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A two-phase decision making based on the grey analytic hierarchy process for evaluating the issue of park-and-ride facility location

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ABSTRACT

Planning a Park-and-Ride (P&R) system in an urban area of a city depends on a group of transportation planning professionals with different areas of expertise in mobility, agreeing on which criteria or set of criteria are the most important. In addition to analysing the criteria established as mobility policies in the Sustainable Urban Mobility Plan (SUMP), when establishing a set of facilities belonging to the P&R system. To find out which criterion is the most important one when combining the mobility criteria established in the SUMP with the criteria of transportation planners with different expertise, this paper applies the multi-criteria method known as the Grey Analytic Hierarchy Process (G-AHP). In this method, at first the main and secondary criteria are determined at two levels that allow building a hierarchical structure, then transportation professionals are surveyed, and finally, the formulation of the multi-criteria method is designed. The result of the study illustrates the effectiveness and usefulness of the proposed multi-criteria method to determine the hierarchy of criteria from most to least important to solve the problem of locating a P&R system. Also, the results are compared with two different multicriteria methods (FAHP and BWM) to see how they are alike and how they are different. The finding suggests that the planning of a P&R system and the criterion for the accessibility of public transport go hand in hand, regardless of the multi-criteria method employed.

1. Introduction

From the perspective of an urban environment, a city's P&R system comprises a set of facilities that are distributed throughout the city and are designed with the main objective of facilitating modal interchange between private vehicles and public transport. Consequently, their location is related to a set of specific parameters associated with public transport, and with parameters related to private vehicles. In order to explicitly evaluate multiple conflicting criteria in decision-making between the two modes of transport that are combined in the P&R system, multi-criteria methods have been developed.

The criteria for establishing a P&R system may vary depending on the mobility policies that a city has established in its Sustainable Urban Mobility Plan (SUMP). For example, a city establishes a mobility policy to reduce traffic in the city center and establishes a P&R system as an action that helps fulfill the mobility policy. On the other hand, a city that has a mobility policy that aims to reduce car dependency in the daily commute of its citizens: it employs the P&R system as a modal interchange point to increase the number of public transport users. In addition to the set of criteria of the city's mobility policy, the background of the transport planner must be taken into account. For example, a planner whose specialty is infrastructure will set the parking structure as the main criterion for establishing P&R. A planner whose specialty is the environment would set the reduction of pollutant gases as the main criterion for implementing the P&R system.

While it is clear that studies on the location of P&R systems focus mainly on mathematical models, there is uncertainty about how to combine the mobility policies established by the city in the SUMP and the approach established by the transportation planner to implement a P&R system (Fan et al., 2014; Mock & Thill, 2015). However, the application of multi-criteria techniques that rank the order of relevance is the method that can assist in determining which criteria are the most pertinent ones for determining the place of a P&R system(X. Chen et al., 2018).

Several multi-criteria approaches have already been used to conduct studies on transportation. However, no multi-criteria studies have been developed in which the mobility policies established in the SUMP concerning parking and also the planner's specialization are involved in

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order to tip the balance toward a certain mobility policy. Therefore, this article develops a survey of transportation planners with different specializations based on the mobility policies on parking established in the SUMP and applying the multicriteria method known as Grey-AHP to determine which criterion is the most important one on a two-level scale to establish a P&R system.

In the light of previous research in the field of P&R location using multi-criteria methods, this study proposes as a scientific contribution a two-level scale approach using the analytical hierarchy process to prioritize the criteria based on the opinions of transportation experts and the parking mobility policies established in the SUMP. The second contribution is through the construction and development of the G-AHP formulation to determine which criteria are the most important to take into account when establishing a P&R system.

This paper is structured as follows. In the second section, the research on P&R and multicriteria methods in the literature is discussed. System criteria for the location of a P&R system are described in Section 3. The hierarchy structure of P&R facilities location is constructed in Section 4. The survey and how it is applied are described in Section 5. Grey Analytic Hierarchy Process is described in detail together with its formulation as part of Section 6. The results according to the formulation and the established criteria are presented in Section 7. A discussion of the results obtained is presented in Section 8. Finally, the conclusion shows the findings and future studies to be carried out.

2. Literature review

This section provides an overview of the various studies conducted on the P&R system's location and evolution over time. Furthermore, a sub-section describes the multi-criteria analyses performed on the P&R system.

2.1. Location of P&R

Depending on the type of city they serve, P&R systems may be placed in the urban centre or urban periphery of a metropolis (Molan & Simicevice, 2018). As a point of exchange between public transportation and private vehicles, their location is likely near public transportation stations (Norlida et al., 2007). On the other side, this would demand a P&R station at every public transportation terminus. Throughout the inquiry, numerous possibilities regarding the location of a P&R system have been proposed. In other words, city-specific criteria and parameters have been taken into account (Cherrington et al., 2017). The P&R system is dependent not only on the quantity and location of public transportation stations but also on the willingness of prospective users to utilise the system (Song et al., 2017). This suggests that a user whose residence is closer to the P&R system is a likely candidate to use the P&R system (Liu et al., 2018).

P&R systems are critical components of a potential user's journey from their house to the downtown area. Because the user or likely user chooses to utilise the system on a regular schedule for work or business purposes, the decision of the plan depends on various aspects.

In this regard, it has been discovered that the decision factors vary according to the distance travelled and the amount of time it takes to reach the P&R system (Islam et al., 2015; Lam et al., 2001). To put it another way, the position of the P&R system is the decisive factor in determining whether or not the user will make use of it (Z. Chen et al., 2014).

As it is generally accepted that the physical location of the P&R system is one of the factors that play a role in determining whether or not a potential P&R user will use the system, the authors examine which criteria ought to be taken into account, bearing in mind the perspectives of the transportation planner as well as the researcher. In this context, the issue has been complicated by employing intrinsically advanced methodology and approaches by planners and researchers (X. Chen et al., 2021; Kepaptsoglou et al., 2010; Sharma et al., 2019). For instance, using geospatial software is a way that is extensively utilised to determine the ideal site for a P&R system (Faghri et al., 2002). These types of investigations might include additional criteria like the amount of time it will take for the P&R user to go from their starting point to the P&R system, or the amount of time it will take for them to get from the P&R system to their final destination using public transportation (Farhan & Murray, 2005). Several studies (Farooq et al., 2018a, 2018b, 2021) have utilised Geographic Information Systems (GIS) and multi-criteria methods, such as the Analytical Hierarchical Process (AHP), to determine the optimal mode of transportation. There have been six modes of transport investigated. The GIS and multi-criteria analysis suggest that the construction of a new high-speed rail line is the best option.

The journey time is a cost function in an analysis that places many P&Rs in various locations across a city (Carlson & Owen, 2019; Pang & Khani, 2018). In other words, the P&R system was assessed based on its cost. The fact that the P&R system initially requires the use of a private vehicle before transferring to the P&R system and arriving at the destination by public transportation must be considered. In addition to the cost linked with the use of public transport, there are fees related to the use of private vehicles and the P&R system (Islam et al., 2015; Liao et al., 2012). Understanding that the location of the P&R system can either increase or decrease the cost of its utilisation necessitates a cost-based examination of the location. Consequently, the potential customer will choose the alternative that does not only result in the shortest length of time but also imposes a minor financial burden.

The placement of a P&R system can be calculated more precisely by incorporating additional criteria, such as travel time. In addition, research methodologies have gotten progressively more complex. The multi-objective spatial optimizations include three criteria for the location of the P&R system (Macioszek & Kurek, 2021): (i) covering as much potential demand as possible, (ii) situating P&R facilities as close to essential roadways as possible, and (iii) situating such facilities within the context of an existing system are the criteria above. It is a necessity that the demand for the P&R system is modelled as a function of both distance and coverage (Holguı´n-Veras et al., 2012; Syed Adnan & Kadar Hamsa, 2013). Consequently, a discrete linear model for the location of P&R facilities shows the adaptability and usefulness of the modelling technique developed to address a more extensive range of planning challenges. This model encompasses a broader scope of planning challenges (Wang & Du, 2013). It is also possible to use mode choice as a function of P&R usage rates to maximise benefits and reduce societal costs. The number of P&R facilities in a city has been determined by utilising linear models (Aros-Vera et al., 2013; Cavadas & Antunes, 2019; Yang & Wang, 2002). This study aims to establish the model's criteria that most closely represent reality.

A formulation of mixed linear programming is used to determine the optimal location of a predetermined number of P&R facilities to maximise their use and yield the highest benefit (Lam et al., 2007; Tsang et al., 2005; Zhao et al., 2017). A statistical method can be used to determine which P&R system facility is the most utilised, and GIS and mathematical methods need to be employed to determine where the P&R system facilities are located (Fan, 2012; Liu & Meng, 2014; Pineda et al., 2016). Passengers choose to conclude their journeys in either automobile mode or P&R mode, depending on their preference. According to the findings, factors such as the frequency of subway travels, the degree of parking capacity usage, and fees substantially impact the reliability of P&R facilities. Due to their location, it is quite probable that P&R facilities will contribute to the problem of traffic congestion (Memon et al., 2014; Parkhurst, 2000). This is because the number of automobiles that would generally circulate through the city centre is decreased by parking these vehicles in a P&R facility. Depending on the number of variables considered, the process of choosing where P&R facilities should be positioned in the urban context of a city might become increasingly complex. Demand, connection, transit design, and economic viability are some of these requirements. As previously stated, the placement of P&R systems is studied utilising a vast array of methods (mathematical models and software) and approaches (statistics) (García & Marín, 2002; Islam et al., 2015; Lu & Guo, 2015).

2.2. Multi-criteria methods applied to the P&R system

For the purpose of determining the opinion of a group of experts regarding the location of the P&R system, investigations employing multi-criteria methods with multiple primary criteria and multiple secondary criteria have been conducted. Experts analyzed the criteria to be considered when determining the location of the P&R system in the light of the findings of these investigations. There are a handful of studies worth additional examination, which are given below.

The concept of symmetry is crucial to multi-criteria decision support (MCDA) due to the fundamental characteristics of binary relationships utilised to reflect decision-makers' preferences. The study aims to evaluate the P&R system location issue from an expert's perspective, the well-known Analytic Hierarchy Process (AHP) was implemented in a fuzzy environment, where fuzzy sets can manage vague notions (Yaliniz et al., 2022). That study's primary criterion was public transportation accessibility. Comparable research employs the same criteria set but uses the Best Worst multi-criteria method (BWM). This methodology requires fewer comparisons than the traditional AHP method. This is the primary reason why the AHP-BWM model was adopted. The main criterion remained public transportation accessibility. The same set of criteria was then applied to a specific case study utilising the multi-criteria technique using only the BWM, which resulted in the accessibility of public transport as the main criterion for establishing a P&R system (Ortega, et al., 2020).

There are few multi-criteria studies that apply two-phase decision making to the P&R system location problem; thus, our research, which employs the Grey-AHP multi-criteria method, makes a significant contribution to filling this gap in the literature.

The primary and secondary criteria for locating a P&R system are defined as part of the mobility policies that a city has established in its SUMP. In addition to the transportation planners' own criteria and area of expertise. These criteria for evaluating P&R facilities have not been formulated utilising the multi-criteria technique known as the Grey-AHP.

The primary criteria and previously defined sub-criteria are described in this article. The adaptation of these criteria to the Saaty scale is described, as this scale implies a link between a linguistic interpretation and a numerical scale of expert surveys conducted for the application of the multicriteria technique. Furthermore, the Grey-AHP for determining the location of the P&R is explained.

Table 1
Main criteria for establishing a P&R system.

Criterion	Explanation
C1	Distance
C2	Traffic conditions on the route (origin-destination)
C3	Accessibility of public transport.
C4	Transport aspects.
C5	Economic
C6	Environmental

3. Criterion system for locating a P&R system

Based on previous research on multi-criteria methodologies for P&R siting, the researchers have established six main criteria and 19 secondary sub-criteria (Ortega, et al., 2020).

Table 1 presents the six main criteria and their corresponding definitions. These main criteria are numbered from C1 to C6. Some of them are part of the mobility policies established in the SUMP and other criteria are part of what transportation experts consider important and fundamental when establishing a P&R system.

Table 2 shows the sub-criteria. The primary criteria are numbered from one to six (C1 to C6). The sub-criteria carry the preceding code of the criterion to which they belong: C2 is the fundamental criterion, and its sub-criteria are listed in the following order C2.1 and C2.2.

Fig. 1 shows a clear overview of how the main and secondary criteria for establishing a P&R system should be chosen from the mobility policies of the Mobility Plan and from the expertise of the transportation planner.

4. The hierarchy structure of P&R facilities location

In order to use AHP, we should first understand the system's hierarchy structure, which serves as the basis for planning and rating the variables that can be used or considered in determining the location of P&R system facilities. The technique is established by the hierarchical structure of the criteria, in which the criteria of the same category are arranged according to their configuration in the decision criteria tree. Fig. 2 displays the coding for each key criterion comprising the first level. Additionally, the sub-criteria that correspond to level 2 of the scale are depicted. Fig. 1 is a graphical representation of the P&R system's operation, or the journey from origin to destination. Fig. 2 depicts a two-step decision-making process without requiring a graphical explanation of the operation of the P&R system, thereby facilitating the explanation of the formulation of the Grey-AHP (Fig. 3)

Table 2
Sub-criteria for establishing a P&R system.

Sub-criterion	Explanation
C 1.1	Distance from the zones to the P&R system.
C 1.2	Distance from the P&R to the CBD.
C 2.1	Time of travel by private car.
C 2.2	Time of travel by public transport.
C 2.3	Time of travel by P&R system.
C 3.1	Frequency of public transport operations.
C 3.2	Transfer time from P&R to public transport stop.
C 3.3	The distance of the P&R from the nearest public transport stop.
C 4.1	Reduction of trips by private car in CBD.
C 4.2	Increase of demand by public transport in CBD.
C 4.3	Number of public transport connections available.
C 4.4	Demand for parking at a P&R system.
C 5.1	Cost of implementation for the project.
C 5.2	Cost of land use.
C 5.3	Cost of the implementation of the telecommunication infrastructure.
C 5.4	Total cost of investment maintenance.
C 6.1	CO_2 reduction.
C 6.2	Noise reduction.
C 6.3	Area occupied by existing green areas.

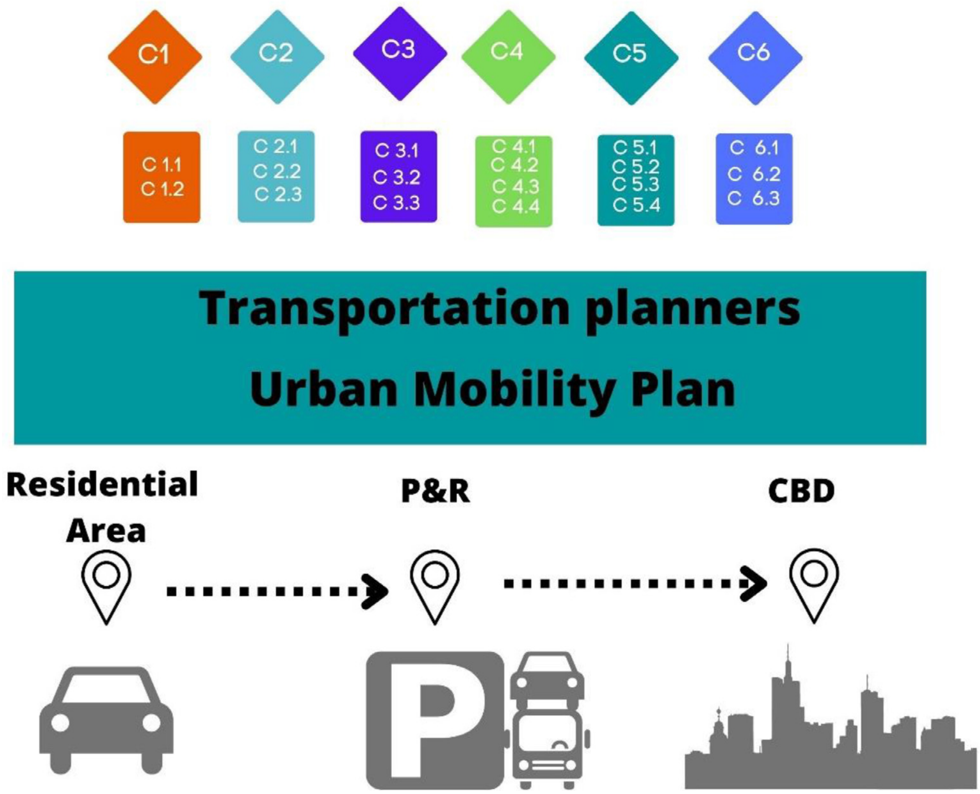

Fig. 1. Criteria related to the planning of a P&R system.

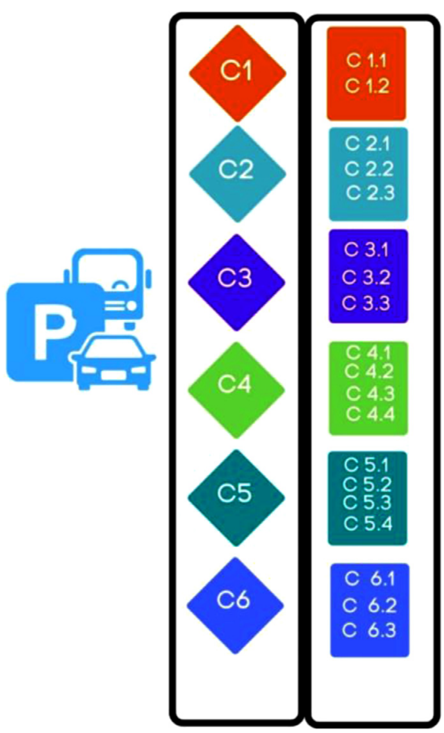

Fig. 2. Criteria related to P&R facilities location.

Table 3
Linguistic scales and the Grey numbers utilized for the pairwise comparisons of G-AHP.

Importance value	Linguistic scale	Grey number
1	Equally Important	[1,2]
3	Weakly Important	[2,4]
5	Important	[4,6]
7	Strongly Important	[6,8]
9	Absolutely Important	[8,10]

5. Survey

Using the established criteria and sub-criteria, questionnaires were developed to determine the most important criteria for adopting a set of facilities within a P&R system. The survey has 6 main questions that represent the criteria for level one on the multi-criteria method scale. The questionnaire also has 19 questions that represent the sub-criteria for level two.

As shown in Table 3, the responses are arranged on a linguistic scale. This enables the comparison of the principal criteria at both the first and second levels. Lastly, the adoption of this linguistic scale makes it possible to convert it into a numerical scale that can be utilised in the proposed multicriteria method.

Ten experts employed by the Cuenca Municipality were asked to participate in the survey. The experts are transportation planning specialists with diverse backgrounds in mobility-related fields.

The survey, which was conducted digitally in May 2022, took between 25 and 30 minutes to complete for each expert. The experts were chosen from the Municipality of Cuenca because the SUMP was developed by the Municipality of Cuenca and one of its transportation policies includes the development of P&R in the city's urban environment.

5.1. Case study

Cuenca, a city in southern Ecuador with a population of 659 317, carried out a Sustainable Urban Mobility Plan (SUMP) study in 2015. This investigation focused on the urban area of the city. It was designed to create a more sustainable city for its residents through a set of transport policies and provide solutions to mitigate the negative effects of private

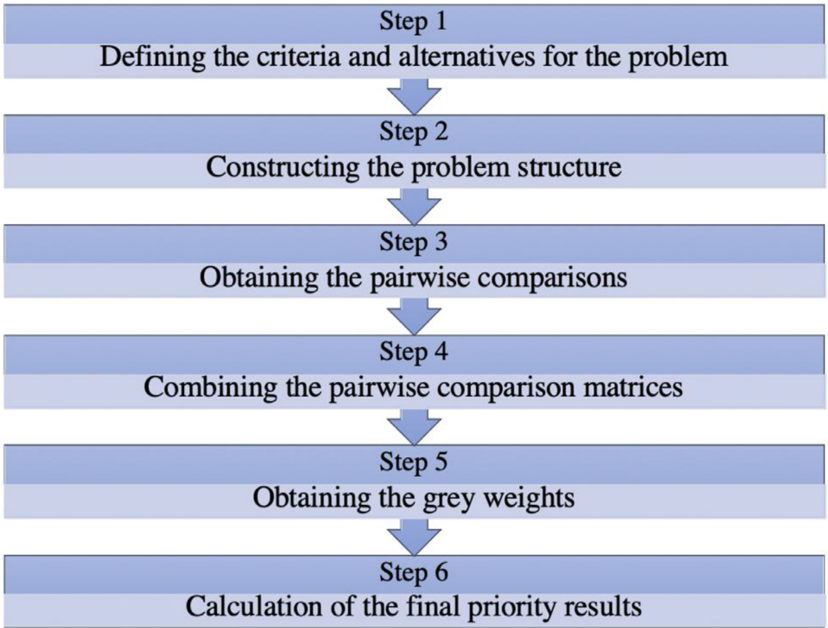

Fig. 3. Process for applying the multi-criteria method.

vehicles, such as traffic congestion and air pollution, particularly in the city centre. The SUMP divides the city into fifteen zones, or districts. There are 474 buses available, and one-way fares are $0.35 USD. There are 3,557 taxis in the metropolitan area. Additionally, a tram system exists.

6. Grey analytic hierarchy process

The adopted Grey Analytic Hierarchy Process (Grey-AHP) stems from the studies of Çelikbilek (Moslem & Çelikbilek, 2020), and it is applied to estimate P&R facility locations. The basis of the conventional AHP methodology was firstly introduced by Saaty (Saaty, 1977). The proposed evaluation model is basically a combination of Grey theory and the classic version of the AHP approach.

The proposed Grey AHP model steps for the evaluation of P&R facility location are given in detail below.

Step 1*: Defining the Aim and the factors:* Solutions of all AHP problems start with defining the aim, and then defining the factors and the alternatives related to the aim to construct the hierarchy tree.

Step 2*: Constructing the Hierarchical Structure:* The hierarchical structure of the problem is constructed by using the aim, alternatives and factors of the problem. In this problem, there are only factors related to the aim. So, the hierarchical structure has two levels.

Step 3*: Pairwise Comparisons:* Factors of the aim are compared pairwise in this step, as in classic AHP. However, linguistic scales given in the following table are used instead of the crisp scales in classic AHP.

As an example, the pairwise comparison is given in Eq. (1). $\otimes X^e_{ij}, = [\underline{X}^e_{ij}, \overline{X}^e_{ij}]$ represents the pairwise comparison of the ith criterion and jth criterion done by expert e. The main diagonals of the pairwise comparisons are filled with [1, 1] given in Eq. (2), and the upper parts of the main diagonals are filled by using the opposite forms to multiplication operation of the pairwise comparisons at the lower parts of the main diagonals given in Eq. (3).

$$D^e = \begin{bmatrix} \otimes X^e_{11} & \otimes X^e_{12} & \dots \otimes X^e_{1j} & \dots & \otimes X^e_{1n} \\ \otimes X^e_{21} & \otimes X^e_{22} & \dots \otimes X^e_{2j} & \dots & \otimes X^e_{2n} \\ \vdots & \vdots & \ddots \ \vdots & \ddots & \vdots \\ \otimes X^e_{i1} & \otimes X^e_{i2} & \dots \otimes X^e_{ij} & \dots & \otimes X^e_{in} \\ \vdots & \vdots & \ddots \ \vdots & \ddots & \vdots \\ \otimes X^e_{n1} & \otimes X^e_{n2} & \dots \otimes X^e_{nj} & \dots & \otimes X^e_{nn} \end{bmatrix} \tag{1}$$

$$\otimes X^e_{ij} = \left[\frac{1}{\overline{X}^e_{ij}}, \frac{1}{\underline{X}^e_{ij}} \right] \tag{2}$$

$$\otimes X^e_{ii} = [1, 1] \tag{3}$$

Step 4*: Combining the Pairwise Comparison Matrices of the Experts:* All of the pairwise comparisons of the expert opinions are combined by using the Eq. (4), which is geometric mean formulation like the classic AHP.

$$\otimes a_{ij} = \sqrt[D]{\prod_{d=1}^{D} \otimes a^d_{ij}} \tag{4}$$

The difference is that the geometric means are calculated for the upper parts and the lower parts separately. After the combination of the pairwise comparison of the experts, the main pairwise comparison matrix D given in Eq. (5) is obtained.

$$D = \begin{bmatrix} \otimes X_{11} & \otimes X_{12} & \dots \otimes X_{1j} & \dots & \otimes X_{1n} \\ \otimes X_{21} & \otimes X_{22} & \dots \otimes X_{2j} & \dots & \otimes X_{2n} \\ \vdots & \vdots & \ddots \ \vdots & \ddots & \vdots \\ \otimes X_{i1} & \otimes X_{i2} & \dots \otimes X_{ij} & \dots & \otimes X_{in} \\ \vdots & \vdots & \ddots \ \vdots & \ddots & \vdots \\ \otimes X_{n1} & \otimes X_{n2} & \dots \otimes X_{nj} & \dots & \otimes X_{nn} \end{bmatrix} \tag{5}$$

Step 5*: Normalization of the Pairwise Comparison Matrix:* The normalization of the pairwise comparison matrix is calculated by using the Eqs. (6–7) to obtain the normalized pairwise comparison matrix given in Eq. (8).

$$\underline{X}^*_{ij} = \left[\frac{2\underline{X}_{ij}}{\sum_{i=1}^{n} \underline{X}_{ij} + \sum_{i=1}^{n} \overline{X}_{ij}} \right] \tag{6}$$

$$\overline{X}^*_{ij} = \left[\frac{2\overline{X}^*_{ij}}{\sum_{i=1}^{n} \underline{X}_{ij} + \sum_{i=1}^{n} \overline{X}_{ij}} \right] \tag{7}$$

$$D^* = \begin{bmatrix} \otimes X^*_{11} & \otimes X^*_{12} & \dots \otimes X^e_{1j} & \dots & \otimes X^*_{1n} \\ \otimes X^*_{21} & \otimes X^*_{22} & \dots \otimes X^*_{2j} & \dots & \otimes X^*_{2n} \\ \vdots & \vdots & \ddots \ \vdots & \ddots & \vdots \\ \otimes X^*_{i1} & \otimes X^*_{i2} & \dots \otimes X^*_{ij} & \dots & \otimes X^*_{in} \\ \vdots & \vdots & \vdots \ \vdots & \ddots & \vdots \\ \otimes X^*_{n1} & \otimes X^*_{n2} & \dots \otimes X^*_{nj} & \dots & \otimes X^*_{nn} \end{bmatrix} \tag{8}$$

Table 4
Final aggregated Grey comparison matrix (6 × 6) for the main criteria in level 1.

	C1		C2		C3		C4		C5		C6		Final weight
C1	1	1	0.9347	1.7818	0.2554	0.3969	0.3865	0.6300	0.9635	1.4678	0.2435	0.3709	0.0924
C2	0.5612	1.0699	1	1	0.4263	0.6300	0.3550	0.5612	0.4472	0.6538	0.4472	0.6538	0.0917
C3	2.5198	3.9149	1.5874	2.3459	1	1	1.7508	2.6153	2.8845	4.6600	2.8845	4.6600	0.3394
C4	1.5874	2.5873	1.7818	2.8173	0.3824	0.5712	1	1	2.0396	3.5636	0.4292	0.7418	0.1731
C5	0.6813	1.0379	1.5294	2.2361	0.2146	0.3467	0.2806	0.4903	1	1	0.2527	0.3891	0.0904
C6	2.6960	4.1071	1.5294	2.2361	0.2146	0.3467	1.3480	2.3300	2.5698	3.9572	1	1	0.2129

Table 5
Final aggregated Grey comparison matrix (4 × 4) for the sub-criteria in level 2. (Transport aspects branch).

	C4.1		C4.2		C4.3		C4.4		Final weight
C4.1	1	1	0.3305	0.5503	1.0000	1.5874	3.8127	5.9876	0.2849
C4.2	1.8171	3.0262	1	1	1.3480	2.1777	2.6960	3.9572	0.4127
C4.3	0.6300	1.0000	0.4592	0.7418	1	1	1.2599	1.9064	0.1992
C4.4	0.1670	0.2623	0.2527	0.3709	0.5246	0.7937	1	1	0.1033

Table 6
Final aggregated Grey comparison matrix (4 × 4) for the sub-criteria in level 2. (Economic branch).

	C5.1		C5.2		C5.3		C5.4		Final weight
C5.1	1	1	0.6310	1.1487	1.5157	2.7595	0.5957	0.9221	0.2680
C5.2	0.8706	1.5849	1	1	1.0592	1.8882	1.4310	2.2974	0.3116
C5.3	0.3624	0.6598	0.5296	0.9441	1	1	1.2457	2.0000	0.2135
C5.4	1.0845	1.6788	0.4353	0.6988	0.5000	0.8027	1	1	0.2068

Table 7
Final aggregated Grey comparison matrix (3 × 3) for the sub-criteria in level 2. (Traffic conditions on the route (origin-destination) branch).

	C2.1		C2.2		C2.3		Final weight
C2.1	1	1	0.2184	0.3467	0.2184	0.3467	0.1211
C2.2	2.8845	4.5789	1	1	0.6300	0.9347	0.4009
C2.3	2.8845	4.5789	1.0699	1.5874	1	1	0.4780

Table 8
Final aggregated Grey comparison matrix (3 × 3) for the sub-criteria in level 2. (Accessibility of public transport branch).

	C3.1		C3.2		C3.3		Final weight
C3.1	1	1	4.3379	6.4907	2.4915	3.9487	0.6524
C3.2	0.1541	0.2305	1	1	0.3222	0.5000	0.1089
C3.3	0.2532	0.4014	2.0000	3.1037	1	1	0.2386

Step 6: *Computing the Relative Weights:* The relative weights are computed by using the normalized pairwise comparison matrix and Eq. (9). The obtained relative weights are also with Grey numbers.

$$W_i = \frac{1}{n}\sum_{i=1}^{n}\left[\underline{X^*_{ij}},\ \overline{X^*_{ij}}\right] \quad (9)$$

Step 7: *Ranking of the factors:* The relative weights used as final weights in this study are ranked from the highest to the lowest. The most important is the one that has the highest weight, and the less important factor is the one that has the lowest weight.

7. Results

The scores obtained from raters were calculated using the Grey-AHP method. It was necessary to construct Grey-AHP pairwise comparisons for all attributes of the decision structure, as shown in Tables (Tables 4–11), in which the scores of all respondents are summed. These tables are displayed below.

According to the data shown in the Tables, the Grey weight scores for every criterion at every level reflected the possible scenarios as minimum and maximum values. Scores at Level 1 were displayed as numeric values between 0 and 1, denoting a decreased degree of significance for one criterion relative to another, and so on.

In our study, “Accessibility of public transport” (C3) is the main criterion, while "Distance" (C1), "Traffic conditions on the route (origin-destination)" (C2) and "Economic" (C5) are the secondary criteria.

The AHP technique’s each-vector method can be used to complete the necessary calculation to determine local scores. Researchers were able to decide on the significance of each component in the decision structure by calculating the eigenvector scores and weight scores, respectively. In this particular instance, the planners’ scores represented the impact of public transportation. A higher score on the criterion indicated a greater level of significance. The score ranking highlighted the importance of public transport and its connection to the P&R system. This is a significant concept to help transportation planners implement the P&R system and improve public transportation service.

Table 4 shows in the first level which criterion is the most important, which proved to be C3 (0.3394) followed by C6 (0.2129). However, the criterion with the lowest weight is C5 (0.0904). Table 5 shows criterion C4 at the second level with its respective sub-criteria. Thus, the most important is sub-criterion C4.2 (0.4127). However, the lowest is criterion C4.4 (0.1033). Table 6 represents criterion C5 at the second level

Table 9
Final aggregated Grey comparison matrix (3 × 3) for the sub-criteria in level 2. (Environmental branch).

	C6.1		**C6.2**		**C6.3**		**Final weight**
C6.1	1	1	3.0262	4.7524	2.8619	4.5359	0.6480
C6.2	0.2104	0.3305	1	1	0.8409	1.4142	0.1796
C6.3	0.2205	0.3494	0.7071	1.1892	1	1	0.1724

Table 10
The weight scores for park and ride facilities main criteria in level 1.

Criteria	Weight	Rank
C1	0.0924	4
C2	0.0917	5
C3	0.3394	1
C4	0.1731	3
C5	0.0904	6
C6	0.2129	2

Table 11
The weight scores for park and ride facilities sub-criteria in level 2.

Main criteria	Sub-criteria	Local weight	Rank	Global weight	Rank
C1	C1.1	0.8294	1	0.0767	4
	C1.2	0.1706	2	0.0158	18
C2	C2.1	0.1211	3	0.0111	19
	C2.2	0.4009	2	0.0368	10
	C2.3	0.4780	1	0.0438	7
C3	C3.1	0.6524	1	0.2215	1
	C3.2	0.1089	3	0.0370	9
	C3.3	0.2386	2	0.0810	3
C4	C4.1	0.2849	2	0.0493	6
	C4.2	0.4127	1	0.0714	5
	C4.3	0.1992	3	0.0345	12
	C4.4	0.1033	4	0.0179	17
C5	C5.1	0.2680	2	0.0242	14
	C5.2	0.3116	1	0.0282	13
	C5.3	0.2135	3	0.0193	15
	C5.4	0.2068	4	0.0187	16
C6	C6.1	0.6480	1	0.1380	2
	C6.2	0.1796	2	0.0382	8
	C6.3	0.1724	3	0.0367	11

in which the highest criterion is C5.2 (0.3116), and the lowest is C5.4 (0.2068).

Table 7 shows criterion C2 and its respective sub-criteria at level 2. The highest criterion with the highest weight is C2.3 (0.4780), and the criterion with the lowest weight is C3.2 (0.1089). Table 8 shows criterion C3 and its sub-criteria at level 2, in which the criterion with the highest weight is C3.1 (0.6524), and the one with the lowest weight is C3.2 (0.1089). Table 9 shows criterion C6 and its sub-criteria, the highest being C6.1 (0.6480) and the lowest C6.3 (0.1724).

Table 10 displays the local and global weights for all main criteria in level 1 and their rankings as well. Table 10 shows the level one criterion. The most crucial criterion is C3 (0.3394) followed by criterion C6 (0.2129). However, criterion C5 is the last with the lowest weight (0.0904).

Table 11 shows the local and global weights for all sub-criteria in level 2 and their rankings as well. Table 11 shows the level 2 criteria. For example, among the set of sub-criteria, the one with the highest weight is C3.1 (0.2215) followed by C6.1 (0.1380). However, the lowest criterion is C2.1 (0.0111).

8. Discussion

This section begins with a discussion of the results obtained using the Grey-AHP multi-criteria method, followed by a comparison with the multi-criteria methods used in the literature (FAHP and BWM) to solve the P&R system location problem.

Each score on this evaluation represents a consideration that should be made during the implementation of a P&R system. The survey questions for a peer comparison were designed to evaluate multiple aspects of the P&R system.

Accessibility is of the utmost importance when developing a P&R system from a public transportation standpoint. Regarding the application of P&R, the economics component is the least significant. Numerous public transportation-related requirements should be considered in order to properly implement a P&R system, as is evident from the table presented previously (Table 11).

Taking a more analytical approach to the examined case study, it is reasonable to conclude that the frequency of public transportation is the most critical sub-criteria at level two. In other words, the installation of the P&R system is something that must be considered if public transportation is accessible and frequent. The level 2 factor with the lowest value is the amount of time spent travelling in a private vehicle. This result was expected, considering that the objective of transport planners when building a P&R system is not to reduce the time required to travel by private car. Public transportation should be given greater consideration if a P&R system is to be implemented, as it is the most influential factor in a multi-criteria analysis.

According to the findings obtained using the Grey-AHP model, to put into practice a P&R system, it is necessary, first and foremost, to ensure that public transportation is accessible. Transport planners concur that P&R planning depends heavily on the planning of public transportation to P&R facilities. In other words, public transportation frequency must be synchronised with the P&R system's peak demand. It is recommended that the planners analyse the timetables of the urban lines, because this factor is highly significant in attracting potential users of public transportation (VATANEN et al., 2000).

The findings make it abundantly evident that the used Grey-AHP model can provide the possibility of an in-depth study to support the decisions about the development of the P&R system. The criteria and the research approach can be utilised to analyse and solve random P&R development issues in any city.

A graphical representation of the rankings that were obtained from the primary criteria is presented in Fig. 4.

Fig. 5 depicts the relative position of levels one and two. When reading and analysing the radar graph, its hierarchical structure is taken into account; starting from the centre and moving towards the different levels of nodes located around the main concept, the centre of the graph represents the minimum value (C3.1) and the edge represents the maximum value (C2.1).

A multicriteria F-AHP analysis has already been performed (Ortega, et al., 2020), and the dominant result or main criterion is the accessibility of public transport. A multi-criteria analysis known as BWM (Ortega, et al., 2020) was also performed, with the main criterion being the accessibility of public transport. These studies applied the level one and two criteria developed in this G-AHP research to the city of Cuenca, Ecuador.

Table 12 compares the ranking of the main criteria of the three methods used, FAHP, BWM, and G-AHP, which was developed in this article. The main criterion C3 has the same priority in all three methods; however, the criterion in position 2 of the ranking is C6 for G-AHP, which is the same as in BWM, but in the FAHP method, C6 is in position 4 of

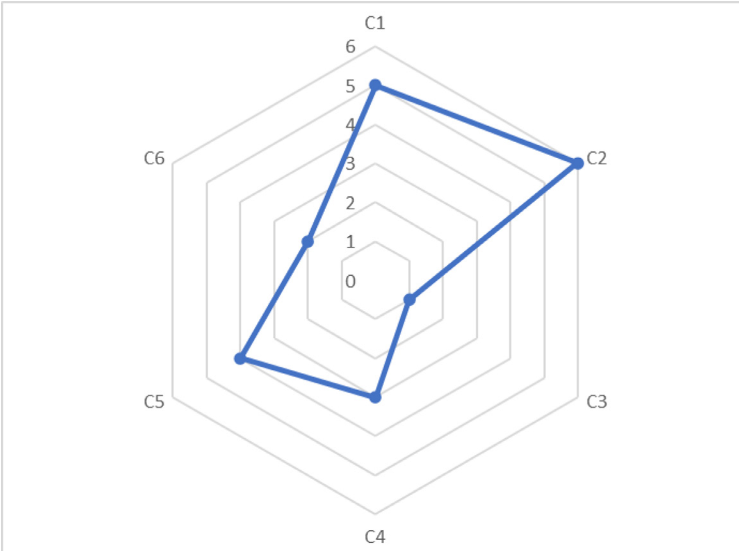

Fig. 4. Priority ranking of main criteria.

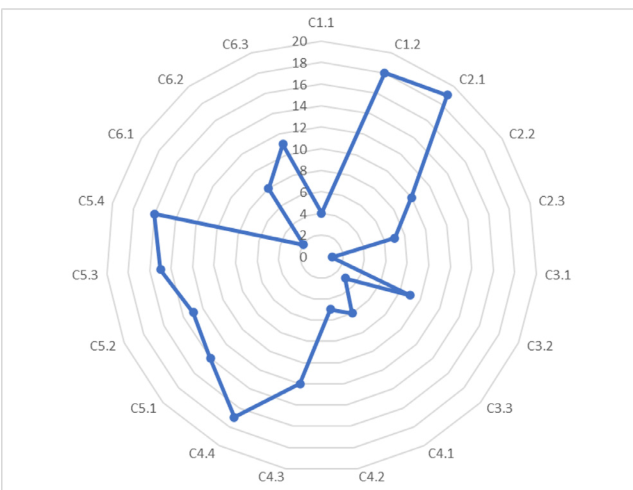

Fig. 5. Priority ranking of sub-criteria.

Table 12
The weight scores for the P&R facilities regarding the criterion of Level 1 FAHP (Ortega, Tóth, et al., 2020), BWM (Ortega, Moslem, et al., 2020) and G-AHP.

FAHP		BWM		G-AHP	
Criteria	Rankings	Criteria	Rankings	Criteria	Rankings
C1	5	C1	5	C1	4
C2	6	C2	6	C2	5
C3	1	C3	1	C3	1
C4	3	C4	3	C4	3
C5	2	C5	4	C5	6
C6	4	C6	2	C6	2

Table 13
The weight scores for the P&R facilities regarding the sub-criteria in case of Level 2 FAHP (Ortega, Tóth, et al., 2020), BWM (Ortega, Moslem, et al., 2020) and G-AHP.

FAHP		BWM		G-AHP	
Factors	Rankings	Factors	Rankings	Factors	Rankings
C1.1	5	C1.1	3	C1.1	4
C1.2	18	C1.2	15	C1.2	18
C2.1	19	C2.1	19	C2.1	19
C2.2	13	C2.2	16	C2.2	10
C2.3	11	C2.3	10	C2.3	7
C3.1	1	C3.1	1	C3.1	1
C3.2	8	C3.2	8	C3.2	9
C3.3	3	C3.3	4	C3.3	3
C4.1	7	C4.1	9	C4.1	6
C4.2	4	C4.2	5	C4.2	5
C4.3	9	C4.3	12	C4.3	12
C4.4	17	C4.4	17	C4.4	17
C5.1	14	C5.1	13	C5.1	14
C5.2	12	C5.2	7	C5.2	13
C5.3	15	C5.3	14	C5.3	15
C5.4	16	C5.4	18	C5.4	16
C6.1	2	C6.1	2	C6.1	2
C6.2	6	C6.2	6	C6.2	8
C6.3	10	C6.3	11	C6.3	11

the ranking. The most notable difference in the ranking is criterion C5, which does not match in the ranking with any of the three multi-criteria methods.

Table 13 compares the sub-criteria of the three methods, FAHP, BWM and G-AHP, developed for this work. Criterion C3.1 is the most essential sub-criterion for each of the three methods. In contrast, the G-AHP and FAHP method assigns criterion C3.3 the third most significant position, while the BWM method assigns criterion C3.3 the fourth most significant position. Ranking criteria C1.1, C2.2, C2.3, C4.1 and C5.2 do not match any of the three multi-criteria approaches.

The FAHP can categorise assessment factors into three levels: target, criterion, and factor. The BWM method makes comparisons in a more structured manner, which makes them simpler and more comprehensible, and leads to more coherent comparisons, resulting in more reliable weightings. The selection of criteria, the hierarchy, and the expert judgement used to determine the level of significance of each criterion in the FAHP and BWM methods have a significant impact on the final decision (Rezaur Rahman et al., 2019; Sabilla Ajrina et al., 2018). The G-AHP method that combines the advantages of classical AHP and grey theory for the accurate estimation of weighting coefficients (Duleba et al., 2022)

It is difficult to determine the best multi-criteria method, because it depends on how the criteria are chosen, ranked, and an expert determines their relative significance. In other words, importance rankings can vary based on the aforementioned factors. The Grey-AHP developed in this paper provides a more accurate estimation of weights based on previous research. The need for additional research on multi-criteria methods for the P&R system location problem is a limitation of this work. This means that more multi-criteria methods must be applied to the two levels of decision making to determine which one to use based on the mentioned factors.

9. Conclusion

The Grey-AHP multicriteria model can determine the criteria weights for the P&R system location problem with greater precision. This characteristic makes it a highly effective tool. In addition, the Grey-AHP model provided information on the criteria of transportation planners that work in the municipality of Cuenca Ecuador in relation to the deployment of a P&R system. This covers a list of criteria, including the environment. As a limitation of this study, it is crucial to note that only a single municipality and a single group of planners participated in the research presented.

The implementation of a P&R system through applications based on Grey theory exemplified how a specific set of criteria could be used to determine which implementation criteria are the most important. To demonstrate the efficacy and viability of the proposed method, a real-world case was applied in Cuenca, Ecuador.

Regarding the application of this case study to Cuenca, it is crucial to note that there are no differences in the order of weighting between the Grey-AHP, FAHP and BWM results in determining the main criteria for the P&R system location problem. To support the implementation of a P&R system, it is recommended to enhance the accessibility and frequency of public transportation.

The Grey-AHP model proved successful based on the results we collected. Because not all raters had the same level of comprehension regarding the relevance of ratios in pairwise comparisons, having numbers that were more malleable contributed to more reliable scoring and ranking. According to our survey results, the Grey-AHP technique can be recommended for all decision support situations in which professional participants analyse decision structure components. This holds especially true for paired comparisons. A Grey-AHP approach is a tool that can be utilised while implementing a P&R system to obtain the expert's perspective. Theoretically, every other city could gain from the methodology, survey method, and analysis offered here.

Future research should focus on integrating Grey theory with other MCDM approaches (such as the analytical network process, for example). In addition, other multi-criteria methods should be applied to the set of criteria established in this research in order to determine which method may be most appropriate based on the type of city and the set of experts.

Declaration of Competing Interest

Please check the following as appropriate:

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

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