UNCERTAINTY ANALYSIS METHODS TO SELECT THE OPTIMAL ALTERNATIVE IN THE DESIGN OF PARKING FACILITIES

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ABSTRACT

The selection of the preferred alternative in a parking facility project is usually made in a state of uncertainty. Decision-making methods are a useful tool to systematically arrive at a final decision between different alternatives and reduce subjectivity in decision making by creating a series of filters. However, the selection of the appropriate variables to be considered in the analysis may be problematic as well. Performing sensitivity analyses on entry variables is a key feature to ensure that the final choice is stable when initial conditions experience changes. This paper suggests a methodology to select the best alternative when considering parking facilities. The methodology compares the results from two different sensitivity analyses techniques. The changes in preference experienced as the applied weights change through the process are analyzed and the most critical criteria are identified.

1. INTRODUCTION

Urban mobility planning is a fundamental aspect of sustainable development. Sustainable mobility is thus understood as a transport system that allows the movement of people and goods in better conditions of functional quality (travel time, punctuality, comfort, safety, etc.), with more rational use of resources (energy, space, etc.) and a lower environmental impact (reduction of emissions derived from these consumptions. Parking facilities planning is a very significant element of urban transport system planning and sustainable city development, both at local and strategic levels.

A parking facilities policy can be an appropriate strategy to address congestion problems (Ibeas et al., 2014). In general, proper parking management will result in less search traffic and a better use of available parking space (European Union, 2005). On average, a car can spend up to 23 hours a day parked and uses several parking spaces each week (Litman, 2016). Problems related to parking planning are among the most common problems faced by designers, planners, operators and public sponsors. These problems often materialize as a lack of supply (few spaces are available, more need to be built) or deficient management (available facilities are used inefficiently and need to be better managed). Also, parking facilities come at a high cost to society, (Litman, 2016). Therefore, proper planning of parking facilities is necessary and new alternatives need to be studied taking into account all the variables that determine their efficiency and sustainable development.

Multicriteria decision-making (MCDM) methods are tools used regularly for the selection of infrastructure alternatives. 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. The construction of the decision matrix itself helps to analyse the problem and synthesise the possible solutions, as well as the relative importance of the different requirements (Mullur et al., 2003). However, they have some drawbacks that need to be highlighted: Firstly, potentially optimal alternatives may be discarded because they never receive the highest total score, yet they are the alternatives that best meet the main requirements; Secondly, depending on the method used for weighting criteria, this process has a subjective component and is influenced by the preferences of the decision-maker.

Furthermore, the usefulness of any model depends on the accuracy and reliability of its results. Therefore, it is highly desirable to develop MCDM methods that are less sensitive to the relative importance of the criteria (weighting), or to build strategies that help to assess the sensitivity of the model and the uncertainty of the outcome, (Maliene et al., 2018).

In this research, the results provided by a MCDM for the selection of alternatives in parking facilities projects are analysed by comparing results from the application of two different methods, that are based on sensitivity analysis. For this purpose, the changes in the ranking of alternatives by varying the weights in the selection criteria are analysed and the most critical criterion is determined.

2. LITERATURE REVIEW

MCDM methods are tools that have been extensively used for the selection of infrastructure alternatives. Practitioners often rely on simple decision methods such as the weighted sum method or the Pattern method (Sigford and Parvin, 2013), (Suarez Galarza, 2015).

These methods are characterized by a direct assignment of weighting criteria, which is very subjective. Similarly, sensitivity analysis is limited to changing the weighting of criteria to determine how the ranking of alternatives changes, without analysing the critical criteria or threshold values that determine changes in the ranking.

In the academic literature, there is a broad body of knowledge focused on the selection of alternatives in infrastructure projects in different fields. MCDM methods are applied with different objectives: to assess the sustainability of the different alternatives (Penadés-Plà et al., 2016), (Sierra et al., 2018), (Zavadskas et al., 2018); to take into account the correlation between input variables, (Mardani et al., 2015); to obtain a ranking of suitable alternatives to optimise and/or prioritise investments in early stages of infrastructure planning; (Belošević et al., 2018); to assess risks, (Mohsen and Fereshteh, 2017); to determine the optimal location, (Wu et al., 2019).

MCDM methods have many advantages because they allow complex problems to be solved systematically and simply. Nevertheless, the results of the different decision methods are affected by a certain degree of uncertainty. It is therefore important to identify and understand the different sources of uncertainty and to quantify, as far as possible, the uncertainty and its influence on the results of the decision method. However, recognising and quantifying uncertainty is a complex and multifaceted issue, (Azzini et al., 2020). The uncertainty in the data, procedures and approaches used for its resolution justify making a study of the behaviour of the decision-making process as complete as possible, (Moreno-Jiménez et al., 1998). In this sense, the analysis of the behaviour should be carried out at three levels that respond, respectively, to the effectiveness, efficacy and efficiency of the decision process: (1) the approximation (validity); (2) the modelling (robustness); and (3) the solution (stability), (Moreno-Jiménez et al., 1998).

Sometimes the concepts of uncertainty analysis, sensitivity analysis and robustness analysis of the decision method are confused due to their similarity. All these concepts target the quality of the decision method, but there are differences between them, (Azzini et al., 2020), (Song and Chung, 2016). Uncertainty analysis aims to quantify the uncertainty in the solution provided by the decision method due to the uncertainty in the inputs (criteria and alternatives) of the method, (Azzini et al., 2020). To determine the robustness of the methods, an analysis of the behaviour of the solution is usually performed, assessing the possibility of change in rank between alternatives when relevant aspects (alternatives, criteria, dependencies, etc.) are added or removed, (Moreno-Jiménez et al., 1998). Finally, sensitivity analysis measures the stability or behaviour of the solution to small changes in preferences that occur during the resolution process, or to small changes in the values of the parameters. Thus, sensitivity analysis is a process of investigating the behaviour of an uncertain system, process or method, (Medeiros et al., 2017).

Different types of sensitivity analyses can be grouped into three main categories: mathematical, probabilistic and graphical (Frey and Patil, 2002). Among the sensitivity analyses applied, two stand out: weight variation of the criteria in a given interval and the most critical criterion method. The first method allows to determine independently the effect of each criterion on the solution. For this, the weight of each criterion is modified (increasing and decreasing) by a small percentage - for example, 5%- and by a large percentage – for instance 50%-, while maintain the weight of the rest of the criteria. In this way, the relative sensitivity coefficients of each criterion can be calculated as the number of changes in the ranking of alternatives due to these changes, (Davies et al., 2012). The most critical criterion method is a sensitivity analysis method to assess the impact of uncertainty on the determination of the most critical criterion and on the results, (Triantaphyllou and Sánchez, 1997). In addition to these two sensitivity analysis methods, there are other methods based on uncertainty analysis by optimising the distance metric, (Hyde and Maier, 2004).

3. MATERIALS AND METHODS.

3.1 MCDM methods.

First of all, it should be noted that not all MCDM are perfect for all decision problems. MCDM can be classified into the following groups, (Penadés-Plà et al., 2016), (Hajkowicz and Collins, 2007), (de Brito and Evers, 2016):

- Methods based on a utility/value function or Multi-attribute Utility Theory (MAUT). The objective of these methods is to find an expression through which the decision-maker's preferences are reflected by using a utility/value function.
- Paired comparison methods. These methods allow different alternatives to be assessed according to qualitative criteria by comparing them two by two. They can also be used to establish the relative importance and weighting of criteria, by paired comparisons of the criteria, i.e. the question of how much more important criterion A is compared to criterion B.
- Methods based on the concept of distance. These methods determine a classification of the alternatives according to their distance from an ideal solution. An ideal solution is the hypothetical alternative that is obtained from the combination of the different alternatives, choosing the variables that "behave" best concerning each criterion.
- Outranking methods. This term includes all those MCDM that revolve around the theoretical concept of overcoming relationships.

3.1.1 SAW Method

The Simple Additive Weighting (SAW) method, also known as the weighted sum method, is the simplest and most widely applied method, (Kittur, 2015). For ech alternative, it obtains the weighted sum of the performance ratings for all criteria, (Br Sembiring et al., 2019), (Wira Trise Putra and Agustian Punggara, 2018).

The overall performance rating of each alternative, P_i, is given by the expression:

$$P_i = \sum_{j=1}^{n} w_j * x_{ij} \quad (1)$$

Being w_j the weight of each decision criterion, C_j, and x_{ij} the normalized value of the evaluation of alternative A_i concerning criterion C_j, i.e. the element a_{ij} of the decision matrix after normalization. The alternative that obtains the highest value of P_i is considered the best alternative.

Normalization of the decision matrix's elements is necessary to evaluate the different alternatives concerning decision criteria that have different units of measurement. In this way, normalization converts the elements of the decision matrix into dimensionless values.

In the SAW method, the normalized values are obtained by summing the values of each row of the transposed decision matrix and then dividing each element of that row by that sum, (Ginevičius, 2008). For the normalization of the elements of the decision matrix it is necessary to take into account whether the criterion is a beneficial criterion or a cost criterion, so that the normalized values are obtained according to the following expressions:

$$x_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}}, if\ C_j\ is\ a\ beneficial\ criterion \tag{2}$$

$$x_{ij} = \frac{1/a_{ij}}{\sum_{i=1}^{m} 1/a_{ij}}, if\ C_j\ is\ a\ cost\ criterion \tag{3}$$

Being m is the number of alternatives of the decision problem.

3.1.2 AHP Method

The Analytic Hierarchy Process (AHP), was developed by the mathematician Thomas Saaty in the late 1970s, (Saaty, 1990). It is a MCDM based on paired comparisons that allows the decision-maker to express his or her preferences for weighting the different criteria. To do this, the Saaty scale (Saaty, 1990) is applied and the criteria are compared two by two. The differences between these two elements are established verbally and these descriptive preferences are represented by numerical values. In this way, when two elements are equally preferred or important to the decision-maker, the pair of elements will be assigned a "1"; a "3" when there is moderate importance of one element over another; a "5" indicates strong importance of one element over another; a "7" indicates very strong importance of one element over another; and finally a "9" indicates extremely preferred or importance of one element over another. Even numbers are used to express intermediate situations, (Saaty, 1990).

The weight eigenvector is calculated for the criteria that determines which is the most ideal solution. This is done by making a paired comparison of them for each project (Martínez Rodríguez, 2007), (Yepes et al., 2015). It must be taken into account that the weight eigenvector is not the same for each project, since certain criteria may have bigger importance in comparison to the others, depending on the characteristics of the project. It is necessary to remember that AHP measures the global inconsistency of the views by the Consistency Proportion, calculated by dividing the Consistency Index and the Random Index, and it should be less than 10%. The Consistency Index measures the consistency of the comparison matrix, (Saaty, 1990):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

Being λ_{max} the biggest value of the paired transposed comparison matrix, and n the matrix range. The Random Index is an index that measures a random matrix, whose values are given in Table 1.

Matrix range	2	3	4	5	6	7	8	9	10
Random Index	0,00	0,58	0,90	1,12	1,24	1,32	1,41	1,45	1,49

Table 1 – Random Index, AHP method.

Therefore, this allows for an acceptable level of confidence that the decision process has been carried out correctly. On the other hand, through AHP we can establish the ‘behaviour’ of each alternative for each of the qualitative criteria that are part of the decision making processes, to obtain a quantitative assessment for qualitative criteria.

3.2 Sensitivity analysis

The two main methods of uncertainty analysis in which decisions are made are the weights variation of criteria in a given interval and the most critical criterion method. In the first method, the objective is to independently determine the effect of each criterion on the results of the MCDM. For this purpose, the weight of each criterion is increased or decreased by 5% (small change), 50% (large change) and 95% (very large change). The weights of the remaining criteria are similarly increased or decreased to ensure that the sum of the weights of all criteria remains equal to 1. This results in relative sensitivity coefficients calculated as the number of changes in the ranking of alternatives due to changes in the criteria weights.

In the most critical criterion method, the impact of uncertainty is assessed by determining the criterion whose effect produces the greatest changes in the results, (Triantaphyllou and Sánchez, 1997). To do this, it calculates the minimum change (δ) to the weight of a criterion (w_k), to reverse the ranking of the alternatives. It is calculated for each pair of alternatives A_i and A_j for each criterion C_k, as follows:

$$\delta_{k,i,j} = \frac{P_j - P_i}{x_{jk} - x_{ik}} \tag{5}$$

Being P_j and P_i the positions occupied by alternatives A_j and A_i in the ranking and x_{jk} and x_{ik} the normalized ratings of each alternative concerning criterion C_k. The condition $\delta_{k,i,j} \leq w_k$ must be satisfied for the change in the ranking of the alternatives by changing the weights of the criteria to be feasible. Sometimes, it may be impossible to reverse the existing ranking by changing the weights of the current criteria. However, when the conditions are met, the modified criterion weight, w_k^*, can be calculated from the following equation:

$$w_k^* = w_k - \delta_{k,i,j} \tag{6}$$

The percentage change of the criteria weights can be calculated as:

$$\%w_k^* = \frac{w_k^*}{w_k} * 100 \tag{7}$$

The criticality degree of each criterion C_k, D_k, is defined as the minimum absolute value of $\%w_k^*$. From here, the sensitivity coefficient of each criterion, $sens_k$, can be defined as a measure of the sensitivity to the change in the weighting of the criterion C_k as follows:

$$sens_k = \frac{1}{D_k} \tag{8}$$

So the most critical criterion will be the one with the highest sensitivity coefficient.

3.3 Data collection

In this paper, a case study is developed applying to the construction of parking facility in Cordoba City’s centre the two sensitivity analyses previously described. The problem of parking in the historic centre and its periphery was outlined in the Advance of the Sustainable Mobility Plan for the city of Cordoba, drafted in April 2011, (Cordoba City Council, 2011).

In the historic centre there are different types of parking for different usages: private parking for residents, blue zone parking for visitors and loading and unloading parking for good delivery.

On Cordoba’s periphery the implementation of regulated or blue zones is insufficient for the proper management of parking, making it is necessary to limit traffic and better manage mobility.

Three alternatives for a new parking facility are evaluated, (Vimcorsa, 2010):

- Alternative 1: Parking on Gran Vía Parque Ave. on the corner of Manolete Ave. The parking consists of one floor above ground level, uncovered and landscaped, and two floors below ground level.

- Alternative 2: Surface parking in Gran Vía Parque Ave. on the corner of Manolete Ave. in the same location and conditions as alternative 1, but building only the surface level, surface parking.
- Alternative 3: Surface parking in the street Pintor Racionero. Due to the limitations to underground works due to the existence of important archaeological remains, the installation has only the surface parking level.

Ten selection criteria have been considered for the evaluation of the alternatives: C1, Number of parking spaces; C2, Utility value to the user (relationship between users' willingness to pay to save time looking for a parking place and the tariff parking); C3, Number of current parking spaces in the target area; C4, Ratio of inhabitants to existing residential parking spaces in the area; C5, Intermodality; C6, Cost of parking (construction cost and maintenance cost); C7, Environmental impact; C8, Population; C9, Proximity to commercial areas, C10, Proximity to administration areas and offices.

Table 2 includes the evaluations of each alternative concerning each selection criterion, and table 3 shows the normalized decision matrix, according to equations (2) and (3).

Criteria	Alternative 1	Alternative 2	Alternative 3
C1	508	218	246
C2	0.618	0.618	0.653
C3	527	527	688
C4	6.18	6.18	3.82
C5	1005	1005	1970
C6	8525.57	2709.3	2485.16
C7	0.6753	0.0817	0.2431
C8	15275	15275	7540
C9	97532	97532	27139
C10	30150	30150	6797

Table 2 – Evaluations of each alternative concerning each selection criterion

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A1	0.055	0.067	0.023	0.013	0.019	0.017	0.017	0.063	0.012	0.008
A2	0.024	0.067	0.023	0.013	0.019	0.054	0.146	0.063	0.012	0.008
A3	0.027	0.070	0.018	0.008	0.010	0.059	0.049	0.031	0.003	0.002

Table 3 – Normalized decision matrix.

The vector of weights is determined according to the AHP method as described in section 3.1.2. The weight vector obtained is $w = (0.1056,\ 0.2037,\ 0.0638,\ 0.0350,\ 0.0475,\ 0.1310, 0.2124, 0.1559, 0.0270, 0.0181)$. It is important to remember that the consistency of the comparison matrix must be identified. After determining the consistency following equation (4), we obtain CI = 0.0953. Since the Consistency Proportion is under 0.1 the assessments made can be considered as consistent.

To determine the best solution, the SAW method is applied as previously described, resulting in alternative 2 as the best ranked alternative, followed by alternative 1, and finally alternative 3.

4. RESULTS AND DISCUSSION.

To determine the stability of the solutions obtained by the MCDM, a sensitivity analysis is performed as described above. First, the most critical criterion is determined using equations (5) to (8). For this purpose, the alternatives are compared in a pairwise manner, obtaining the degree of criticality of each criterion and the corresponding sensitivity coefficients (Figure 1).

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1-2	-424.50	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F
1-3	61.83	-466.29	N/F	N/F	N/F	-41.88	-56.13	55.59	N/F	N/F
2-3	-4975.18	-2496.73	N/F	N/F	N/F	-3084.47	N/F	N/F	N/F	N/F

Table 4 – Criticality degree of each criterion (minimal values). N/F: no feasible change

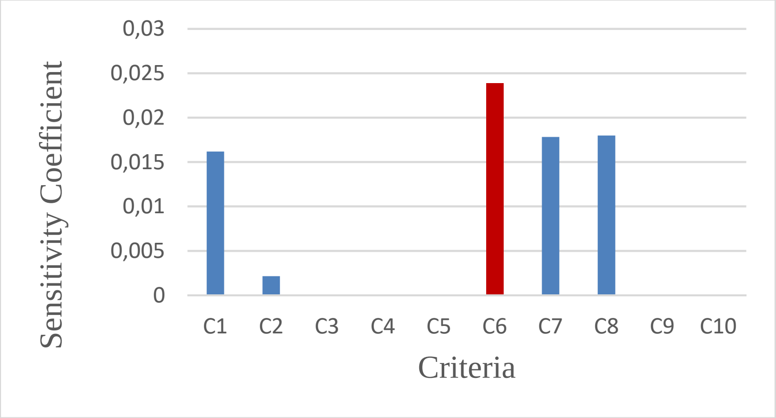

Fig. 1 – Sensitivity Coefficient of each criterion

The results obtained are shown in Table 4. It can be determined that alternative 2 remains the best alternative in almost all cases. Alternative 2 could only be surpassed by alternative 1 if the weight of criterion C1 is increased by 424.50%, and by alternative 3 if the weights of criteria C1, C2 and C6 were increased by 4975.18%, 2496.73% or 3084.47% respectively. However, the most likely changes in the ranking of alternatives 1 and 3.

Relatively small changes in the weights of the criteria can produce changes in the second best alternative. Moreover, it can be deduced that criterion 6 is the most critical criterion, followed by criterion 8, because for the smallest change in the weight of this criterion (41.88%) a change in the ranking of alternatives occurs, which is also reflected in Figure 1.

Next, independent changes in the weight of each criterion are introduced (5%, 50% and 95%). The relative sensitivity coefficients are obtained, that is, the number of changes that occur in the ranking of alternatives due to these changes. The results obtained are included in Table 5.

	Increase (%)			**Decrease (%)**		
	5%	**50%**	**95%**	**5%**	**50%**	**95%**
C1	0	0	0	0	0	1
C2	0	0	1	0	0	0
C3	0	0	0	0	0	0
C4	0	0	0	0	0	0
C5	0	0	0	0	0	0
C6	0	1	1	0	0	0
C7	0	1	1	0	0	0
C8	0	0	0	0	0	0
C9	0	0	0	0	0	0
C10	0	0	0	0	0	0

Table 5 – Relative sensitivity coefficients calculated as a number of changes in the alternative ranking due to change of criteria weights.

The results obtained confirm that changes only occur in one position of the ranking of alternatives. Alternative 2 remains for these weights the best alternative. It is also confirmed that for relatively small changes in the weight of criterion 6 the largest changes in the ranking occur, together with criterion 7. However, criterion 7, according to the analysis of the most critical criterion, has a lower sensitivity coefficient value than criterion 8, which has the second-highest sensitivity coefficient value after the most critical criterion. Given these results, it can be stated that the uncertainty and stability analysis of the solutions of the MCDM must be performed with two different techniques to verify the results because there may be small discrepancies depending on the method used.

5. CONCLUSIONS

MCDM are a very useful tool for the selection of alternatives in a simple way. The decision process however takes place in an environment of uncertainty, because the input variables may vary. Moreover, the results obtained depend on the nature of the selection criteria and, especially, on the weights assigned to these criteria. In most cases, the assignment of weights to the criteria is done by experts, so there is a subjective component and the results may change depending on these weights. Therefore, it is necessary to analyse how the variation in the relative importance of the decision criteria influences the solution of the MCDM. In this paper, we have analysed how changes in the weighting of the selection criteria can influence the solution of the MCDM by using two different sensitivity analysis and comparing the results. It is proposed that whenever possible these sensitivity analyses are carried out to confirm the results and to study the effect of the weights of the criteria on the selection of alternatives. Although the sensitivity analyses carried out have some limitations since they study each criterion independently and do not apply to all MCDM, they are a simple first approximation that allows determining the robustness of the solution obtained and can be the basis for a more exhaustive study of those criteria.

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