Non-parametric Multi-criteria Optimisation of Park and Ride Facility Locations

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Abstract. A significant increase in car ownership has been recognised as one of the main reasons for traffic congestion, especially in city centres. Park-and-ride (P&R) facilities are often included as parts of a multimode transportation strategy, featuring car parks where users can switch to public transportation to carry on their journeys; they have thus long been used as an effective solution to mitigating congestion issues without affecting traffic demand. Feasible locations of park-and-ride facilities are thus of crucial importance not only for users, but also local authorities and the environment. Many factors of different importance affect the optimal locations of P&R facilities, which further complicates the process of decision making. In order to systemise the process of criteria weighting, a non-parametric approach is thus used in this paper to test three key aspects of the P&R facility localisation process. These are user coverage, accessibility from major roads, and area availability. An Analytic Hierarchy Process (AHP) is used to develop a resilient weighting system that can be updated for each case, and the case study used in this research is the Iraqi city of Kerbala. The results show that the AHP method is a powerful technique for evaluating and comparing the influence of multiple factors on each other and on the final outcome. The paper concludes with a discussion of the findings, practical implications, research limitations and future research directions.

Keywords: Analytic Hierarchy Process; non-parametric optimisation; park-and-ride facilities; public transportation

Introduction

The significant increase in car and motorbike ownership in recent years, especially in less developed parts of the globe, has exacerbated several public transportation challenges, including road accidents, traffic congestion, excessive travel times, and air pollution [1]. Dealing with private cars has rapidly become one of the most complex problems related to urban transport system development [2]. Requirements for parking of the constantly increasing number of individual cars creates impetus for extensive and intensive exploitation of urbanised areas despite land in cities being scarce. Park and ride (P&R) facilities are a logical solution for this problem, as they allow cars to be kept somewhat separate from urban areas. This suggests that the anthropogenic environment of urban transportation systems and their relevant operational merits ought to be fully investigated with a view to installing a new, more extensive P&R system.
Initial ideas of using passenger cars in combination with mass transportation systems were developed throughout the first five decades of the twentieth century[3]. These approaches developed due to the prevailing lobbying policy stimulating the growth of quantity of passenger cars, causing the transit system infrastructure to be saturated [4] and reducing performance of public transit and the options of city inhabitants [5]. P&R facilities offer a widely recognised strategy for traffic demand management that aims to mitigate traffic congestion and localised air pollution [6]. Travelers using private cars are encouraged to switch temporarily to mass transport system, such as buses and subways, by the provision of P&R facilities. These facilities, which both ease traffic demand and motivate users to take public transport to visit the city centre, have also attracted growing scholarly attention [6].

Various modelling analyses of P&R facilities can be found in the literature. Fernandez et al., [7] adopted mode choice models to evaluate demand for various travel modes, including P&R facilities, before applying user equilibrium models to determine traffic demand on each segment. Similarly, Garcia et al., [8] studied the design of P&R facilities in terms of capacity and pricing, proposing that parking facilities were situated before such systems were developed. Li et al., presented a network equilibrium formula to model P&R facilities in a multimodal transit system with flexible demand [9], identifying several factors that impacted the efficacy of P&R services including capacity in central urban areas and parking tariffs along with frequency and cost of public transport systems. Similarly, Liu et al., introduced a continuum equilibrium model to assess travellers’ modal choice attitudes in a multimodal system with a continuum of P&R facilities along a journey path [10], and later modelled a stochastic user equilibrium problem featuring a bus-based P&R system and congestion pricing in a multimodal system [11]. Using data gathered from surveying P&R users in Melbourne, Islam et al., [12] examined means of changing the attitudes of P&R users, concluding that travel time and parking tariff are the major aspects affecting traveller behaviour in terms of choice of transport mode. Finally, Pineda et al.,[13] suggested a unified stochastic equilibrium model to define flow distributions between car, bus, and P&R modes, advancing a solution algorithm using a successive averages methods to resolve the equilibrium state.

Despite the fact that these modelling analyses of P&R systems have been widely examined [14, 15] there is still a lack of understanding around where to position P&R facilities, despite this being a key determinant of P&R planning. Some agencies have introduced a set of principles for choosing P&R locations [16, 17, 18, 19]. Based on such criteria, the Florida Department of Transportation (FDOT) has used an expert system to rank possible P&R locations, for example [20]. Faghri et al.,[21] also advanced a hybrid knowledge-based expert system to pinpoint P&R locations; however, such methods usually produces ambivalent and somewhat inconsistent results, as the criteria are chiefly based on empirical evidence [22]. Research has also been implemented to directly optimise the locations of P&R services[23], yet the majority of existing procedures have a range of limitations. Researchers, including Horner et al.,[24], Farhan et al.,[25], and Aror-Vera et al.,[26], have not yet considered the ways in which travellers respond to the provision of P&R facilities, and while Fan et al.,[27] used a stochastic user equilibrium model to capture traveller’s reactions, the model was not able to deal with compound transport networks such as those with common-line segments.

Other research has studied extremely basic settings such as a linear city [3, 22]. However, the appeal of P&R services not only depends on strategic deployment of P&R facilities but also on the levels of service of the transport systems serving these P&R facilities. For example, in the San Francisco Bay Area, some P&R parking lots are overloaded whilst the others are almost empty, and users would rather travel to work using their private cars than use the a poorly situated and uncovered P&R facility [28].

The aim of this paper is to measure the effect of user coverage, accessibility from major roads, and area availability on P&R facilities’ locations in Karbala city in Iraq using a AHP approach to multi-criteria decision-making. A sustainable solution is sought for the transportation problem in Kerbala city by redirecting private car trips onto public transport. For this purpose, the research focuses on the most important factors (available area, demand, and main roads) by giving them high priority in locating candidate P&R facility locations. Traditional decision-making methods generally consider quantitative criteria, while the multi-criteria approach denotes both qualitative and quantitative criteria. Therefore, this study tries to measure influence of each factor on the location of P&R facilities.
Methodology

The study area for this research is Karbala, Iraq. Karbala is located 110 Km to the south west of Baghdad, the capital city of Iraq, at latitude of 32°N and longitude 44°E, as shown in Figure (1). The total population is estimated at 1 million, and it is also one of the most famous destinations for religious tourism in Iraq [29].

1.1 Analytic Hierarchy Process (AHP)

The AHP method was originally presented by Saaty [30] as an instrument for complex decision making problems to help those in senior positions to prioritise relevant factors and make better decisions. AHP is focused on a set of judgement elements leading to a set of alternate choices, from which the most favourable decision can be selected. As some of criteria may be conflicting, the best option is less likely to be one that satisfies every single criterion and instead to be the one that achieves the best trade-off between various criteria. The AHP approach allocates a weight to every judgement variable, with reference to a decision maker’s pairwise comparisons of the criteria. The more the weight allocated, the higher importance placed on the corresponding criterion. In terms of fixed criteria, the AHP allocates a weight to each choice depending on the decision maker’s pairwise comparisons of the choices based on those criteria such that, the more the weight, the more favourable performance of the choice with reference to each criterion under consideration. Finally, the AHP approach merges the weight of each criterion and choice in order to determine a global weight for every choice to develop a ranking order. The global weight for a particular choice is thus a weighted combination of the weights it has gained with regard to all the criteria [31].

1.2 Specifying the criteria and data collection method

Spatial distribution of P&R facilities in an urban area is a function of a number of inter-correlated factors. The starting point for determining P&R locations should be the pattern of areas offering demand, which strongly influences potential traffic. In addition, access/egress points are a major consideration in the location of a P&R facility, and thus access to main roads is a very important factor. Finally, the planning process requires development of an average daily demand estimation due to the nature of P&R services. Three variables were identified as significant factors related to P&R locations, and AHP was chosen as a powerful technique to measure the influence of each criterion in locating P&R facilities. However, this study did not seek to actually locate P&R facilities, but rather to determine the weights of each factor associated with P&R location.

After highlighting the importance of the criteria used, a questionnaire was designed on a fully electronic basis using Google Forms. Questions were thus directed to experts in the field of Transportation...
Engineering about the ratings of relative importance for demand, available area, and main roads with regard to each other (see table 1) to determine which criterion was more important with respect to AHP priorities, and by how much more on a scale 1 to 9. A total of 24 responses were received. The method was based on the use of a pairwise comparison matrix \( A=\{a_{ij}\} \) (i, j=1,2,..., m), as shown in Equation 1, where m is the number of compared criteria. In this case, \( m=3 \).

| A-Importance – or B? | Equal | How much more? |
|----------------------|-------|---------------|
| Demand               | Available area | 1   | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Demand               | Main roads    | 1   | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Available area       | Main roads    | 1   | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |

*Table 1: Survey form*

The experts evaluated the pairwise sets of each aspects and criteria on a scale of importance. Afterwards, a quantitative analysis was carried out to form a comparison matrix \( A \) (Equation 1). Numerical ratings based on Saaty’s scale were written on the upper triangular matrix, while the inverse of these ratings was shown on the lower triangular of the matrix.

\[
A = \begin{bmatrix}
  a_{11} & a_{12} & \cdots & a_{1q} & a_{21} & \cdots & a_{2q} & \cdots & a_{q1} & a_{q2} & \cdots & a_{qq} \\
  a_{12} & a_{22} & \cdots & a_{2q} & a_{21} & \cdots & a_{2q} & \cdots & a_{q1} & a_{q2} & \cdots & a_{qq} \\
  \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
  a_{q1} & a_{q2} & \cdots & a_{qq} & 1 & \cdots & 1/a_{21} & \cdots & 1/a_{q1} & 1/a_{q2} & \cdots & 1/a_{qq}
\end{bmatrix}
\tag{Equation 1}

After consolidating the pairwise comparisons, the scores in the matrix were summed up to normalise the values. Normalisation further involved dividing each element by the total score in a particular column and computing the average of each row to obtain the priority vector or weights.

To ensure that consistent judgments were made, a final procedure, consistency verification, was incorporated in AHP. This procedure measured the degree of consistency among the pairwise comparisons in matrix \( A \) by calculating a consistency ratio (CR, Equation 3) using the value of the consistency index (CI, Equation 2) and the random index (RI).

\[
CI = (\lambda_{\text{max}} - n) / (n - 1) \tag{Equation 2}
\]

\[
CR = CI / RI \tag{Equation 3}
\]

The CI value was calculated using the maximum eigenvalue \( \lambda_{\text{max}} \) and order \( n \) of the comparison matrix, while \( \lambda_{\text{max}} \) was calculated as the summation of the product of the priority vector and the column total of the pairwise comparison matrix of each corresponding criterion. The CR value was calculated as the ratio of CI to random index (RI). Random RI values for various \( n \) were proposed by Saaty [30] (see Table 2). A CR ratio of 10% or less implies that the comparisons are relatively consistent or acceptable. Conversely, a CR ratio higher than 10% means that an appropriate corrective measures or inconsistency identification are required.

*Table 2. Proposed random index Saaty [30]*

| N  | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RI | 0   | 0   | 0.58| 0.9 | 1.12| 1.24| 1.32| 1.41| 1.45| 1.49|
Results and Discussion
Using the criteria of available area, demand, and main roads, a survey using pairwise comparisons was conducted among various experts to assess and rank these criteria. The sample experts included scientists, professors, and researchers. The pairwise comparisons were quantified using AHP. Based on Equation 1, Table 3 shows the pairwise comparison matrices of the three main aspects from the survey results, while Table 4 represents the comparison matrix of the eigenvector for matrix (A).

Table 3. Pairwise comparison matrix of the different criterion (matrix A)

| Criteria      | Demand | Area | Main Roads |
|---------------|--------|------|------------|
| Demand        | 1      | 0.5  | 3          |
| Area          | 2      | 1    | 2          |
| Main Roads    | 0.33   | 0.5  | 1          |

Table 4. Eigenvector decomposition matrix

| Criteria      | Demand | Area   | Main Roads |
|---------------|--------|--------|------------|
| Demand        | 2      | 1      | 2          |
| Area          | 0      | 0.335  | 0.67       |
| Main Roads    | 0      | 0      | 2          |
| Sum           | 2      | 1.335  | 4.67       |

Note: $\lambda_{max} = 3$, $CI = 0.03$, $CR = 0.04$

Upon normalisation of the comparison matrices, the computed CR (using Equation 3) was less than 0.1 (<10%) for all aspects. Thus, the pairwise comparisons were consistent and suitable for use in decision-making processes. The result of AHP shows the high influence of demand on P&R locations at 73%, while the effect of main roads is only 14% and available area 13%. This highlights the significance of public transport demand in terms of locating P&R facilites compared with access to main roads and available areas. This in turn provides additional evidence of the importance of deploying such systems at highly populated zones, such as city centres and other major activity centres.

Figure 2 shows the variance between all factors. While previous studies have extensively focused population rates in locating P&R facilities, this study focuses on demand, suggesting that taking demand into consideration may result in more accurate results, as raw population may not always reflect the actual need for such facilities. The 73% result is likely to reflect the fact that the five major entrances to Karbala city offer high demand for P&R facilities linked to the nearby city centre, which attracts thousands of pilgrims every day. Despite the low percentages of availability of area and main roads, local authorities must ensure that P&R facilities are constructed in viable locations by means of land acquisition and road.
construction, and these P&R facilities should be constructed as necessary to meet the highest demand possible.

**Conclusion**

P&R facilities are an essential element of mass transport systems, such that positioning services is a key step in urban planning. Covering as much potential demand as possible, siting P&R facilities in the context of available area and addressing the need to have selected sites as close as possible to major roadways are important considerations. This paper developed an AHP-based approach to examine the extent of impact of each factor on P&R location. The results of the study showed that demand criterion was given higher importance over the other criteria. Future studies should thus take these results into consideration when determining the optimal locations of P&R facilities.

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