

Yin, Jie; Su, Bohao; Fan, Chenjing; Li, Qiuyuan

Article

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Location of the public service facilities in an urban comprehensive park using a multi-hierarchy and multi-constrained configuration model



Jie Yin*, Bohao Su, Chenjing Fan, Qiuyuan Li

College of Landscape Architecture, Nanjing Forestry University, Nanjing, 210037, China

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ABSTRACT:

The spatial layout of the public service facilities in urban comprehensive parks has to be optimized dynamically in accordance with user needs and local conditions. In this study, we present a multi-level hierarchical and multi-constrained model for locating public service facilities in an urban comprehensive park. In this study, the service facilities of the park were classified into multiple levels based on the site selection of the facilities by integrating and processing current data with the use of ArcGIS. The different constraints for evaluating each level with respect to the construction quantity, accessibility, service area, and service object were also identified in this study. A traversal algorithm solution was used to obtain the corresponding optimal scheme in MATLAB. In the latter half of this study, Xuanwu Lake Park in Nanjing, China is presented as an example, the application of the model is introduced, and the model with the current situation of the park is compared with the traditional facilities configuration model. The planning and configuration model proposed in this study can be potentially used in the configuration of public service facilities in urban comprehensive parks in the future. This study provides a reference for the efficient operation and sustainable development of urban comprehensive parks.

1. Introduction

Urban comprehensive parks are a relatively significant type of greenspace in cities. These types of parks are a main location for residents to recreate and relax, and a significant public open space (Li & Jin, 2011). In addition to a large area of green land, urban comprehensive parks have numerous public service facilities (Yang, Lu, & Yang, 2018). In the transformation from scale expansion to new urbanization represented by high-quality and livable construction among cities in China, problems have emerged related to the supporting construction of public service facilities in urban parks. For instance, due to the unbalanced distribution of public service facilities in some parks, park users are less willing to visit certain areas in the park, resulting in the loss of vitality of some public spaces. A more common problem is that the differences in the service capability and function orientation of park service facilities are ignored. The type, quantity, and configuration of different levels of service facilities are poorly matched, resulting in homogeneous disordered competition among various service facilities. These park facilities include small drink shops, kiosks, small teahouses, and catering shops. Disorderly planning leads to the wastage of park construction resources (Fuster, 2012; Liu, 2010; Zhong, Yang, & Chen, 2016).

In this study on urban planning, the problem of the location of facilities (Wolf, 2011; Yeh & Chow, 1996) was widely applied to

* Corresponding author.

E-mail addresses: yinjie@njfu.edu.cn (J. Yin), Subohao1998@163.com (B. Su), fanchenj@mail.tsinghua.edu.cn (C. Fan), lqy@njfu.edu.cn (Q. Li).

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the category of facilities for preventing disasters (Chen, Zhai, Fan, Jin, & Xie, 2017; Fan, Zhai, Zhou, Zhang, & Qiao, 2017; Wang, Zhu, Huang, & Zhang, 2010, pp. 202–205) and avoiding risks (Anhorn & Khazai, 2015; Trivedi & Singh, 2017). Such decision-making models mostly set constraints for the parameters, such as the holding capacity and accessibility (Orloff, 1977; Pareja Anda, 2013; Yu, Solvang, & Yang, 2014) of the facilities in order to attain the optimal solution to the facility planning and configuration. For the service facilities intended for culture, sports, medical treatment, and other types (Gu, Li, & Lu, 2014; Liu, Zhang, Xu, Li, & Xian, 2012; Shariff, Moin, & Omar, 2012; Zheng et al., 2019), a geographic information system (GIS)-based position distribution model (Alshwesh, 2014; Cliquet, 2013; Lo Porto, de Girolamo, Garnier, & Passarella, 2003; Suárez-Vega, Santos-Peñate, & Dorta-González, 2012) was used to categorize the facilities into two to three levels (Alexandris & Giannikos, 2010; Wan, 2012) and to conduct a solution operation by level. However, the model only had a single constraint for the facilities of some levels (Tang, 2008). For the position distribution of certain types of facilities (Alarcón-Rodríguez, 2009; Comber, Dickie, Jarvis, Phillips, & Tansey, 2015; Farahani, Hekmatfar, Fahimnia, & Kazemzadeh, 2014), this model ignored levels, set multiple constraints for a single facility, and established a model to determine the solution. The existing scheme mostly adopted a single constraint or a single objective to execute the solution operation, and it had no qualitative analysis of the capacity of the facility or the number of tourists.

The innovation of this study rests with the combination of multiple levels and multiple constraints. In this study, constraints corresponding to every level of public service facilities were proposed. In solving multiple constraints, the data were exported via GIS, and a MATLAB traversal algorithm was used (i) to determine the optimal facility configuration scheme and the consequent optimal spatial layout of the service facilities in the park, (ii) to provide an effective model support for future planning of urban parks, and (iii) to enrich relevant theories regarding the site selection of facilities. With these efforts, this study provides a reference for the efficient operation and sustainable development of urban comprehensive parks.

2. Methodology

2.1. Brief introduction of the case area and data resources

Xuanwu Lake Park is located in Xuanwu District, Nanjing City (Fig. 1). Xuanwu Lake Park is a comprehensive park and a national AAAA-level scenic spot with an area of 502 ha (including 378 ha of water). It is open to the public free of charge throughout the year. Thousands of visitors visit the park on a typical day and use its facilities. The park is surrounded by residential areas, rendering it a vital part of the urban open space. However, its plan was set 10 years ago, and the public service facilities lack timely adjustments. Hence, the visitors are dissatisfied. The spatial layout of the park, which has 39 facility points, is presented in Fig. 1.

The research data was primarily obtained from three characteristics: field interviews and survey data, network big data, and spatial information data. The data included: (1) Information collected from a questionnaire survey, interviews, and trace data for the

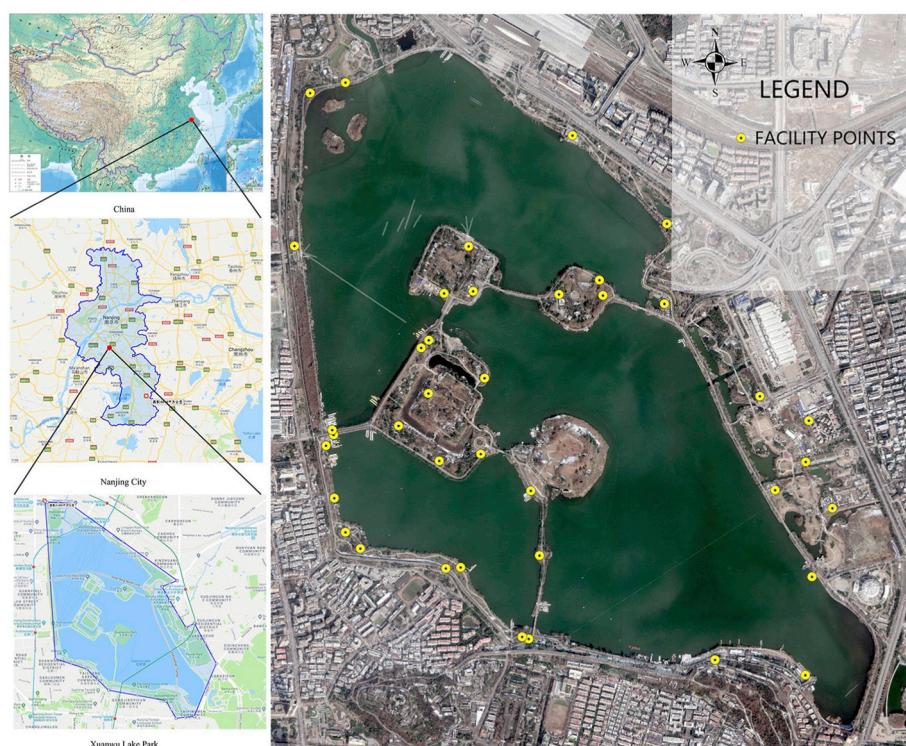


Fig. 1. Location of Xuanwu lake park and the layout of facility points in Xuanwu lake park.

touring routes among park users, obtained by conducting a three-month field survey. (2) The evaluation of the service facilities in Xuanwu Lake Park by the park users on an OTO (Online to Offline) platform. The data were derived from the facility evaluation opinions among the network big data, which was retrieved using crawling software and which was used to evaluate the service capacity and accessibility of the service facilities. (3) A topographic map, which could be used to retrieve the facility point locations, evaluate land suitability, and generate the tourist area (the park area apart from the water area, unreachable forest, and other inaccessible areas) in ArcGIS.

The following parameters were based on the field survey results: (1) According to the questionnaire, the maximum acceptable walking time for people to arrive at the nearest facility point was 15 min. If the walking speed was assumed to be 5 km/h, the service radius of a facility point was about 1200 m. (2) To meet tourist needs, the coverage area of all of the facility points needed to exceed 80% of the total tourist area of the park. (3) All of the service facilities were divided based on the service requirements into low-hierarchy facility points and high-hierarchy facility points. The low-hierarchy facility points mainly consisted of rest shops and buffets targeted at users of the park throughout the day. The high-hierarchy facility points primarily consisted of comprehensive dining shops and rest sites, mainly serving various users at important landscape nodes and traffic nodes at peak times (11:00–13:00 and 17:00–19:00) within the park. The analysis of the tourist consumption behavior indicated that the covered population of low-hierarchy facility points reached 80% of the daily tourists, and that of the high-hierarchy facility points reached 60% of the visitor capacity in the park (the maximum number of visitors in the park at the same time during peak hours).

2.2. Basic assumptions and technical route

Existing research on public service facility locations has focused on (1) accessibility, (2) coverage, and (3) capacity. However, these single-objective models scarcely match the practical situation. Therefore, the most optimized facility location and configuration scheme should be a comprehensive multi-objective problem.

With mathematical models as coupling points based on the field survey, along with the modeling in GIS, this study was divided into three steps:

Step I included the collection and retrieval of data. For investigations on the present state of public service facilities in parks, the comprehensive evaluation of internal facilities from users is obtained using various methods, including the most fundamental semantic method, tracing method, and big data evaluation method. The internal population distribution density data were organized using the Baidu thermodynamic chart (<https://map.baidu.com>) and the internal tracing and investigation data. In addition, a geographic space data cloud was used in the study and other platforms could provide spatial data based on a topographic map for the verification and enhancement of various spatial data.

Step II was the establishment of a status quo service facility evaluation model for existing park service facilities, mainly including the following two procedures: (i) The first procedure was the evaluation of the attributes of each facility point in order to divide the types of facilities. The facilities were divided by service quality (including service satisfaction and service capacity) and accessibility (including walking satisfaction and prediction of visitor population covered) via the analytic hierarchy process (AHP) and to evaluate the overall service hierarchy of each facility point and the entire park. (ii) The second procedure was the evaluation of the quantity configuration and spatial distribution of the facility points using an ArcGIS service area analysis to evaluate whether the coverage of the service scope of all of the facility points reached 80% of the tourist area of the park. Whether the population in the covered area of the high-hierarchy service facilities reached 60% of the visitor capacity of the park was then evaluated with the population density considered.

Step III involved the establishment of a planning configuration model based on the evaluation model. The first stage was the determination of the low-hierarchy facility points. The facility points that were in accordance with the facility point evaluation, land suitability analysis, and “maximal coverage” model in the location distribution were defined in the alternative area as alternative points. The grid network for the daily average population density in a $5\text{ m} \times 5\text{ m}$ area within the entire park was regarded as a demand point for calculating the distribution of the planned facility points of the largest area covering the whole park. The result was regarded as the distribution program for low-hierarchy facility points. The second stage was the determination of high-hierarchy facility points. The facility points needed to be optimized to areas of higher hierarchies with high location suitability but low facility distribution. Therefore, these service facilities were intended to serve as many visitors as possible, and the accessibilities of the spatial locations were controlled within an appropriate scope. Due to multiple constraints, in this study MATLAB was used to call data from the geographical information database in ArcGIS. A traversal iterative algorithm was used to compare programs and record those that satisfied the constraints and then output the characteristics of their various data points to ultimately determine the best facility optimization program with minimal construction (The technical route map can be seen in Fig. 2).

2.3. Mathematical formulation of the model

2.3.1. Model parameters

N_Opt—Total number of facility points available for optimization.

Loc—Locating point.

N_Loc—Total number of locating points.

S_Opt—Alternative sites for optimization ($S_{\text{Opt}} \in [1, 34]$).

Jud(Judge) O—When the facility point was within the selected scheme, $\text{Jud}_O = 1$; otherwise, $\text{Jud}_O = 0$.

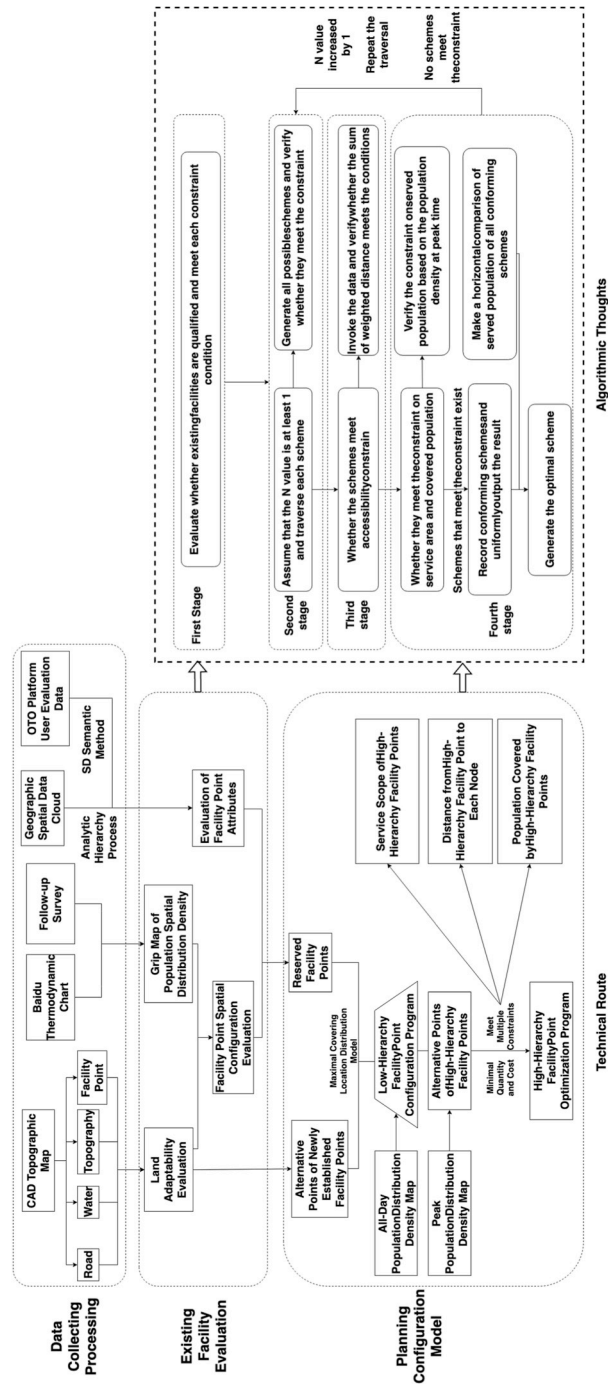


Fig. 2. Technical route map and algorithmic thoughts of the solution to the site selection model.

Cro(Crowd)L—Equivalent covered population of the locating points.

T(Total)—Ultimate effectively served population.

CovLO—A two-valued variable with values equal to 0 and 1. When the i locating point was within the coverage scope of the service zone of the j facility point, $COVLO = 1$; otherwise, $CovLO = 0$.

CovL—A two-valued variable with values equal to 0 and 1. When the i locating point was within the general service scope, $CovL = 1$; otherwise, $CovL = 0$.

ϕ —Coverage coefficient, which was set to 0.6 in this formula.

DisLO—The calculated distance in the road network from the locating point i to the alternative site j for optimization.

DisLa—The sum of the road network distance from the alternative site j for optimization to each landscape node.

DisLb—The sum of the road network distance from the alternative site j for optimization to the entrance and exit.

2.3.2. Mathematical description of the model

Four stages were identified: The evaluation of whether the facility layout of the target park met the standard, the determination of the minimum of the facility points to be optimized, meeting the accessibility constraints, and the determination of the maximum population covered by the service in accordance with the aforementioned constraints (Fig. 2).

First stage: Evaluating whether the layout of the low-hierarchy facilities of the target park met the standard

$$\text{goal } T \geq \phi \sum_{Loc=1}^{N_{Loc}} CroL, \quad (1)$$

$$\text{subject to } \sum_{Loc=1}^{N_{Loc}} COVLO \geq 0.8w, \quad (2)$$

$$\sum_{Loc=1}^{N_{Loc}} y_i Jud_j CroL = T \quad \begin{cases} y_{Loc} = 0 & DisLO \geq 1200 \\ y_{Loc} = 1 & DisLO < 1200. \end{cases} \quad (3)$$

Formula (1) represents the target function. Formula (2) implies that the coverage area of all of the facility points exceeded 80% of the total tourist area in the park. Formula (3) implies that the covered population of low-hierarchy facility points reached 80% of daily total number of tourists. When these constraints were met, the existing facilities in the park could efficiently serve its users in site selection.

Second stage: Identifying the minimum amount of the high-hierarchy facility points with minimal cost

$$N = \min \sum_{S_{Opt}=1}^{S_{Opt}} Jud_j, \quad (4)$$

$$\text{subject to } \sum_{Loc=1}^{N_{Loc}} y_i \geq 0.8w \quad \begin{cases} y_i = 0 & DisLO \geq 1200 \\ y_i = 1 & DisLO < 1200 \end{cases} \quad (5)$$

the j point is the closest to point to the i point (5)

$$\sum_{Loc=1}^{N_{Loc}} y_i Jud_O CroL = Q \quad \begin{cases} y_i = 0 & DisLO \geq 1200 \\ y_i = 1 & DisLO < 1200 \end{cases} \quad (6)$$

$$Q \geq \phi \sum_{Loc=1}^{N_{Loc}} CroL, \quad (7)$$

where the target formula, Formula (4), indicates the selection of the minimum number of N facilities to be optimized to save on construction costs. Formulas (5) and (6) are constraint functions, which ensured that more than 80% of the locating points were within the 15-min walking service scope of the facility points. Constraint Formula (6) ensured that only the locating points covered by the selected facility points were included in the calculation. Constraint formula (7) ensured that the population covered by the service of the selected optimized facility points exceeded certain coefficients representing the total number of persons. In this study, the coefficient ϕ was set to 0.6 based on the pre-survey, in which nearly 60% of the tourists considered public service facilities necessary in the comprehensive park.

Third stage: Determining whether high-hierarchy facility points met the accessibility requirements.

The target Formula (8) implies that the sum of the weighted distances from the selected high-hierarchy facility points to each node, entrance, and exit of the park were within the constraint. α is the sum of the average weighted distance from the low-hierarchy facility points to each node and each entrance and exit of the park. The purpose of such a constraint was to reduce the high-hierarchy facility points in remote locations and improve their service to tourists and the main users of the public space near the nodes and landscape:

$$\sum_{S_{Opt}=1}^{S_{Opt}} Jud_O (DisLa + DisLb) < \alpha \quad (8)$$

Fourth stage: Determining the solution to maximize the served population subject to the N value constraint

$$\text{Max} \sum_{Loc=1}^{N_Loc} y_i Jud_O Cro_L \quad (9)$$

$$\text{subject to} \sum_{Loc=1}^{N_Loc} y_i \geq 0.8w \begin{cases} y_i = 0 & Dis_{LO} \geq 1200 \\ y_i = 1 & Dis_{LO} < 1200, \end{cases}$$

the Opt or optimized facility point in the formula is the closest to the locating point Loc (10)

$$\sum_{Loc=1}^{N_Loc} y_i Jud_O Cro_L = T \quad \begin{cases} y_i = 0 & Dis_{LO} \geq 1200 \\ y_i = 1 & Dis_{LO} < 1200 \end{cases} \quad (11)$$

$$T \geq \phi \sum_{Loc=1}^{N_Loc} Cro_L, \quad (12)$$

where the N value represents the minimum number of high-hierarchy facilities. The target formula (9) implies that the maximum of the covered population was sought in order to satisfy the demands of more users and easily meet the population density at the peak time of dining. Formulas (10)–(12) are constraint functions similarly defined to Formulas (5)–(7). The scheme solved by $\text{Max} \sum_{Loc=1}^{N_Loc} y_i Jud_O Cro_L$ was the solution to the maximum served population subject to constraints such as accessibility and coverage scope.

Finally, the minimal optimized facility points, maximal service coverage, and maximal served population were derived from the alternatives as the optimal output (Fig. 2).

Based on the mathematical model, this study provided a solution to the model using MATLAB. The solution was obtained by (1) inputting the initial conditions, (2) analyzing the site selection scheme, (3) determining whether the constraint was met, (4) assessing whether the scheme was optimal, and (5) analyzing the subsequent group of site selection schemes. An iterative algorithm was adopted.

The realization of the model algorithm for key technologies is introduced in the following paragraphs.

3. Case study

3.1. Data collection

3.1.1. Preprocessing of the spatial data

In this study, the park road map was improved based on a topographic map, the network was generated using ArcMap, and the roads were categorized into the main road, branch, and alley based on their width and paving. The topographic altitude data were transformed using the topographic map to ensure that the precision exceeded 2 m.

3.1.2. Preprocessing of the type data of the public service facilities

The spatial location of the public service facility was input into the system, and the service type, service level, and other information were recorded in the single-column data segment. The accessibility value of the road network of the spatial location where each facility point was located was given to the facility point and functions as an independent field.

3.1.3. Trace data preprocessing of the spatial touring route of a user

The sampling estimation program was adopted. It was determined whether the user had passed a series of nodes in the park. The population density at each node was indicated in the results of the questionnaire survey, and the distribution of the daily tourists in the park was obtained in order to select the low-hierarchy facility point. In addition, the population density distribution map when the user demand reached its peak was determined using the route trace data combined with the Baidu thermodynamic chart of hundreds of people to select the high-hierarchy facility point.

3.1.4. Preprocessing of the post-occupancy evaluation data among park users

- (1) The AHP was used to evaluate the quality of service (including service satisfaction and service capacity, among other factors) and accessibility (including walking satisfaction and prediction of the visitor population covered). User ratings for each facility point were assigned based on the questionnaires. The weighted calculation, which was based on the weight given by the expert scoring system, was conducted to obtain the score of each facility point.
- (2) As a standard of facility coverage in the service area analysis, the longest accessible distance in the park facilities that was acceptable to users was ascertained from the questionnaire survey results. Different spatial information for Xuanwu Lake Park was imported into ArcGIS. The service areas were then examined based on the established road network (Fig. 3) using network analysis.

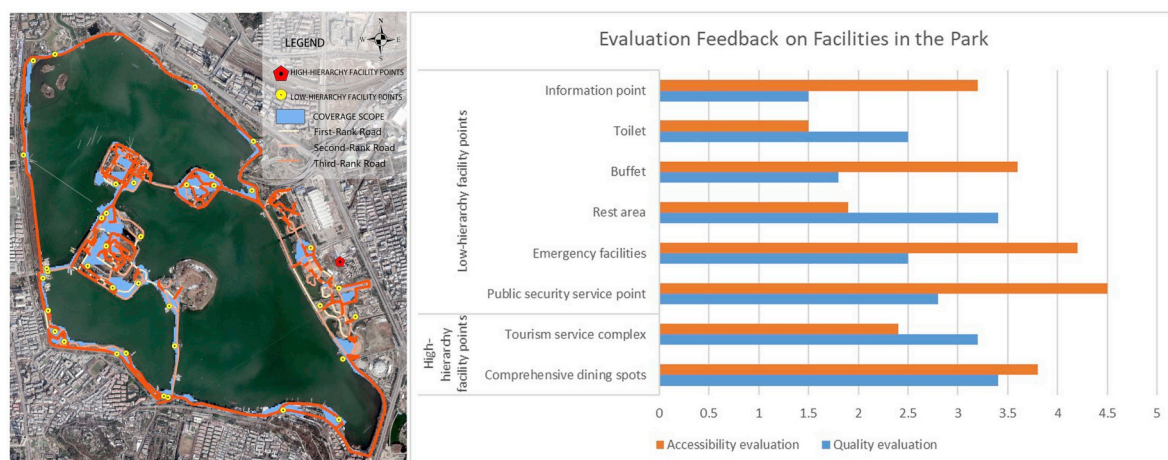


Fig. 3. Facility evaluation (a) Schematic of the service areas of the service facilities and the road network of Xuanwu Lake Park. (b) Evaluation of the facilities in Xuanwu Lake Park.

The population density data for the entire day were input in order to generate the thermodynamic chart of the population density at the peak time (Fig. 4a) and the thermodynamic chart of the population density for the whole day (Fig. 4b). The grid for the thermodynamic chart was converted into points. The table of correlation between each point and the plane of the service area were then exported for data invocation in MATLAB.

3.2. Comprehensive evaluation of the service facilities

The service facilities in Xuanwu Lake could be categorized into the following: food and drinks (including snacks stalls, medium size eateries, large hotels, clubs, etc.), convenience service facilities (toilets, firefighting facility points, and so on), and comprehensive facilities (tourist service center). Most of these facilities were related to food and drinks, which were largely consumed and demanded by tourists. Relatively fewer facilities were associated with the two remaining categories. After data crawling on the OTO platform, relevant key words were extracted as tourist evaluations of these facilities. The AHP was subsequently used to calculate the weighted superposition. The evaluation feedback is presented in Fig. 5. The result showed that some service facilities exhibited low-service capacity or accessibility, and that these service facilities could be improved. The facilities with scores below the standard line



Fig. 4. Thermodynamic Chart (a) Population density at the peak time (b) Population density for the whole day.



Fig. 5. Evaluation of the land use suitability and existing facilities with regard to the service facilities.

(a score of 2.0) might be reconstructed (as indicated by red dots in Fig. 5).

Additionally, the land-use suitability with respect to the geography, water, and road network (Fig. 5) was evaluated. The evaluation of land use suitability generally considered the road network as the main identification factor. The reason for this was that the park was largely blocked by vast water and it had a generally flat terrain. The two aforementioned evaluations suggested that the facilities in Xuanwu Lake Park currently did not meet the user service demand or the requirements for land use suitability with respect to either the service capacity or the quantities. Therefore, the current state could be optimized.

3.3. Research on the optimization of the site selection for the service facilities in Xuanwu Lake Park

3.3.1. Alternative sites for low-hierarchy facilities

The thermodynamic chart of the whole-day population density (Fig. 4), combined with the network analysis in ArcGIS, the facilities with higher evaluation scores and appropriate locations (as determined from the land use suitability evaluation) was reserved among all of the existing facility points. A location distribution model was then established. The existing facility points were compulsory sites, and new alternative sites were explored. With the maximum coverage model considered, the distribution of the spatial locations of the low-hierarchy facilities was ascertained, and the number of low-hierarchy facility points was set to 34.

3.3.2. Alternative sites for high-hierarchy facilities

Based on the thermodynamic chart of the population density shown in Fig. 4, all of the data on the positioning of the crowd were exported to the database, along with the alternative facility points. The data included 10,881 positioning data points and 34 alternative facility points (as described in Section 3.3.1). The database included the spatial coordinates of each positioning data point, the equivalent number of persons for the positioning data point, and the spatial inclusion relationship between the facility points and the positioning information point.

Based on the actual situation of the park and the use demand analysis described in Section 3.1.4, the following parameters were set in MATLAB for a three-phase analysis of the site selection for the high-hierarchy facilities:

1. The analysis of the park evaluation by users and the results of the questionnaire survey indicated that for users, the maximum acceptable time for walking to the facility points was 15 min. Therefore, the service scope of the facilities was set to 1200 m.
2. The coefficient of the covered population was determined by analyzing the user demand and the statistics of the network big data. About 60% of the visitors used public service facilities in the park at least once. Thus, ϕ was set to 0.6.
3. The distance matrix between the facility points referred to the DisLO parameter in the mathematical model and it was calculated from the OD matrix model of the ArcGIS network analysis module. The values of row n and column m of the array matrix

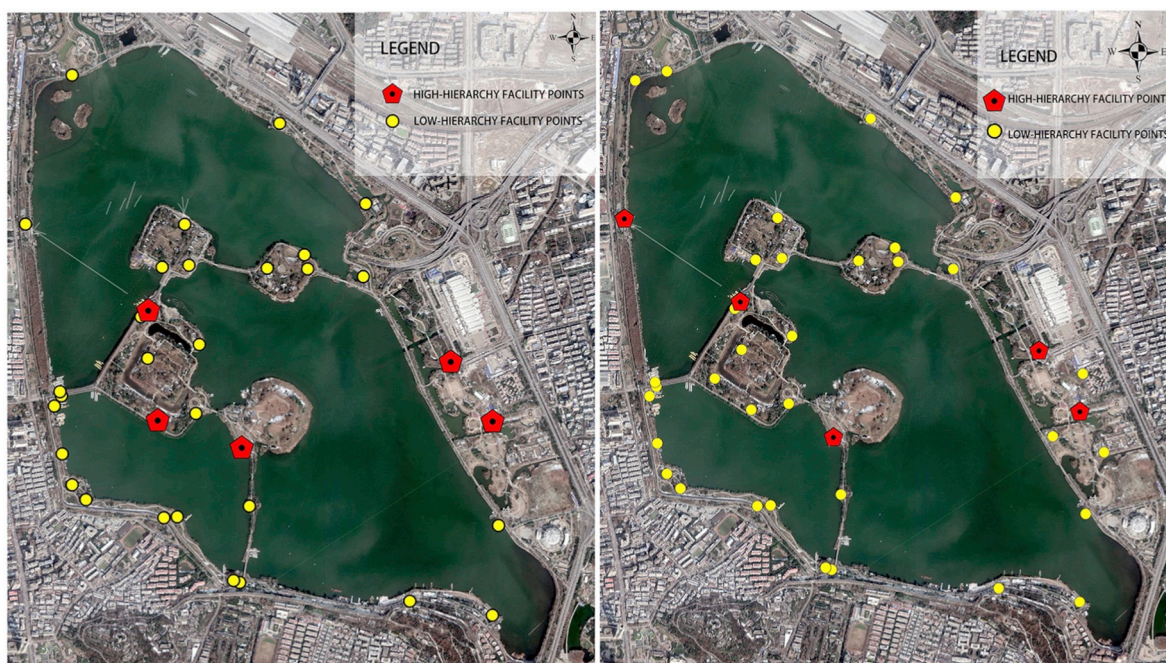


Fig. 6. Optimal scheme of (a) the solution and (b) the schematic generated by the ArcGIS location distribution model.

indicated the distance from the positioning data point L to the facility point O. With the aforementioned setting of input parameters, the output was obtained.

3.3.3. Final outcome for the service facilities in Xuanwu Lake Park

Based on the analysis of the model, a scheme was proposed for the site selection of public service facilities in Xuanwu Lake Park in Nanjing City. The field in the geographical information database was updated, and a planning scheme was drawn to guide the planning of public service facilities (Fig. 6a).

3.4. Validity test of the model

Compared with the classic layout of public service facilities solved by ArcGIS, this study sought the optimal solution from multiple aspects, including coverage area, served population, and node distance. Fig. 6b presents the solutions in which the low-hierarchy facility points were treated using ArcGIS's maximum coverage area and the high-hierarchy facility points were treated with the maximum population flow. In selecting the high-hierarchy facility points, some locations were laid out along the lake because the coverage area of the facility points at these locations was less than that of the facilities inside the island. This type of layout evidently caused an imbalance of the spatial layout of high-hierarchy facility points and nonconformity with the actual crowd distribution in which tourists were mainly concentrated in the southeast area and three central islands. The comparison in Fig. 6b shows that the spatial distribution of the facilities for the solution of this model was more balanced and more efficient with respect to the coverage of the served population.

4. Conclusion

The spatial layout of the public service facilities in comprehensive parks should meet the needs of users and optimize the planning dynamically according to the constraint conditions. In the existing programming research, the quantitative configuration models mostly adopt a single constraint to perform the solution operation, lacking the qualitative analysis of the facility point level. This research mainly carried out work with respect to three aspects: (1) a city comprehensive park public service facility location multi-level, multi-constraint model was proposed. (2) ArcGIS was used to evaluate the constraint of the data and MATLAB was used to solve the data traversal algorithm. (3) Through the verification in Xuanwu Lake Park in Nanjing, the model could obtain a more comprehensive scheme for facility configuration than the traditional model. The innovation of this study lies in the combination of multi-level facility points and multi-level facility point constraints. The planning configuration model utilized multi-level facility points and combined the peak changes in the number of people to meet different user needs at different time periods. Compared with a single-constraint model in traditional GIS, this model not only considers users' demands for service facilities and planners' demands for the efficient use of land but also satisfies multiple-constraint conditions.

To summarize, this study provides theoretical support for the establishment of an efficient allocation model, facilitates the

construction and related planning of public service facilities in future urban comprehensive parks, and provides theoretical enlightenment for other spaces that require efficient public service facilities. What is worth further attention is the fact that the configuration model proposed in this study still needs to be improved upon and optimized, especially in terms of the database coordination between ArcGIS and MATLAB. This algorithm can also be optimized to improve the operation speed. In the future research, it is expected that a systematic and quantitative public service facility allocation model will be established to help developing countries conduct facility allocation in the field of public space.

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Data availability declaration

Some or all of the data, models, or code that support the findings of this study are available from the corresponding authors upon reasonable request.

Declaration of competing interest

The authors declare no conflict of interest.

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