Research On Urban Charging Pile Layout Based on Hierarchical Analysis and Facility Location Optimization --A Specific Region in China

Yujun Huang [#], Jiageng Chen [#], Han Jin [*], Xiaofeng Chen

School of Civil Engineering and Transportation, Guangzhou University, GuangZhou, China, 510006

* Corresponding Author Email: 13352870289@163.com

[#]These authors contributed equally

Abstract. As China's new energy vehicle industry rapidly evolves, Panyu District in Guangzhou City, a central urban region serving residential, commercial, and transportation purposes, is encountering issues related to uneven distribution of charging facilities and inadequate service efficiency. This study provides a systematic solution that combines the Analytical Hierarchy Process (AHP) with a facility placement optimization model, focusing on the scientific assessment and enhancement of the charging facility layout. The charging pile evaluation system is developed using multi-source data for layout assessment, with indicator weights defined by the AHP model. The findings indicate that Site D achieved a total score of 90 points, attributed to its exceptional performance in distribution density and coverage. A mixed integer linear programming model is developed for optimal site selection using GIS data, revealing that the second location excels across several indicators and exhibits the most advantageous layout. The sensitivity analysis indicates that increasing the number of sites from 3 to 5, while maintaining the same coverage radius, can enhance the number of individuals covered by up to 22.2 percent. This study assesses the adequacy of the current charging infrastructure in Panyu District, Guangzhou City, and recommends an optimal location strategy for charging pile stations, which is crucial for achieving the objectives of urban planning in the relevant locations.

Keywords: Facility location optimisation, Hierarchical analysis, Urban charging pile layout, Geographic Information System, Mixed integer linear programming.

1. Introduction

Amid the global response to climate change and the extensive promotion of low-carbon development strategies, the new energy vehicle industry has experienced spectacular growth. China, as the largest market for new energy vehicles, faces significant challenges in charging infrastructure development, which is a critical constraint on the industry's sustainable growth [1-3].

Current literature on charging infrastructure planning reveals several critical limitations. Existing research predominantly addresses macro-planning strategies without sufficient attention to the unique characteristics of specific urban contexts. The evaluation frameworks commonly employed are often restricted to singular dimensions—such as spatial coverage or device quantity—rather than providing an integrated analysis. This fragmented approach fails to consider the complex interplay between geographic distribution, transportation networks, user demand patterns, and service effectiveness, ultimately hindering scientific decision-making.

In the economically vibrant and densely populated metropolis of Guangzhou, the strategic arrangement of charging stations significantly influences user experience and marketing efficacy. Panyu District, a significant metropolitan region in Guangzhou, exhibits a blend of residential, commercial, and industrial purposes, with its charging demand characterized by uneven spatial distribution and diverse usage situations. Nonetheless, there are considerable issues with the charging infrastructure in this region: inadequate distribution density in certain areas creates blind spots, limited accessibility diminishes users' willingness to utilize the facilities, and the regional disparity between coverage and service quality intensifies the conflict between supply and demand.

This study focuses on the Panyu District of Guangzhou City and extensively investigates the optimization of charging pile placement. Initially, a multi-tiered evaluation framework encompassing "distribution density—accessibility—coverage—service quality" is developed through the aggregation of multi-source data to acquire geographic information regarding charging facilities, technical specifications, and attributes of new energy vehicles. Subsequently, a hierarchical decision-making model is formulated utilizing the AHP to quantitatively analyze the significance of each criterion and evaluate the rationality of the current station configurations [4-6]. Finally, the existing optimization system for charging station layouts is integrated with the Geographic Information System (GIS) [7,8]. We utilize technology to examine the spatial attributes of regional population distribution, traffic networks, and demand hotspots. Subsequently, we amalgamate two facility location optimization models, p-center [6,9] and p-coverage [6], to develop a site selection framework that considers service efficiency and cost constraints. Finally, we propose an enhancement scheme for charging facility layout based on multi-objective optimization, offering methodological support for the planning of new energy infrastructure within the city.

2. Reasonableness evaluation of charging pile setting based on hierarchical analysis method

2.1. Data collection

To evaluate the feasibility of the new energy vehicle charging infrastructure in Panyu District, Guangzhou, it is essential to carefully gather fundamental data regarding both charging stations and vehicle utilization. The compilation of charging pile data must encompass multi-faceted information: firstly, the geographical distribution of each charging pile should be precisely documented via GPS coordinates, serving as the foundation for evaluating the rationality of spatial arrangement; secondly, it is imperative to distinguish the technical specifications of the charging piles, including the categorization of fast and slow charging types along with their respective maximum output power (e.g., 60 kW, 120 kW, etc.), while concurrently ascertaining the maximum load capacity of the charging pile connected to the power grid. Simultaneously, it is essential to ascertain the maximum load capacity of the charging stations linked to the power grid to evaluate their demands on the regional power supply system. Data on usage frequency should be employed to calculate the average daily service times of each charging station, thereby illustrating the efficiency of facility utilization based on actual operations. To enhance the utilization of new energy vehicles, it is essential to consolidate the vehicle registration information database, emphasizing the extraction of critical data such as the distribution of new energy vehicle types (e.g., pure electric, plug-in hybrid), ownership scale, and regional vehicle registration locations.

2.2. Calculation of indicators

After collecting the necessary data, it is crucial to calculate the following key indicators to assess the authenticity of the charging stations. Initially, we must examine the geographical distribution map of charging stations to identify any significant gaps or an excess of stations in specific areas, as this influences the efficacy of the service network. Secondly, the average distance between charging facilities and traffic nodes on key roadways should be measured, since these metrics will objectively reflect user accessibility to charging stations; a decreased distance threshold correlates with improved service response efficiency. To assess the effectiveness of service coverage, it is crucial to simultaneously analyze the dual alignment of static population distribution and dynamic vehicle density while evaluating the suitability of the service load at each charging station by integrating resident population data and new energy vehicle registration information within a 5km radius. It is essential to integrate the technical specifications of charging equipment, the expediency of repairs and maintenance, and user perceptions to formulate a comprehensive evaluation model that assesses charging efficiency, operational effectiveness, and user satisfaction, ensuring that equipment performance and service quality align with user expectations.

2.3. Comprehensive evaluation using hierarchical analysis

Utilizing AHP for the assessment of the charging pile arrangement requires the establishment of a hierarchical decision-making model comprising a goal layer, a criterion layer, and a scheme layer [5, 6]. The primary purpose is to assess the rationale of the charging pile configuration, emphasizing the infrastructure's adaptability to facilitate the proliferation of new energy vehicles. The intermediate layer comprises four evaluative dimensions: Distribution density evaluates the equilibrium of charging facilities within a region to prevent service gaps or resource duplication; accessibility measures user convenience in reaching the service by calculating the average distance between charging stations and the primary road network; coverage considers both geographical and demographic requirements, analyzing the population and density of new energy vehicles within a designated radius and assessing the service network's responsiveness to regional demand; and service quality incorporates both geographical and demographic factors. Coverage must consider geospatial and demographic requirements, evaluating the population within a designated radius and the concentration of new energy vehicles, while also examining the service network's responsiveness to regional hotspots. Ultimately, a systematic comparison of site arrangement, service radius, and operational data of specific charging stations at the program level will underpin scientific decision-making.

The essence of the hierarchical analysis method lies in the formulation of a judgment matrix via scoring. The significance of each criterion in relation to others is established through pairwise comparisons, often employing a scale from 1 to 9, yielding a judgment matrix A of the specified format.

$$A = \begin{bmatrix} 1 & 3 & 0.5 & 4 \\ 1/3 & 1 & 0.25 & 2 \\ 2 & 4 & 1 & 5 \\ 0.25 & 0.5 & 0.2 & 1 \end{bmatrix} \tag{1}$$

A consistency test is then required, which is a key step in ensuring the logical soundness and consistency of the judgment matrix. Firstly, the maximum eigenvalue λ_{max} is calculated, and then the consistency ratio CR is calculated using the consistency index CI and the random consistency index RI.

where CR is calculated by the formula:

$$CR = \frac{CI}{RI} \tag{2}$$

CI is calculated by the formula:

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{3}$$

Let n represent the quantity of criteria. The RI value is established depending on the quantity of criteria. If CR < 0.1, the judgment matrix's consistency is acceptable; otherwise, it requires readjustment. Upon verification, the A matrix is deemed plausible.

Upon acquiring a judgment matrix with satisfactory consistency, the weights W are determined, typically with the eigenvector approach. Initially, the eigenvectors of the judgment matrix A are calculated, and from the judgment matrix A, the weight vector W can be derived by solving the subsequent eigenequation:

$$AW = \lambda_{\max} W \tag{4}$$

Subsequently, the feature vectors are normalized to guarantee that the total of all elements equals 1, resulting in the final weight vector. The weights indicate the significance of each criterion in the comprehensive assessment, and the resultant weight vector W will be utilized in the subsequent phase of the evaluation computation. The ultimate representation of the indicator weights is executed by radar charts, as illustrated in Figure 1.

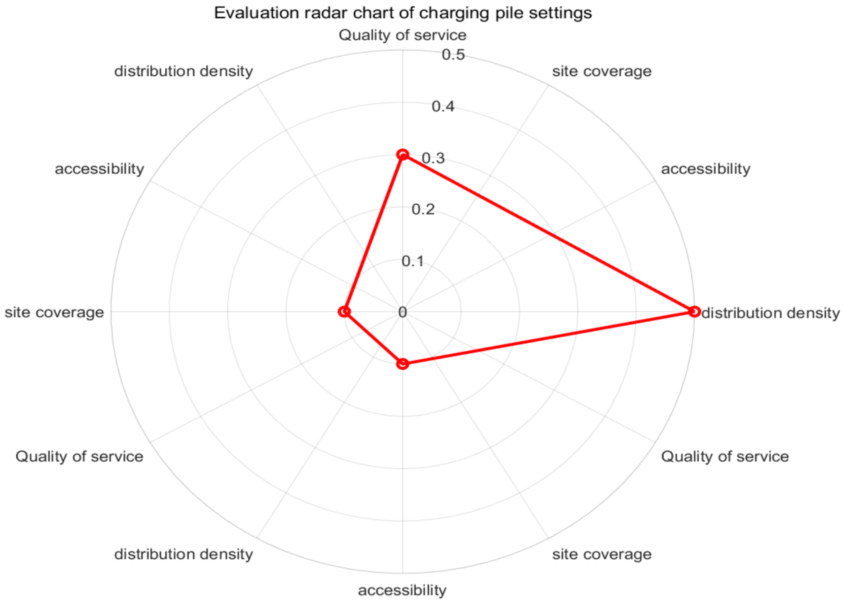

Fig. 1 Evaluation radar chart of charging pile settings

Figure 1 indicates that the distribution density possesses the maximum weight score of 0.5, underscoring the necessity to prioritize the arrangement of charging piles to achieve equal geographical distribution. The weight score for service quality is 0.3, signifying that users prioritize charging efficiency, equipment maintenance, and service response time. Conversely, accessibility and coverage receive the lowest weight of 0.1, likely due to enhancements in the urban transport network, which have mitigated accessibility issues, while the density advantage of distributed sites may indirectly enhance the coverage metric.

Figure 1 indicates that the distribution density possesses the maximum weight score of 0.5, underscoring the necessity to prioritize the architecture of charging piles to achieve equal geographical distribution. Service quality possesses the second highest weight score of 0.3, signifying that users prioritize charging efficiency, equipment maintenance, and service response time. Conversely, accessibility and coverage are assigned the lowest weight of 0.1, likely attributable to enhancements in the urban transport network, which have mitigated accessibility issues, while the coverage metric may be indirectly enhanced by the density advantage of distributed locations.

2.4. Hierarchical Analysis Model Solving

Upon acquiring the weights for each criterion, the subsequent step is to utilize these weights to conduct a thorough assessment of the charging stations. The study acquired performance scores for each charging station based on each criterion from the dataset, which can be utilized to compute the total score for each charging station through a weighted summation technique.

For each charging station i, the total score Si can be determined using the following equation:

$$S_i = w_1 x_{1i} + w_2 x_{2i} + w_3 x_{3i} + w_4 x_{4i} \tag{5}$$

where S_i denotes the composite score of the charging station (i=1,2,3,4, etc.), W_j denotes the weight of the j-th criterion (j=1,2,3,4, etc.), and X_{ji} is the score of charging station i under the j-th criterion (i=1,2,3,4, etc., j=1,2,3,4, etc.)

Out of these, charging station i's performance score under criterion j is xi. Criterion j's weight is wj. The four charging stations yielded the following comprehensive evaluation scores, and Figure 2 displays the outcomes.

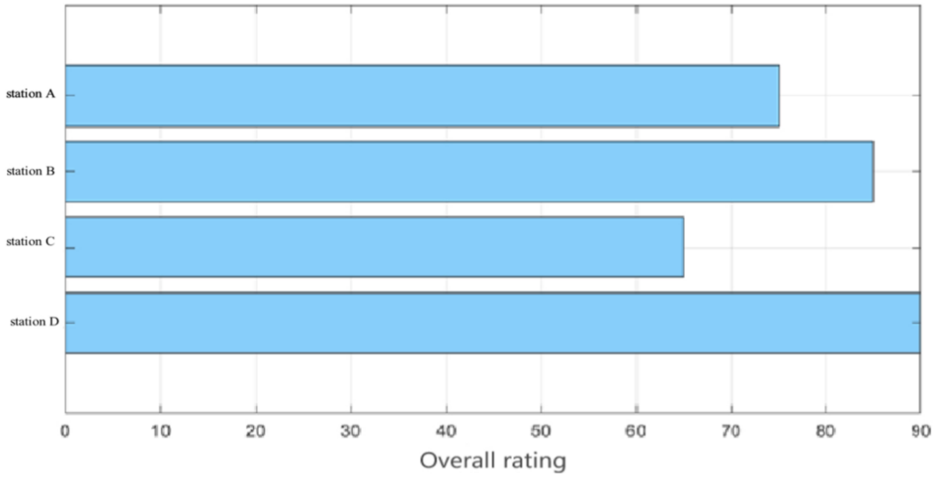

Figure 2 Comparison of charging station composite scores (partial)

The comparison of the four charging stations' overall scores in Figure 2 reveals that the performance of each charging station varies greatly when it comes to distribution density, accessibility, coverage, and service quality, all of which have an impact on the stations' overall scores. While the charging speed and user satisfaction scores fall into the middle to upper range, Station A's exceptional performance in terms of coverage and service quality—particularly the density of people and cars inside the coverage radius—is the primary reason for its higher total score. Its physical distance from places with high demand or its lack of connectivity to nearby transportation networks, however, may be the cause of its comparatively low distribution density and accessibility scores. With a greater coverage score and marginally better accessibility than Site A, Site B exhibits a more balanced distribution of metrics and a higher overall score than Site A. Nonetheless, there are issues with service quality (such as maintenance frequency), which lead to a still low total score. Site C has the lowest overall score, primarily because its accessibility and distribution density scores are far behind. This data indicates that, despite its fair coverage, the site's layout is too centralized or remote from major roads, making it challenging to satisfy users' needs for convenient access. Its exceptional coverage and distribution density give Site D the highest overall score. Its geographical distribution uniformity is much better than that of other charging stations, and the population and new energy vehicles within 5 km of the site cover a wide range of areas, fully meeting the demand. At the same time, its accessibility reduces the access distance by being close to the main roads, and its service quality, while not excellent, is maintained at a medium level, which does not significantly lower the overall score.

The results of the thorough assessment demonstrated that Site D's success was attributable to its "wide coverage and rational distribution." To further improve the quality of service and user experience, it will be necessary in the future to expand the number of facilities in low-density areas, optimize accessibility by rerouting traffic, optimize the balanced distribution of areas, and expedite the upgrading of charging technology and routine maintenance.

3. Charging station siting study based on GIS and location optimisation model

3.1. Data preparation

The study develops a thorough decision-making framework based on GIS and a facility optimization model to guarantee that the placement of new energy vehicle charging pile locations satisfies the actual demand while accounting for cost-effectiveness [7, 8]. The following three phases comprise the implementation process: In order to create a new energy model registration distribution mapping, the study first uses the GIS to obtain vector data of Panyu District's administrative boundaries, main road networks, and significant landmarks; builds a heat map of residential area density using census data; incorporates real-time traffic flow data of bus routes and transport hubs provided by the traffic management department; and methodically gathers GPS coordinates, technical parameters, and operation logs of existing charging piles and linkage vehicle management depart.

3.2. Modelling

First, a demand analysis is conducted. The study can pinpoint hotspot locations of charging demand by examining population distribution data and new energy vehicle registration data. Future charging pile building will concentrate on these hotspot regions; therefore, coverage and services there must be guaranteed.

To find the ideal location for the charging post, a special optimization model must be built after the requirements and data have been analyzed. The p-center problem and the p-coverage problem are two frequently utilized facility location models that are used in this process. To make sure that the model outcomes satisfy the particular business requirements, these two models take into account several optimization objectives.

Reducing the maximum distance between each user and their closest amenities is the aim of the p-center challenge [6,9]. This strategy is especially appropriate in circumstances where it is necessary to guarantee that every user can access the service within the permitted maximum distance. The following is a mathematical expression for the p-Center problem model: intended.

x_{ij} : A binary variable that is 1 if user j's needs are satisfied by facility i and 0 otherwise.

y_j : A binary variable that is 1 if the facility is established at location i and 0 otherwise.

z : Maximum distance variable indicating the maximum distance from all users to their service facility.

The objective function is minz, and the following constraints need to be satisfied as well:

Each user demand point is met by at least one facility:

$$\sum_{i=1}^{n} x_{ij} = 1, \forall j \tag{6}$$

If facility i satisfies the demand of user j, then there must be a facility at point i:

$$x_{ij} \le y_j, \forall i, j \tag{7}$$

Ensure that all users are no closer than z to their services:

$$d_{ij} \cdot x_{ij} \le z, \forall i, j \tag{8}$$

The number of sites selected does not exceed p:

$$\sum_{i=1}^{n} y_j = p \tag{9}$$

Covering the greatest amount of demands with the fewest facilities is the aim of the p-coverage problem [5]. By establishing a coverage radius, this model guarantees that at least one facility covers every demand point inside it. The following is the mathematical expression:

y_j :A binary variable that is 1 if the facility is established at location i and 0 otherwise.

x_j :Binary variable, 1 if demand point j is covered, 0 otherwise.

Objective function: $\max \sum_{j=1}^{m} x_j$

The constraints are:

If demand point j is covered by at least one facility, then $x_j = 1$:

$$x_j \le \sum_{i \in I_j} y_j, \forall j \tag{10}$$

where I_j is the set of facilities covering demand point j.

The number of sites selected does not exceed p:

$$\sum_{i=1}^{n} y_i = p \tag{11}$$

3.3. Model solution

Because it can effectively handle both continuous and binary choice variables in large-scale facility location problems, the Mixed Integer Linear Programming (MILP) approach was selected for the study to address these two site optimization challenges [10, 11].

The study tackles the problem of minimizing the maximum distance z to guarantee that every user has the shortest feasible distance to their closest charging station by first defining the objective function and constraints using the p-center problem model. Finding an equilibrium that meets the greatest number of user needs while staying under a tight budget is the key to the model solution.

The goal of the p-coverage problem is to cover as many demand points as possible. In order to maximize the number of demand points covered without going above the number of facilities, a predetermined radius of coverage is specified and solved for. This paradigm works especially well for decisions involving resource optimization.

In order to confirm that the maximum distance z and the number of demand points covered satisfy the intended optimization goal, the solution results are first tentatively validated. The rationale of the geographical arrangement is then confirmed by comparing the improved locations with the current sites using GIS software.

3.4. Performance evaluation and sensitivity analysis

Calculating average and maximum distance metrics, evaluating the population and number of vehicles covered, and assessing the project's economic feasibility while accounting for construction and running expenses are all part of the performance evaluation of the charging post layout that has been solved. Figure 3 displays the final evaluation results.

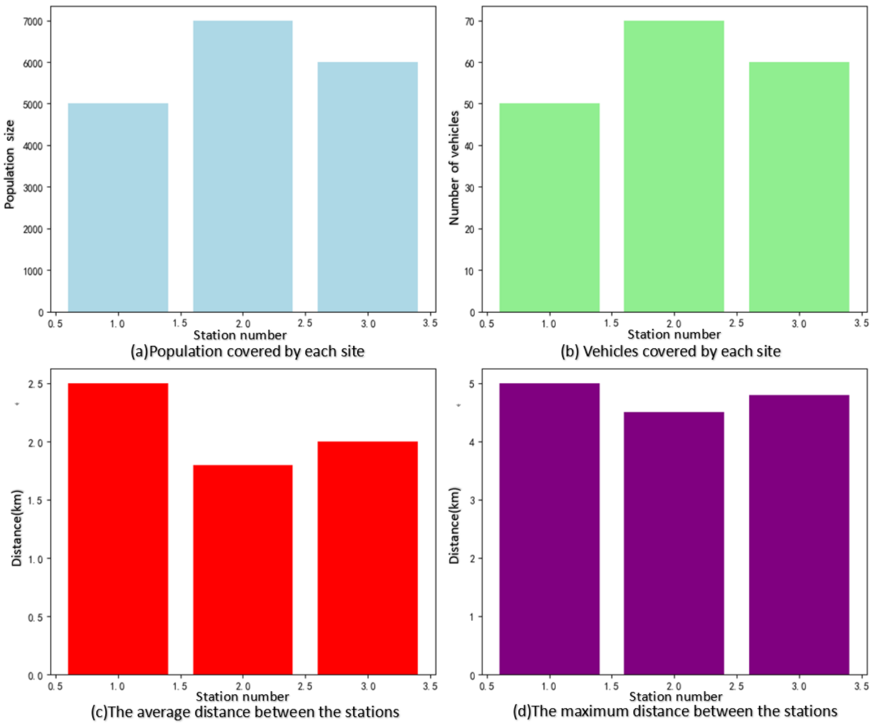

Fig. 3 Performance evaluation diagram: (a) population covered by each site; (b) vehicles covered by each site; (c) average distance of each site; (d) maximum distance of each site

The second site covers the most people—nearly 7,000—among the population covered by each site, whereas the first site covers the fewest—slightly less than 5,000—as shown in Figure 3(a). This implies that site 2 might have more charging stations or be situated in a more populous region. The sites' coverage of automobiles is comparable to that of the population, as seen in Figure 3(b). Site 2 likewise has the best vehicle coverage, covering about 70 vehicles. Site 1, which covers about 50 automobiles, had the lowest performance on this parameter. This might be a result of the site's strategic design and the prevalence of new energy vehicles nearby.

All of the locations have rather close average distances, as shown in Figure 3(c), while site 1 has the largest average distance, at about 2.5 kilometers. At roughly 1.8 kilometers, Site 2 has the shortest average distance. This suggests that site 2 is better positioned and easier for users to reach. With site 1 having the largest maximum distance of roughly 5 kilometers and site 2 having the smallest maximum distance of roughly 4.5 kilometers, it is evident from Figure 3(d) that all of the sites' maximum distances are somewhat near to one another. With lower maximum distances suggesting better service coverage, this measure is especially crucial for evaluating the sites' service boundaries.

Site 2 has the best layout and performs better on a number of important metrics, as seen in Figure 3. Site 1 may need to think about improving its position or installing more charging stations to increase service coverage, even if it covers fewer people and has fewer cars. It also has longer average and maximum distances.

Last but not least, a sensitivity analysis is necessary to evaluate how changes to important parameters—like the number of facilities, the coverage radius, and financial limitations—will affect the solution. Figure 4 displays the findings of the sensitivity analysis.

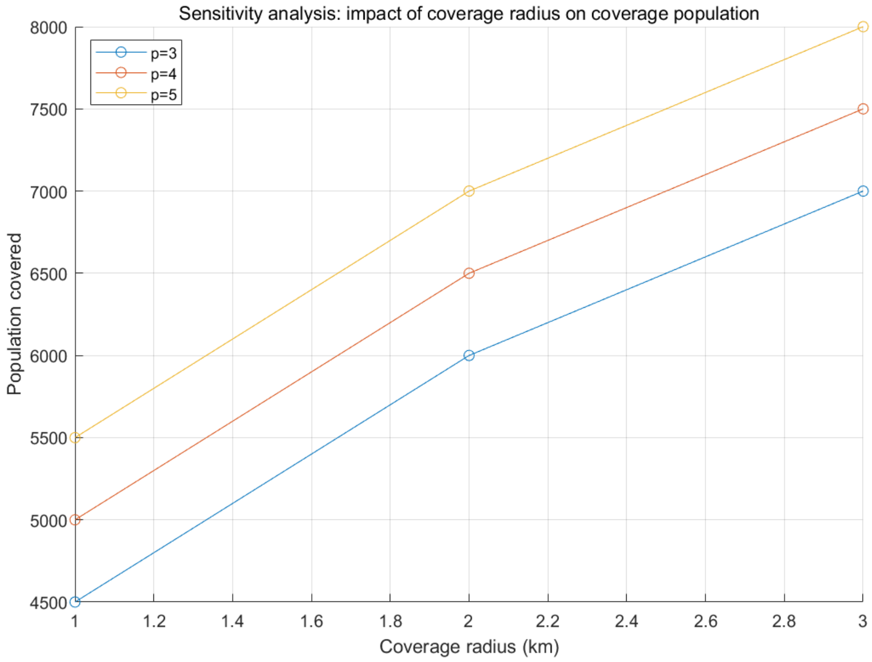

Figure. 4 Sensitivity analysis: impact of coverage radius on coverage population

Figure 4 illustrates that when the coverage radius grows, the number of covered populations rises noticeably. An increase in the number of facilities also results in an increase in the population covered for each given coverage radius. The service area can be increased to accommodate more dispersed individuals by adding more charging stations, particularly in crowded urban areas. The number of covered populations dramatically increases from 14.3% to 22.2% when p is increased from 3 to 4 and then to 5 for the same coverage radius, indicating that expanding the number of charging stations is a useful strategy for enhancing service coverage.

4. Conclusion

AHP and the facility placement optimization model (p-center, p-coverage problem) were used in this study to thoroughly evaluate how reasonable the charging pile layout is in Panyu District, Guangzhou City, and to suggest the best locations for them. GIS-based hot zone analysis of the demand and validation of the mixed-integer planning model demonstrate that synergistic optimization of the charging pile coverage radius and the number of facilities can significantly improve service efficiency. The study finds that Site D performs the best overall because it has a strategy of "wide coverage and reasonable distribution," and its even spread, closeness to main roads, and average service quality show how important a balanced layout is. The mixed-integer planning model and GIS-based hot zone analysis show that by working together, the number of facilities and the charging pile coverage radius can be improved to significantly boost service efficiency. This study offers a theoretical foundation for the ideal arrangement of charging stations. It also assesses the practicality of the current charging stations in Guangzhou's Panyu District and suggests the best places for them.

Notwithstanding the findings of this investigation, certain limitations remain. By incorporating the AHP weights into the optimization model parameters in real time (e.g., by dynamically adjusting the radius of coverage or the maximum distance threshold), the responsiveness can be improved. In terms of model construction, the hierarchical analysis method may weaken the decision dynamics when used with the facility location optimization model. By applying a research idea and framework to urban planning-related fields, this paper demonstrates the method's feasibility and offers a reproducible scientific paradigm for the layout of new energy infrastructure and the distribution of public service resources. It does this by combining quantitative assessment and spatial modeling.

References

[1] PAN Jingmin, LI Yanyang, CHEN Zhiyin. A study on the spatial layout characteristics of public charging stations for new energy vehicles in Wenzhou based on POI data [J] Low Carbon World. 2024; 14(04):73-75.

[2] Li Guoqiang, Jiang Kejun, Li Jinyuan, Yang Ping. Optimisation of Public Charging Pile Layout for New Energy Vehicles [J] Automotive Test Report. 2023; (08):140-142.

[3] Zhang Bo, Dou Gang, Wu Pengfei, Wang Na. A study on the rational spatial layout of public charging facilities for new energy vehicles in cities [J] China Auto. 2021; (06):41-45+50.

[4] [4] CHEN Fangyu, WU Shuangpin, JIANG Huixian, LIU Xulime. Optimisation of spatial layout of charging piles for new energy vehicles [J] Fujian Computer. 2019; 35(09):19-24.

[5] Pan Ying, Cao Xiaoli. Service capacity assessment of electric vehicle public charging network based on hierarchical analysis [J] Journal of Xi'an Engineering University. 2024; 38(04):106-112.

[6] Wan, Delong. Research and Evaluation Modelling on the Siting Problem of On-Campus Service Facilities [D]. Nanchang University, 2011.

[7] WANG Manfu, PAN Fuquan, ZHANG Lixia, GUO Xuanming, YANG Jinshun, LUAN Yiliang. Characterisation of spatial distribution of urban new energy vehicle charging piles based on GIS [J] Inner Mongolia Highway and Transport. 2024; (06):37-42.

[8] Yang Xiaohan, Jimin, Qu Yu, Zhang Chao. Spatial Characterisation of New Energy Vehicle Charging Piles in Xuzhou City [J] Surveying, Mapping and Spatial Geographic Information. 2022; 45(03):24-27.

[9] Wu Ying, Lu Guaishi. A study on the location of emergency rescue station in urban rail transit network based on P-centre model [J] Urban Rail Transit Research. 2024; 27(09):80-86.

[10] ZHANG Xiaofeng, WAR Yu, LIU Yuting, ZHAO Tingbo, FU Ang, HE Lv. Study on multi-objective optimal allocation of residential integrated energy system considering new energy vehicles [J] Thermal Power Generation. 2023; 52(12):38-48.

[11] Dou Xinrui, Peng Chen, Wu Youlong, Niu Yajie, An Geng. Optimal Scheduling of Charging Pile Groups Based on Mixed-Integer Linear Programming [J] Electronic Fabrication. 2023; 31(15):48-51.