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Spatial Layout Analysis and Evaluation of Electric Vehicle Charging Infrastructure in Chongqing

Zixuan Wang, Qingyuan Yang *, Chuwen Wang and Lanxi Wang

School of Geographical Sciences, Southwest University, Chongqing 400715, China;
w20020220@email.swu.edu.cn (Z.W.); wcw227@email.swu.edu.cn (C.W.); swu22202@email.swu.edu.cn (L.W.)
* Correspondence: yizyang@swu.edu.cn; Tel.: +86-023-6825-3911

Abstract: This study considers the spatial analysis and evaluation layout of electric vehicle charging infrastructures, taking the central urban area of Chongqing as an example. Mathematical model analysis, ArcGIS spatial analysis, field investigation, questionnaire measurement, and hierarchical analysis methods are utilized to discuss the current distribution characteristics and supply–demand matching of the electric vehicle charging infrastructure in this region. The resulting data can provide references for the optimal layout of charging infrastructure. The main conclusions of this study are as follows: (1) The configuration and demand of charging infrastructure in the central urban area of Chongqing have obvious spatial differentiation and show strong centrality. (2) It is a common phenomenon that the charging infrastructure in the central urban area of Chongqing is in short supply, and it is pressing that a new charging infrastructure be built. (3) In the process of construction and operation of charging infrastructure, various factors, such as economy and traffic, should be comprehensively considered; at the same time, incidents of inefficient operation, such as being crowded out by nonelectric vehicles and unmaintained facility failure, should be minimized.

Keywords: electric vehicle charging infrastructure; matching supply and demand; optimizing the layout

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1. Introduction

General Secretary Xi Jinping pointed out in the report of the 20th Party Congress that we should promote green development and harmonious coexistence between human beings and nature. In this context, the promotion of new energy vehicles can accelerate the green transformation of development and actively yet steadily promote the carbon peak and carbon neutralization. To achieve the optimal layout of charging infrastructures, scholars at home and abroad have conducted in-depth research on it from multiple perspectives in the fields of operation research [1–5], economics [4–10], power engineering [10–12], and consumer behavior [13–21]. The operation research approach is the early model widely used to study charging infrastructure, mainly seeking the optimal layout with the lowest cost [3–5]; based on this, to prevent the oversupply of charging infrastructure, the economics takes into account the demand factor and advocates "demand to supply" [7], which is still widely used in recent studies on the layout of charging posts. If a charging infrastructure is built in dense electricity-using areas, the influence of voltage load and power distribution on the siting of capacity needs to be considered in the field of electrical engineering [11,13]; consumer behavior is a popular area for recent studies on the layout of charging infrastructure, and customer behavior and psychological preference factors have been studied [14–19], and it is believed that a single cost, demand, or power indicator cannot meet the research objectives. This research is guided by the philosophy of humanism, which attempts to quantify the diverse needs of people to get as close as possible to the real needs of charging consumers for charging infrastructure layout. In addition, a variety of other factors have been incorporated into charging infrastructure studies to enrich the breadth of research, which reminds us that laying out charging infrastructure is an extremely complex process. For example, some studies are based entirely on a certain comprehensive model for evaluation [20–22] or consider time costs and existing infrastructure to deploy charging stations [23], and there are also studies of optimal models for siting mobile charging stations that can flexibly respond to complex traffic conditions [24]. Based on the previous research results, this paper utilizes the spatial perspective of geography, with the objectives of "scientific layout, balanced supply and demand, and cost-saving". This study compensates for the lack of measurement of charging infrastructure accessibility in past research, and it focuses instead on factors that can optimize the layout of the charging infrastructure. Focusing on these factors can support new energy vehicle users and governmental scientific planning and decision-making efforts.

As a pioneer in the new energy vehicle industry, Chongqing has a relatively complete new energy vehicle industry chain, and its level of charging infrastructure construction is the highest in western China. With the steady increase in new energy vehicle ownership in Chongqing, the existing charging infrastructure cannot meet the needs of users, affecting the healthy development of the new energy vehicle industry. Meanwhile, due to inexperience in early planning and construction, problems such as unreasonable layouts, low utilization rates of charging posts, low coverage rates of charging networks, and a mismatch between the power supply and demand for an electric vehicle charging infrastructure need to be solved. In response to these problems, this paper hopes to understand the characteristics of the current distribution of the electric vehicle charging infrastructure in the central city of Chongqing, and to obtain the supply and demand matching situation of the electric vehicle charging infrastructure in the central city of Chongqing, so as to propose the objectives and ideas of optimizing the spatial layout of the electric vehicle charging infrastructure in the urban area of Chongqing, and finally to establish the site selection and capacity determination scheme of the electric vehicle charging infrastructure. This is to achieve the following goals: avoiding the construction of unnecessary charging facilities as much as possible in order to save construction and operating costs, and use land rationally; the scientific planning of the charging infrastructure network, improving its coverage, and reducing the driving range limit on users and users' concerns about charging inconvenience, so as to increase users' desire to buy and promote the popularization of new energy vehicles; laying the charging infrastructure out properly, improve the efficiency of charging facilities, determining the fast charging station and slow charging station layouts in a systematic way to meet the charging needs of users under different circumstances; and promoting green development, contributing to the goal of the carbon peak and carbon neutralization, and further achieving sustainable development.

2. Research Methods and Data Sources

2.1. Study Area

Chongqing is located in the southwest of inland China, with geographical coordinates of 105°11′–110°11′ E and 28°10′–32°13′ N. It is the center of economy, finance, scientific innovation, and shipping, trade, and logistics in the upper reaches of the Yangtze River. On 9 May 2020, Chongqing announced at the symposium on the main city metropolitan area that the main city metropolitan area consists of 9 districts in the central urban area and 12 districts in the new main urban area. This paper takes the central urban area of Chongqing as the research area, including 9 administrative districts of Yubei District, Jiangbei District, Nanan District, Shapingba District, Dadukou District, Banan District, Yubei District, Jiulongpo District, and Beibei District (Figure 1). The total area of this area is 5541.95 km^2, with a permanent population of 10.4776 million in 2022 and a regional GDP of 109.763 billion yuan.

2.2. Research Approach

Based on the background of the opportunities and challenges of EV charging infrastructure coexisting, taking the central urban area of Chongqing as an example, through data collection and processing, this paper selects several indicators to establish a location evaluation model. The supply and demand situation of EV charging infrastructure in the central urban area of Chongqing is obtained. Finally, a map is created to summarize the distribution characteristics and clarify the layout problems. Combined with field research, the above results are used to determine the matching degree of supply and demand balance of the EV charging infrastructure in the central urban area of Chongqing, to clarify the target of spatial layout optimization of charging infrastructure, and to establish the index system of EV charging infrastructure site selection. The questionnaire measurement method and hierarchical analysis method are used to propose the spatial layout optimization plan for EV charging infrastructure in the central urban area of Chongqing (Figure 2).

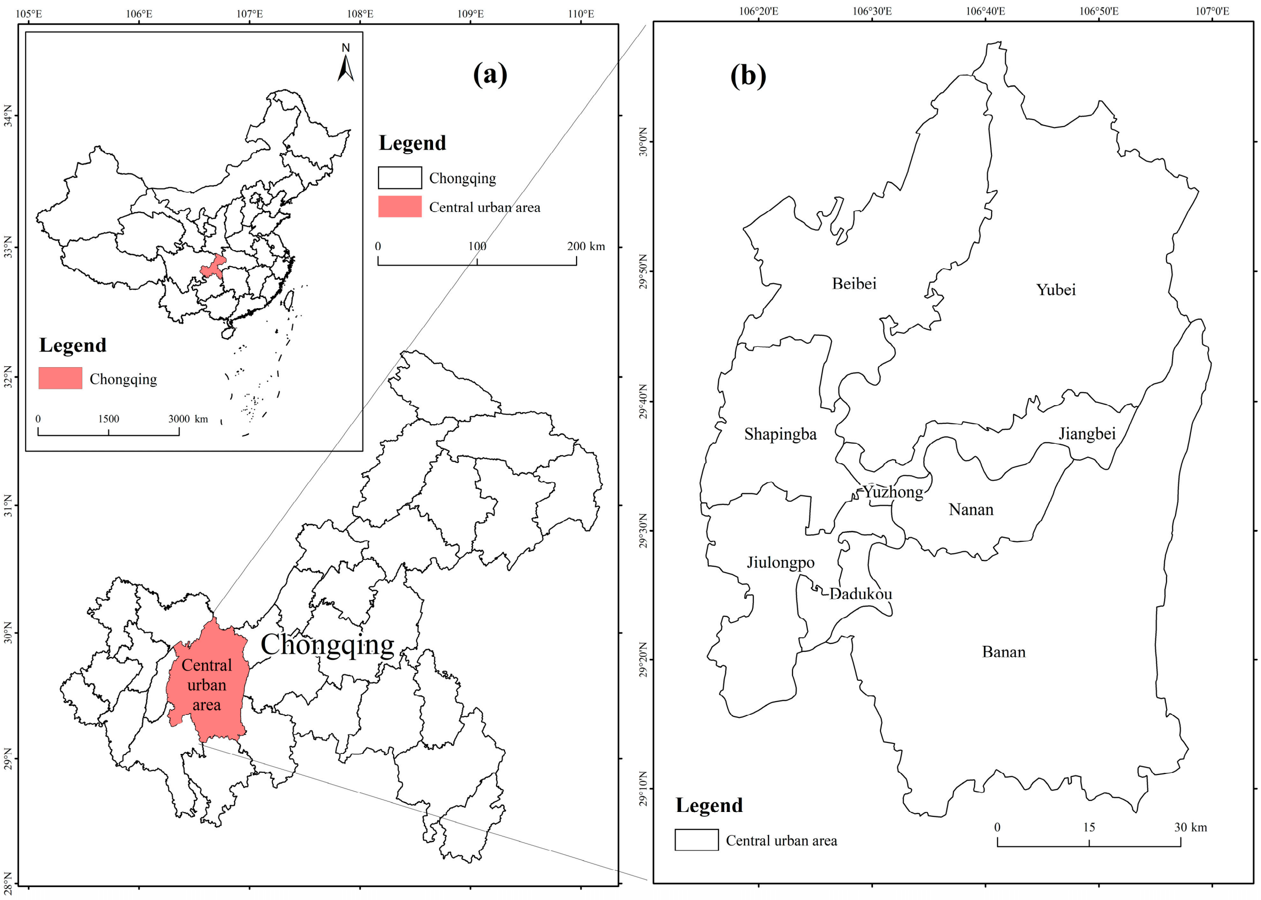

Figure 1. The study area: (**a**) the location of central urban area in Chongqing; (**b**) administrative division of the central urban area.

2.3. Methodology and Model

The supply and demand models of EV charging infrastructure are established separately to represent the actual supply and demand of EV charging infrastructure in each location. In this manner, the matching degree of supply and demand balance of EV charging infrastructure in the Chongqing central urban area is obtained. An optimization plan is then proposed.

2.3.1. EV Charging Infrastructure Supply—Accessibility

This paper defines the accessibility of EV charging infrastructure as the ease of accessing charging posts for EV users at different locations. The stronger the service capacity of charging stations is, the lower the total charging cost at charging stations, and the closer to charging posts the users are, the greater the accessibility. Therefore, based on the actual distribution data of EV charging infrastructure in the central urban area of Chongqing, several locations are randomly selected. Next, the service capacity, the total charging cost, and the distance of users from charging posts are combined, and a model to calculate the accessibility of charging infrastructure at each location is established.

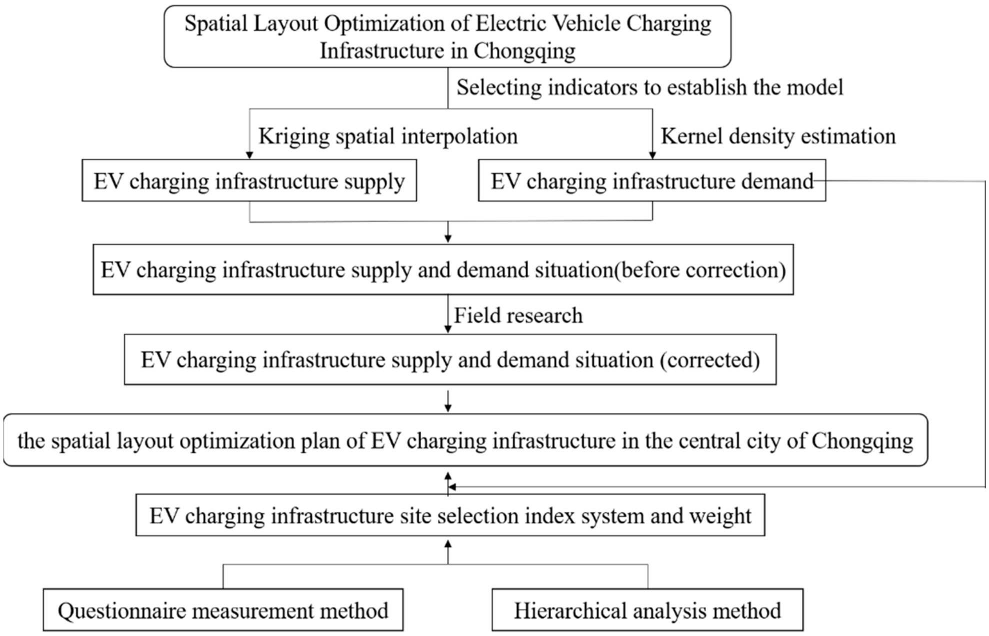

Figure 2. Research approach.

(1) Charging station service capability

The service capacity of charging stations is an important factor in constructing the accessibility model of EV charging infrastructure. It reflects different charging post types, charging service efficiency, charging station service time, and intervehicle influences (such as the time taken by vehicles using the same charging post in succession). The service capacity of charging stations is s:

$$s = 2\sum_{j=1}^{2} n_j \beta_j C_0 t \tag{1}$$

In the equation, n_j is the number of different types of charging posts, n_1 is fast charging posts, and n_2 is slow charging posts. β_j is the charging service efficiency of different types of charging posts. The time taken to charge a vehicle using the fast-charging mode is assumed to be 0.5 h, and the time taken using the slow-charging mode is 6 h [25]. Therefore, the charging service efficiency of different types of charging posts is 2 vehicles/h for the fast-charging mode and 1/6 vehicles/h for the slow-charging mode. C_0 is the reserve factor of the impact between vehicles (charging stations cannot be used all the time) and generally takes the value of 0.8 [26]. t is the service time of the charging station and takes the value of 24 h.

(2) The total cost of charging at the charging station

Considering the charging fees and parking fees of charging stations, the total cost at the charging stations is p:

$$p = \sum_{j=1}^{2} \frac{n_j\left(e_{kj} \times p_{kj} + p_{tj}\right)}{n_1 + n_2} \tag{2}$$

In the equation, e_{kj} is the number of charging degrees. The number of fast charging degrees is taken as 24 degrees, and the number of slow charging degrees is taken as 30 degrees. p_{kj} is the price of charging one degree. p_{tj} is the cost of parking while charging.

(3) The accessibility value of EV charging infrastructure at sample sites

If the user is too far from the charging station, the user's willingness to go to the charging station is almost negligible, so this paper determines the charging station selection range distance of 8 km by sending a questionnaire to 300 users. A charging station within 8 km from the road of the sample point is selected, its service capability and total cost of charging are calculated, and the accessibility value is obtained as follows:

$$a = \sum_{i=1}^{n} \frac{bs_i}{p_i d_i} \tag{3}$$

In the equation, b is a constant that takes the value of 5/32 according to the value of the constant in $\frac{s_i}{p_i}$ to adjust the value range; d_i is the road distance of the charging station within the distance range of the selected sample point.

(4) Accessibility value of electric vehicle charging infrastructure in the central urban area of Chongqing

Kriging spatial interpolation, which utilizes the theory of variation function and structural analysis, is a method of linear unbiased and optimal estimation for determining unknown sample point values based on the data of relevant variables at known sample points in an area. By Kriging interpolation analysis based on the accessibility of charging posts at the sample points, the availability value of EV charging infrastructure at each location in the central urban area of Chongqing can be obtained, and it can be used to determine the actual supply of EV charging infrastructure.

2.3.2. EV Charging Infrastructure Demand—Kernel Density Value

Point of interest (POI) refers to an attraction or landmark on an electronic map, which indicates the location of government departments, commercial organizations, monuments, tourist attractions, transportation facilities, etc. [27]. It also represents a location to which people are interested in traveling; areas with more POIs are predominantly travel destinations [28]. Kernel density estimation (KDE) is based on a movable cell and transforms discrete points in a given area into a continuous density map for estimation [29]. Kernel density analysis is performed for each POI in the central urban area of Chongqing. The density values obtained reflect the attractiveness of different locations to the surrounding people; if the density value is high, the traffic demand is higher, and the charging demand for electric vehicles is greater. Therefore, the density value can be recorded as k, representing the charging demand of electric vehicles at different locations.

2.3.3. Balance of Supply and Demand of EV Charging Infrastructure—Balance Index

After obtaining the accessibility values a and kernel density value k to express the supply and demand of EV charging infrastructure, respectively, we can calculate the matching degree of supply and demand balance of EV charging infrastructure. We use the balance index (o) to measure the matching degree of supply and demand balance.

$$o = \frac{ca}{k} \tag{4}$$

In the equation, c is a constant to regulate the balance index, which is obtained from the field survey. "$o = 1$" indicates that the supply and demand of EV charging infrastructure at the site are in balance; "$o > 1$" indicates that the supply of EV charging infrastructure is greater than the demand of users; and "$o < 1$" indicates that the supply of EV charging infrastructure is less than the demand of users.

2.3.4. Spatial Layout Optimization of EV Charging Infrastructure—Optimization Value

When the value of the balance index is 1, namely, the accessibility $a' = k/c$, the EV charging infrastructure at that location is in a supply–demand matching equilibrium, and the demand of users at different locations can be roughly regarded as a constant. When optimizing the spatial layout of EV charging infrastructure to achieve the accessibility of EV charging infrastructure in each grid, a should be equal to or slightly greater than a'. We let the optimization value $\beta = a - a'$: when $\beta > 0$, the number of charging infrastructures in each region should be reduced appropriately, considering the actual situation and the increase in the number of EVs in a certain period in the future; when $\beta = 0$, the number of charging infrastructures in each region is reasonable at the current time; and when $\beta < 0$, the number of charging infrastructures in the region should be increased.

2.3.5. EV Charging Infrastructure Location and Capacity Setting Options—Questionnaire Measurement and Hierarchical Analysis

With reference to the existing research results, a questionnaire is designed on "siting factors of EV charging infrastructure", which is distributed to individuals who are familiar with EV charging infrastructure. The questionnaire consists of 15 items (i.e., 15 evaluation indicators) in five categories: geographical factors, economic factors, consumer demand and behavior factors, policy factors, and safety factors. It is based on a five-point Likert scale, which assigns "5, 4, 3, 2, 1" to "very important", "important", "average", "unimportant", and "very unimportant", respectively [30]. The respondents are asked to rate each indicator according to their actual experience. In this way, their views on the importance of each evaluation indicator to the site selection of EV charging infrastructure are accurately reflected. Additionally, its reliability and validity are then analyzed. The results of the questionnaire are taken as the judgment value in the hierarchical analysis method to set the judgment matrix. The weights of each index are then obtained by applying the hierarchical analysis method. This process establishes the indicator system for selecting EV charging infrastructure locations.

2.4. Data Source and Processing

We run a web crawler program through Python programming to capture a total of 843,637 POI data points in the central urban area of Chongqing from Gaode Map, which is one of the most popular providers of navigation and location service solutions in China. The data include 16 major categories of POI, such as food service, road accessory facilities, scenic spots, shopping service, and transportation facility service. The information related to POI is obtained and includes the district and county where the POI is located, the WGS84 coordinates of the POI after conversion, and other data. (WGS84 Coordinate System stem is the abbreviation of the 1984 World Geodetic Coordinate System. It was established by the U.S. Defense Mapping Agency in 1984 as a reference datum for GPS satellite ephemeris and a type of protocol Earth reference frame). This paper uses this information to obtain the number of fast and slow charging stations, charging prices, parking prices, etc., in the Gaode map, which provides the basis for the calculation modeling.

3. Analysis of the Results

3.1. Analysis of Electric Vehicle Charging Post Supply

Figure 3a shows the "accessibility" of electric vehicle charging infrastructure in the central urban area of Chongqing, which reflects the charging infrastructure supply of the area. As shown in Figure 3a, the spatial heterogeneity of the charging infrastructure configuration in each administrative district of the Chongqing central urban area is obvious, and the accessibility value gradually decreases from Yuzhong District to the surrounding areas. The accessibility value in more than 80% of the central urban area is less than 0.05, while the maximum accessibility value is close to 1.

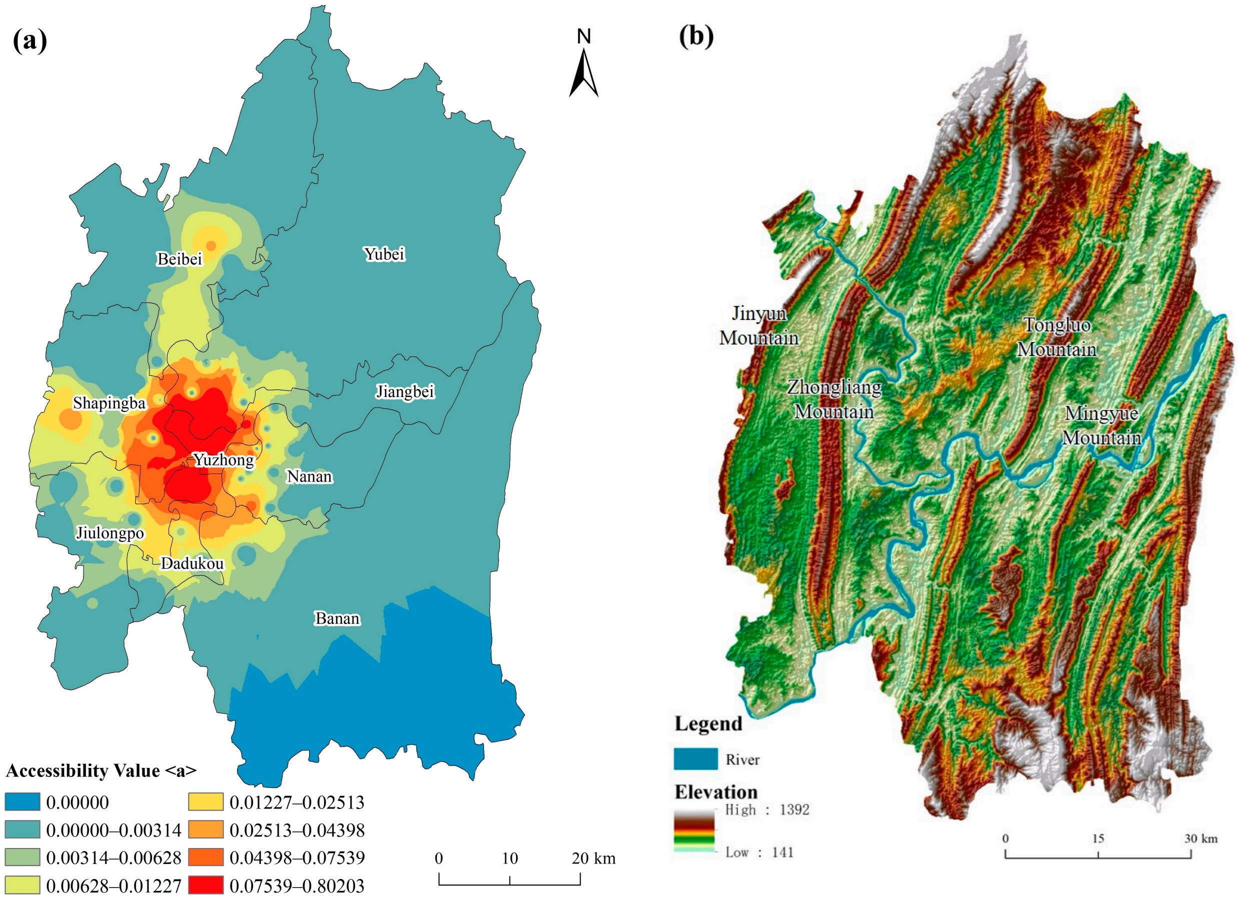

Figure 3. (**a**) The accessibility value of electric vehicle charging in the central urban area of Chongqing; (**b**) topographic map of the central urban area in Chongqing.

To some extent, this phenomenon is caused by the difference in economic development level and population density between regions. The higher the level of regional economic development and the denser the population is, the higher the accessibility value, and vice versa. The accessibility value is higher in the area around Yuzhong District. These areas have the highest accessibility values, due to their relatively complete charging infrastructure construction, relatively dense distribution, high traffic accessibility, a large number of charging stacks, and strong service capacity. Meanwhile, these areas are mainly economic centers and densely populated areas in the central urban area, and the three central business districts, Guanyin Bridge, Jiefangbei, and other large business districts are located here. Its substantial traffic flow and charging demand also led it to be the first area where charging infrastructure was distributed; hence, the supply of charging services is relatively good. The accessibility value of the remaining regions is low, of which Banan District and Yubei District are the most prominent, and the accessibility value in the south of Banan District is even less than 0.003, indicating the severe shortage of charging infrastructure supply. These areas are partly affected by the topography (Figure 3b). For example, their locations lie in mountainous, hilly areas where constructing layouts is difficult, they are located within the ecological protection red line, which prohibits development and construction, or parts of these areas are currently not covered by the road network; hence, traffic accessibility is poor. On the whole, most areas are relatively economically underdeveloped and sparsely populated. Therefore, from the above analysis, we can summarize the characteristics of charging infrastructure supply as having large interregional differences, an uneven level within regions, and an overall "single-peak" feature. The charging infrastructure supply is positively correlated with the level of economic development and population density.

3.2. Supply–Demand Matching Analysis of Electric Vehicle Charging Posts

The kernel density analysis of POI data in the central urban area of Chongqing is carried out using ArcGIS software (Figure 4a), and the kernel density value of POI is used to reflect the demand for electric vehicle charging infrastructure. As seen in Figure 4a, the demand for EV charging infrastructure varies widely in space within the central urban area of Chongqing and is mainly concentrated in the central areas of districts and counties with mature infrastructure and better development levels; these areas are densely populated and economically dense and have a greater demand for EV charging infrastructure. Comparisons with Figure 3 show that, in general, the accessibility values of the regions with larger kernel density values are also larger, which to some extent, indicates that the supply and demand of charging infrastructure in economic center regions tend to be balanced.

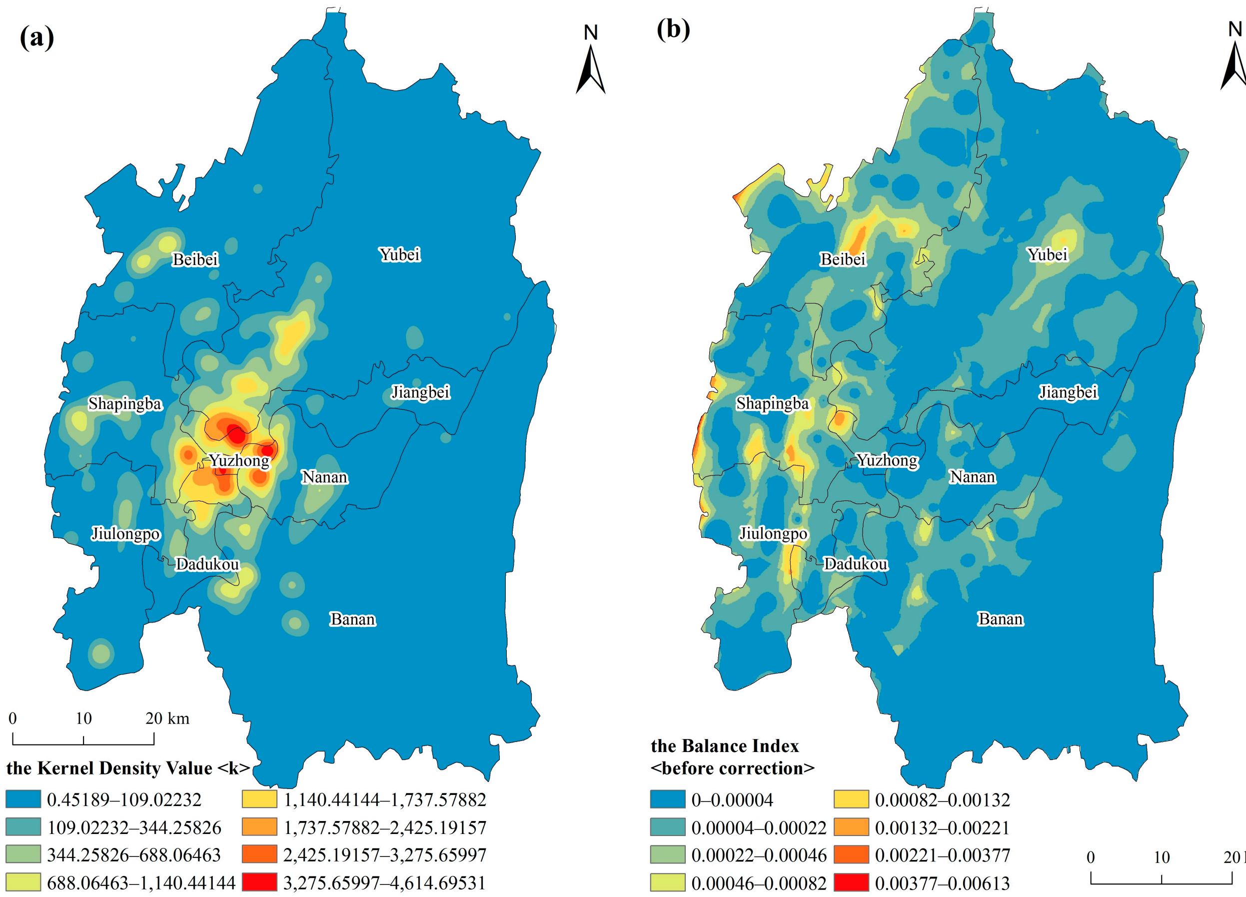

Figure 4. (**a**) Analysis of the nucleus density of points of interest in the central urban area of Chongqing; (**b**) Map of supply and demand of electric vehicle charging infrastructure in the central urban area of Chongqing (before correction).

The spatial analysis of the supply and demand of electric vehicles can be combined with field research to determine the supply–demand matching relationship of the electric vehicle charging infrastructure in Chongqing. According to the uncorrected balance index grading in Figure 4b, the central area of Chongqing can be divided into six levels (the last three levels in the figure are merged into the sixth level), and the balance index increases from the first level to the sixth level. The area of the sixth level is too small to be considered in the field investigation. A random sample of 20 charging posts in the level 1–3 area is selected, which represents 12–40% of the charging piles depending on the level area. In levels 4–5, because only one charging post exists within the study area, there is only one sample. Additionally, the field investigation is combined with online data to qualitatively evaluate the charging post usage. In this way, a constant c is obtained to correct the balance index. The evaluation results of charging posts at each level are shown in Table 1:

Table 1. Evaluation results of each grading area.

Region Grade	Evaluation Results
Level 1 area	There is no shortage of supply unless there is an exceptional circumstance.
Level 2 area	There are occasional shortages of supply except during special peak periods. It is recommended that charging posts be added to such points only when the planning targets are not met, as appropriate.
Level 3 area	There is mostly a supply shortage problem during the peak period. It is recommended to use the value of this section as the balance value.
Level 4 area	Only one sample exists within the study area, and this sample site is undersupplied only at particular times.
Level 5 area	Only one sample exists within the research area, and the charging post is not open to the public.

Figure 5a shows the matching situation of the supply and demand of the EV charging infrastructure in the central urban area of Chongqing. This figure indicates that the supply for charging infrastructure in the central urban area of Chongqing exceeds the demand in more than 80% of the areas, and the supply exceeds the demand in less than 20% of the areas. There is a large gap between the extreme values in each area, with a value difference close to 30, which indicates that the design of the charging infrastructure is vastly unscientific. Beibei, Shapingba, Jiulongpo, and Yuzhong Districts each have a balanced index of 20 or more in some areas, and the charging stations are set up en masse, which wastes significant amounts of funds, land, and energy and results in a large number of charging stations being idle and unattended. Therefore, valuable land cannot be fully utilized, the economic and social benefits are low, and these redundant stations should be appropriately dismantled or relocated. The locations of the undersupplied areas partially overlap with Jinyun Mountain, Zhongliang Mountain, Tongluo Mountain, and Mingyue Mountain (Figure 3b), which are affected by force majeure factors, hindered by the terrain and are mostly along the highway, and can thus be disregarded. The remaining areas, such as Yuzhong District, Jiangbei District, and Nanan District, which are the three central business districts, should be expanded appropriately for charging infrastructure to facilitate the daily commuting and recreation of new energy vehicle users.

3.3. EV Charging Posts Spatial Layout Optimization Goals and Ideas

Preferential governmental policies, combined with rising awareness of environmental protection among residents, have led to steadily growing increases in new vehicle ownership in Chongqing, which has further expanded the market size of charging infrastructure, so existing charging facilities are unable to meet the charging demand. Therefore, the construction of EV charging infrastructure should be planned for multiple periods: in terms of construction quantity, the construction can be properly advanced under the premise of satisfying the charging demand, and in terms of the construction sequence, the area with greater charging demand should be considered first.

According to the obtained optimization values β, the optimized spatial layout of EV charging infrastructure in the central urban area of Chongqing is calculated and drawn by ArcGIS software (Figure 5b). As seen from the figure, only a few areas have optimization values less than 0, and they are concentrated in the central urban area. Areas with large optimization values are scattered in the western part of the central urban area. Most of the areas are located between -0.05 and 0. According to the analysis of Figure 5b, the numbers of charging infrastructures in Yuzhong District, Jiulongpo District, central Jiangbei District, western Nanan District, and southern Yubei District, which are close to the economic center, are obviously insufficient and need to be increased accordingly. The number of charging infrastructures in the periphery of a number of economic centers, such as western Jiangbei District and eastern Shapingba District, and the prosperous areas of each district are obviously excessive, and consideration should be given to eliminating facilities with low utilization rates as soon as possible or appropriately reducing the scale to save more space. The number of charging infrastructures in other areas, such as the northern part of Yubei District, the eastern part of Jiangbei District, and Banan District, is basically kept within a reasonable range, and only a few areas need to increase the number of charging infrastructures appropriately. Addressing problems such as the charging infrastructure that cannot be used as expected will be the goal of these areas.

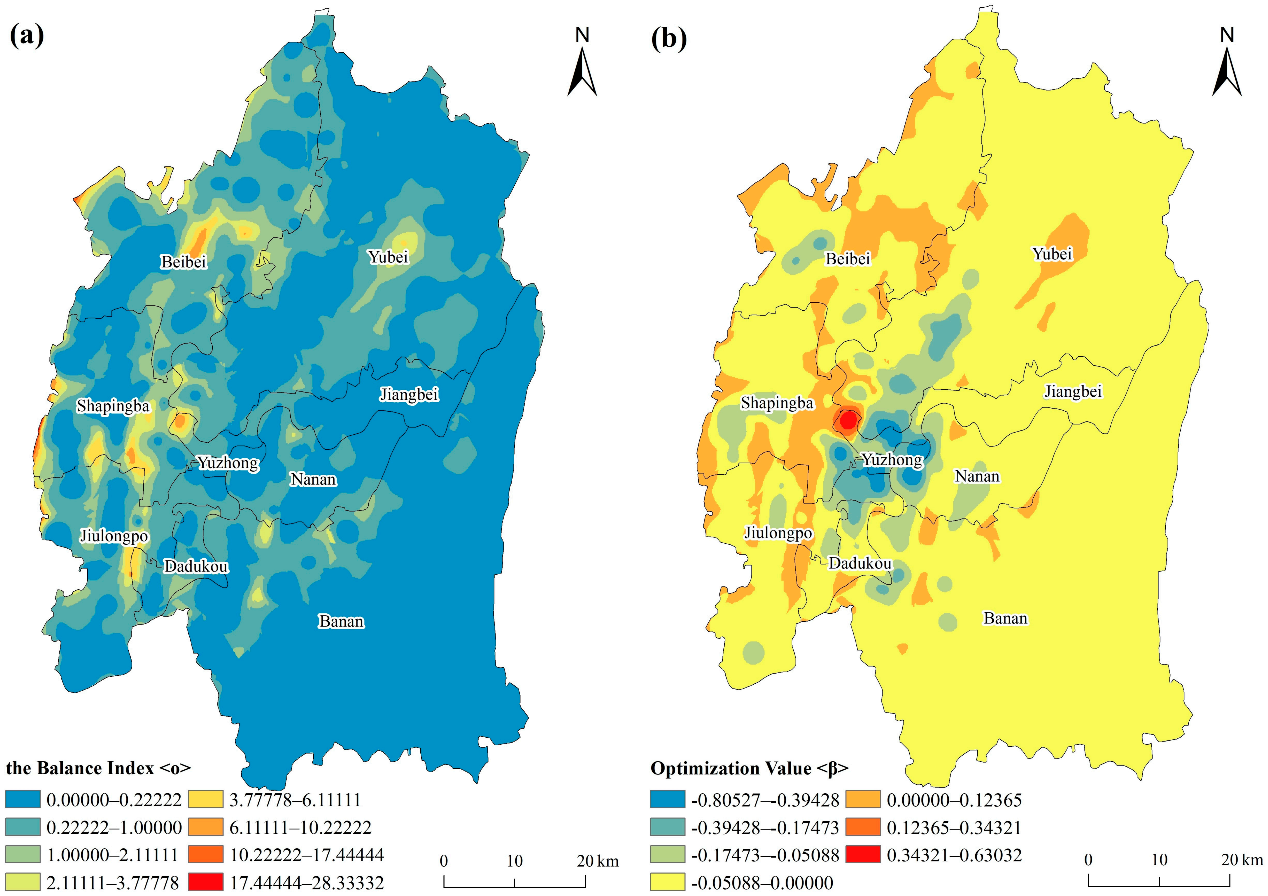

Figure 5. (**a**) Matching supply and demand of EV charging infrastructure in the central urban area of Chongqing (corrected); (**b**) spatial layout optimization map of EV charging infrastructure in the central urban area of Chongqing.

3.4. Spatial Layout Optimization Scheme of Electric Vehicle Charging Stack

Through the above quantitative research process, the spatial layout optimization map of the electric vehicle charging infrastructure in the central urban area of Chongqing was obtained. In order to make the site selection of charging posts practical, this paper will establish an electric vehicle charging infrastructure site selection index system and provide a reference for actual site selection based on the demand for charging infrastructure.

3.4.1. Electric Vehicle Charging Infrastructure Site Selection Index System and Weight

In this paper, a questionnaire measurement method is used to form an electric vehicle charging infrastructure site selection index system, and a hierarchical analysis method process is used to determine the weight of each index to provide standards and tools for the actual site selection of electric vehicle charging infrastructure.

(1) Building the Hierarchical Structure Model

Combined with the analysis of the literature, this paper determines the hierarchical evaluation model of electric vehicle charging infrastructure siting, as shown in Figure 6.

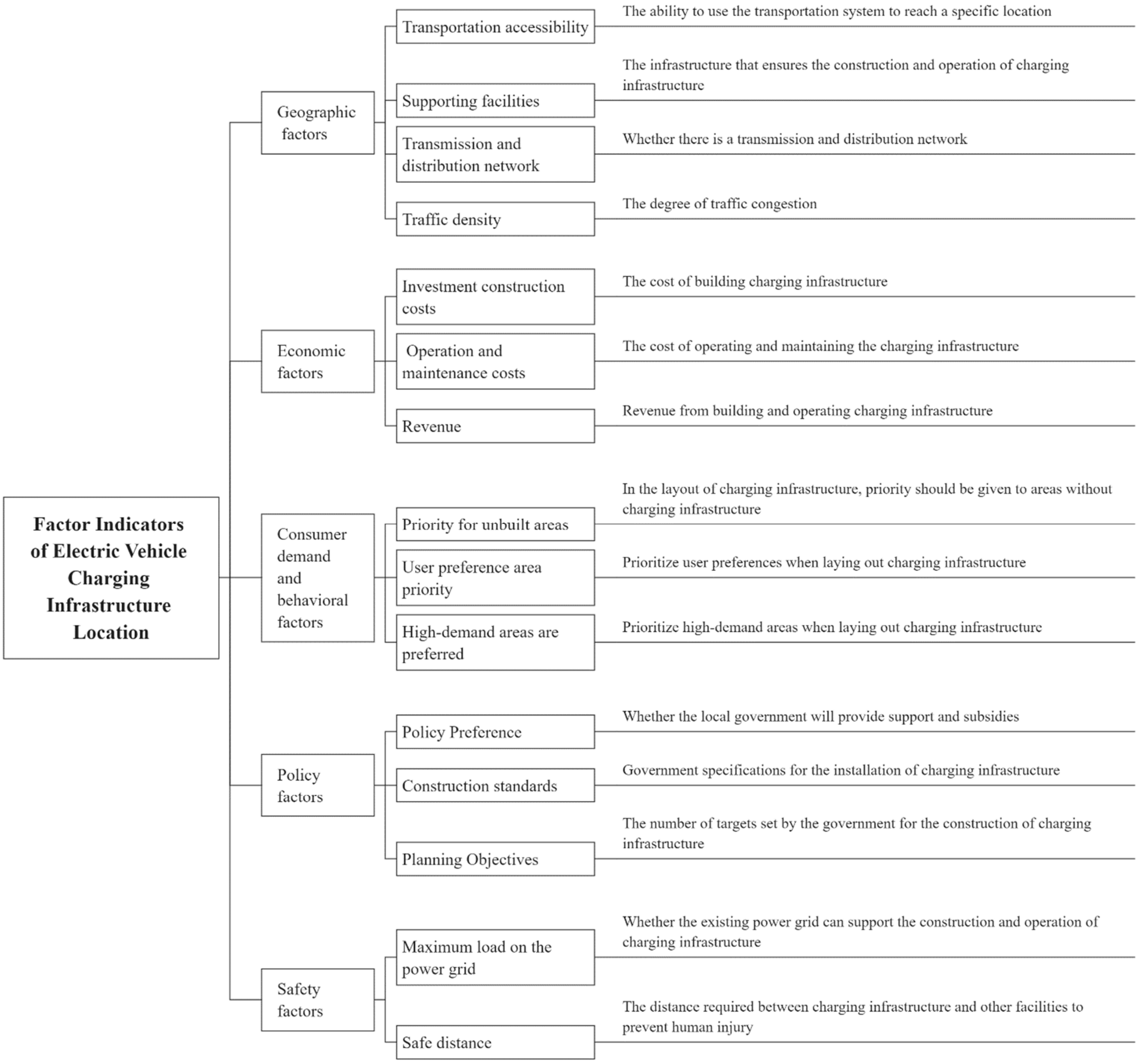

Figure 6. Factor indicators of electric vehicle charging infrastructure location.

(2) Reliability and Validity Analysis of the Measurement Questionnaire

Reliability is an index that reflects the true degree of the measured features in the measurement process, namely, the consistency and reliability of the measurement [31]. In this paper, the half-measure reliability is used as an index to evaluate the reliability of the measurement questionnaire. According to this calculation, the reliability coefficient is 0.895, which indicates that the results of the measurement questionnaire are basically reliable.

Validity is an index to measure whether the electric vehicle evaluation system can accurately reflect the purpose and requirements of the electric vehicle evaluation; it assesses the validity and correctness of the questionnaire [32]. Kaiser-Meyer-Olkin (KMO) and Bartlett sphericity tests were used in this paper, and the results are shown in Table 2.

Table 2. Test results of KMO and Bartlett effect degree.

KMO sampling appropriateness measure		0.879
Bartlett sphericity test	Approximate chi-square	1009.770
	Degrees of freedom	190
	Significance	0.000

According to the validity test results in Table 2, the KMO coefficient is 0.879, which means that the sample has validity. According to the results of Bartlett's sphericity test, the significance level Sig is 0, indicating the significance of Bartlett's sphericity test.

(3) Construction of the Judgment Matrix

According to the measurement results of the questionnaire, the arithmetic mean of the respondents' importance scores for each level of evaluation indicators was aggregated, and the Saaty scale was determined by the difference in the mean values of each indicator. The specific method is as follows:

Z_{ij} and Z_{ik} are the mean importance values of any two indicators in a given evaluation system. We can use the value of Z_{ij} minus Z_{ik} to get to the corresponding Saaty scale (Table 3).

Table 3. The Saaty 1–9 scaling.

$Z_{ij} - Z_{ik}$	Content	The Saaty Scale
0	Z_{ij} is of equal importance to Z_{ik}	1
(0.18, 0.36]	Z_{ij} is slightly more important than Z_{ik},	3
(0.54, 0.72]	Z_{ij} is considerably more important than Z_{ik}	5
(0.90, 1.08]	Z_{ij} is more important than Z_{ik}	7
(1.26, $+\infty$)	Z_{ij} is more important than Z_{ik}	9

The Saaty 1–9 scaling method is used to make pairwise comparisons of indicators, thus establishing a judgment matrix [33].

(4) Index Weight and Consistency Test

In this paper, MATLAB is used to calculate the weight and consistency of each level of indicators.

The weights of geographical factors, economic factors, consumer demand and behavioral factors, political factors, and safety factors are 0.2376, 0.0949, 0.3632, 0.1257, and 0.1795, respectively. The weights and combination weights of the secondary indicators are shown in Table 4. The CR value of the judgment matrix of the primary indicators is 0.029, and the CR values of the judgment matrix of the secondary indicators are 0.053, 0.0462, 0.0462, 0.0462, and 0, respectively, which are all less than 0.1, indicating that the matrix has relative consistency.

3.4.2. Electric Vehicle Charging Infrastructure Layout Optimization Scheme

Considering the influence of electric vehicle range, battery power, user demand preference, and charging station planning service target on the service radius of charging facilities, and based on the "10 min charging ring construction" principle, that is, where electric car users can drive to the charging infrastructure within 10 min, the service radius is calculated as follows [26]:

$$R = \frac{20\ \text{km/h} \times 10\ \text{min}}{1.1} \approx 3\ \text{km} \tag{5}$$

Therefore, to ensure the charging demand for electric vehicles, the central urban area of Chongqing is divided into electric vehicle survey areas by a regular hexagon with a tangent radius of 3 km (Figure 7). Based on the fact that the POI data can reflect the traffic density, consumer preference, and demand of a certain region to a certain extent, the high and low core density values of the POI in the central urban area of Chongqing are referenced to determine the location and capacity of charging infrastructure in the survey area.

Table 4. Index weight table.

Indicators	Weight	Combination Weight
A. Geographic factors	0.2376	-
A1. Transportation accessibility	0.2656	0.0631
A2. Supporting facilities	0.4228	0.1005
A3.Transmission and distribution network	0.1744	0.0414
A4. Traffic density	0.1372	0.0326
B. Economic factors	0.0949	-
B1. Investment construction costs	0.1958	0.0186
B2. Operation and maintenance costs	0.4934	0.0468
B3. Revenue	0.3108	0.0295
C. Consumer demand and behavioral factors	0.3632	-
C1. Priority for unbuilt areas	0.1958	0.0711
C2. User preference area priority	0.3108	0.1129
C3. High-demand areas are preferred	0.4934	0.1792
D. Policy factors	0.1257	-
D1. Policy Preference	0.3108	0.0391
D2. Construction standards	0.1958	0.0246
D3. Planning Objectives	0.4934	0.0620
E. Safety factors	0.1795	-
E1. Maximum load on the power grid	0.6667	0.1197
E2. Safe distance	0.3333	0.0598

When the optimization value β is less than 0, the amount of electric vehicle charging infrastructure needs to be increased. In this paper, the area with a negative optimization value is divided into four levels according to the reclassification results in Figure 7. The higher the level, the lower the optimization value is, and the more charging infrastructure needs to be added. The optimization results are shown in Figure 7.

To implement the site selection point to the specific location, considering the space limitation, this paper takes only the alternative points shown as an example to analyze the site selection. Table 5 shows the information on the selected points:

Table 5. Information on additional reference points.

Sample Information	01	02	03	04
Coordinates of additional reference points (CGCS2000)	638,485.524 3,301,976.728	634,897.446 3,299,056.463	648,089.202 3,274,887.625	652,518.551 3,272,672.95
Specific address	Chongbai Shopping Center parking lot, Tiansheng New Village No. 63, Beibei, Chongqing.	Haiyu Hotel parking lot, No. 198 Shuangyuan Avenue, Beibei, Chongqing.	Longhu North Shore Constellation underground parking lot, Beicheng Tianjie No. 4, Guanyin Bridge, Jiangbei Chongqing.	Da Rong City underground parking lot, Yingli No. 26 Minquan Road, Jiefangbei, Yuzhong, Chongqing.

Combined with the indicators of each level and their weights shown in Table 4, the specific situation of this point is fully considered. Geographical factors of the first sample include its location in the commercial center of the old city of Beibei, Chongqing, with dense POI and good traffic accessibility. The mall is equipped with parking facilities, with good conditions for the construction of charging posts. There is no nonconformity to the power grid. It is a transportation hub with two primary schools nearby, which causes peak traffic congestion and high traffic density. Economically, the economic condition of the construction subject should be considered. For consumer demand and behavior factors, a lack of loading docks built near the business district indicates that consumer demand is great. A field visit showed that the relevant consumers generally support having the charging posts in their area. In terms of policy factors, Chongqing released the "Chongqing Municipal Action Plan to Promote the Construction of Intelligent Networked New Energy Vehicle Infrastructure and Services (2022–2025)", which proposes that by the end of 2025, the central urban area will have the conditions necessary for full coverage of charging posts in public parking spaces. The Beibei local government has a series of policies to accelerate the development of intelligently networked new energy vehicles and new community charging posts. Other policies support construction. For safety factors, the point is that in an electricity-intensive environment, many people gather together, so professionals should be asked to assess safety.

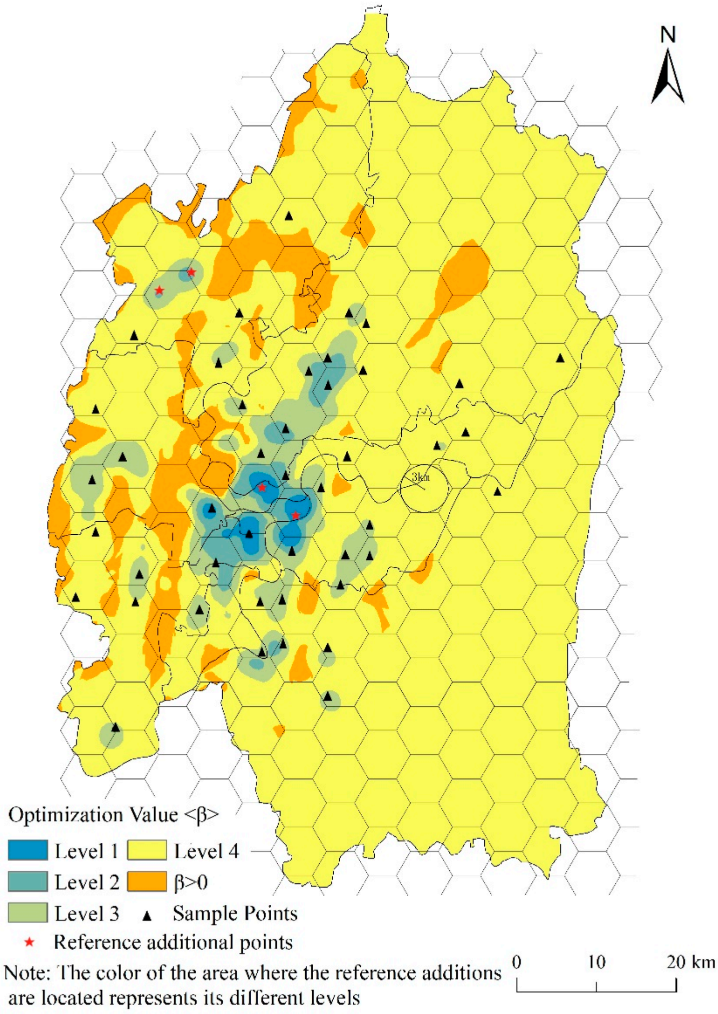

Figure 7. Electric vehicle charging infrastructure layout optimization reference map.

The second sample is located in a residential gathering point near the commercial center of the new town of Beibei District, Chongqing, with dense points of interest and good traffic accessibility. The hotel has a small number of charging posts that have been built internally and can be further expanded on this basis, with good conditions for the construction of charging posts. There is no nonconformity with the grid load condition. This area is located in a traffic hub with high traffic density. For economic factors, it is located in the hotel's internal parking lot, which may not be open to the public and requires approval. The economic situation of the construction object must be taken into consideration. For consumer demand and behavior factors, this commercial area is densely populated and has a large flow of people, which has a large consumer demand. After field visits, the relevant consumers generally support the establishment of charging posts. In terms of policy factors, Chongqing released the Chongqing Action Plan to Promote the

Construction of Intelligent Networked New Energy Vehicle Infrastructure and Services (2022–2025), which proposes that by the end of 2025, the coverage rate of charging posts in new communities will reach 100%. The Beibei local government has a series of policies to accelerate the development of intelligently networked new energy vehicles and new cell charging posts. Other policies support construction. Safety factors are the same as for the previously mentioned sample point.

For the third sample, the underground parking garage in North City Tianjie, the commercial center of Guanyinqiao, Jiangbei District, Chongqing, has dense interest points and good traffic accessibility. The parking garage has already built charging posts and can continue to expand on this basis, with good conditions for the construction of charging posts. There is no nonconformity with the grid load condition. The site has high traffic density and many roads mixed with walking and pedestrian–vehicle traffic, which will lead to congestion. For economic factors, it is necessary to consider the economic condition of the construction subject. The consumer demand and behavior factor and the safety factor are the same as in the first sample.

For the fourth sample, the underground garage of Yingli-Darong City, located in Jiefangbei, Yuzhong District, Chongqing, has dense interest points and good traffic accessibility. A small number of charging posts have been built in the parking lot, which can be further expanded on this basis, with good conditions for the construction of charging posts. There is no nonconformity to the grid load condition. The area contains many pedestrians and mixed roads for pedestrians and vehicles. The economic factor, the safety factor, and the consumer demand and behavior factor are the same as in the last sample.

Combined with the indicators and their weights at each level shown in Table 3, the specific locations of the remaining charging posts can be considered based on the specific conditions of these samples using the method described above.

4. Discussion

At present, there is little research on the accessibility of charging infrastructure in the academic literature, and traditional models, such as the two-step floating catchment area method and potential model, are mostly used to calculate accessibility. There is almost no design model or improvement in the traditional model based on the characteristics of the charging infrastructure itself and the characteristics of users' charging behaviors to calculate the accessibility. Moreover, when providing an optimization layout scheme, the selection of site selection factors is one-sided, unable to achieve all aspects. This paper fills the research gap in measuring the accessibility of charging infrastructure, independently establishes a mathematical model, and constructs a more comprehensive index system, paying more attention to the influence of comprehensive factors on the optimal layout of charging infrastructure. The results of this paper are of great significance to various stakeholders. For users of new energy vehicles, charging will be more convenient, the situation of "having a car without a post" will be alleviated, and the sense of user experience will be improved. For enterprises, it can provide location suggestions for setting charging infrastructure, save construction costs and operation costs, and improve coverage rate and service efficiency so as to stimulate consumer behavior and improve economic benefits. For local governments, it is beneficial to use land more economically, implement the concept of green development, develop a sustainable and low-carbon economy, and actively promote the realization of the national goal of the carbon peak and carbon neutralization, providing a reference for other provinces and cities.

Although there are important discoveries revealed by these studies, there are also limitations: (1) this paper takes the central urban area of Chongqing as the research scope, and does not consider the differences and unevenness between the urban area and the surrounding townships. It is necessary to discuss the urban area separately from the surrounding townships in subsequent studies, so as to investigate the spatial differentiation of electric vehicle charging infrastructure between urban and rural areas and the differences in consideration of optimal layout factors. (2) The POI data used in this paper are only from Gaode Map; some location data and the number of charging post settings are not available, which limits the depth of this study. It is necessary to improve the relevant information in combination with field research to improve the accuracy and breadth of this study. (3) In this paper, the road network distance is used to characterize the distance impedance, without taking into account the characteristics of Chongqing as a mountainous city with complex terrain and variable traffic conditions. The use of time distance for calculation could be considered in subsequent studies, comparing the differences between the results to enhance the rigor of this study.

5. Conclusions

This paper takes the "double carbon" goal and "new infrastructure" as the background, Chongqing downtown as the research area, and the spatial optimization layout of electric vehicle charging infrastructure as the research object. Through the comprehensive use of mathematical model analysis, ArcGIS spatial analysis, field investigation, questionnaire measurement, and the analytical hierarchy process, the current distribution characteristics and supply–demand matching of the electric vehicle charging infrastructure in this region are discussed. Finally, a reference for optimizing the layout of the charging infrastructure is provided. The main conclusions are as follows:

(1) The spatial differentiation of charging infrastructure configuration and demand in the central urban area of Chongqing is obvious and shows strong centrality. On a large scale, the core density value, availability value, and optimization value all gradually decrease from Yuzhong District to the surrounding area. On a small scale, some local centers also produce similar phenomena in local areas. The main reason for this phenomenon is the difference in regional economic development levels and population differences.
(2) It is a common phenomenon that the demand for charging infrastructure in the central urban area of Chongqing exceeds the supply. The speed and quality of the construction of charging infrastructure cannot meet the growing demand for electric vehicles. Approximately 80% of the areas are in short supply, and building new charging infrastructure is urgently needed.
(3) Local centers should be considered first when optimizing the construction of charging infrastructure. When selecting a specific construction site, a field survey should be conducted, taking into account various factors such as economy and traffic. At the same time, the charging infrastructure should ensure the operation process to reduce the impact of nonelectric vehicle crowding and equipment failure without maintenance on the operation efficiency.

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