Optimal Siting of Park and Ride Facilities Using Geospatial Approach

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Abstract

The significant increase in car ownership has been recognized as one of the main reasons for traffic congestion worldwide, especially in city centers. Park-and-ride (P&R) facilities, which are car parks where users can adjust to public transportation to carry on their journeys, have long been used as an effective solution to mitigate congestion issues without affecting traffic demand. However, literature on the optimal localization of these facilities using geospatial approaches are still emerging. Feasible locations of P&R facilities are of crucial importance not only for users but also to local authorities and the environment. The aim of this paper is to explore the significance of several factors affecting optimal locations of P&R using Analytic Hierarchy Process (AHP) and to propose a multi-criteria geospatial approach to locate optimal park and ride facilities in Karbala, Iraq. Three key aspects are tested in the localization process, including users' coverage, accessibility to major roads, and area availability using Geospatial Tool. The case study on the holy city of Karbala in Iraq was implemented and the results show that the optimization model is proved to be powerful in providing more optimal locations of P&R facilities. The paper concludes with a discussion of the practical implications, research limitations and future research directions.

Keywords: Geospatial approaches; Optimal localization; Park-and-ride; Public Transportation; Traffic congestion;

1. Introduction

The growing increase in population and obsolete road networks around the world constitute a pressing need to more effective mass transport infrastructure [1]. Efficient public transport system is capable to reduce traffic congestion by offering people more equitable and reliable service [2]. Park-and-ride (P&R) is a system where travelers adjust their journeys into public transport means, leaving their cars in designated parking lots [3]. The P&R system has been attracting growing scholarly attention as an effective tool to alleviate parking demand in cities centers, reduce traffic congestion at peak hours, conserve energy, decrease pollution levels, and reducing travel time [4, 5] . Several cities around the globe started to equip rail transport systems with P&R services to mitigate issues related to traffic and environment. As such, travelers are encouraged to leave their private cars at P&R facilities and carry on their trips using public transportation (e.g. bus, or subway). Hence, an efficient P&R facility should be capable of accommodating traffic demand in a way that lowers traffic issues in central areas [6].

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Literature related to the P&R locations can be categorized into three distinct research streams. The first stream involves the empirical evidence coming from experiential studies (e.g.[7,8,9,10]). For example, Transportation Research Board (TRB) [10] provides a range of observations depending on empirical research concerning the distance between travelers' origin and destinations as well as P&R facilities. These observations show wide ranges, which are hard to apply them directly in particular P&R localization decision.

The second research stream comprises mathematical modeling work with various optimization objectives, including minimizing vehicle miles traveled (VMT), maximizing market coverage, or

a combination. For example, Farhan [2] suggested a multi-objective optimization model integrating optimization measures of proximity to main roads, supplement to current facilities and coverage maximization. This P&R function handled the impact of distance decay where value of expected P&R users plummeted along with the distance between P&R facility and travelers' trip origins. In a recent study, Holguin-Veras [11] introduced a P&R optimization model aiming at maximizing its market, that was defined as the scope of feasible P&R trip origins and destinations, where travel charges by P&R were less than that by automobile. Holguí n-Veras [12] presented an assessment of the economic feasibility of alternative P&R locations based on four performance measures: expected demand, market share, weighted average savings, and present value of benefits. The results indicate that P&R facilities could bring significant benefits to commuters.

The third stream is the studies focused on exploring P&R location solutions using computer-aided techniques. Schneider [13] designed an interactive graphic system to help users to concurrently calculate the location and size of bus-based P&R parking lots. The results showed that even less experienced individuals using this system could find a high quality solution in timely and cost-effective manners. Horner [14] developed an assessment method using geographic information system (GIS) to envisage the process of comparing and selecting possible locations of rail-based P&R facilities. Faghri [3] introduced an expertise-based GIS model to support positioning P&R services with the possibility of handling nonquantitative criteria through designed expert system. However, the work leaves the demand on P&R facilities prespecified and unchanged by the final location solution.

In this study, a sustainable solution is sought for the transportation problem in Karbala city by redirecting private car trips into public transport. For this purpose, part of wider study focused on the most important factors (available area, demand, and main roads) by giving them high priority in locating candidate P&R facilities locations. Conventional decision-making processes often consider quantitative criteria whereas the multi-criteria approach involves both qualitative and quantitative criteria. Therefore, this study measures the influence of each factor on the locations of P&R facilities.

Previous studies defined several factors influence the process of determining the locations of P&R facilities. Nevertheless, despite the fact that one factor may in fact outweigh the other, literature usually considers them on an equal scale [3,2]. While previous studies have extensively focused population rates in locating P&R facilities, this study has focused on demand instead. That is, taking the demand into consideration may therefore result in more accurate results since population may not always reflect the actual need for such facilities.

The main contribution of this research is eliciting experts' experience using multicriteria decision making process based on geospatial analysis to help determine the optimal location for P&R facilities.

2. Methodology

The research method includes three main steps: data preprocessing, data analysis, and cartographic outputs. The more detailed steps about this research method are shown below in Figure 2.

2.1. Study Area

The sample network is part of Karbala which is an Iraqi city with an estimated population of 1.25 million capita [15], located at 110 km to the South West of Iraqi capital Baghdad, on the latitude of 32°N and longitude 44°E. The city is around 36 meters above the mean sea level. It is considered as one of the most important destinations for religious pilgrimage in Iraq. Among other Iraqi cities, Karbala receives 30 million pilgrims around the years of [16]. Figure (1) shows the study area.

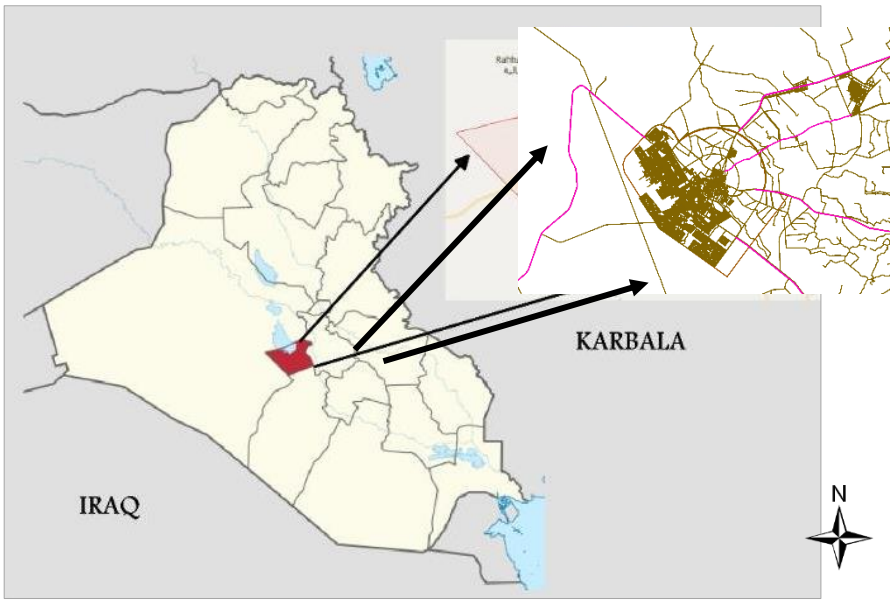

Figure 1: Karbala location and its major roads

2.2. Specifying the Criteria and proposed approach

Spatial distribution of P&R facilities in urban space is a function of a number of factors related to the potential demand. Based on previous studies and guideline books on P&R, the starting point to determine P&R locations should be the pattern of areas accommodating demand, which strongly influences the potential traffic. In addition, Access/Egress Points: A major consideration in the location of a P&R facility is the access to, and egress from, the lot, therefore main roads are very important factor. Finally, daily demand: the planning process has developed 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. After highlighting the importance of the criteria used, a questionnaire was designed on fully electronic basis. Using Google Forms, the questions were directed to experts in the field of transportation engineering. Questions were about the rating of the relative importance of the demand, available area, and main roads to each other. A total of 24 responses were received. The method is based on the use of pairwise comparison matrix A=|aij| (i, j=1,2..., m) as shown in Equation 1, where m is the number of compared criteria. In our case m=3.

$$A = \begin{bmatrix} a_{11} & a_{12} \dots & a_{1q} \\ a_{21} & a_{22} \dots & a_{2q} \\ \vdots & \vdots & \vdots \\ a_{q1} & a_{q2} \dots & a_{qq} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \dots & a_{1q} \\ 1/a_{21} & a_{22} \dots & a_{2q} \\ \vdots & \vdots & \vdots \\ 1/a_{q1} & 1/a_{q2} \dots & a_{qq} \end{bmatrix} \quad \text{.....(Equation 1)}$$

AHP approach, which was developed by Saaty [17], is an efficient tool to deal with complex decision making, and help decision makers to set priorities and make better decisions.

Finally, we classified each layer according to their importance. That is, the available area layer can be classified into two categories. Category one includes the land, which covers car parks, petrol station, shopping malls, roads, open areas, and green zones, with a total area of almost 20,000 m2. These areas have been given high weights whereas less areas have been given less value as category two. This also applies to the main roads within 1000m which have been given high weight whereas more than 1000m has been given less value.

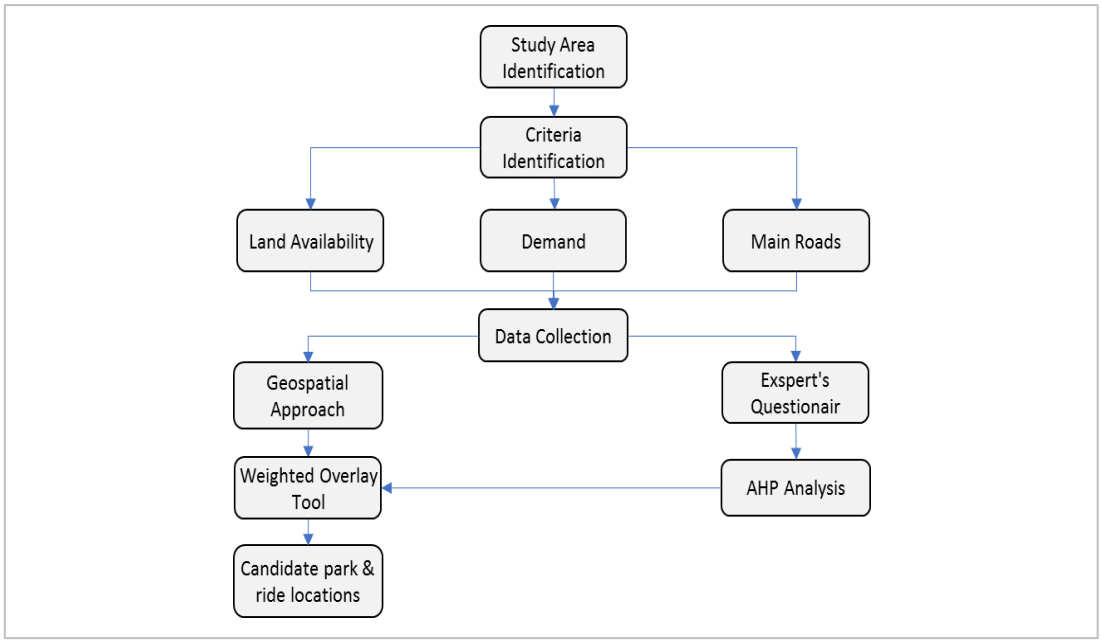

Figure 2. The interaction among parties involved in locating P&R facilities

Each value class in each input raster is assigned a new reclassified value on an evaluation scale of 1 to 9, where 1 represents the lowest suitability and 9 the highest. For instance, in the raster, vacant land is highly suitable, while other land use is not. In the demand raster, suitability values are high in high-density areas and low for low-density areas. In the distance to parks raster, suitability increases with distance from existing pars because areas far from existing parks are inadequately served. Geospatial analysis is one of the powerful techniques which are facilitated by GIS packages such as Spatial Analyst within ArcGIS tools used to solve this problem. Specifically, Overlay Analysis Tools within Spatial Analyst Tools allocates weights to several input layers and then it combines them into a single output [18]. The combination of these technologies helped us achieve our goals, as the AHP performs the evaluation, and the GIS handles the graphical operations representing the urban network on which the P&R sites are evaluated.

2. Results and Discussion

Using the criteria of available area, demand, and main roads, a survey using pairwise comparisons was conducted, eliciting its responses from different experts to clearly assess and rank these criteria. The sample experts included national scientists, professors, and researchers. The pairwise comparisons were quantified by using AHP. Using Equation 1, Table (1) shows the pairwise comparison matrices of the three main aspects.

Table 1: 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

This analysis is dependent on each of the three-input raster are weighted, the result of AHP shows a high influence of demand on the P&R locations at 73%. Both the effect of main roads and land availability were low at 14% and 13%, respectively Figure (3) shows the variance between all factors. Consequently, these weights were inserted on GIS model to rank key areas within the case study. The resulted ranked areas were exported to Polygon Feature Classes to represent best candidates of P&R locations. The input raster to the weighted overlay are displayed in the figures. Figure (4) shows legend 1 which represents zones outside 1000m while legend 2 represents those inside 1000m. Figure (5) is divided into two zones: purple color indicates areas less than 20000m^2 while green areas indicates zones of more than 20000m^2. Figure (6) represents the demand concentration in each zone as shown in the colored legend.

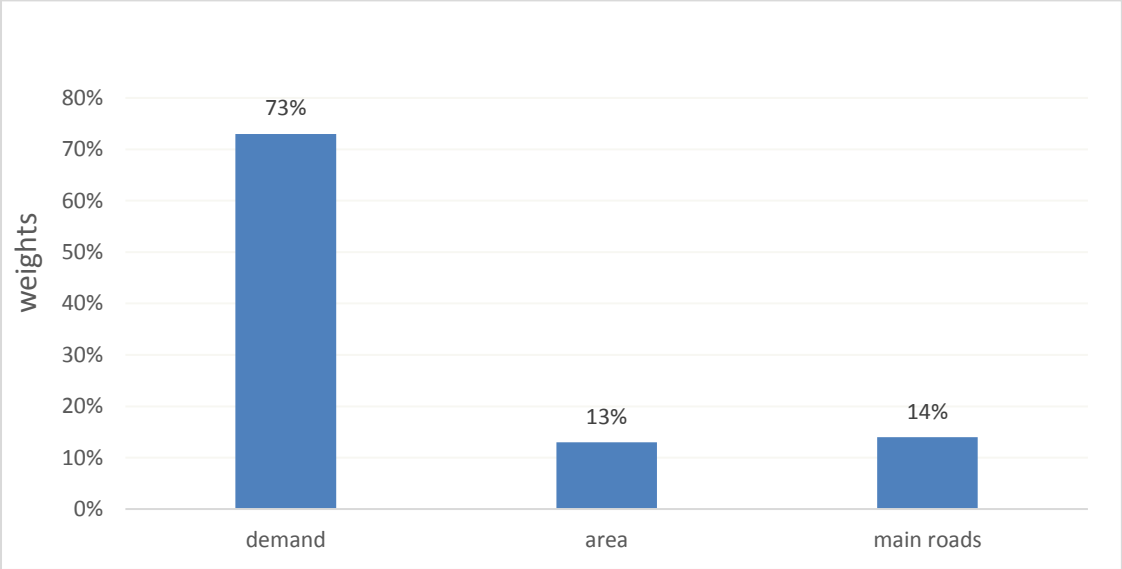

Figure 3. The percentages of factors influencing P&R locations

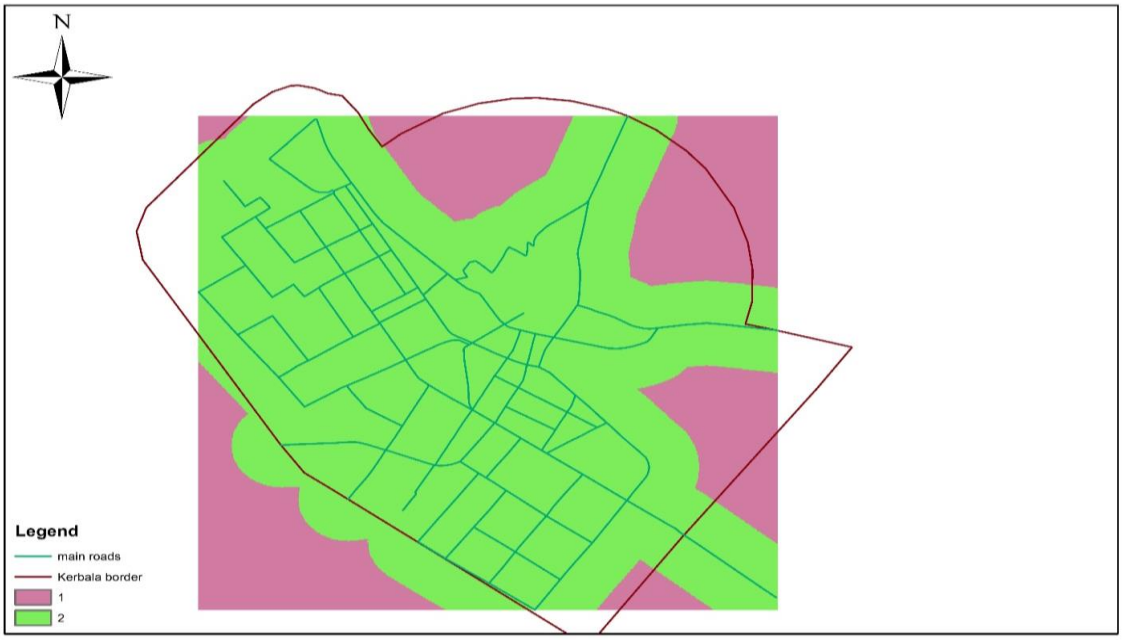

Figure 4: Access Distance Raster

Figure 5: Service Areas Raster

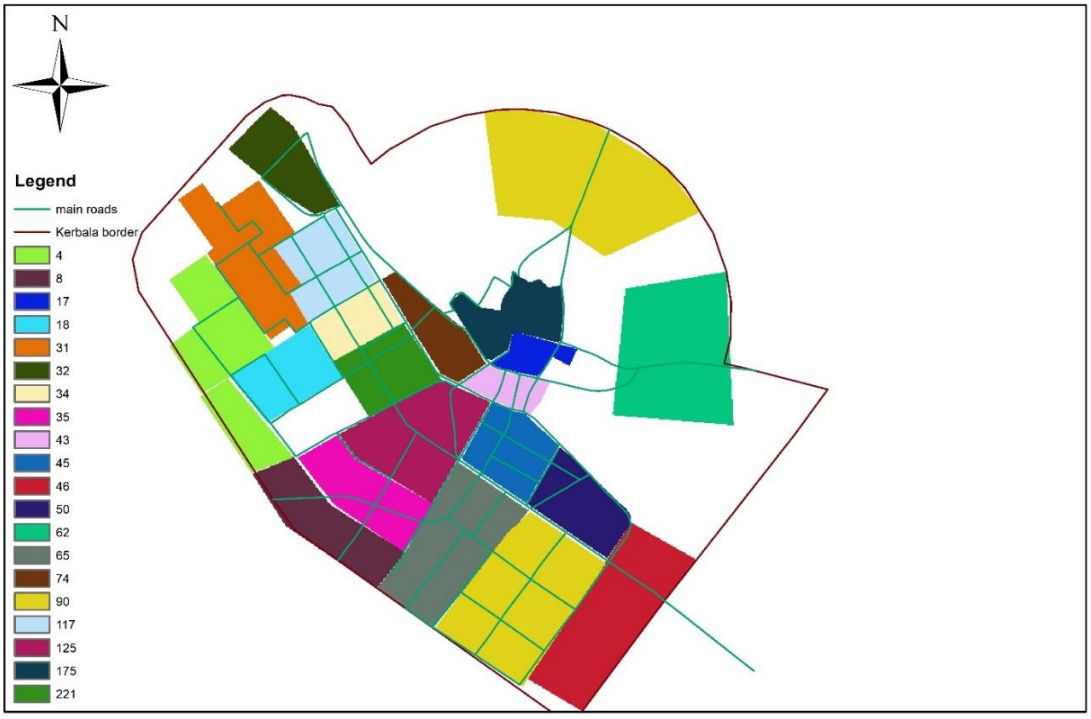

Figure 6: Demand Zones Raster

Figure (7) shows the resulted of best candidates for P&R locations of Karbala city according to different criteria. The most suitable areas are shown in green color with weight ranges from 8 to 9. Brown color comes the second zones in importance with weight ranges from 4 to 7 which is shown in the figure legend. Green areas represent the importance of P&R facilities, the significance of expert opinion, and the capabilities of computer models. Green color denotes the zones whereby much of the specified criteria has accumulated. By contrast, the brown color refers to the zones satisfying less criteria. Figure (7) illustrates that:

1. The dark-green zones represent most important locations resulted from the accumulation of depended criteria. These zones have achieved the highest demand among other zones of around 221 vehicle per day (see Figure 6) and according to AHP analysis offered 73% more than other criteria.

Moreover, it has achieved the requirement of other factors in terms of land availability and accessibility to main roads. Hence, this zone offers the highest weight.

2. Light-green color reflects low importance zones because of demand variance at these zones.
3. The brown color zones offered better results in terms of main roads and land availability as shown in Figures (4&5). However, they offered less demand with respect to other criteria around 4 vehicles per day as shown in Figure (6) and thus AHP analysis achieved high level for demand according to experts' opinion.

Hence, the used tool follows the approach of accumulating criteria weights on the map to Highlight candidate locations of P&R facilitates. P&R locations can be distributed as follows:

1. The demand in Karbala city can be divided into two parts. External demand comes from three governorates (Najaf, Hila, Baghdad) and internal demand comes from the city neighborhoods.
2. P&R locations that are represented in the numbers 1, 2, and 3 in Figure (7), cover external demand from these governorates. Moreover, location them upstream of congestion, this allows the P&R service to reduce traffic congestion in the most sensitive areas, i.e., those that directly feed into the worst rush-hour bottlenecks. Figure (6) shows the zones that cover the area of the highest demand
3. P&R location 4 has area with 500000 m^2 is considered as very suitable to accommodate internal demand to around 935 vehicles per hour. However, the level of service (LOS) in main road cannot carry this capacity which is estimated to be around 7792 vehicles per hour considering that 0.12 from demand that used park. This value exceeds 3800 vehicles per hour for two lanes.
4. We have therefore divided Karbala city into three sectors as shown in Figure 8 in order to distribute demand on P&R locations 5, 6, 7, 8, 9, 10, and 11. Moreover, this distribution can facilitate traffic movement, promote mobility convenience, reduce traffic jam and hence reduce travel time.

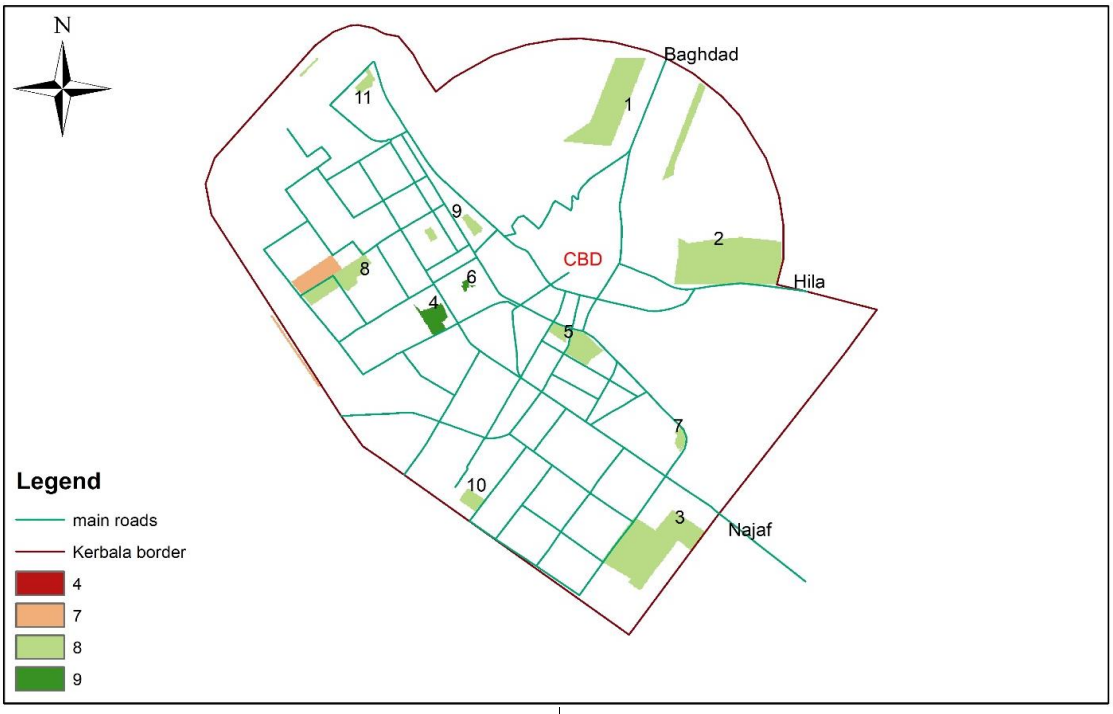

Figure 7: P&R Locations

4. Conclusions and Further Studies

P&R services are an integral element of public transportation. Locating P&R facilities is an important step when planning for such services. Covering as many potential users as possible, locating such facilities as close as possible to major roadways, and providing required areas for park are of key importance to design a P&R facility. This paper has developed a GIS model to locate P&R locations. Findings from this study, using Geospatial Approach to locate best locations for P&R facilities

depended on three most important criteria that weighted using AHP analysis, show several locations have been selected as the best locations for P&R facilities.

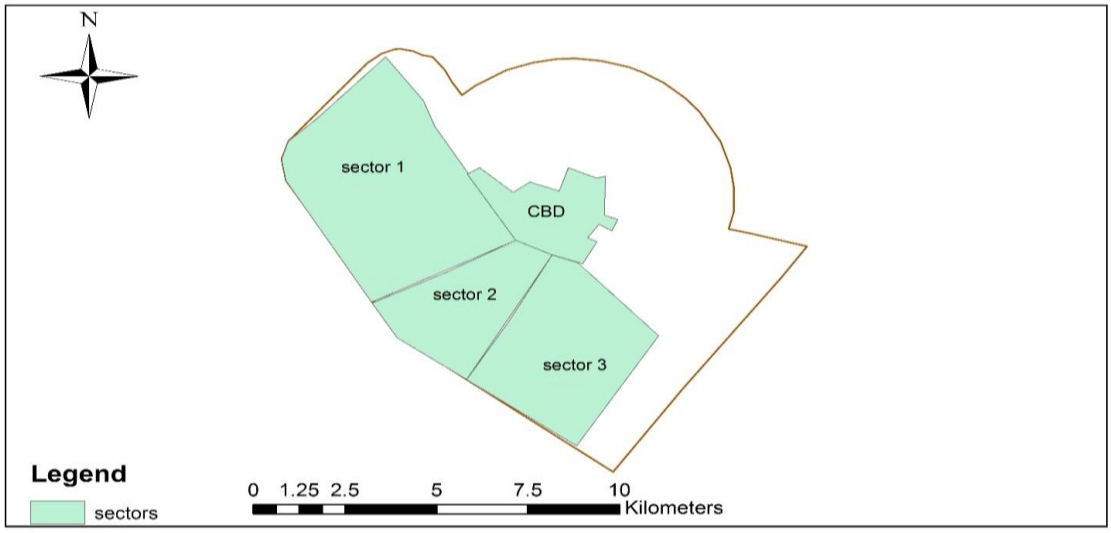

Figure 8. Distribution Karbala city into three sectors

The knowledge obtained from the literature and experts in the field that careful P&R planning and implementation is effective in reducing urban congestion. Thus, expert opinion becomes very useful in planning models for P&R facilities. In addition, the use of AHP has allowed systematic representation of the human decision-making process using a rule-based methodology. When one combines this feature with the data storage and graphical capabilities of GIS, a powerful and user-friendly evaluation program is created that acts as a practical and accurate tool for P&R planning. It has been shown that more than half of the demand for P&R comes from population coming from other governorates as Karbala attracts thousands of pilgrims every day. However, this result has not taken only demand into consideration, but also road connectivity and availability of area altogether. Hence, efficient P&R facilities should be capable of accommodating traffic demand in a way that lowers traffic issues in central areas. Despite the difference between the importance of P&R zones, human judgement has a crucial impact over these results.

This study tried to offer a model to pinpoint optimal park and ride facility locations using the AHP and ArcGIS Geospatial approach depending on several criteria. This model is timely and much-needed due to the growing need to efficient transport facilities that decrease traffic congestion, travel time and carbon emissions. The proposed modeling framework provides practitioners with an effective tool to determine the optimal locations of P&R facilities. The framework can also be easily expanded to consider other operation strategies, e.g., congestion pricing, to achieve a higher level of social welfare.

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تحديد أفضل المواقع لمحطات ركن المركبات الخاصة ومن ثم أستعمال النقل العام بأستخدام طريقة التحليل المكاني

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الزيادة المستمرة في ملكية السيارات هي واحدة من الاسباب الرئيسية في الاختناقات المروربة حول العالم وخصوصا في مراكز المدن، محطات الركن والركوب هو احدى الوسائل التي تمكن مستخدمي السيارات الخاصة لركن سيارتهم في الاماكن مخصصة لها ومن ثم استخدام وسائل النقل العام لغرض اكمال رحلاتهم دون ان يتسبب ذلك في الاختناقات المرورية، في هذا البحث ركزنا على تشخيص اهم العوامل التي تحدد هذه المحطات كالطلب على النقل وتوفر الطرق الرئيسية وتوفر المساحة المناسبة لها، بعد ذلك استخدمنا عملية التحليل الهرمي (AHP) لغرض معرفة تاثير كل عامل على تلك المحطات ومن ثم ادراج تلك العوامل مع مدى تأثيرها في برنامج الـــGIS لتحديد الاماكن المناسبة لتلك المحطات.

الكلمات الدالة: التحليل المكاني، المواقع المثلى، الركن ومن ثم الركوب، النقل العام، الاختناقات المرورية.