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Spatial Optimization of Park Green Spaces by an Improved Two-Step Optimization Model from the Perspective of Maximizing Accessibility Equity

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Abstract: As a type of public land, park green spaces (PGSs) carry the daily recreation and social communication of urban residents, and the inequity of their space accessibility has been widely confirmed. However, the optimized suggestions based on evaluations of accessibility and equity in previous studies cannot guide actual planning effectively because the reasonable locations and scales of construction of PGSs were difficult to accurately identify. This study first constructed two equity objective functions: the minimum standard deviation (SD) and the minimum Gini coefficient (GC) in accessibility; then an improved two-step optimization method considering location-allocation was adopted to maximal accessibility equity (MAE) for optimizing the spatial layout of PGSs and doing comparisons of these two objectives for further analysis. The results showed that the improved method based on covering the accessibility blind area and preserving the existing PGSs could optimize the location selection and rationally determine the area. The two objective functions were both effective for optimization, but the GC minimization is more advantageous than the SD for achieving the MAE. The accessibility value increased significantly in a higher proportion of regions, and the overall accessibility median increased by 0.0445. It is worth mentioning that the MAE optimization would lead to a new imbalance between supply and demand in some regions. This indicated that the strictly restricted area standard may lead to the oversupply of PGSs in some areas, while the improvement of equity might not mean the improvement of accessibility. The proposed optimization framework could achieve the optimal layout of PGSs on the goal of MAE. Our findings also could provide inspiration for the equity allocation of other types of public facility lands and support decision-making for government departments regarding management and planning.

Keywords: park green spaces; spatial accessibility; maximal equity; two-step optimization model; Gini coefficient

Citation: Mu, L.; Xing, L.; Jing, Y.; Hu, Q. Spatial Optimization of Park Green Spaces by an Improved Two-Step Optimization Model from the Perspective of Maximizing Accessibility Equity. *Land* **2023**, *12*, 948. https://doi.org/10.3390/land12050948

Academic Editor: Thomas Panagopoulos

Received: 15 March 2023
Revised: 12 April 2023
Accepted: 21 April 2023
Published: 24 April 2023

1. Introduction

As a type of land use closely related to nature in urban settings, park green spaces (PGSs) provide many benefits in the sustainable development of the urban ecological environment, including noise reduction [1], mitigation of the urban heat island effect [2], and air pollution reduction [3]. PGSs are also important places for residents' daily activities, which have positive effects on residents' physical and mental health. However, the World Urbanization Prospects: the 2018 Revision published by the United Nations emphasizes that the proportion of global urban population will be as high as 60% by 2030, with most of the world's megacities with a population of more than 10 million being located in developing countries [4]. The continuous development of global urbanization gradually throws off the balance in the relationship between the supply and demand of PGSs, and seriously threatens the equity concerning residents' use and accessibility of park green space. As the largest developing country, China is currently in a period of accelerated urbanization. Its urban population reached 63.91% of its total population in 2020, and most of its cities have been facing the inequity of PGS accessibility [5]. Therefore, ensuring residents equitably enjoy the services of PGSs has become an important concern for the country's urban planners.

Most existing studies proposed relevant optimization suggestions by either evaluating the accessibility of green spaces to identify vulnerable areas or exploring the influencing factors on the accessibility of green spaces [6–9]. Accessibility is defined as the potential opportunities for residents to access public facilities and is an important indicator in measuring spatial equity [10,11]. Various miscellaneous measurements of spatial accessibility have been used, such as impedance (which is the distance or time) to the nearest services [12], container approaches [13], and the gravity model [14]. The latest two-step floating catchment area (2SFCA) method and its improved forms were widely used in studies evaluating the spatial equity in green space accessibility and were advantageous in reflecting the supply and demand of green spaces [15–18]. Many studies have confirmed the existence of the spatial inequity of PGS accessibility among different age groups [17,19,20], races [21], social statuses [22], and education levels [23]. Significant spatial disparities in accessibility are affected by both objective factors such as physical distance [24], the characteristics of PGSs [25], and environmental safety [26] and by subjective factors such as personal preference and travel mode [18]. Existing studies have also drawn consistent suggestions on the equity optimization of existing PGSs, mainly including improving traffic convenience [9,27], increasing entrances [28], building small PGSs [6,29], improving the quality of PGSs [29], government policy adjustment [30], and improving PGSs for groups [31]. However, these suggestions are closely related to accessibility results and influencing factors and thus cannot effectively guide the optimal layout of green spaces in actual urban planning. More importantly, the limited number and area of PGSs is the most direct reason for their low accessibility in many cities. Therefore, accurately identifying the location of PGSs and determining their reasonable area are pivotal in effectively guiding and realizing their optimal layout.

Optimization modeling has been proven to be effective for location selection and area optimization of PGSs. Maximal ecological benefits were widely taken as objectives for PGS optimization, including the mitigation of the urban heat island effect, the absorption of CO2 and PM2.5, the retention of precipitation, and the maintenance of species diversity [8,32–34]. In some studies, PGS accessibility was considered for minimizing the travel cost as the optimization objective [28,35]. However, maximal accessibility equity in the supply and demand of PGSs still needs further exploring. Fortunately, the deepening of quantitative studies on the equitable allocation of public facilities also brings new inspiration to the equitable layout of PGSs. Wang and Tang [36] first developed a maximal equity model based on the 2SFCA method to minimize the accessibility inequality by deallocation resources. Although the model is conducive to solving the Maximal Accessibility Equity (MAE) Problem, the capacity of public facilities, including PGSs, healthcare facilities, and schools has been strictly controlled in the planning process. Thus, there may be a gap between the deallocation of resources and the actual planning. Further, a two-step optimization (2SO) model was proposed by Li et al. [37], which includes both location optimization and capacity optimization. The first step includes the classic location-allocation model, which includes the p—median problem, the maximum covering location problem (MCLP), and the minimax problem to select the location of public facilities, which help to realize travel efficiency. In the second step, the equity of facility supply and demand can be achieved by selecting relevant equity measurement indicators. For example, Luo et al. [38] adopted accessibility standard variance to maximize the equity of health resource allocation in rural areas; and Li et al. [39] compared five equity indicators including variance and the Gini coefficient to equalize the spatial accessibility of emergency medical services in Shanghai. Both aforementioned studies confirm the feasibility of the MAE model in the spatial layout of medical facilities, but the applicability in the optimal layout of PGSs must be verified.

The Gini coefficient (CG) has also been proven as an effective indicator in evaluating the spatial equity of PGSs in spatial analysis [18,40]. The value is usually between 0 and 1, with a larger value indicating a more obvious inequity. The CG corresponds to the relevant equity levels and intuitively reflects the equity of PGSs accessibility, which makes up for the limitation that accessibility needs to be visualized to reflect spatial equity [41]. Moreover, the CG can show the overall equity of PGSs on a larger scale, rather than a community or a more microscopic scale, and can thus be used as an important indicator to achieve overall social equity in PGS planning [5,42]. Therefore, the latest two studies used the CG as an equity objective in the spatial optimization of green spaces. Wu et al. [43] used CG to explore the impact of closed community opening on green equity. Another study also used the genetic algorithm to maximize the equity of urban green spaces (UGSs) with the objective of CG, and realized the optimal layout of UGSs under the consideration of spatial equity and costs [44]. Although standard variance (SD) and the CG are applied to the optimal layout of green spaces and other facilities as the objective for MAE, the difference of the optimization results obtained by the two objectives is not compared in PGS layout. The two objectives should be further explored to find the better one for realizing the MAE of PGS layout.

Considering these limitations, our study uses the 2SO model to optimize the location and size of PGSs and takes Wuhan as the specific example. Specifically, the following steps are done: (1) the MCLP model is used to optimize the selection of park location to achieve the coverage of accessibility blind spots and meet the equity of all residents in accessing PGSs; (2) for MAE, the genetic algorithm is used to optimize the size of PGSs for achieving equity in supply and demand of PGSs; (3) two equity objectives of minimum SD of accessibility and minimum CG based on supply and demand of PGSs are constructed, and the differences between those two objectives in realizing the equity in supply and demand of PGSs was further explored. The achievement of these aims provides the following contributions: first, a framework of optimization modeling for realizing the equity of PGSs is constructed, which makes up for the lack of actual planning operation in the existing optimization suggestions. Second, by comparing the two MEA objectives, a more appropriate one is provided to solve the equity of PGSs. Last, the MAE model designed herein provides a feasible reference for urban planners to achieve equitable allocation of other public facilities.

2. Materials and Methods

2.1. Research Framework and Optimization Modeling

A framework for the optimization of new PGSs proposed in our study included three parts (Figure 1): (1) based on the G2SFCA method, the accessibility of existing PGSs was calculated for the identification of blind spots. We used the population, road network, and existing PGSs to calculate the spatial accessibility of existing PGSs for each hexagonal grid within a specific threshold time. The aggregated point of the communities within each hexagonal grid and the centroids or entrances of the existing PGSs were taken as the origins and destinations; (2) the remaining hexagonal grids were converted into centroids as potential candidate locations after removing the hexagonal grids containing the existing PGSs and water. Then, the MCLP model was used to select the final locations and the number of new PGSs within the above threshold time to cover all community aggregation points; (3) based on the GA, the area of the new PGSs was optimized to MAE. The minimum SD and the minimum CG in accessibility were used for the optimal layout of PGSs, and the total capacity of new PGSs was taken as the constraint condition. Finally, the more suitable modeling scheme for PGSs optimization was determined by comparing these two objectives.

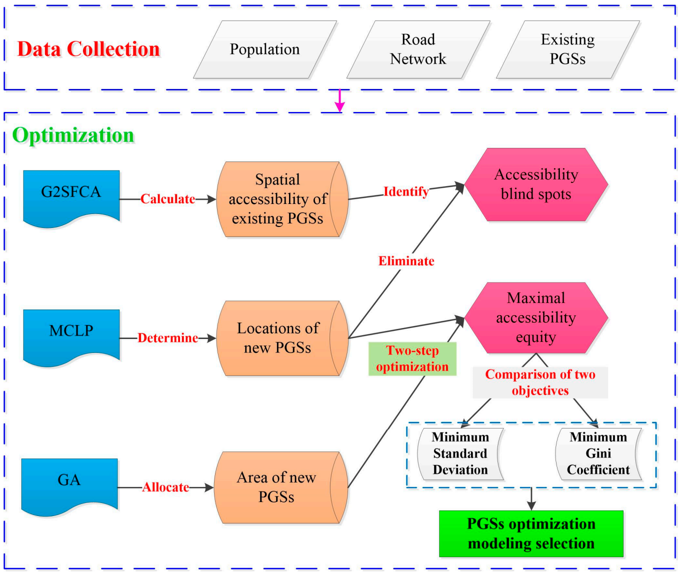

Figure 1. Framework for Spatial optimization of New PGSs.

2.2. Gaussian Two-Step Floating Catchment Area (G2SFCA) Method

The G2SFCA is an improved method by adding a distance decay function to characterize the spatial relationship between supply and demand of public facilities [15]. This method consists of two steps. The first step is to calculate the supply-to-demand ratio of each PGS j. For each PGS j (supply), all communities within a threshold time t_0 from PGS j are identified based on the road network, and then population (demand) of all communities within the catchment is summarized as potential demand. In order to accurately reflect the population distribution, the Gaussian function is introduced to weight the population in community i. The supply-to-demand ratio (R_j) within the catchment area is calculated as:

$$R_j = \frac{S_j}{\sum_{i \in \{t_{ij} \le t_0\}} G(t_{ij}, t_0) P_i} \quad (1)$$

where P_i is the population of community i within the catchment ($t_{ij} < t_0$) from PGS j; S_j is the area of PGS j; t_{ij} is the travel time between PGS j to community i; t_0 is the threshold time; G is the Gaussian function applied to weight the population in community i by the time distance between PGS j and the community i. It is calculated as:

$$G(t_{ij}, t_0) = \begin{cases} \frac{e^{-\frac{1}{2}\times\left(\frac{t_{ij}}{t_0}\right)^2} - e^{-\frac{1}{2}}}{1 - e^{-\frac{1}{2}}}, & t_{ij} \le t_0 \\ 0, & t_{ij} > t_0 \end{cases} \quad (2)$$

The second step is to calculate the PGS accessibility for each community i. For each community i, all PGS j within the threshold time t_0 from community i are identified based on the road network, and then the supply-to-demand ratio of all PGS j within the catchment is summarized as the PGSs accessibility of community i. The PGSs accessibility (A_i) is calculated as:

$$A_i = \sum_{j \in \{t_{ij} \le t_0\}} G(t_{ij}, t_0) R_j \quad (3)$$

where R_j is the supply-to-demand ratio of PGS j within the catchment ($t_{ij} < t_0$) from the community i, and all the other variables are explained above.

2.3. Objectives of MAE

Recently, considerable studies have proved that the supply-demand of PGSs is inequity, but maximal equity is rarely used as the objective function for spatial optimization of PGSs.

2.3.1. Objective 1: The Minimum SD in Accessibility

We use the minimum SD in accessibility as an objective function for MAE and apply it to the area optimization of new PGSs in this study. The calculation formula is as follows [38]:

$$minimize \sqrt{\frac{\sum_{i=1}^{m} P_i (A_i - a)^2}{\sum_{i=1}^{m} P_i}} \tag{4}$$

$$a = \sum_{i=1}^{m} \left(\frac{P_i}{P}\right) A_i = \frac{1}{P}(P_1 A_1 + P_2 A_2 + \ldots + P_m A_m) = \frac{S}{P} \tag{5}$$

$$s.t. \ \sum_{j=1}^{n} S_j = S \tag{6}$$

In Equation (4), P_i is the population of community i; A_i is the PGS accessibility of community i; a is the weighted average accessibility which is calculated by Equation (5). Equation (6) is the constraint parameter, where S is the total area of all new PGSs; P is the total population of all communities; and S_j is the area of the new PGS j.

2.3.2. Objective 2: The Minimum CG in Accessibility

This study attempts another objective function, CG. CG is an indicator of inequality and is closely related to the Lorenz curve, which is usually between 0 and 1, where 0 means absolute equality and 1 means absolute inequality. In this study, CG is also used for the area optimization of new PGSs. The calculation formula is as follows [43]:

$$minimize \ \ Gini = 1 - \sum_{i=1}^{n} (P_i - P_{i-1})(Q_i + Q_{i-1}) \tag{7}$$

$$s.t. \ \sum_{j=1}^{n} S_j = S \tag{8}$$

where n denote the number of communities sorted by park accessibility from low to high; P_i is the cumulative proportion of the population; Q_i is the cumulative proportion of the PGS accessibility. Equation (8) is the constraint parameter, where the S is the total area of all new PGSs; and S_j is the area of the new PGS j.

3. Case Study: Optimization for Equity Maximization of PGSs in Wuhan

3.1. Study Area

Wuhan is the capital of Hubei province, which is located at the intersection of the Yangtze River and the Han River (see Figure 2). Long-term rapid urbanization has led to the proportion of resident population in Wuhan from 2000 to 2021 increasing by 64.2% (Wuhan Municipal Statistics Bureau, 2022). In 2021, the per capita PGSs of the city was 14.82 m^2, which is lower than the national average (14.87 m^2) (Wuhan Municipal Bureau of Garden and Forestry, 2022). The rapid growth of urban population and the relative lag of PGS construction make conflicts between supply and demand of PGSs. Wuhan is presently committed to building a park city with swampy and floriferous characteristics and a high-level national ecological garden city. Realizing the equity of supply and demand of PGSs is a focus that cannot be ignored to achieve these above goals. This study takes the area within the 3rd ring road of Wuhan as study area, where the urbanization is close to 100% and the PGS resources are limited. It is inevitable for urban planning to improve the equity of PGSs under limited construction conditions.

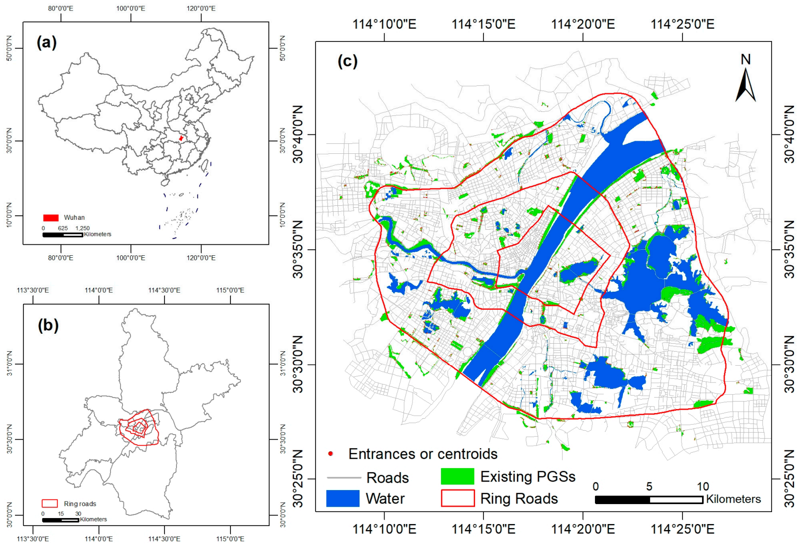

Figure 2. The location of Wuhan in China (**a**), the location of study area in Wuhan (**b**), and the study area and spatial distribution of PGSs (**c**).

3.2. Data Source and Processing

(1) Extraction of PGSs

Firstly, city parks were obtained from the data in 2021 issued by the Wuhan Municipal Bureau of Garden and Forestry (http://ylj.wuhan.gov.cn/ (accessed on 4 March 2023)). Then, Python was used to obtain the POI data of these city parks from Amap (https://www.amap.com/ (accessed on 4 March 2023)). These POI data have the latitude and longitude position of city parks, which can provide important location information for the extraction of city parks. Secondly, we imported the location of these parks on Google earth, and then manually vectorized the green space of these parks. We also extracted some relatively well-equipped green spaces with certain entertainment and leisure functions as community parks, which meet Standard for planning of urban green space (GB/T51346-2019) with an area between 1 and 10 ha. In the above process, we excluded the green spaces in residential communities and some city parks that need to be charged to ensure the accessibility and availability for more residents. Moreover, the extension lines of main roads were used to segment the long-narrow PGSs for avoiding the influence of these PGSs on the experimental results. For example, the PGSs along the Yangtze River is long-narrow and with a large spatial area. Finally, we obtained 345 PGSs, and in order to ensure that the research results are more realistic, we used the entrances as destination points for PGSs with an area greater than 5 ha, and the centroids are used as destination points for PGSs less than 5 ha.

(2) Demographic data

More refined population data units have an important impact on the accuracy of PGSs accessibility results. China conducts a national census every ten years. Due to the confidentiality of data, it is difficult to obtain refined population data. Some recent studies have begun to obtain the number of households in the residential communities from the real estate rental service platform and speculate on the population data [45,46]. Therefore, we crawled the POI data of the residential communities within the 3rd ring road in 2021 from the well-known real estate rental service platform “Anjuke” in China (https://wuhan.anjuke.com/ (accessed on 4 March 2023)), including the name of the residential communities, latitude and longitude coordinates, and the total number of households. After correcting and eliminating invalid data, 5250 residential communities were obtained. Regular hexagonal grids with a side length of 250 m were constructed to ensure the convenience and effectiveness of data calculation [35,47] based on the 3rd ring road of Wuhan. They were used as the basic population data units, and the residential community points inside each grid were aggregated to the center of gravity of the latitude and longitude coordinates (Figure 3a). Finally, 1594 demographic units were aggregated

(Figure 3b). The total population calculation formula for each demographic unit was as follows:

$$P_k = \sum_{i \in G_k} H_i \times \overline{P} \quad (9)$$

where P_k is the total number of population in aggregated point k; G_k is the hexagonal grid around aggregated point k; H_i is the number of households; and $\overline{P}$ is the number of persons per household, which is 2.73 in 2021 from the Wuhan Municipal Bureau of Statistics (http://tjj.wuhan.gov.cn/ (accessed on 4 March 2023)).

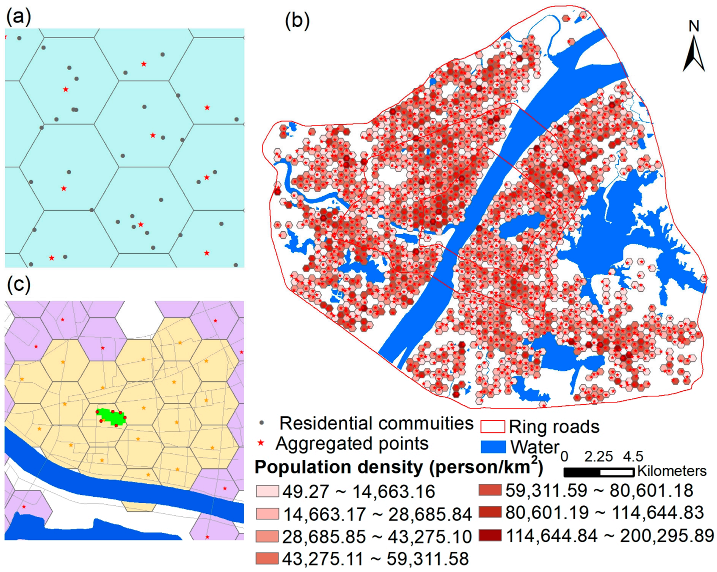

Figure 3. The aggregation points (**a**), the spatial distribution of population density (**b**), and aggregation points that can be reached by the PGS in 15 min (**c**).

After calculation, it was found that there were 9.3567 million people within the 3rd ring road without considering the vacancy rate. Based on the census data of the Wuhan Municipal Bureau of Statistics in 2018, we speculated that the expected population in 2021 within the 3rd ring road is 7.6217 million, and the population difference is 1.7351 million. Although the population may be significantly higher than the actual population, the population growth rate in Wuhan has stabilized at 10% in the past two years (from Wuhan statistical yearbooks of 2020 and 2021). This indicated that the capacity of 9.3567 million people is in line with the expected population for a certain period of time, and the planning needs to ensure a certain space reservation. Finally, the aggregation points of the residential communities were taken as the starting point.

(3) Road network

Road network is an important factor in calculating PGS accessibility. We obtained the road network data of Wuhan in 2021 from Open Street Map (http://www.openstreetmap.org/ (accessed on 4 March 2023)). After correcting and eliminating invalid data, the main roads, secondary roads, and branches are retained as the basic road network structure of the city.

3.3. Parameters Setting

3.3.1. The Time Threshold and Selection Principle of New PGSs' Locations

Regarding the location selection of new PGSs, we referred to the construction of 15-min community life circle in Urban residential area planning and design standards (GB50180-2018). Taking 15 min as the time threshold, the accessibility of each aggregated point to the PGSs was calculated by walking (Figure 3c) with speed 5 km/h.

Then, the places that cannot reach the PGSs within 15 min were identified based on the spatial accessibility of the existing PGSs. Meanwhile, the hexagonal grids within the 3rd ring road were transformed into centroid points as the potential candidate locations for new PGSs. The grid centroids that containing large lakes, rivers and existing PGSs were removed to avoid the irrationality of site selection and the destruction of ecological protection areas.

Finally, the MCLP model under the location-allocation module in the network analysis tool of ArcGIS 10.3 software was used to realize the selection of the locations of new PGSs for fully covering all aggregated points. It also could realize the complete coverage of aggregated points out of reach the PGSs within 15 min walking.

3.3.2. Parameters Setting of the GA Model

GA is a kind of algorithm based on animal behavior, which could achieve the multi-objective optimization of green space [35]. This study used a high-performance evolutionary algorithm toolbox, namely Geatpy (http://geatpy.com/index.php/home/ (accessed on 4 March 2023)), to achieve the optimal solution of the objective function. The strengthen elitist GA algorithm (SEGA) module is used to predict the area of new PGSs for the maximum equity in two objectives.

The specific parameters of the GA model are set as shown in the Table 1. The number of populations is 30 and the maximum number of iterations is 1000. According to the Standard for planning of urban green space (GB/T51346-2019), the required community park would be created under the condition of the 15-min community-life circle. The lower limit of the new PGS area is set to 10,000 m^2, and the upper limit of the new PGS area is set to 100,000 m^2. The dimension of each population is n − 1 ($\{S_1, S_2, \ldots, S_{n-1}\}$) (n is the number of new PGSs in the result of location-allocation model in the next section), then the remaining dimension $S_n = S - S_1 - S_2 - \ldots - S_{n-1}$ [48].

Table 1. Parameters setting of the GA model.

Parameter	Value
Number of populations	30
Maximum number of iterations	1000
Area range of new PGSs	10,000–100,000
Dimension of populations	n − 1

The constraint condition in the area optimization model of new PGS is the total area, which is the multiplication of the total population in the aggregated points without existing PGSs and the median accessibility of all aggregated points. The reason is that the accessibility values of PGSs may have a large degree of dispersion. The median represents the medium level of data, which is of greater practical significance in the calculation of the total area of all new PGSs in this study [49].

4. Results

4.1. Accessibility and Supply-Demand Balance Pattern of Exsisting PGSs

Figure 4a showed the spatial disparities of the accessibility of each hexagonal grid within the 3rd ring road of Wuhan. The grids with high PGS accessibility (>9.0000) accounted for 9.47% of the total grids, mainly distributed near the beach parks along the Yangtze River and the Hanjiang River, or around the East Lake Scenic Area and the 3rd Ring Road. The main reason is that the area of PGSs around these grids is large (more than 20 ha), and the population density is relatively low. The grids with a transitional level of PGS accessibility (3.0000~9.0000) accounted for 12.94% of the total grids, mainly distributed in Shahu Park, Shouyi Park, Yuehu-Guishan Scenic Area, Moshuihu Park, and around the city parks in Hankou. The population density of these residential grids is relatively large, but it is close to the PGSs. Therefore, the accessibility level of PGSs is maintained at a medium transition level. The grids with low accessibility (≤3.0000) accounted for 71.89% of the total grids. These grids were concentrated and contiguous, indicating that most communities in Wuhan have limited ability to obtain the services of PGSs within 15 min. The actual accessibility level in most grids is far lower than the per capita value of PGSs (14.82 m^2)

in 2021 announced by Wuhan Municipal Bureau of Garden and Forestry. Additionally, the residents in 298 hexagonal grids (18.70%) within the 3rd Ring Road cannot share the services of PGSs within 15 min. These grids are concentrated in Baishazhou, between Xiongchu Avenue and Luoyu Road, Guanggu-Guanshan Avenue, both sides of Hankou Railway and so on. The proportion of non-service areas is relatively large, indicating that the overall PGSs accessibility needed to be improved in Wuhan City.

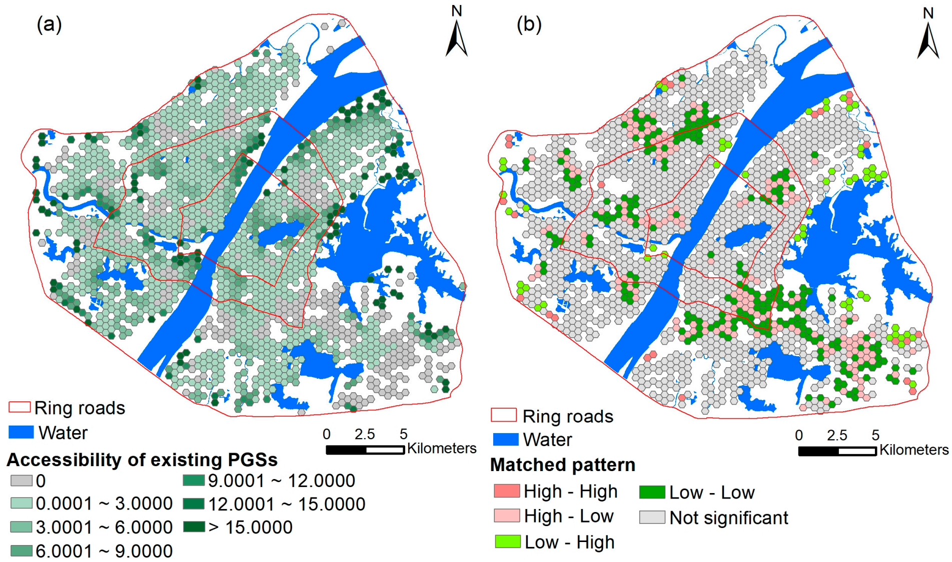

Figure 4. The spatial accessibility distributions of existing PGSs (**a**), and supply-demand balance pattern (**b**).

The Geoda software was further used to perform bivariate local Moran's I analysis on the demand (population) and supply level (accessibility of PGSs) in the hexagonal grids. The supply and demand balance pattern (p-value $\leq$ 0.05) in each hexagon is shown in Figure 4b. The high-high agglomeration indicated that the supply of PGSs and population demand were both in high levels, which belonged to the high balance; the high-low agglomeration indicated a higher population demand but a lower supply, which presented a serious imbalance; low-high agglomeration indicated "oversupply" that fewer people had access to more services of PGSs; and low-low agglomeration showed low levels both in the supply of PGSs and population demand, which suggested low balance. As shown in Figure 4b, 71.13% grids showed a balance between the supply and demand within the 3rd ring road of Wuhan, but the high-low agglomeration grids accounts for 10.79%. This indicated that the level of services of PGSs would be strengthened in these places. So it is necessary to optimize the spatial distribution of the PGSs within the 3rd ring road of Wuhan. That means not only constructing new PGSs to solve the problem that some grids lack services of PGSs within 15 min but also coordinating the balance between supply and demand.

4.2. Determination and Analysis of New PGSs

This section determines the location of the new PGSs by using the MCLP model under the location-allocation module in the network analysis tool of ArcGIS 10.3 software. The entrances of the existing PGSs are selected as the required points, and then the hexagonal grids within the 3rd ring road are constructed and transformed into the centroid points. After removing the centroid points including the existing PGSs and water, the remaining points are used as candidate points for the new PGSs. The threshold time under the MCLP model is controlled at 15 min. By gradually increasing the number of required facilities to the model, the pre-optimization speed is very fast. For example, 10 new PGSs for the first time adding have increased the PGSs accessibility of 124 aggregation points shown in

Figure 5. When the number of new PGSs reaches 60, the number of aggregation points with green space accessibility has reached 1591. Therefore, after the new PGSs reaches 60, the simulation result needs to be viewed every time a new PGS is added. Finally, 64 new PGSs are obtained, which can meet the maximum coverage of all residential aggregation points within the 3rd ring road (see Figure 6a). Figure 6b showed the impact of the new PGS locations on the travel distance of residents. The travel distance cost of 476 aggregation points reduced, and the aggregation points with a significant decrease in travel distance are around Guanggu-Guanshan Avenue, concentrated in area between Xiongchu Avenue and Luoyu Road. The highest decline was more than 2000 m, which effectively solved the lack of the services of PGSs in these places within 15 min. After the location optimization, it effectively controlled the visible service blind spots.

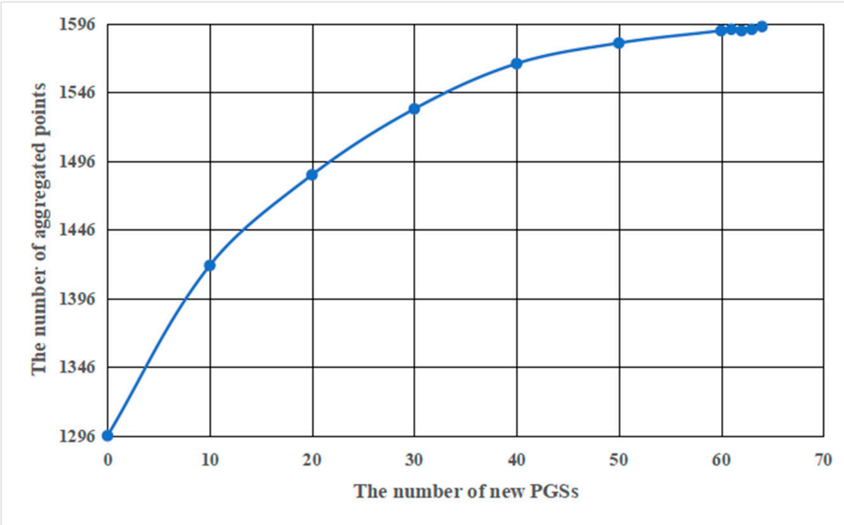

Figure 5. The relationship between the number of new PGSs and the number of covered aggregation points.

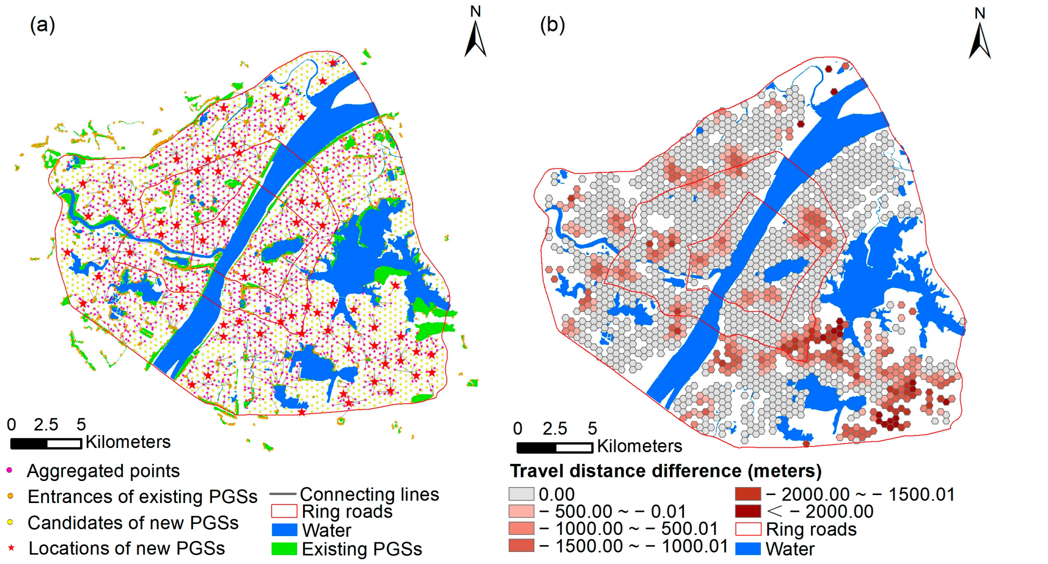

Figure 6. The results of new PGSs location (**a**), and travel distance difference before and after optimization (**b**).

4.3. Area Optimization Results and Analysis

4.3.1. Model Iterations and Final Results

Figure 7 shows the whole process of optimization iteration of two spatial equity model. The convergence speed of the minimum SD in accessibility (Objective 1) is very fast. After

400 iterations, the value of standard deviation gradually tends to be stable. However, the convergence speed of the minimum CG in accessibility (Objective 2) is relatively slow, and the value of CG has been in a downward trend till 800 iterations. After 800 iterations, there is a steady trend of objective 2. From the convergence process, the optimization speed of objective 1 will be faster than that of objective 2, but it does not mean that the results of objective 1 will be better than objective 2.

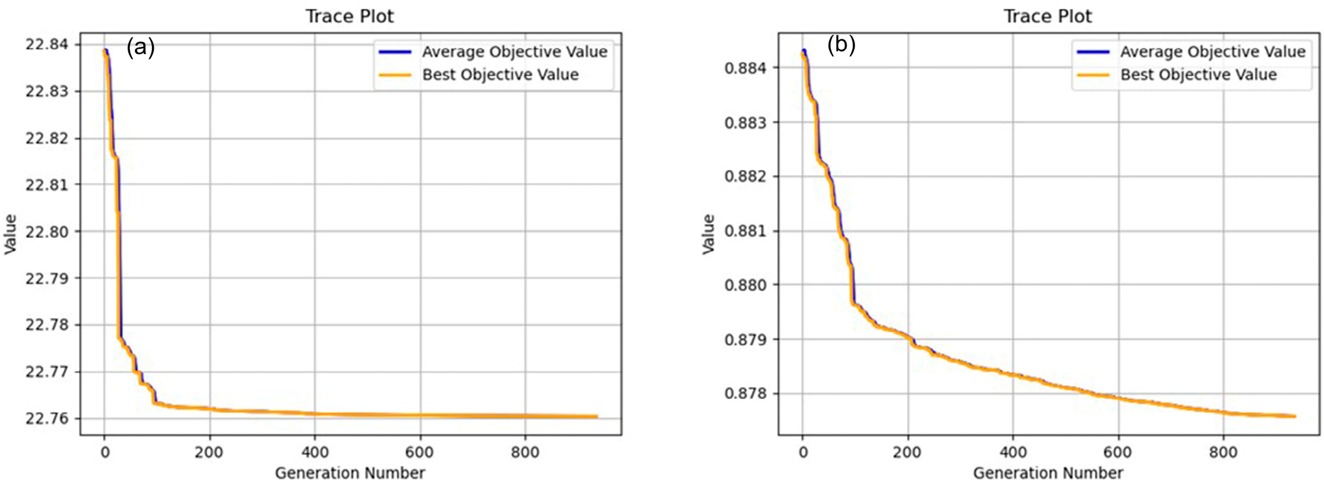

Figure 7. The iteration results of objective 1 (**a**), and objective 2 (**b**).

From the results of area optimization, it shows that the optimization results of the two MAE objectives are different (Figure 8). For example, the area of new PGSs No. 3, No. 10, No. 25, No. 27, No. 50, No. 52 and No. 60 in objective 1 is much larger than that in objective 2. The area of new PGSs No. 17, No. 22, No. 39, No. 43, No. 53, No. 56 and No. 59 in objective 2 is much larger than that in objective 1. At the same time, it can be seen that the new PGSs No. 1, No. 2, No. 13, No. 16, No. 19, No. 23, No. 35, No. 36, No. 37, No. 48, No. 54, No. 57, No. 62 and No. 63 take the lower limit of community park area set in both objectives, indicating that the actual construction area of these PGSs may be lower than the lower limit of area.

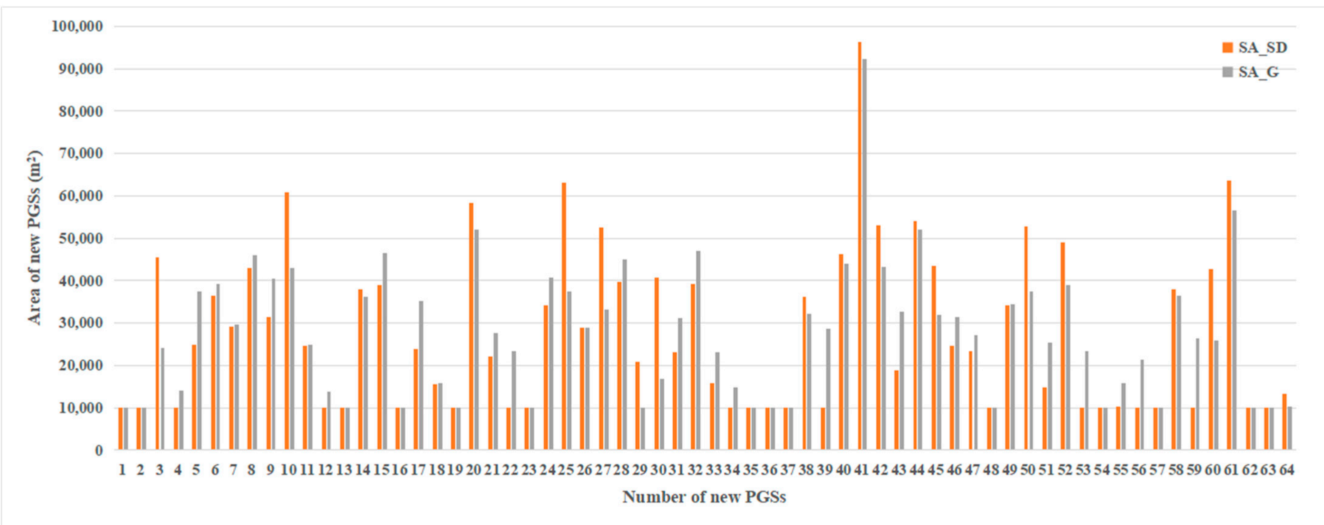

Figure 8. The area of new PGSs under the two MAE objectives (note: SA_SD is the area of new PGSs under the objective 1, SA_G is the area of new PGSs under the objective 2).

4.3.2. Optimized Spatial Distribution of PGSs Accessibility

Figure A1 shows the spatial distribution characteristics of park green space accessibility under the two optimal objectives. It can be seen that the grids without services of PGSs before optimization have PGS accessibility. However, the spatial disparities of accessibility under the two optimal objectives cannot be seen in Figure A1, and the coincidence degree between the two objectives is extremely high. The statistical results (Table 2) also confirm that it is almost difficult to have difference levels of accessibility in the two optimal objectives. Therefore, further difference analysis of the results is needed to determine whether the two models are truly different. Figure A2 shows the spatial distribution of the accessibility difference between the two objectives before and after optimization. It can be seen that in objective 2, the accessibility around Xiongchu Avenue-Luoyu Road, south of Mengzehu Park, and Baishazhou is significantly higher than that of objective 1. The statistical results (Table 3) also confirm that the grids with a higher level of accessibility improvement (Value > 1.0000) in objective 2 accounts for a higher proportion than objective 1. These indicate that the accessibility optimization results obtained with the CG as the optimization objective may be more impressive.

Table 2. Statistics of the number of grids in different grade intervals of PGSs accessibility before and after optimization.

Value of PGSs Accessibility	Ai	Ai_SD	Ai_G
less than 3.0000	1146	1138	1137
3.0000~6.0000	206	209	209
6.0001~9.0000	91	92	93
9.0001~12.0000	44	45	45
12.0001~15.0000	26	27	27
>15.0000	81	83	83

Note: Ai is the PGS accessibility of existing PGSs; Ai_SD is the PGSs accessibility of optimal objective 1; Ai_G is the PGS accessibility of optimal objective 2.

Table 3. Statistics of the number of grids in different grade intervals of accessibility difference before and after optimization.

Value of Difference	D_SD	D_G
0.0001~0.5000	390	396
0.5001~1.0000	165	177
1.0001~2.0000	88	72
2.0001~4.0000	3	1
>4.0000	7	7

Note: The grids without changing in PGS accessibility were excluded. D_SD is the difference of PGS accessibility between existing PGSs and optimal objective 1; D_G is the difference of PGS accessibility between existing PGSs and optimal objective 2.

In addition to analyzing the spatial distribution characteristics of PGS accessibility after optimization, the accessibility level of PGS between different ring roads before and after optimization is also analyzed from a statistical perspective (Figure 9). On the whole, the median accessibility and average accessibility have improved after optimization. The average accessibility of the existing PGSs is 8.5113, and the median is 1.0712; under the objective of minimizing the variance, the average accessibility is 8.7553, and the median is 1.3174. Under the objective of minimum CG, the average accessibility is 8.7660, and the median is 1.3556. On the whole, the objective of minimum CG can be obtained with better accessibility results than the objective of minimum SD, indicating that the objective of minimum CG can bring more services.

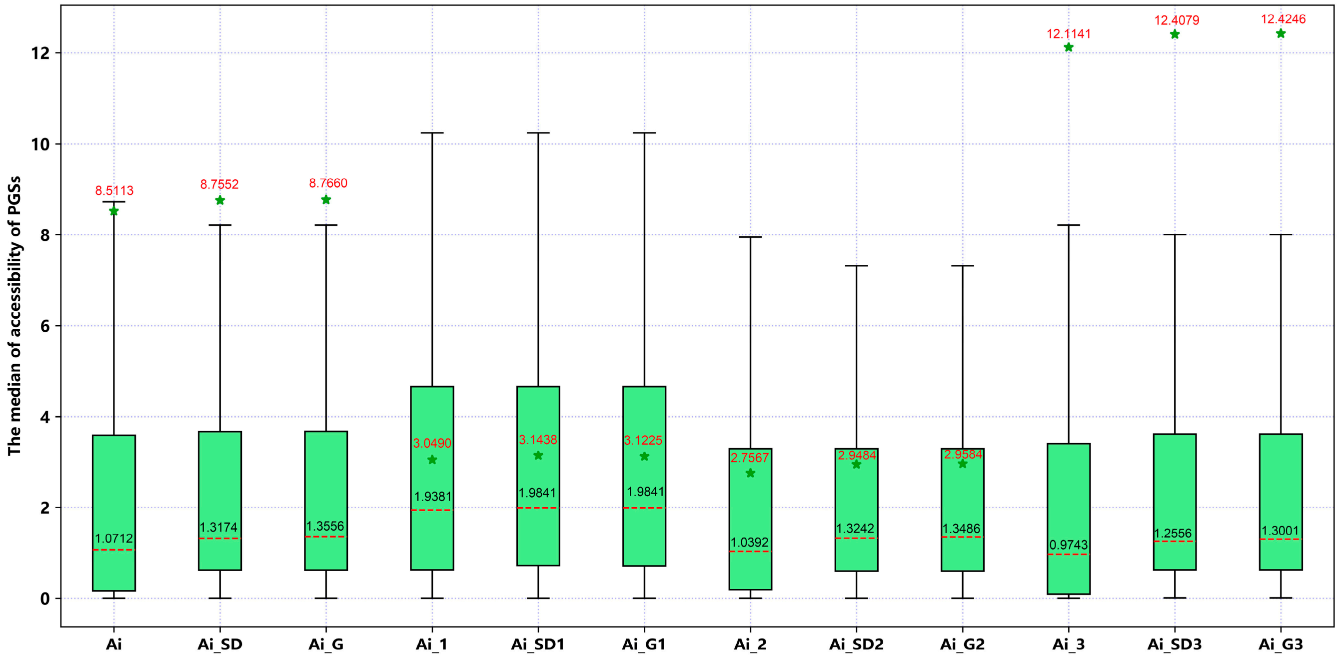

Figure 9. Boxplot of PGS accessibility before and after optimization (note: the star is the mean value of PGS accessibility, the dotted line is the median of PGS accessibility, Ai is the PGS accessibility before optimization, Ai_SD is the PGS accessibility of objective 1, Ai_G is the PGS accessibility of objective 2, and the numbers 1, 2 and 3 in the same name in the remaining X-axis labels represent the area within the 1st ring road, between 1st to 2nd ring roads, and between 2nd to 3rd ring roods respectively).

The average value of accessibility maintains a high level between the 2nd and 3rd ring roads. The average value of accessibility within the 1st ring road is higher than that between the 1st and 2nd ring roads. The average value shows an inverted U-shaped from city center to suburban, indicating that the population between the 1st and 2nd rings is large, but the green space resources are limited. Moreover, both optimization objectives have promoted the increase in the average and median accessibility of PGSs, indicating that the spatial accessibility brought by an optimal layout of PGSs is more obvious. It is worth noting that the average accessibility of objective 1 within the 1st ring road is slightly larger than the average accessibility of objective 2, but the median is balanced; between the 1st and 2nd ring roads, and between the 2nd and 3rd ring roads, the average accessibility and median accessibility of objective 2 are greater than the model, indicating that CG is superior to SD in dealing with local and global spatial equity.

4.3.3. Disparities of Spatial Equity

This section compares the real equity of the two MAE objectives. Firstly, the population-accessibility (supply-demand) balance models of the two objectives before and after optimization are compared (see Table 4). Under objective 1, 74.81% of the total grids is in supply-demand balance, and the proportion of the grids with high-low agglomeration decreases to 10.34%. It is worth noting that objective 1 has a significant impact on grids with low-low agglomeration, which is reduced by 3.11%, effectively reducing low-supply grids. However, the objective 2 only makes 73.54% of the grids in supply-demand balance, but the proportion of grids with high-low aggregation is 11.1%, which is 0.31% higher than that before optimization, indicating that the minimum CG objective slightly increases the grids in serious supply-demand imbalance.

Table 4. Statistics of the supply-demand balance pattern before and after optimization.

Balance Pattern	Before Optimization	Objective 1	Objective 2
High-High	1.46%	1.40%	1.40%
High-Low	10.79%	10.34%	11.10%
Low-High	3.49%	3.43%	3.43%
Low-Low	13.13%	10.02%	10.53%
Not significant	71.13%	74.81%	73.54%

Note: Some isolated aggregated points were automatically eliminated in the calculation of bivariate Moran' I, and 1576 aggregated points were retained.

In order to make the two MAE objectives comparable, the CG is also calculated for the minimum SD objective. The results are shown in Figure 10. Globally, the accessibility CG before optimization is 0.9036, and the accessibility CGs of objective 1 and objective 2 are 0.8778 and 0.8776, respectively. Locally, the CGs in the 1st ring road, between the 1st and 2nd ring roads, and between the 2nd and 3rd ring roads before optimization are 0.6346, 0.7190 and 0.9332, respectively. The CGs within the 1st ring road, between the 1st and 2nd ring roads, and between the 2nd and 3rd ring roads under the objective 1 are 0.6062, 0.6540 and 0.9128, respectively. The CGs within the 1st ring road, between the 1st and 2nd ring roads, and between the 2nd and 3rd ring roads under the objective 2 are 0.6135, 0.6538 and 0.9122, respectively. From the results, the equity of PGS accessibility within the 1st ring road is the highest, and there is a serious inequity between the supply and demand of PGSs between the 2nd and 3rd ring roads. From the difference between the average accessibility in Figure 9 and the actual CG, the imbalance between the supply and demand of PGSs between the 2nd and 3rd ring roads is the most obvious. PGSs with a large area account for a relatively high proportion, making resources concentrated and service coverage limited. From the figures of the Lorenz curves, the equity levels of the objective 1 and the objective 2 are comparable, and the difference is not very obvious. However, from the specific value, the objective of minimum CG still has a weak advantage.

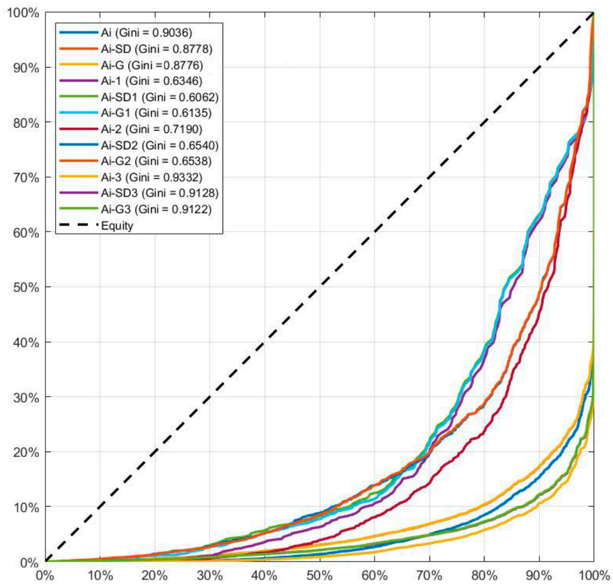

Figure 10. Comparison of CG before and after optimization.

5. Discussion

5.1. Advantages of the Improved Optimization Models

This study explores the optimal layout of PGSs under the objective of maximal accessibility equity. Standard variance (or variance) has been used as an objective for solving the MAE problem in optimizing the layout of healthcare facilities [6,36,38]. Meanwhile, the CG is widely used as an indicator to measure spatial equity in PGSs, but it is limited in its use as an objective to optimize the layout of PGSs. Compared with the previous optimization model, our study has the following two improvements: One is considering a higher number of PGSs. Results show that 18.70% of the total aggregated points without the enjoyment of PGS services within the 15-min threshold time, which means the realization of blind spots access to the PGSs is the premise of improving overall equity. Another is allocating the area of new PGSs rationally based on the existing PGSs, but not directly optimized the area of all the PGSs [36]. Furthermore, the planning and layout of PGSs is under strict control, and existing PGSs are generally not demolished and rebuilt due to their increased costs and negative social and ecological pressures.

The existing optimization modeling of green spaces is both similar and different from our research, but it also provides a new way of thinking for the objective of MAE. First, previous studies have effectively solved the problem of location selection but remain limited in the size for specific guidance planning of PGSs. For example, Neema et al. [35] used the GA model to select the location of new PGSs based on the suitability evaluation of six objectives, although the size of the PGSs was given according to fixed standards (such as 300 acres for urban parks and 500 acres for local parks). Second, some studies used grid units as land use units. After determining the location of parks, grid area represents the planning and construction scale of green space. Although the grid unit operation is simple, this leads to a large number of isolated grids in the optimization [50]. The selection scheme brought by grid cells presents exponential growth, which will also reduce the overall computing speed of the algorithm [34,51]. Unlike the traditional square grid, the center of mass of the hexagonal grid we adopted is the same distance from each adjacent region [52]. Meanwhile, the grids were only used in the site selection of park green space and the aggregation of communities in our study, and the PGSs are still the actual area reasonably allocated from the perspective of supply and demand. Third, some of existing studies exploring the equity objective of PGS optimization also provide some inspiration for the study. Wu et al. [43] and Li et al. [44] introduced the CG into the optimal layout of green spaces to achieve the equity in supply and demand of green spaces, which coincides with the current study's goals, but are more focused on the equity of residential green space and UGSs. Until now, there has been no study on PGSs. As public facilities planned by the government, the improvement of the overall spatial equity of PGSs seems to be more positive for the sustainable development of the city and the daily recreation of residents.

With the goal of MAE, the optimal layout of PGSs will still lead to the imbalance between supply and demand in some places. From the results of size optimization, the size of some new PGSs under the two objectives of MAE is equal to or close to the planning lower limit of the community park, indicating that the demand around these PGSs may be lower than the optimized PGSs services, referring to an "oversupply". Large PGSs will promote the green gentrification phenomenon, which indicates that having enough green space is more suitable, making it seem as if it is necessary to build smaller PGSs [53,54]. Therefore, our study only considered community parks with a size generally between 1~10 ha. Strictly limited size standards may lead to the emergence of oversupply in some places. Interestingly, we found a phenomenon on the balance of supply and demand: the CG objective not only achieved more aggregation points with a balance on supply and demand, but it also exacerbated the imbalance between the supply and demand of more aggregation points. When only considering equity, the change of PGSs accessibility is not always consistent with equity [43]. The construction of new PGSs promotes access to PGSs in blind spots, but indirectly leads to the inequitable distribution of PGSs in local regions, thus possibly aggravating the imbalance between supply and demand. More importantly, there remains a considerable number of hidden blind spots in the city with an imbalance in the supply and demand of PGSs. The median of accessibility in this paper is far lower than the mean of accessibility, meaning that more than half of the aggregation points have not reached the rational allocation of supply and demand. Therefore, it is not enough to achieve the goal of MAE from the optimal layout of PGSs. The imperfect traffic network may hinder residents from accessing to the PGSs, thus improving the traffic network has positive significance in helping realize PGS accessibility [9,27]. We consider the optimization of community parks in the context of the 15-min community life circle, although some PGSs are more than 10 ha. The actual service radius level of these PGSs was ignored, and the step-by-step optimization considering hierarchical characteristics of PGSs in the optimization process seems to be more feasible [55].

Notably, the CG better presents the realization of the MAE of PGSs. The SD value decreases slightly under the objective of minimum SD. The standard deviation of accessibility before optimization is more than 3 times the value after optimization of medical facilities resources in previous studies [36,48]. Meanwhile, in the application of the 2SO model, the change of accessibility standard deviation is obviously limited. Luo et al.'s study [38] showed that the standard deviation of accessibility before and after optimization is 0.5695 and 0.5656 respectively, which coincides with our study. This shows a significant difference between the reallocation of existing resources and the 2SO model in realizing MAE. Owing to the fixed capacity of existing public facilities including green space, the 2SO model is more suitable for realistic planning. Under the objective of CG, the CGs before and after optimization are 0.9036 and 0.8776, respectively. A study on the spatial optimization layout of UGSs with similar background found that its CG decreased from 0.6760 in 2019 to 0.6263 in 2025, indicating that the objective of CG can meet the optimal layout of green space in the central area of Wuhan City for short-term planning [44]. More importantly, by comparing the optimization results of both MEA objectives, we found that the minimum CG objective still has a significant downward trend after the optimization iteration process is completed, and the optimization convergence process is also longer. Compared with the minimum SD objective, the ratio of the CG in the grids with a higher level of accessibility improvement (difference value > 1.0000) (15.01%) is higher than that of the minimum variance model (12.25%), and the overall accessibility median is 0.0445 more. Moreover, except for the area within the 1st ring road, the equity of the minimum CG objective is higher than that of the minimum SD objective. This shows that the CG, as a MAE objective, has certain advantages in the study of PGSs optimization.

5.2. Implications and Limitations

Our results provide the following suggestions for the future planning of PGSs: First, accurately identify accessibility blind spots and build a corresponding number and capacity of PGSs by primarily ensuring the accessibility of demand. For example, accessibility blind spots within the 3rd ring road of Wuhan are mainly concentrated between the 2nd and 3rd ring roads, which is different from the relevant results of other cities, but it is nonetheless consistent with the relevant study of Wuhan [48,56]. This is because these areas have many colleges and universities and government agencies. The developed railway transportation has caused the separation between urban green space and demand points. Meanwhile, the average accessibility and median accessibility in these places are significantly different, indicating that PGSs should be decentralized to avoid excessive concentration of the PGSs. Second, it is suggested to pay attention to the park location and scale configuration in future planning. Currently, actual city planning does not consider the actual supply and demand to configure the scale of the PGSs, instead often paying more attention to the location of the park for regional development [34,50,51]. This does not guarantee the actual use efficiency of residents and it also aggravates the inequity of PGS accessibility in different regions. Third, using a reasonable plan for the needs of different regions to carry out accurate location selection and capacity is recommended when considering optimization of PGSs. Our study has confirmed that prioritizing the improvement of equity does not mean that accessibility can also be improved. Simultaneously, it is a more accurate and effective way to identify the place where the accessibility and equity of PGSs are inconsistent, and to allocate the PGSs of different schemes accordingly.

This study has some limitations which need further improvement: The first is trading off the "social-economic-ecological" multi-objectives to achieve the equity of PGSs. Although this study realizes the optimal layout of PGSs under the objective of MAE, it is still a single-objective model. Some studies have focused on the cost of green space construction and its impact on housing prices [22,44]. Besides, most of the optimized layout of green spaces have considered ecological benefits [34,50,51]. The balance of "social-economic-ecological" multi-objectives provides more choices and references for urban planners in planning PGSs. A second opportunity for improvement is combining the data form of "big data" and questionnaire survey to achieve a more reasonable measurement in accessibility. Some web maps provide API services where users can enter the origin and destination to obtain the shortest travel route [57]. Moreover, mobile phone signaling data can provide specific trajectories of PGS visitors, which helps identify the service radius of PGSs [58,59]. Questionnaire survey data can help obtain the population attributes, behavior characteristics, and preferences of PGS tourists, thus helping improve the accessibility measurement indicators and optimize the reasonable setting of objectives [60]. Third, hidden blind spots should be considered in the optimization of layout. A considerable number of grids with PGS accessibility lower than 3.0000 existed in this study, which are also the places with low supply. Moreover, grids with PGS accessibility lower than the median (excluding grids without accessibility) are hidden blind spots. These places are neglected in the actual optimization process and should therefore be areas of concern in future studies.

6. Conclusions

With rapid urbanization, the agglomeration of urban populations has caused inequity in the supply and demand of PGSs. Since then, the goal of focusing on per capita indicators and total area of PGSs in the urban planning in China has been divorced from the actual demand of residents, and thus cannot properly solve the MAE problem of PGSs. Therefore, it is very important to explore a reasonable and scientific model for PGS optimization to solve the inequity in the supply and demand of PGSs. Based on the 2SO model, this paper maximized accessibility equity through location and size optimization. By comparing the minimum SD and the minimum CG models, the model suitable for realizing the MAE of PGSs was selected. Our findings confirmed the feasibility of the 2SO model in optimizing the layout of PGSs. The size optimization based on location selection both retains the existing PGSs and meets the objective of MAE. The model results have high reliability and simple operation and have certain applicability to the optimization of park green space in other cities. Comparing the results of the two MAE objectives shows that CG is more suitable for achieving the MAE of PGSs and has more advantages in improving the overall accessibility. Our study suggests that 64 community parks need to be built in Wuhan to achieve the accessibility of the whole study area, although there is also an oversupply of PGSs services in some places. While it can achieve higher overall equity under the objective of minimum CG, it places more places in a supply-demand imbalance, which needs further attention from urban planners. While considering the overall equity of PGS accessibility, the construction of PGSs still needs to achieve local equity from other perspectives, including improvement of urban road network and dispersion of PGS layout. Furthermore, it is feasible for urban planners to use the CG for the spatial optimization of other facilities. However, it should be clear that some limitations of this study need further exploration, such as the balance of multi-objectives, and that equity is only one of the references for formulating planning policies.

Author Contributions: Conceptualization, L.X.; methodology, L.M. and L.X.; software, L.M.; validation, Y.J.; formal analysis, L.M.; investigation, Q.H.; data acquisition and processing, L.M. and Q.H.; writing—original draft preparation, L.M. and L.X.; writing—review and editing, Y.J. and L.X.; visualization, L.M.; supervision, L.X.; project administration, L.X.; funding acquisition, L.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Education, Humanities, and Social Science Fund of China, grant number 21YJCZH185; the National Natural Science Foundation of China, grant number 42201214; and the Open Foundation of Key Laboratory of Regional Development and Environmental Response of Hubei Province, grant number 2022(A) 001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not available.

Acknowledgments: The authors would like to give sincere thanks to all the research participants. The authors also wish to express their appreciation to the editors and reviewers for their insightful comments and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

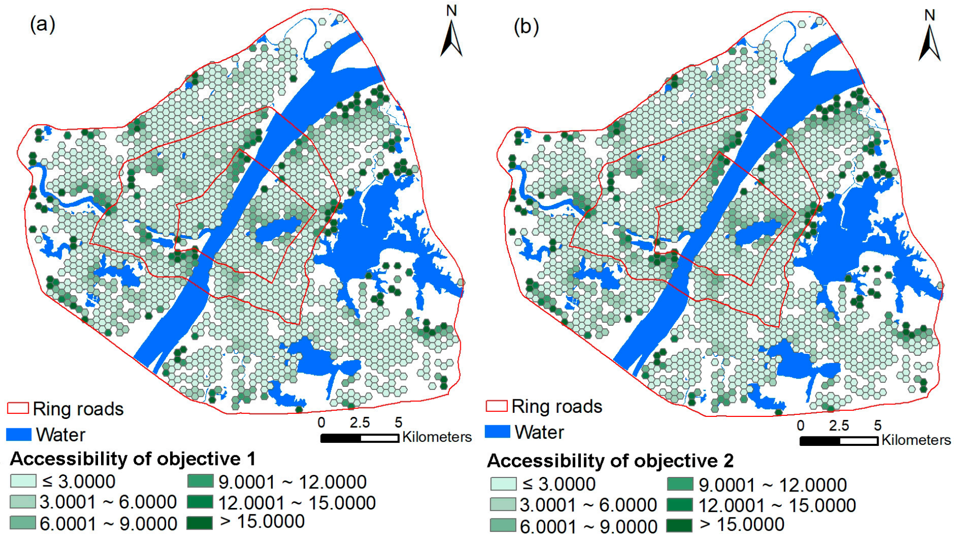

Figure A1. The PGSs accessibility of objective1 (**a**), and objective 2 (**b**).

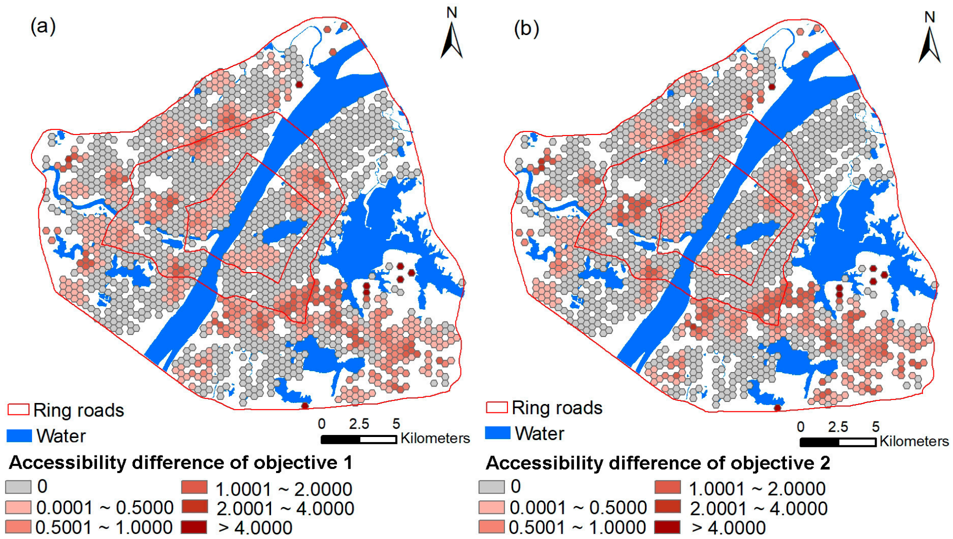

Figure A2. The accessibility difference before and after optimization of objective1 (**a**), and objective 2 (**b**).

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