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Evaluation and Promotion of the Service Capacity of Urban Public Open Spaces Based on Improving Accessibility: A Case Study of Shenyang City, China

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Abstract: The service capacity of urban public open spaces is an important indicator of the justness and soundness of the allocation of public space resources, such as parks and green spaces, in the process of urban development. Improving the service capacity of urban public open spaces is conductive to healthy, sustainable urban development. In this study, taking Shengyang City, China as a case study, a Gaussian-based two-step floating catchment area method (2SFCA) is used to calculate an accessibility index and identify residential areas with a poor accessibility to urban public open spaces. Then, a particle swarm algorithm (PSA) is used to optimize the locations of new open space developments. Finally, the optimization results are verified using the analytic network process (ANP). The results show that the service capacity of public open spaces in the center of Shenyang City (covering six districts) is relatively low and exhibits an uneven spatial distribution. In the service scope of the existing urban public open spaces, the accessibility for 48.6% of the residential estates is moderately poor or poor. The layout is optimized when the number of optimization points is set to 8. These points are mainly located in old town areas such as the Tiexi, Huanggu, and Dadong districts. The optimization increases the green space area accessible by motor vehicles (60 min), bicycles (60 min), and walking (30 min) by 4.67%, 5.38%, and 8.03% of the study area, respectively. Finally, green space planning recommendations are offered from two perspectives: spatial layout and transport system optimization.

Keywords: urban public open space; accessibility; Gaussian-based two-step floating catchment area method (2SFCA); particle swarm algorithm (PSA); Shenyang City

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1 Introduction

In the past three decades, the construction and development of urban public open spaces in China has made cities greener, providing urban residents with spaces for everyday outdoor activities and alleviating the stress brought about by high-density urban development (Chen and Qiu, 2019). However, in the urbanization process, the importance of urban public spaces was easily neglected, and their area was compressed. Under this background, some urban public spaces are facing the risk of privatization, challenging the ‘public’ nature of public spaces. This is compounded by the noninvolvement of users in the traditional administration model and the unclear definition of the real service capacity of public open spaces in relevant standards, resulting in the

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inappropriate allocation of resources, loss of green justice (Geng et al., 2019), poor utilization of some urban public spaces, and insufficient provision of a comfortable living experience for urban residents.

Foreign scholars introduced spatial accessibility into the public service domain and have conducted an abundance of empirical studies on urban public service facilities, such as education facilities (Talen, 2001), medical resources (McGrail, 2012; Wan et al., 2012; Deborah et al., 2018; Naylor et al., 2019), sports venues (Higgs et al., 2015), and public green spaces (La Rosa, 2014; Wolch et al., 2014). In the existing research, there are three main methods commonly used for investigating the accessibility of urban public open spaces: 1) the nearest neighbor method, in which the network or Euclidean distance to the nearest green space is used to measure the accessibility (Comber et al., 2008; Kessel et al., 2009); 2) area-weighted proportion method, in which the total area of green spaces in individual subareas is used to estimate the accessibility (Potestio et al., 2009; Richardson et al., 2010); and 3) gravity model method, in which a gravity model is used to measure the attractivity of green spaces with respect to a subarea, and the sum of the activities is used as the measure of the green space accessibility for that subarea (Hillsdon et al., 2006). The first two methods assume that residents choose the nearest green spaces; however, residents do not make choices that way in real life. The third method considers the free choices by residents but does not consider the supply-demand relationship between green spaces and populations (Wu et al., 2020a).

To overcome the limitations of these methods, Dai (2011) introduced a Gaussian-based two-step floating catchment area (2SFCA) method into the evaluation of the green space accessibility in metropolitan Atlanta, United States, and achieved satisfactory results (Dai, 2011). The 2SFCA method, which is an improved version of the floating catchment area (FCA) method, effectively handles the scenario in which the supply-demand distance in the spatial scope of the FCA may be greater than the preset distance or in which the facilities in the spatial scope do not serve needs exclusively in the spatial scope (Luo and Qi, 2009; Dai, 2010). Therefore, the 2SFCA is more practical, as it considers not only the availability of public open spaces in the periphery of individual communities but also the needs of the populations of the neighboring communities. It is thus of greater practical significance to the urban public open space accessibility investigated in this study.

In this study, based on the needs of residents for everyday walking activities, a 2SFCA method is used to analyze the current service capacity of urban public open spaces in Shenyang, China, correctly evaluate the accessibility for the communities, and identify areas with insufficient public open space. Then, the optimal sites for new park developments are determined. This study provides a reference for reconstructing urban public spaces, enhancing the environmental quality of public spaces, and improving residential comfort.

2 Materials and Methods

2.1 Study area

Shenyang is a core city in Northeast China and a core city of the Shenyang Economic Circle. Its urban public open spaces have both research and reference values (Wu et al., 2020b). In this study, recreational urban public open spaces (Comber et al., 2008) were selected, which are primarily urban parks, plazas, community parks, and some large residential estate-level parks and green spaces. This study took the center of Shenyang City as the study area (123°18′E–123°48′E, 41°36′N–41°57′N). The following six districts defined in the Shenyang City Master Plan (2011–2020) (Shenyang Municipal People’s Government, 2017) were selected: Huanggu, Dadong, Tiexi, Shenhe, Heping, and Hunnan. These six districts have higher population densities and are facing a more severe crisis of green equity.

During the past decade, Shenyang showed a steady trend of development and expansion, driven by policies such as ‘Revitalizing the Old Industrial Base in Northeast China’ and ‘Building the Shenyang Economic Zone’, as indicated by the transformation of the Tiexi District and the development of the Hunnan New District. In addition, a large-scale transformation of urban interior space has been implemented, resulting in the continuous expansion of the urban impervious surface area.

2.2 Data sources and pretreatment

2.2.1 Data of urban public open spaces

According to the current code for the classification of urban public open spaces and the needs of this study, data of the urban public open spaces were thoroughly interpreted using Landsat-8 satellite imagery in 2018. The sets of images with a 15 m spatial resolution were derived from the United States Geological Survey (USGS, https://www.usgs.gov/) (Wu et al., 2021). The urban public open space classification was verified with investigations in the field, showing an interpretation accuracy of 85%. This is acceptable for use as a data source in our study. Considering the recreational nature of urban public open spaces, those with an area smaller than 0.1 ha or a width less than 15 m were not included. Fig. 1 shows the distribution of the public open spaces in the study area.

2.2.2 Other data

This study also used data of urban road networks and populations of communities in Shenyang City. Road networks data were obtained from Open Street Map and were vectorized and modified according to Google Earth v.7.3.3. Population density distribution data with a 100 m resolution were generated using a random forest model based on the inversion of 2018 nighttime light data of Shenyang City by Ye et al., (2019), which were used in this study. Because parks and green spaces in the study area serve an area larger than the study area, population data covering an area larger than the study area were collected. Data of the geographical locations of communities were verified using the point-of-interest (POIs) data of the Baidu Map Open Platform. Based on the data mentioned above, in our study area, there are

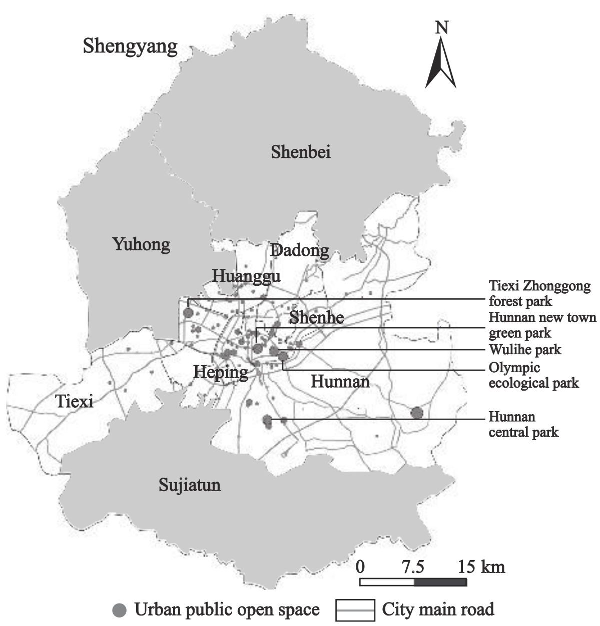

Fig. 1 Distribution of public open spaces in the center of Shenyang City

totally 52 subdistricts, 126 urban public open spaces (including residential estate-level public open spaces), and 2826 residential communities.

2.3 Methods

2.3.1 2SFCA method

The service capacity of the existing urban public open spaces was analyzed using the 2SFCA method. The accessibility for the residential estates in the service scope was rated using the natural break method provided in ArcGIS 10.2 (ESRI INC, 2013), thereby identifying residential estates with poor accessibility in the service scope. Next, the residential estates with poor accessibility in the service scope of the existing urban public open spaces were counted, and the optimal number of clustering points was determined through repeated trials. The 2SFCA method-based accessibility evaluation involved two steps (Dai, 2011).

Step 1: The spatial scope for a point of provision (an urban public open space) j was defined as a circular area with the point of provision as the center and a preset radius d_0. The numbers of residents at the points of need (communities) k in the spatial scope were searched and weighted according to the distance between the points of provision and need using a Gaussian equation. The weighted numbers of residents (potential demanders) were summed, and then the ratio of the size of the point of provision to the sum number of residents R_j was calculated, as shown in Equation (1):

$$R_j = \frac{S_j}{\sum_{k \in \{d_{kj} \le d_0\}} |D_k \times g(d_{ki})} \tag{1}$$

where S_j is the service capacity of the j-th urban public open space and is expressed as the area of the available open space; D_k is the number of residents in the k-th community in the search area ($d_{kj} \le d_0$); d_{kj} is the spatial distance between the j-th urban public open space and the k-th community in the search area; and g (d_{kj}, d_0) is a distance decay function, as shown in Equation (2):

$$g\left(d_{kj}, d_0\right) = \begin{cases} \frac{e^{-\left(\frac{1}{2}\right)\cdot\left(\frac{d_{kj}}{d_0}\right)^2} - e^{-\left(\frac{1}{2}\right)}}{1 - e^{-\left(\frac{1}{2}\right)}}, d_{kj} \le d_0 \\ 0 \qquad\qquad\qquad\quad , d_{kj} > d_0 \end{cases} \tag{2}$$

Step 2: A spatial scope was established with a point of need i as the search center and a preset search radius. All points of provision h in the spatial scope were searched and weighted according to the spatial distance between the points of provision and need using a Gaussian equation. The weighted ratios of the size of the point of provision to the size of the population R_j were summed to obtain the accessibility for the i-th point of need A_i^F, as shown in Equation (3):

$$A_i^F = \sum_{k \in \{d_{ih} \leq d_0\}} g(d_{ih}) \cdot R_j \tag{3}$$

where d_{ih} is the spatial distance between the i-th community and the h-th urban public open space in the i-th search area and R_j is the supply-demand ratio for the h-th urban public open space in the i-th search area ($d_{kj} \leq d_0$). According to the calculation process of the equation, the value of A_i^F can be understood as the weighting-based area of urban public open space per capita, which is the accessibility: a larger value of A_i^F indicates a greater urban public open space accessibility for the i-th community.

An appropriate service radius is an important basis for planning and layout (Zhai and Zhou, 2019). This study classified urban public open spaces according to their service radius (Table 1) by referencing the standards for the classification of urban public open spaces provided in the Standard for Classification of Urban Green Space (CJJ/T85-2017) and the Code for Urban Residential District Planning and Design (GB 50180-1993).

Considering the longest distance of resident walking travel and referencing the research results of Fan et al. (2017) on the mode of resident travel, residents were assumed to travel to community-level recreational spaces with a service radius of 300 m exclusively by walking and travel to regional-level recreational spaces with a service radius of 2000 m by walking (50% chance) or public transport (50%) (Fan et al., 2017). The search radius for Step 1 was set to 2 km, which was estimated based on an upper time limit of 30 min and a walking speed of 4.3 km/h.

Based on the '15-min living circle' plan, the travel distance is usually 800 to 1000 m. The search radius for Step 2 was set to 1 km, which was estimated based on an upper time limit of 15 min and a walking speed of 4.3 km/h. If the effect of the area of open spaces on their service capacity is not considered, the service capacity of small-area open spaces may very possibly be overestimated, biasing the results of Wei et al. (2016). Therefore, a distance decay function (at service radii of 500, 1000, and 2000 m) was used to account for the effect of the open space area (Ye et al., 2020). The effects of both the area and the decay distance of urban public open spaces were considered in this study, making the results more reasonable.

2.3.2 Particle swarm algorithm (PSA) method

The positions of the optimal clustering points, i.e., the locations of additional urban public open spaces planned for the future, was determined using the PSA in MATLAB R2018b (MathWorks, 2018). The PSA simulates the predation behavior of bird flocks. Its fundamental core is using the information sharing among the individuals of a flock to enable the movement of the entire flock to evolve from disordered to ordered in the problem-solving space, thereby obtaining the optimal solution of a problem (Kennedy and Eberhart, 1997). In this study, the process of populations choosing urban public open spaces was simulated by conceiving residential estates with poor accessibility as a flock of birds and urban public open spaces as food. In this simulation (Fig. 2), individual residential estates were referred to as particles. Each particle had an optimal fitness value that was determined by a function.

In the initial stage, the PSA generates a population of random particles (i.e., random solutions), and the optimal solution is obtained through iteration. At each step of the iteration, the particles update themselves by track-

Table 1 Service radius-based classification of urban public open spaces in Shenyang

Classification	Principal target population of service	Size (ha)	Service radius (m)	Accessibility by walking (m)
Comprehensive park	Urban residents	≥ 50	4000	2000
		[20–50)	3000	
		[10–20)	2000	
Community park	Community residents	[3–10)	1000	1000
		[1–3)	800	
Residential estate-level park	Residents in the residential estate	< 1	500	500

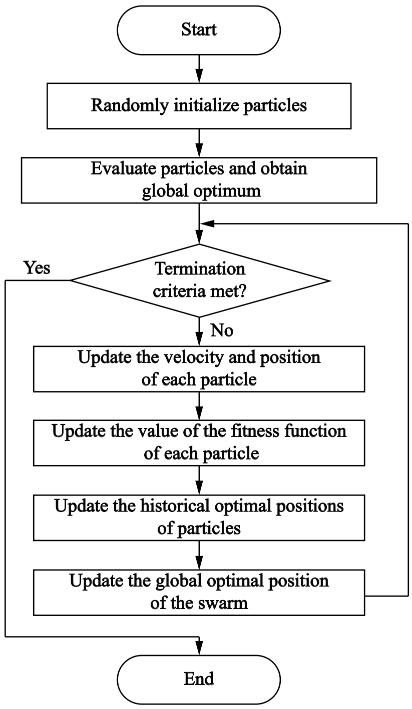

Fig. 2 Flow chart for particle swarm algorithm (PSA) in Shenyang

ing two extrema: 1) the historical optimal solution found by the individual particles, which is referred to as the individual extremum p_{best}, and 2) the historical optimal solution found by all particles in the entire domain, which is referred to as the global extremum g_{best}. The PSA uses Equation (3) to compute the positions of the optimization points (Shi and Eberhart, 1998):

$$v_i = \omega \times v_i + c_1 \times rand() \times \left(p_{best_i} - x_i\right) + c_2 \times rand() \times \left(g_{best_i} - x_i\right) \quad (4)$$

where i = 1, 2, 3,..., N; N is the total number of particles in the swarm; v_i is the velocity of the particles; *rand* () is a random number in the range of (0,1); x_i is the current position of the particles; c_1 and c_2 are learning factors, and $c_1 = c_2 = 2$; ω is an inertia factor that determines the capacity for global optimization; and v_{max} is the maximum value of v_i (larger than 0), where $v_i = v_{max}$ if v_i is larger than v_{max}.

2.3.3 Analytic network process (ANP) method

The ANP is widely used in accessibility evaluation (Xue et al., 2019) and was used to verify the optimization results in this study. Recreational public open spaces were defined as source points, urban road networks as chains, road junctions as nodes, and time spent on roads as resistance measurements. Table 2 shows the behavior configuration.

3 Results and Analysis

3.1 Accessibility rating

The results of the accessibility rating (Table 3) show that the proportions of urban public open spaces rated Good, Moderately Good, Average, Moderately Poor, and Poor were 16.4%, 2.9%, 10.4%, 26.2%, and 43.9%, respectively. According to the principle of calculation of the 2SFCA method, the urban public open space accessibility is, in effect, equal to the distance weighting-based area of urban public open space per capita. According to the Shenyang City Master Plan (2011–2020), the plan is to increase the area of parks and green spaces per capita to 12 m^2/person in 2020. However, the results showed that the urban public open space accessibility index for 48.6% (1374 of 2826) of the residential estates was lower than the planned level.

The public open space accessibility in the center of Shenyang City (covering six districts) exhibited an uneven spatial distribution and was relatively low. More specifically, high-accessibility residential estates were mainly distributed at the boundary between the Huanggu and Tiexi districts, along the Hunhe River, in the core area of the Hunnan New Town Green Park, and near the center of the Dadong District, forming three spatial clusters located in the western, southern, and central parts of the study area, respectively. The western and central clusters were large in size, whereas the

Table 2 Parameters for different modes of transport in Shenyang

Mode of transport		Speed / (km/h)	Time interval / min	Upper time limit / min	Node resistance / s
Walking		4.3	5	30	30
Bicycle		15	5	60	30
Motor vehicle	Arterial road	60	10	60	30
	Collector road	40			
	Frontage road	30			

Table 3 Urban public open space accessibility rating in Shenyang

Accessibility rating	Quantity	Proportion / %
Good (≥ 38.125)	466	16.4
Moderately good [27.380–38.125)	82	2.9
Average [16.636–27.380)	295	10.4
Moderately poor [5.892–16.636)	742	26.2
Poor (< 5.892)	1241	43.9

southern cluster was small, exhibiting an overall characteristic of high accessibility in core areas and low accessibility away from core areas. In particular, in the western cluster, there was the Tiexi Zhonggong Forest Park, which has a relatively large area. In the central cluster, there was the Wulihe Park and the Olympic Ecological Park, and in the southern cluster, there was the Hunnan Central Park. Therefore, the large green parks significantly impacted the urban public open space accessibility, and the accessibility tended to be higher for residential estates closer to the large parks and green spaces. The polarization characteristic of the green space accessibility above is consistent with research results on other metropolitan areas such as Shanghai (Wei et al., 2014; Cheng and Huang, 2020).

The low-accessibility residential estates were mainly distributed in an east-west area spanning from the eastern Tiexi District along the Huanggu District's southern border with the Heping District and an east-west area centering around Baita Street, forming two parallel spatial belts with different lengths. In the northern belt, there were many parks and green spaces; however, they were generally small. In addition, the large population densities in the old town areas resulted in an insufficient per-capita share and markedly low accessibility. The major cause underlying the spatial differentiation of the park accessibility was the mismatch between the populations and green spaces.

3.2 The number and location of optimization points

In the service capacity of the existing urban public open spaces, the accessibility was moderately poor or poor for 48.6% of the residential estates. Theoretically, the accessibility problem for these residential estates can be solved by adding a maximum of 82 urban public open spaces. The optimal number of additions was calculated using the *k*-mean clustering algorithm. The results showed that the appropriate number of additions fell in the range of 7 to 10.

Using the PSA method, optimization was performed with respect to the residential estates with an accessibility lower than 16.636 in the study area. The final results of repeated verifications in light of the actual particularities showed that the spatial layout of the additions was most reasonable when the number of optimization points was set to 8 (Fig. 3, Table 4).

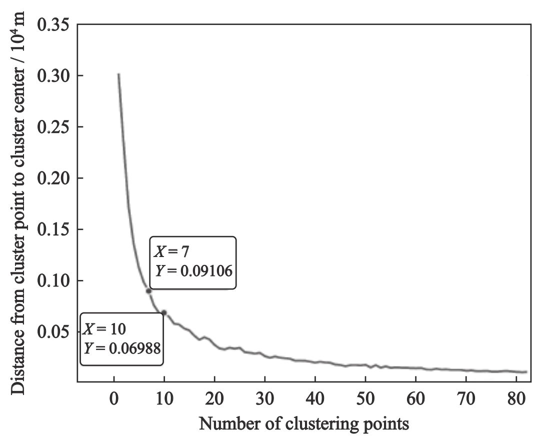

Fig. 3 Results yielded by *k*-mean clustering algorithm in Shenyang

Table 4 Location of optimization points for urban public open space in Shenyang

Optimization point	*X*-coordinate / °	*Y*-coordinate / °	Location
1	123.4702	41.7275	Near Zhenhai Hospital, Fumin Street, Hunnan District
2	123.4565	41.8269	Near Jixiao Alley, Dadong District
3	123.2615	41.7593	Near Fourth Street, Tiexi District
4	123.4622	41.8432	Near Yalu River East Street, Huanggu District
5	123.5156	41.8379	Near East Ertai Street, Dadong District
6	123.3942	41.7317	Near Xiudao Road, Hunnan District
7	123.5301	41.8169	Near Gaoguantai Street, Shenhe District
8	123.3818	41.7999	Near Xiaobei East Road, Tiexi District

The clustering points for the 1983 poor-accessibility residential estates (742 Moderately Poor and 1241 Poor) were optimized through an iterative search (Table 3). Such points are the historical optimal solutions of the accessibility for the surrounding residential estates. Fig. 4 shows the layout of the optimization points—6 and 2 for the northern and southern clusters of low-accessibility residential estates, respectively, bounded by the Hunhe River. More specifically, two of the optimization points are in the Dadong District, two in the Tiexi District, and one in each of the remaining four districts.

A field survey showed that within 300 m of optimization points 1, 3, 5, and 7, there were areas of undeveloped land that could be developed into new urban public open spaces. Optimization points 2 and 8 were in residential estates, with no land available for developing new urban public open spaces. However, Shenyang University was located within 300 m of point 2. Thus, the pressure from the lack of parks and green spaces in the vicinity of this point can be alleviated through open-campus development. The pressure from the lack of parks and green spaces in the vicinity of point 8 can be alleviated by developing new residential estate-level green parks. Optimization point 4 was located near a railroad. There was no large green space in the vicinity, but there were many small strip- or dot-shaped green parks. Hence, an option for the future is to improve the connectivity between these small green spaces and the surrounding residential estates.

The additional urban public open spaces yielded by the optimization are mainly distributed in old town areas such as the Tiexi, Huanggu, and Dadong Districts, which also indicates an overall insufficient provision of urban public open spaces in the current stage of urban construction and development, particularly in old town areas. The distribution of open spaces is characterized by a large number but small area in old town areas and a small number but large area in new town areas.

3.3 Verification results from the perspective of transport capability

The accuracy of the optimization results yielded by the algorithm was verified by analyzing how the service capacity of public open spaces varied with the mode of transport using the ANP. The modes of transport included motor vehicle, bicycle, and walking. For all modes of transport, the time spent for passing through a crosswalk, underpass, or overpass was set to 30 s, i.e.,

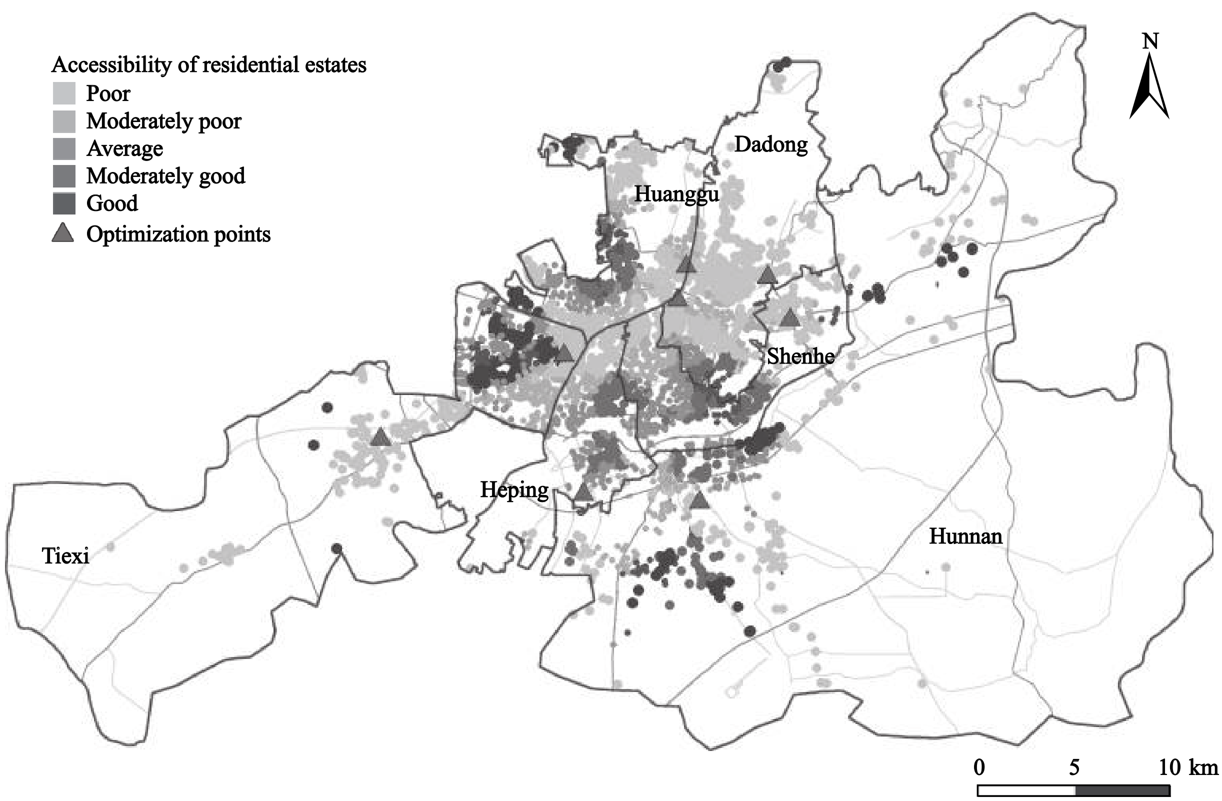

Fig. 4 Layout of optimization points in Shenyang

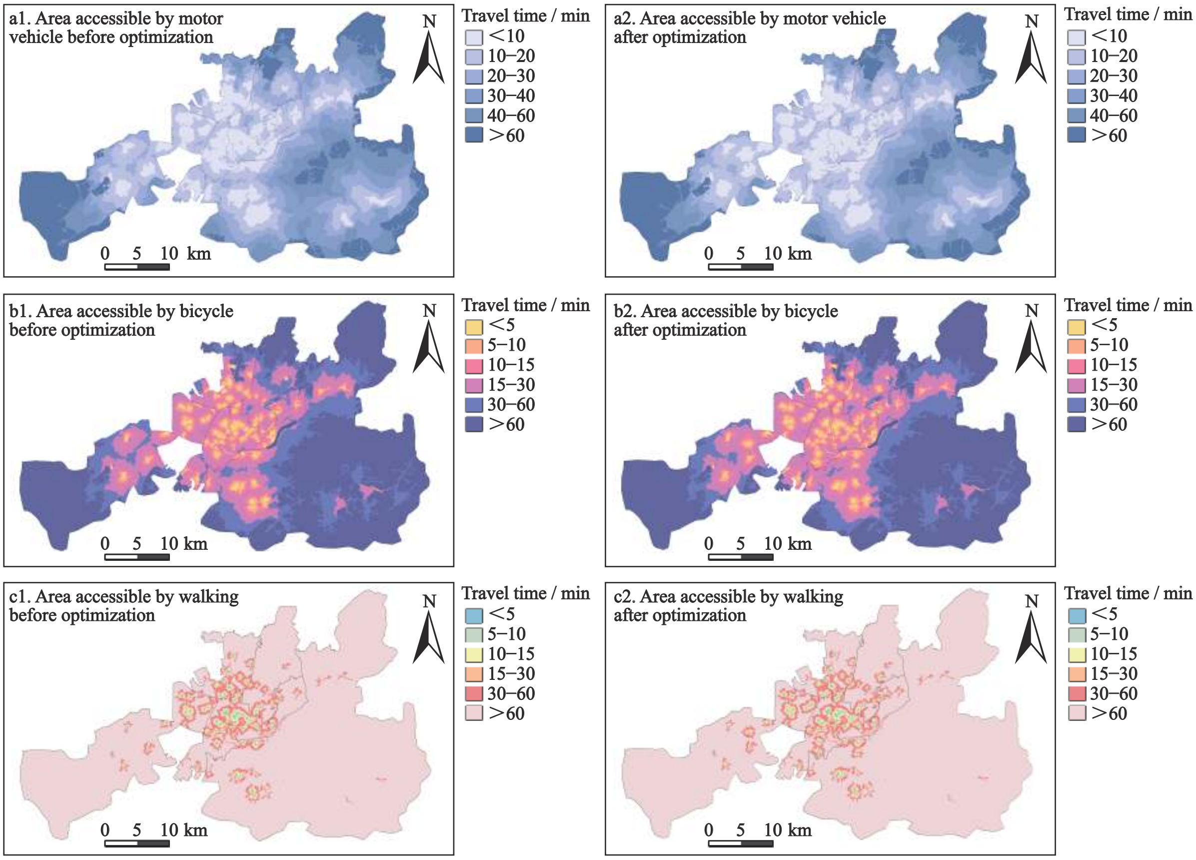

Fig. 5 Transport accessibility of three different modes of transport in Shenyang

the node resistance was set to 30 s. The results (Fig. 5) show that the urban public open space service ranges obtained for the three different modes of transport exhibit layer structures. Walking and bicycle travel have relatively invariant speeds and are not significantly affected by the road category; therefore, the corresponding service ranges exhibit relatively regular patterns. Motor vehicles are significantly affected by the road category, conditions, and intersections and have different speeds on different road sections; therefore, the corresponding service range exhibits an irregular pattern. Overall, the motor vehicle mode of transport has the largest service range, followed by those of bicycle and walking.

The longest travel distances within the upper time limit above for the three different modes of transport were calculated. The results (Table 5) show that an area of 1165.72 km^2 (88.91% of the study area) can be accessed within 60 min by motor vehicle before the optimization, and the optimization increases the area accessible within 60 min by motor vehicle by 4.67%. Bicycles can access an area of 380.03 km^2 (28.98% of the study area) in 60 min before the optimization, and the optimization increases the accessible area by 5.38%. Walking

Table 5 Proportions of accessible urban public open spaces before and after optimization in Shenyang

Motor vehicle / min	a1 / %	a2 / %	Bicycle / min	b1 / %	b2 / %	Walking / min	c1 / %	c2 / %
< 10	2.33	2.54	< 5	0.29	0.31	< 5	0.05	0.05
10–20	7.93	8.40	5–10	1.22	1.33	5–10	0.21	0.22
20–30	15.53	16.43	10–15	2.95	3.21	10–15	0.49	0.53
30–40	25.26	26.47	15–30	7.98	8.49	15–20	0.90	0.97
40–60	37.86	39.22	30–60	16.55	17.19	20–30	2.21	2.39
> 60	11.09	6.94	> 60	71.02	69.46	> 30	96.14	95.83

Note: See Fig. 5 for definitions of acronyms can access an area of 50.66 km^2 (3.86% of the study area) in 30 min before the optimization, and the optimization increases the accessible area by 8.03%. Overall, the optimization significantly improves the open space accessibility in the central Tiexi District, northeastern Shenhe District, and eastern Huanggu District and the area spanning from Baita Street, Hunnan New Area, to the Hunhe River.

The magnitudes of the change in the accessible area for the three different modes of transport were compared. The accessibility for 5 min of walking does not change, whereas that for motor vehicle travel increases by 0.21%. This is because walking has a low speed, and the accessible area in a shorter period of time is even smaller. Therefore, compared with developing more urban public open spaces at locations far from residential areas, improving the transport accessibility and public transport in the periphery of residential estates is more conducive to improving the urban public open space accessibility.

4 Discussion

4.1 Limitations of the modeling method

The modeling method used in this study considered the amount of available green spaces and the needs of populations. This consideration is critical. However, in the model, the size of the green spaces was used as the only indicator of their attractivity, whereas the actual situation was more complex. For example, the inertia of resident activities may affect the selection of green spaces. For cold-climate cities such as Shenyang, seasonal factors also have a major effect. For example, Wulihe Park is a relatively new riverside park with a variety of facilities and a good environment, but the number of visitors decreases sharply as the weather cools down. To address these factors, the model must be improved in the future (Jorgensen and Anthopoulou, 2007). For example, the carrying capacity of green spaces can be characterized using a comprehensive system of indicators rather than the green space area alone, or the number of residential estates with insufficient green space provision can be maximally reduced by converting low-efficiency industrial lands of appropriate sizes and locations into parks (Li et al., 2019). All these measures are subject to further quantitative investigation.

4.2 Optimization recommendations

This study applied the 2SFCA method to analyze the service capacity of urban public open spaces and adopted the PSA to optimize the site selection for urban public open spaces with low accessibility. The PSA computes by simulating the predatory behavior of birds with a focus on both 'food' (urban public open spaces) and 'paths' (different results corresponding to different modes of transport). Because people tend to place more value on lower transport costs when selecting sites from accessible urban public open spaces for recreational activities (Yang et al., 2020), space and transport should be focused on in the layout optimization for urban public open spaces.

This study shows that large parks and green spaces significantly impact the overall accessibility in a region, and the planning of urban public open spaces should ensure an appropriate layout of large parks and green spaces to prevent overconcentration and resource imbalance. For residential areas with many small urban public open spaces on the periphery, the service capacity of these urban public open spaces tends to be high if supported by a relatively convenient road transport system. This is because for some spaces, a convenient walking system compensates for the insufficient area of parks and green spaces and enables more people to access them by road, thereby reducing service blind spots and improving the service capacity of the urban public open spaces (Xu and Wang, 2020).

For residential estates with an accessibility index smaller than 16.636 (accessibility rated as moderately poor or poor), first, new urban public open spaces, mainly the size of community parks, should be configured in clusters of residential estates with poor accessibility according to scientific calculations. Second, for those residential estates with accessibility smaller than 5.892 (accessibility rated as poor) after the layout optimization, we recommend improving the walking/bicycling system or urban public transport system in their 400-m periphery to attract more urban residents by rationally reducing the transport cost. This approach simultaneously enhances the service capacity of urban public open spaces near these residential estates. Finally, new strip- or dot-shaped green spaces or small parks should be constructed in the periphery of these residential estates following the principle of 'developing green spaces wherever there is room', thereby optimizing the green space layout and ensuring justice in the urban open space accessibility. Wu et al. (2020a) suggested that an open community policy is a practical measure for improving green justice.

For urban public open spaces, the attractiveness of urban public open spaces that are large but far from residential areas should be improved by improving the road transport system and connectivity and enhancing the green space quality and entertainment, thereby gradually guiding residents to travel farther for recreational activities in urban public open spaces. The service capacity of urban public spaces that cover a small land area but have a high visitor traffic can be improved by improving their infrastructure or green space quality without changing their area.

4.3 Significance of optimization

This study investigated the service capacity and optimized the layout of urban public open spaces based on a comprehensive consideration of the supply of and residential demand for urban public open spaces using the 2SFCA method. The investigation into the accessibility of urban public open spaces from the perspective of residential estates focused on the demand-supply relationship between residents and urban public open spaces based on the population distribution and the road transport system. For residential estates with available park and green space areas less than 12 m^2/person, the layout of urban public open spaces and the allocation of the green space sizes were optimized by referring to the Shenyang City Master Plan (2011–2020). This approach ensured fair green space service in the vicinity of each residential estate to all residents and satisfied residents' basic demand for parks and green spaces, which is conducive to improving the happiness index of residents in the study area (Lu and Fang, 2019).

In recent years, the urban greenway—a new green space structure—has been promoting the blending and coupling of 'city' and 'green'. The urban greenway plays a vital role in achieving 'Urban Double Repair', namely, the restoration of the natural environment that has been damaged by urbanization and the continuous improvement of urban public services (Li et al., 2020). Urban greenway systems are typically constructed near available roads, rivers, and public open spaces to enable connectivity between ecological nodes and to realize the networked connection of the corridors.

The site selection for urban public open spaces is a tradeoff process among multiple factors, including population density, environmental quality, and land use. Zhou et al. (2011) compared the simulation results for the optimal locations of urban parks obtained using a multiobjective location allocation model. They found that the urban air pollution level and heat island intensity affected the simulation results and that rational planning of the locations of urban parks better improved the quality of the urban ecological environment. In contrast, the small number, small size, and poor balance of ecological nodes in the overall urban public open spaces tend to be inconducive to the construction of urban greenway networks and the improvement of the urban ecological environment (Zhou et al., 2011). In a study by Hao et al. (2019), a green ecological network planning scheme model that constructed a green network by utilizing the current conditions and potential landscape, and by exploiting potential ecological patches, resulted in a lower overall degree of landscape fragmentation and considerably better networking and ecological efficacy than a scheme model that constructed a green network based on large-size high-functionality parks and green spaces. The former was associated with a higher landscape connectivity index (0.719 vs. 0.359) and higher landscape evenness index (2.627 vs. 1.136) than the latter. In this study, the construction of small urban public open spaces using the PSA fully utilized the available stock land to expand the urban green spaces. These newly built parks and green spaces are mostly situated in unfrequented regions of existing sites, thus enriching the unfrequented regions in urban public open spaces and promoting the perfection of the urban greenway network.

Because urban public open spaces have multiple functions, their optimization not only contributes to urban construction but also improves residents' quality of life. Xu and He (2020) investigated the impact of community green open space on the self-assessed satisfaction of neighborhood communication using an ordinal logistic regression model. They found that communication activities in green open spaces significantly improved the satisfaction with neighborhood communication (60% of residents were satisfied with neighborhood communication in green open spaces) and that community green open spaces contributed more to the satisfaction with neighborhood communication than estate- and city-level green spaces (Xu and He, 2020). Their findings agree with those of our study that community-level urban public open spaces are the preferential choice. The construction of attractive urban public open spaces with high green coverage and a suitable size can stimulate residents' willingness to communicate and substantially increase their satisfaction with neighborhood communication. The findings of this study have high application value in the national strategy setting of Healthy China.

5 Conclusions

The existing research mainly focuses on the evaluation of the urban public open space accessibility, paying scant attention to the implementation strategies necessary for improving the accessibility, and thus has little relevance to the urban planning practice. This study finds that in the service capacity of the existing public open spaces in Shenyang, the accessibility for 48.6% of the residential estates is moderately poor or poor and is lower than the planned level. Starting from the living needs of residents and based on the measurement of the accessibility, a PSA was used to optimize the site selection for new green space developments. The results show that the layout is optimized by adding eight new green spaces and that the optimization is significantly effective in improving the green justice. The optimization increases the green space area accessible by motor vehicles (60 min), bicycles (60 min), and walking (30 min) by 4.67%, 5.38%, and 8.03%, respectively. The optimized solution can be used to prioritize green space developments and has practical significance at the policy level. In the current stage of urban construction and development, the city has an overall insufficient provision of public open spaces, particularly in old town areas. Determining how resources are allocated scientifically and appropriately is an arduous long-term project, and this study provides guidelines for urban planning and development. The research methods additionally provide references for the appropriate planning and layout of other public service spaces and facilities.

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