,822.19	6,913,000	9,395,500	81,164.86	1,510	154,413	151	82,810	12.88	13	300	9.10	2.7662
Santa Eugenia (7)	661,361.12	770.32	0.1873	12.8475	6,153	2,486.70	1,074,500	3,138,030	16,695.90	307	316,199	307	165,456	9.51	23	300	14.60	3.1613
San Cristobal (8)	446,166.37	519.68	0.1264	20.88	10,000	1,265.63	2,050,000	3,600,000	27,189.70	500	337,231	125	130,490	9.07	12	750	9.70	5.1372
Villaverde Alto (9)	990,014.14	1,153.13	0.2804	18.0799	8,659	3,037.50	1,312,500	3,117,240	20,518.58	375	427,265	375	147,997	13.46	25	600	13.10	10.67
Villaverde Bajo cruce (10)	1,127,722.73	1,313.52	0.3194	470.149	8,112	5,248.80	13,413,600	5,029,440	237,562.55	648	340,088	518	99,205	9.07	32	300	9.70	9.484
Avicación Española (11)	1,473,141.04	1,715.85	0.4173	31.32	15,000	6,075.00	2,625,000	10,875,000	40,784.56	750	450,991	750	107,194	7.76	21	2,700	15.20	5.5323
Colonia Jardín (12)	2,006,428.65	2,337.00	0.5683	725.538	6,250	8,100.00	21,325,000	2,350,000	366,608.87	1,000	98,081	1,000	64,081	5.27	24	400	17.04	7.9033

4. Results

The modified VIKOR and the traditional VIKOR methods were applied once the alternatives were evaluated according to the selection criteria and verified a correlation between the variables through Pearson's correlation coefficients. But the first step was to determine the vector of weights. To do this, the entropy method was applied to determine the weights of each criterion, since it does not have a clear preference over one from another. The weight vector, w_i, is included in Table 6.

Finally, after applying the modified VIKOR and the traditional VIKOR methods, and the results were compared. Table 7 is a summary of the obtained results.

The conditions applicable for the VIKOR method to select the most suitable solution are:

a) Condition 1, acceptable advantage,

b) Condition 2, acceptable stability of the decision-making method.

In the case of the traditional VIKOR method, the "alternative" option that meets both requirements is alternative 12 and is selected as the preferred solution and the other alternatives are excluded. However, if we consider the correlation between variables and apply the modified VIKOR method this alternative is not the best ranked. If we apply the modified VIKOR method, by applying the Mahalanobis distance for the calculation of *S* of each alternative, or *R*, in both cases, we obtain as a solution to the decision problem a set of compromise solutions formed by alternatives 10 and 5, which fulfils Condition 1 of "acceptable advantage". Taking into account that in the traditional VIKOR method the S_i value of alternative *i* is given as the sum of the "*j*-distances" to the ideal solution of the value of alternative *i* for each criterion *j*. The R_i value is the maximum of these "*j*-distances" and can be interpreted as an *S* value involving all criteria, which we call "majority utility". For an *R* value, only that criterion for which an alternative *i* is closer to the ideal solution is considered regardless of the behaviour (value) of an alternative *i* for other selection criteria. So, if we use the Mahalanobis distance for the S_i value of each alternative, we obtain that alternative 10 which is the best ranked, and prioritise the "majority utility", by considering all criteria. While if we use the Mahalanobis distance for the calculation of R_i, the best-ranked alternative is alternative 5, prioritising the alternative that performs better for one of the criteria concerning the ideal solution.

To validate the new decision method, it was necessary to perform a sensitivity analysis and check how robust were the solutions obtained. The results obtained had to be compared with those obtained with the traditional VIKOR method. For the sensitivity analysis, the weights of each selection criterion were increased and decreased (5%, 50%, 95%) and then determined how the ranking of alternatives varies. This was done by analysing the number of changes in the ranking of alternatives in each case and, more importantly, whether there was any change in the set of compromise solutions of the decision method. Table 8 is a summary of the results. For simplification, in Table 8 only the results corresponding to an increase/decrease in the weights of each criterion of 50% and 95% are includ-

Table 6. Weight vector, w_j

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
0.08240	0.08240	0.08240	0.03138	0.04598	0.11938	0.02875	0.02461	0.03089	0.08326	0.04052	0.10347	0.04918	0.00891	0.06624	0.02305	0.03781	0.05937

ed, since in the case of variations in the weights of 5%, although there are small changes in the ranking, in no case do they occur in the set of compromise solutions occur.

As the results in Table 8 reflect, changes in the ranking of alternatives occur mainly when the change in the weighting of the criteria is large (50%) or very large (95%). Furthermore, changes in the set of compromise solutions only occur in the case of a high number of changes in the ranking of alternatives. However, in no case do the solutions that make up the set of compromise solutions rank lower than 6th place in the ranking of alternatives, always ranking in the top five, except in one case, for the 7th place. In most cases, the alternatives that make up the set of trade-off solutions in the decision problem rank in the top three places in all the cases analysed in the sensitivity analysis. Another noteworthy aspect of the sensitivity

Table 7. Ranking of alternatives according to values of *Q*, for traditional VIKOR method, modified VIKOR method, calculation of *S* with Mahalanobis distance application and calculation of *R* with Mahalanobis distance

	Traditional VIKOR method		Modified VIKOR method (S_i Mahalanobis)		Modified VIKOR method (R_i Mahalanobis)	
Alternatives	Q_i	Ranking	Q_i	Ranking	Q_i	Ranking
Pitis (1)	0.7318	8	0.7742	8	0.5060	7
Paco de Lucía (2)	0.8942	10	0.9478	12	0.8461	10
Fuente de la Mora (3)	0.6069	6	0.7807	9	0.5722	9
Valdebebas (4)	0.9434	12	0.9434	11	1.0000	12
Canillejas (5)	0.2467	3	0.1868	2	0.1798	1
Estadio Olímpico (6)	0.7757	9	0.3567	5	0.4190	5
Santa Eugenia (7)	0.6426	7	0.5497	7	0.5220	8
San Cristobal (8)	0.9040	11	0.9334	10	0.8940	11
Villaverde Alto (9)	0.4550	5	0.5247	6	0.4326	6
Villaverde Bajo cruce (10)	0.2500	4	0.1169	1	0.2154	2
Avicación Española (11)	0.1247	2	0.2550	3	0.3306	4
Colonia Jardín (12)	0.0000	1	0.3200	4	0.3200	3

Table 8. Sensitivity analysis modified VIKOR method (S_i Mahalanobis and R_i Mahalanobis)

	Modified VIKOR method (S_i Mahalanobis)				Modified VIKOR method (R_i Mahalanobis)			
	Increase		Decrease		Increase		Decrease	
	50%	95%	50%	95%	50%	95%	50%	95%
Criteria	Number of changes in ranking	Number of changes in ranking	Number of changes in ranking	Number of changes in ranking	Number of changes in ranking	Number of changes in ranking	Number of changes in ranking	Number of changes in ranking
C1	8	9 (*)	11 (*)	9 (*)	8 (*)	8 (*)	7 (*)	8 (*)
C2	4	6	0	2	0	0	0	2
C3	4	6	0	2	0	0	0	2
C4	0	2	0	0	2	4	0	0
C5	9	12 (*)	6 (*)	11 (*)	7 (*)	8 (*)	8 (*)	9 (*)
C6	8 (*)	11 (*)	7 (*)	9 (*)	10 (*)	11 (*)	10 (*)	9 (*)
C7	7 (*)	8 (*)	4	10 (*)	5 (*)	8 (*)	5	7 (*)
C8	4 (*)	4 (*)	6	2	2	3 (*)	2	5 (*)
C9	4	11 (*)	2	6 (*)	3	7 (*)	0	2
C10	9 (*)	9 (*)	8	10 (*)	9 (*)	10 (*)	6	9
C11	4	5 (*)	2	4	2	7	4	4
C12	2	2	5	5	2	0	0	2
C13	8	9	11	11 (*)	5	8 (*)	9 (*)	8 (*)
C14	0	0	0	0	0	0	0	0
C15	5	10	0	2	2	5	0	2
C16	4 (*)	6 (*)	7	6	2	3 (*)	2	5
C17	0	0	0	0	0	2	0	0
C18	2	2 (*)	0	2	2	4	0	0

Note: (*) Changes occur in compromise solution/solutions.

analysis is that, although with the modified VIKOR method with the Mahalanobis distance, the absolute number of changes in the ranking of alternatives is higher than with the traditional VIKOR method, as will be seen below, nevertheless, the ratio of the number of changes in the compromise set to the total number of changes in the ranking of alternatives is lower in the case of the modified VIKOR method, 6.6% versus 7.4%. Therefore, this set of solutions is stable in the face of small changes in the preferences of the decision-maker.

In general, it can be argued that the results obtained with the VIKOR method modified with the Mahalanobis distance present a greater sensitivity when changes occur in the weighting of the criteria, compared to the results obtained with the traditional VIKOR method. This is because a larger number of changes occur in the ranking of alternatives, for large (50%) and very large (95%) changes in the weighting of selection criteria. However, several points need to be mentioned. Although the total number of changes in the ranking of alternatives is higher when considering the correlation between variables, the number of changes in the set of trade-offs is lower than the total number of changes in the ranking of alternatives with the application of the modified VIKOR method.

On the other hand, the criterion with the highest relative sensitivity coefficient can be determined. This criterion will be the one whose variation in weighting produces the greatest number of changes in the ranking of alternatives. Figure 2 shows the results obtained.

As shown in Figure 2, when applying the Mahalanobis distance for the calculation of S_i, the criterion with the highest relative sensitivity coefficient is criterion C1 (CO_2 emission reduction), followed closely by criteria C5 (Land occupation of P&R), C6 (Land not occupied for parking in the centre) and C13 (Traffic), while criteria C14 (Congestion reduction) and C17 (Accident reduction) do not imply any change in the ranking of alternatives in the face of changes in the weighting of these criteria. However, as shown in Figure 2b, when the Mahalanobis distance is applied to calculate R_i, clearly the criterion with the highest relative sensitivity coefficient is criterion C6 (Land not occupied for parking in the centre), and criterion C14 (Congestion

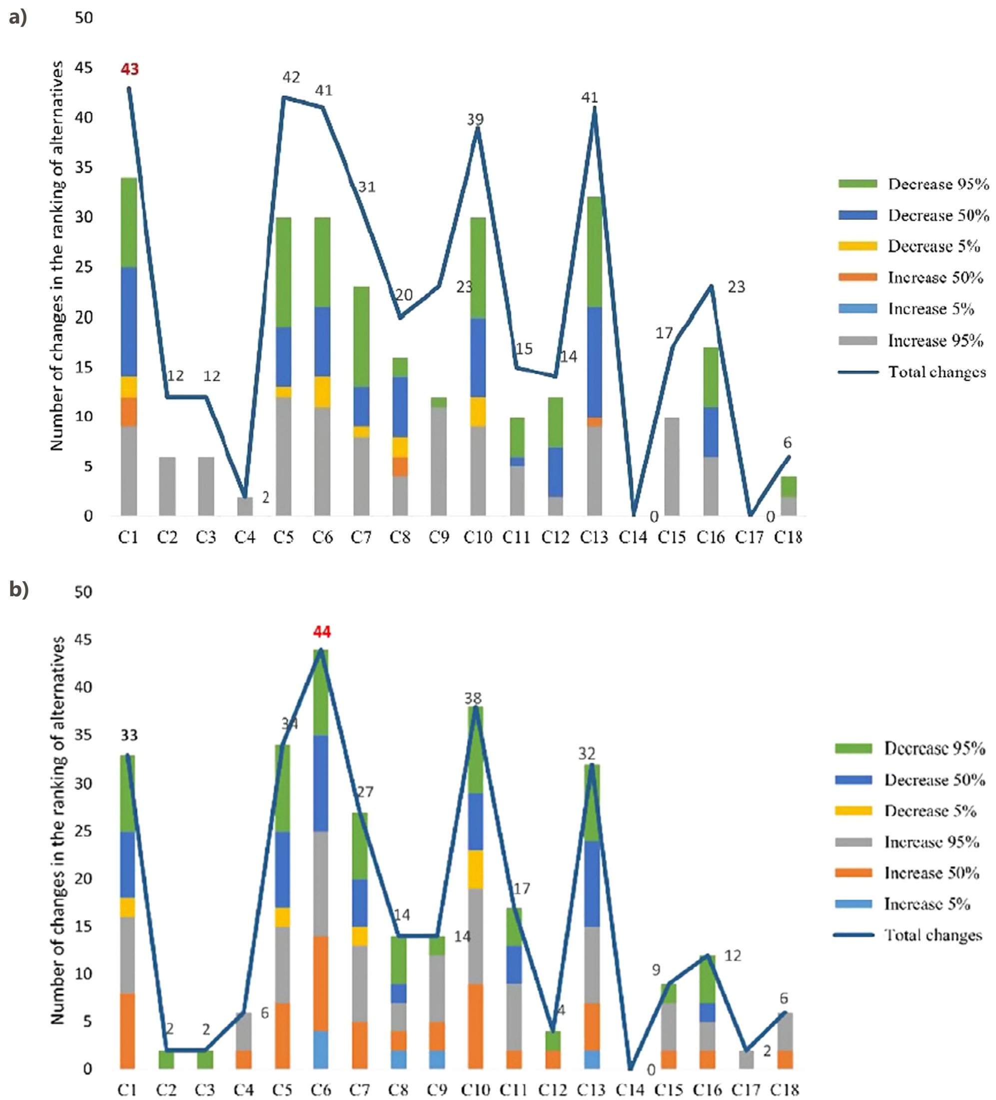

Figure 2. Relative sensitivity coefficients of selection criteria: a – S_i Mahalanobis; b – R_i Mahalanobis

reduction) still does not imply any change in the ranking of alternatives in the face of changes in the weighting of alternatives. The relative sensitivity of the selection criteria should be taken into account in situations where the criteria with high relative sensitivity coefficients have to be given more importance, because of the changes this may cause in the ranking of alternatives and the solution of the MCDM. On the other hand, to validate the results obtained, the sensitivity analysis of the traditional VIKOR method was carried out. The number of changes in the set of compromise solutions is lower when considering the correlation between variables with the application of the VIKOR method modified with the Mahalanobis distance. It should also be noted that with the traditional VIKOR method, which does not consider the correlation between variables, it is not possible to determine with certainty and precision the criteria with the highest relative sensitivity coefficient. This is due to criteria that have a "perfect" or "very strong" correlation with each other behaving in the same way in the sensitivity analysis.

When calculating the Pearson correlation coefficient matrix, it was found that between criteria C1 (CO_2 emission reduction), C2 (NO_x emission reduction) and C3 (Energy efficiency) there was a perfect linear correlation. To test the influence of the correlation between variables in the decision method, the described methodology and the traditional VIKOR method were reapplied by considering only 16 criteria and eliminating two of the three criteria between which there is perfect linear correlation. Specifically, criteria C1 (CO_2 emission reduction) and C3 (Energy efficiency) were eliminated. The results obtained with the VIKOR method modified with the Mahalanobis distance for the calculation of the S_i values were identical to those obtained without simplifying the selection criteria involved in the process. The same results were obtained both for the set of compromise solutions and for the ranking of alternatives, as well as in the determination of the criteria with the highest relative sensitivity coefficient through sensitivity analysis. For the case of the modified VIKOR method for the R_i values, the same results were obtained for the set of compromise solutions although there was an alternation between positions 1 and 2 in the ranking. For this case, there were small changes in the sensitivity analysis. However, with the application of the traditional VIKOR method to this particular case (16 criteria), different results were obtained both in the set of compromise solutions and in the ranking of alternatives, as well as in the determination of the criteria with the highest relative coefficient.

5. Discussion

From the obtained results, it can be seen that by applying a decision methodology that considers the correlation between variables when determining the distance of each alternative to the "ideal solution", alternatives that would otherwise not be considered are defined as solutions to the decision problem. A set of alternatives is obtained as a solution to the decision problem, which form a set of compromise solutions, the ones that are "closest" to the ideal solution. Depending on whether the analysis considers the utility of the majority or the individual behaviour of each alternative concerning what could be called the dominant or preferential criterion, the best-ranked alternative (first position) varies within the set of compromise solutions, since it is the individual behaviour that determines the greatest distance from the ideal solution when using the Chebyshev distance. This would explain why there is an alternation in the first position of the ranking of alternatives between the alternatives that make up the compromise set, alternatives 10 and 5.

Given the above, and based on the results obtained, the most appropriate method is to apply the modified VIKOR method with the Mahalanobis distance if there is a correlation between variables. Specifically, if there is a perfect correlation between some variables involved in the decision process, it is better to apply the VIKOR method modified with the Mahalanobis distance to calculate the values of S_i. If there is, however, a correlation between variables, but in no case, is there a perfect correlation, it is better to apply the modified VIKOR method with the Mahalanobis distance to calculate the values of R_i. This presents less sensitivity, regarding the change in the ranking of alternatives and the set of trade-offs, than if the Mahalanobis distance is applied for the calculation of the values of S_i. For the case where there is no correlation between variables, it is better to apply the traditional VIKOR method, which is less sensitive to changes in the weighting of the criteria. Another noteworthy aspect of the results obtained is that in all the sensitivity analyses carried out taking into account the correlation between variables, in no case are the alternatives that make up the set of compromise solutions placed in the ranking of alternatives in the last positions, not even in the lower half, except in one specific case, in which the best ranked solution moves to the seventh position.

Thus, if the correlation of variables is not taken into account, we would be excluding alternatives that might also be suitable to solve an urban mobility problem with sustainable criteria. In this way, the methodology proposed in the present paper avoids one of the drawbacks of the traditional VIKOR method and other decision methods, which do not consider the correlation between variables. As mentioned above, this has been highlighted by researchers in other studies (Liu et al., 2016; Vega et al., 2014; Saaty, 1996). On the other hand, the new modified VIKOR method allows for simplification in the decision process by reducing the selection criteria between which there is a perfect linear correlation.

For future research, the rank reversal process should be analyzed when adding new alternatives or criteria to the previously chosen set or some of them are eliminated. In this phenomenon, the ordering of alternatives inverts when an alternative is added or eliminated from the list of alternatives. In some cases, this can lead to what is called total rank reversal, where the preference order is completely reversed, i.e., the alternative considered as the best ranked, with the inclusion or elimination of an alternative in the process, becomes the worst alternative (García-Cascales & Lamata, 2012). In this respect, as mentioned above, we can indicate that in the case of eliminating two of the three criteria between which there is a perfect correlation, the same result is obtained when applying the modified VIKOR method with all the criteria, which is not the case with the traditional VIKOR method. The rank reversal is due to the normalization technique used (Ceballos et al., 2018; Mufazzal & Muzakkir, 2018; Mousavi-Nasab & Sotoudeh-Anvari, 2018) and is currently considered as a test to determine whether the decision method is robust (García-Cascales & Lamata, 2012). Therefore, and taking into account that the Mahalanobis distance does not require normalization, this process should be analysed. To complete the study of the goodness of the decision method in future research, the analysis of the change in the ranking of alternatives should also be completed by adding irrelevant alternatives and verifying that the principle of independence of irrelevant alternatives is fulfilled (Rolland, 2013; Aires & Ferreira, 2018, 2019).

Strengths and weaknesses of the new modified VIKOR method

The main strength of the new modified VIKOR method is that the decision process takes into account the correlation between variables or selection criteria. In this way, a stable ranking of alternatives can be obtained with changes in the weighting of the selection criteria and taking into the correlation between variables. Thus, if the correlation of variables is not taken into account, any alternatives would be excluded that might also be suitable to solve an urban mobility problem involving sustainable criteria. Another strength of the methodology is that, although in this case it was applied to determine a sustainable park and ride system, it can also be applied to any urban planning decision problem or selection of alternatives in any infrastructure project. As mentioned above, it simplifies the decision process in the case of perfect correlation between variables. Furthermore, the application is simple and can be computerised.

The main weakness of the modified VIKOR method for considering the correlation between variables is that it is more sensitive to changes in the weighting of the selection criteria than the traditional VIKOR method, resulting in a greater number of changes in the ranking of alternatives.

6. Conclusions

The research carried out and proposed in this paper made it possible to achieve the set of objectives of this study. It should be noted that the main objective was achieved, mainly to develop a decision methodology that takes into account the correlation between variables for a sustainable urban mobility when determining a classification of P&R facilities taking into account sustainability criteria. For this purpose, a new modified VIKOR method has been developed in this paper, which allows taking into account the correlation between the variables for the selection criteria to be considered. The modified VIKOR method has the advantage that the Mahalanobis distance is scale-invariant there is no need to normalise the decision matrix. On the other hand, using the Mahalanobis distance to calculate S_i or R_i allows us to consider the majority utility or to prioritise those alternatives that behave better or are closer to the ideal solution for one of the selection criteria. On the other hand, as discussed in previous sections, the proposed methodology allows the simplification of the decision problem by reducing the criteria between which there is a perfect linear correlation without affecting the results.

Similarly, the secondary objectives have been met by highlighting the following:

- The proposed methodology allows for the sustainable selection of infrastructures alternatives when there is a correlation between variables, thus achieving solutions stable in the case of changes in the weighting of the selection criteria. Moreover, the new modified VIKOR method can also be used to analyse plans, programs, policies and actions in transport, energy, urban planning and to achieve sustainable mobility, when the input variables are correlated. Also, the methodology is easily programmable in any programming software suitable for this purpose. The methodology can be used to prioritize investments so that the solutions adopted will be those that best fit all the needs of the different stakeholders: authorities, designers, users and the general public and society. In the case study, the methodology will allow urban mobility programme managers to plan the implementation of P&R facilities with sustainable criteria and taking into account the relationships between them. The methodology for the implementation of P&R facilities provides solutions that will improve air quality and congestion in city centres.
- Sustainable selection of infrastructure alternatives involves economic, social, environmental and functional criteria. The same is true for the planning of a P&R facility system. Characteristics and sustainable selection criteria have been identified to determine a ranking of alternatives when planning and designing P&R facilities to achieve sustainable urban mobility. The identified selection criteria have been applied in the case of study to identify the best alternative for P&R facilities.
- The proposed methodology has been applied, as a case study, for the selection of P&R alternatives in the city of Madrid. Through the case study, and with an objective weighting of criteria through the entropy method, we show that taking into account the correlation of variables determines a set of alternative solutions that would otherwise be excluded, but still suitable for solving sustainability problems.
- Finally, the sensitivity analysis that was carried out allows for analysing the variations in the ranking of alternatives when the weighting of the criteria varies

and to determine the relative sensitivity coefficients of the selection criteria. The number of changes in the set of compromise solutions was lower when considering the correlation between variables with the application of the VIKOR method modified with the Mahalanobis distance. Thus, the compromise solutions obtained by the methodology proposed remain stable in the case of changes in the weighting of the selection criteria.

The proposed methodology represents a novelty concerning the traditional VIKOR method and other decision methods that modify the VIKOR method by combining it with other decision methods because it considers the correlation between variables. On many occasions, in a decision process, the selection criteria may be correlated, this happens not only to solve a problem of selection of alternatives in infrastructure, as is the case of this study, but this occurs in any decision problem. As determined in previous sections, if the correlation of variables is not taken into account, we would be excluding alternatives that might also be suitable to solve a problem of decision.

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Author contributions

Conceptualization, B. M-M., J. O. and M. G. R.; methodology B. M-M.; software B. M-M.; validation B. M-M., J. O., and M.G.R.; formal analysis V. A.; investigation B. M-M.; writing – original draft preparation B. M-M.; writing – review and editing B. M-M. and V. A.

Disclosure statement

The authors declare no conflict of interest.

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