Hindawi
Journal of Advanced Transportation
Volume 2020, Article ID 8894119, 10 pages
https://doi.org/10.1155/2020/8894119

Research Article

Layout Optimization of Campus Bike-Sharing Parking Spots

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Received 31 July 2020; Accepted 13 October 2020; Published 2 November 2020

Academic Editor: Dongfang Ma

The rapid development of bike sharing has posed some challenges to the traffic management on campus. The bike sharing on campus has problems such as messy parking, and some buildings in the peak hours have no bikes to borrow. Thus, alternative parking spots are proposed based on the layout principle of parking spots for bicycles. An optimization model of the layout of campus bike-sharing parking spots with travel time and construction cost as the optimization goal is established, and the branch and bound algorithm is used to solve the model. Finally, the study analysis is carried out by optimizing the layout of the bike-sharing parking spot of Nanjing University of Science and Technology. The results show that, after optimizing the layout of parking spots, the average travel time of users is reduced by 6.0%, and the total construction cost is reduced by 27.3%. While being convenient for campus bike-sharing users, it also provides scientific decision-making support for the campus traffic management.

1. Introduction

Bike sharing not only helps to alleviate urban traffic pressure but also generates tremendous energy in constructing a green transportation trip system. It also has unique advantages in solving the "last mile" problem [1]. Bike sharing helps to alleviate urban traffic pressure in building a green energy traffic system and has a unique advantage in solving the "last kilometer" problem [2, 3]. The dockless bike sharing has got rid of the limitation of fixed parking piles and has the characteristics of small traffic capacity, flexible operation, good accessibility, and less investment [4], which has gradually covered most of the first- and second-tier cities in China, as well as Singapore, Washington, and other overseas cities. However, due to the regular change process of bikes demand, the bike-sharing system does not guarantee self-balancing, resulting in the phenomenon that a large number of shared bikes are idle in some areas and no bikes are available in some areas [5]. Therefore, it is imperative and necessary to set up a reasonable and convenient fixed storage spot for shared bikes.

The main problem of optimizing the number of parking spots and layout of shared bicycles can be solved by selecting the optimal facility location and related resource allocation based on different optimization objectives and constraints. Some scholars consider maximum coverage to optimize the shared bike system to maximize the demand covered by the shared bike parking spot or meet the limits of available budgets [6]. With the overall imbalance between supply and demand for shared bikes, Hu et al. [7] adopted three optimization models based on CMCLP to optimize the system configuration to achieve maximum service coverage [8–10]. Due to the close connection between the parking spots of bike sharing and the surrounding infrastructure, some scholars have considered the influence of the surrounding environment on the layout of shared bikes. In view of the optimization of the layout of shared bikes parking spots in scenic areas, Guo et al. [11] considered the distribution of subway stations and bus stations around the scenic area, by proposing an optimization model based on clustering and greedy algorithms, and solved the problem with an optimization coverage rate of 89.2%. In establishing the layout optimization model of the shared bikes parking spot, we can also consider the multiobjective optimization model such as travel cost and construction cost [12]. Romero et al. [13] proposed a two-layer mathematical programming model to optimize the location of the base station while minimizing total costs and maximizing the number of system users. Luis Ines Frade et al. [14] proposed the maximum coverage model from the perspective of user demand, with the goal of maximizing demand and the optimized model with the available budget and system benefits as the constraints, so as to get the optimal location and configuration of the parking spot. In addition, George and Xia [15] introduced a queuing theory in the study of the size of the shared bike rental spot. García-Palomares et al. [16] proposed a GIS-based approach to calculate the spatial distribution of potential travel demand, using the location allocation model to determine the location of shared bike parking spots, the capacity of the parking spots, and the demand characteristics of defining the parking spots. At present, the optimization of the bike-sharing layout mainly focuses on scenic spots and cities, which involves the maximum coverage maximization and cost minimization. The model solution involves clustering, particle swarm algorithm [17], genetic algorithm, and ant colony algorithm [18], while there are few studies on the layout optimization of bike-sharing parking spots on campus.

Teachers and students are the main targets of bike-sharing service within the campus. The phenomenon of stopping and parking anywhere is widespread within the campus which can easily lead to the problem of ‘difficulty to find a bike’ thereby reducing the convenience of the user’s travel [19]. According to the characteristics of the parking spot of bike sharing on campus, this paper defines the rules for setting up the parking spots of shared bicycles on campus and establishes the distribution model of the parking spots of bike-sharing on campus with travel time and construction cost as the optimization goal. Finally, the layout plan of the bike-sharing parking spot on campus is designed with specific cases to verify the rationality and feasibility of the model.

2. Problem Description

Considering that the traffic operation status quo is of different areas and the geographical conditions and structure of residents’ travel are also different, it goes without saying that users will have different needs for bike sharing. To begin with, we divide the different functional areas of the campus which are mainly the teaching areas, office areas, living areas, and activity areas, to make certain of the demand for each service area; then, for different service areas, taking into account the reasonable number and location of parking spots, the premise of meeting the bike-sharing needs of each parking spot, the total travel time, and the total construction cost are minimized, and the layout optimization model is perfectly built.

2.1. Parking Lots Layout Planning. According to different service properties of different functional buildings, the campus is divided into several areas that are conducive to the layout of bike-sharing parking spots, and in each divided area, alternative parking spots are set according to different building radiation ranges.

The selection of alternative parking spots for bike sharing is in accordance with the following principles:

(1) Maximum service radius of parking spots: researches have shown that most bike sharing use areas within 300 meters from the station [18], and the maximum service radius of bike-sharing parking spots is fixed to 300 m, as shown in Figure 1

(2) Taking into consideration the nature of building services: the needs of people in different functional buildings for bike sharing are unpredictable, and the impact of user needs on the layout of parking spots should be fully considered

2.2. Layout Optimization Model. The aim of this model is to minimize the total travel time of users and spot construction costs on the premise of meeting the bike-sharing needs of each parking spot. The total travel time of users includes the total time of walking to the station, riding time, and time spent walking to the destination after returning the bike. The spot construction cost includes fixed cost of parking spot and cost of bikes. The model parameter symbols description is shown in Table 1.

The model objective functions are as follows:

$$\min T = \sum_{i\in I}\sum_{i'\in I}\left(\frac{\sum_{j\in J} bs_{i,j,i'}\cdot d_{i,j}}{u_1} + \frac{\sum_{j\in J}\sum_{j'\in J} br_{i,j,j',i'}\cdot d_{j,j'}}{u_2} + \frac{\sum_{j'\in J} rs_{i,j',i'}\cdot d_{i',j'}}{u_1}\right), \tag{1}$$

$$\min P = \sum_{j\in J} y_j \cdot c_0 + \sum_{j\in J} y_j \cdot bn_j \cdot c_1, \tag{2}$$

$$\min \psi = k\cdot T + (1-k)\cdot P. \tag{3}$$

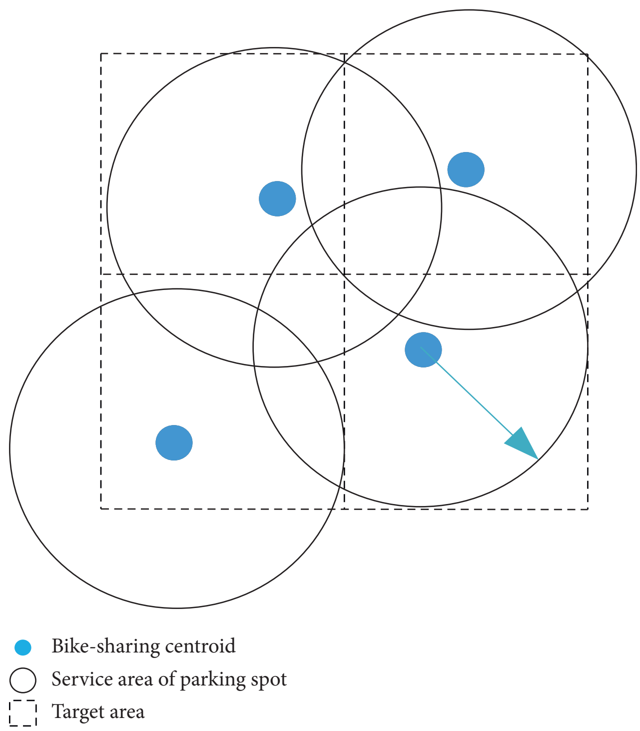

Figure 1: Diagram of the service scope of the bike-sharing parking spots.

Table 1: Model parameter symbols description.

Parameters	
I	Set of target areas, where, $i, i' \in I$
J	Set of alternative bike-sharing parking spots, where, $j, j' \in J$
k	Weight of the objective function
y_j	A binary variable to determine whether the parking spot is optimized, and the value of the optimized parking spot is 1
$bs_{i,j,i'}$	The number of the users depart from the target area i to the target area i', select borrow bicycles at the parking spot j, and the travel route is $i \longrightarrow j \longrightarrow i'$, where, $i, i' \in I$, $j \in J$
bn_j	The number of bikes per spot
$rs_{i,j',i'}$	The number of the users depart from the target area i to the target area i', select return bikes at the parking spot j', and the travel route is$i \longrightarrow j' \longrightarrow i'$, where, $i, i' \in I$, $j' \in J$
$br_{i,j,j',i'}$	The number of the users depart from the target area i to the target area i', select borrow bicycles at the parking spot j, and select return bicycles at the parking spot j'. The travel route is $i \longrightarrow j \longrightarrow j' \longrightarrow i'$, where, $i, i' \in I$, $j \in J$
$d_{i,j}$	Distance from the target area i to the parking spot j, where,$i \in I$, $j \in J$
$d_{j,j'}$	Distance from the parking spot j to the parking spot j',where,$j, j' \in J$
$d_{i',j'}$	Distance from the target area i' to the parking spotj', where, $i' \in I$, $j' \in J$
$S_{\min}, S_{\max}$	The lower limit and upper limit of the number of alternative construction parking spots
C	The service area of the parking spots
$\alpha_{i,j}$	A binary variable determines whether the target area i is within the service range of the optimized parking spot j; when the target area is within the service range of the parking spot, the value is 1, where,$i \in I, j \in J$
u_1, u_2	Walking and cycling speed
M	Maximum service capacity of parking spots
$D_{i,i'}$	The number of vehicles from target area $i$to target area i'

Equation (1) is the objective function, that is, the smallest total travel time of the user, including the walking time, borrowing and returning the bike, and riding time. Equation (2) is the objective function of construction cost. Equation (3) is the synthetic objective function.

Restrictions:

$$S_{\min} \le \sum_{j \in J} y_j \le S_{\max}, \tag{4}$$

$$\alpha_{i,j} = \begin{cases} 1, d_{i,j} \le C \\ 0, d_{i,j} > C \end{cases}, \quad \forall i \in I, \forall j \in J, \tag{5}$$

$$\sum_{j\in J}\alpha_{i,j}\cdot y_j \geq 1, \quad \forall i \in I, \tag{6}$$

$$\sum_{i\in J}\alpha_{i,j} \geq 1, \quad \forall j \in J, \tag{7}$$

$$bs_{i,j,i'} \leq M\alpha_{i,j}y_j, \forall i, i' \in I, \text{and}\, i \neq i', \quad \forall j \in J, \tag{8}$$

$$rs_{i,j',i'} \leq M\alpha_{i',j'}y_j, \forall i, i' \in I, \text{and}\, i \neq i', \quad \forall j' \in J, \tag{9}$$

$$bs_{i,j,i'} = \sum_{j'\in J} br_{i,j,j',i'}, \forall i, i' \in I, \text{and}\, i \neq i', \quad \forall j \in J, \text{and}\, j \neq j', \tag{10}$$

$$rs_{i,j',i'} = \sum_{j\in J} br_{i,j,j',i'}, \forall i, i' \in I, \text{ and}\, i \neq i', \quad \forall j' \in J, \text{ and } j \neq j', \tag{11}$$

$$\sum_{j\in J} bs_{i,j,i'} \geq D_{i,i'}, \forall i, i' \in I, \tag{12}$$

$$y_i = \{0, 1\}, \quad \forall j \in J, \tag{13}$$

$$\sum_{j\in J}\alpha_{i,j}, bn_j, y_j \geq D_i. \tag{14}$$

Equation (4) is to optimize the construction of the number of bike-sharing parking spots, to avoid the situation where the number of parking spots is too small or too much, resulting in inefficient use of shared bike systems or resource redundancy; equation (5) is the target area i within the service area of the optimized parking spot j' s scope of services of binary variable, that is, to ensure that the user can find the parking spot within the maximum tolerable walking distance to complete the borrowing and returning of the bike within the given target area; equation (6) provides a bike borrowing and returning service for at least one bike-sharing parking spot in any target area; equation (7) serves at least one target area for a shared bike parking spot; equations (8) and (9) restrict users to borrow and return bikes at only optimized parking spots; equation (10) constrains the number of borrowed bikes at any one parking spot to be equal to the sum of the number of returned bikes from any parking spot to each parking spot; equation (11) constrains the number of bikes returned at any one parking spot to be equal to the sum of the number of vehicles returned from each parking spot to any one of the parking spots; equation (12) constrains the number of vehicles demanded from each target area to travel to other areas; equation (13) is the binary variable to optimize the parking spot; and equation (14) ensures that the number of vehicles in the target area meets the demand in the target area.

3. Model Solution

Owing to the fact that branch and brand is a basic method for solving integer planning (or mixed integer planning) in operations, it is very efficient to seek the optimal solution of integers. In this paper, the model is solved by the branch and bound method, and the solving steps are as follows:

Step 1: first, the integer constraints of the original problem are not considered, to solve the corresponding relaxation problem, and a graph or simplex method is used to obtain the optimal solution Z.

Step 2: if the optimal solution sought is just the integer solution, the integer solution is the optimal solution of the original integer planning problem.

Step 3: branch: based on our understanding of the importance of variables, we select a value that does not meet the integer constraint X_j in the optimal solution, its value is b_j, where $[b_j]$ represents the maximum number which is less than b_j. Two constraints were constructed, $X \leq b_j$ and $X \geq [b_j] + 1$, joining the original LP problem separately which formed two subproblems because $[b_j]$ and $[b_j] + 1$ have no integers between them, so the integer solution within these two subsets must be consistent with the original feasible solution of the whole number solution.

Step 4: bounding: first, we determine whether there is an integer solution to each subproblem. If there is one, we find out the integer solution corresponding to the maximum value of the target function, fixed as Z^*, and then, the integer solution of the problem is the target function $Z \geq Z^*$, which is the bounding. Also, in the branching process, once there is a subproblem, then $Z^* = Z$.

Step 5: if there is a subproblem greater than Z^*, that needs to be branched out. If there is no integer solution in Step 4, it is also necessary to continue to branch to find the integer solution and to branch the subproblem corresponding to the maximum value of the target function.

Step 6: if the target value of all subproblems is less than or equal to Z^*, there is no need to continue branching, and the corresponding integer solution for Z^* is the optimal solution.

The solution process of branch and bound algorithm is shown in Figure 2.

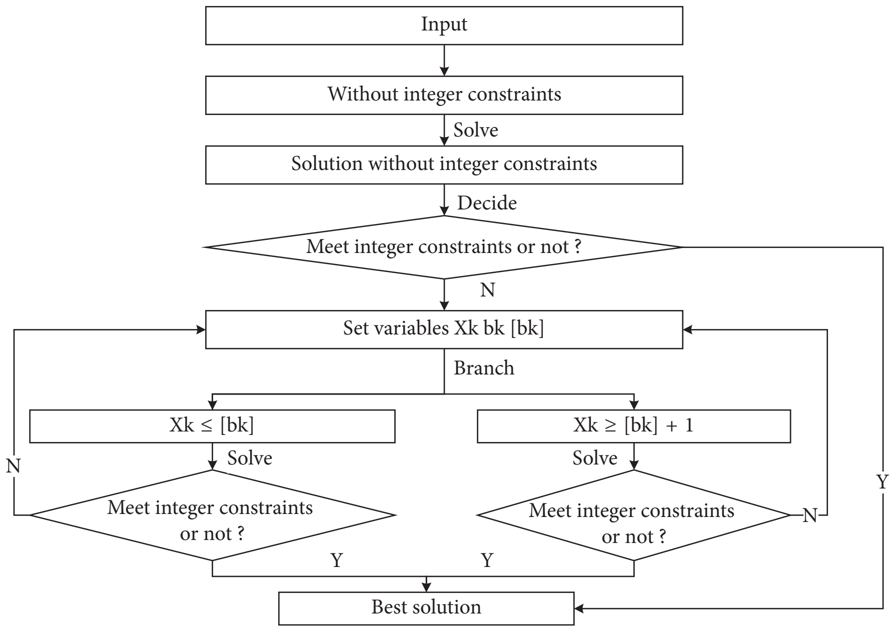

Figure 2: Solution process of branch and bound algorithm.

4. Case Study

In order to verify the accuracy of the layout optimization model of shared bike parking spots and the accuracy of the scheduling optimization model and the effectiveness of solving the genetic algorithm of the abovementioned model, this paper analyzes the genetic algorithm of Nanjing University of Technology as the research object. The school covers an area of 3118 acres, there are more than 30,000 students and more than 3,200 staff, and the travel demand is comparatively greater.

First of all, a statistical assessment was carried out on the number of peopleN_i working in the functional buildings and regions who travel during peak hours. The distribution of alternative parking spots is shown in Figure 3. Different needs for bike sharing for users in different regions are used to calculate the demand for bikes. The percentage of bikes used for different regions is based on the analysis of survey data, as is shown in Table 2.

$$\text{Demand}_i = N_i * b_i, \tag{15}$$

where b_i is the percentage of bikes used for each functional region.

Considering the fact that the teaching area, office area, living area 1 and living area 3, and other space range are large, in order to ensure the reasonable distribution of parking spots and the use of grid layout, taking into account that the service radius of the parking spot is 300 m, the set style size is 300 m × 300 m, to set the target regional center spot coordinates, as shown in Figure 4. Then, the target regional center spots and coordinate values of the alternate parking spots and the shared bike demand between the target areas are entered separately as the parking spot layout optimization model input data.

The parking spot layout optimization model parameter values are as shown in Table 3.

In a global optimal angle, the travel time of all users is the target function, and the layout scheme with the smallest total travel time and the total construction cost is solved. Based on the branch boundary method, this paper uses Matlab to write a program to solve the model, and the optimization results are shown in Figure 5. After optimization, the number of shared bike parking spots has been reduced from 51 to 35, which effectively reduces the operating and maintenance costs of shared bike parking spots.

Because of the convenience of the pile-free shared bikes, when considering the site construction cost, there is no need to consider the cost of building a parking pile, so the site construction cost only considers the fixed cost and the bike operation and maintenance cost.

$$P = \sum_{j\in J} y_j \cdot c_0 + \sum_{j\in J} y_j \cdot bn_j \cdot c_1, \tag{16}$$

where P is the total construction cost, y_j is the binary variable of the alternative site to optimize the site, bn_j represents the number of bikes per spot, c_0, c_1 ,respectively, are the cost of construction of a single site and the cost of operation and maintenance of a single bike, $c_0$equals 200 Yuan/unit, and c_1 equals 500 Yuan/bike.

Compared with the optimization model that only considers the shortest travel time, the model proposed in this paper reduces the average travel time of users by 6.0% and reduces the total construction cost by 27.3%. The comparative analysis of optimization results is presented in Table 4. The number of optimized parking spots and corresponding shared bikes is shown in Table 5. The

Figure 3: Distribution of alternative parking spots at Nanjing University of Science and Technology.

Table 2: Campus zoning planning.

No.	Zone	Spot	Number of people travelling	Bicycle ratio	Demand	Number of spots
1	Entrance	Gate 1	170	0.22	37	8
2		Gate 2	34	0.22	7	
3		Gate 3	272	0.22	60	
4		Gate 7	170	0.22	37	
5		South gate	340	0.22	75	
6		Gate 5	170	0.22	37	
7		Underground tunnel 1	816	0.22	180	
8		Underground tunnel 2	850	0.22	187	
9	Living area 1	Xiyuan District 1	340	0.15	51	6
10		Huayuan District	680	0.15	102	
11		Zhongshan District	680	0.15	102	
12		Campus hospital	272	0.15	41	
13		Zhuyuan District	170	0.15	26	
14		Xiyuan District 2	136	0.15	20	
15	Living area 2	Keyuan District	510	0.13	66	3
16		Zilu hotel	56	0.13	2	
17		Postgraduate canteen	272	0.13	35	
18	Active area	Academic Ex. Center	204	0.11	22	4
19		Art and Culture Museum	68	0.11	7	
20		Sports center	272	0.11	30	
21		School of Foreign Language	306	0.20	61	

Table 2: Continued.

No.	Zone	Spot	Number of people travelling	Bicycle ratio	Demand	Number of spots
22		Sch. of Computer Sci.	782	0.20	156	
23		Sch. of Electrical and Optical Sci.	816	0.20	163	
24		Sch. of Chemical Eng.	408	0.20	82	
25		Transient physical state	17	0.20	3	
26	Office area	Key labs	17	0.20	3	8
27		Civil Explosion building	17	0.20	3	
28		Intelligent building	340	0.20	4	
29		Basic laboratory building 1	374	0.20	4	
30		Basic laboratory building 2	680	0.21	143	
31		Teaching building 1	782	0.21	164	
32		Teaching building 2	816	0.21	171	
33		Teaching building 3	680	0.21	143	
34		Teaching building 4	340	0.21	71	
35		Yifu building	340	0.21	71	
36	Teaching area	Library	170	0.21	36	13
37		Sport Gallery	204	0.21	43	
38		Qian Xuesen College	340	0.21	71	
39		Zhiyuan building	306	0.21	64	
40		Materials research center	170	0.21	36	
41		Printing plant	170	0.21	36	
42		Experiment center	34	0.21	7	
43		Zhizhen building	170	0.12	20	
44		Youth League building	340	0.12	41	
45		2 and 3 canteen	408	0.12	49	
46		Ming Yuan	340	0.12	41	
47	Living area3	Campus supermarket	306	0.12	37	9
48		Gymnasium	306	0.12	37	
49		204 Student Dormitory	340	0.12	41	
50		Int. Students Dormitory	612	0.12	73	
51		Huizhi Pavilion	680	0.12	82	

Figure 4: Grid zoning.

Table 3: Parameter values of the optimized model of the parking spot layout.

Parameter	C	u_1	u_2	M	$S_{\min}$	$S_{\max}$
Value	300	1.4	5	1000	25	40

Figure 5: Planning and layout of optimized parking spots.

Table 4: Comparative analysis of optimization results.

Parameter	Research model	Contrast model
Total travel time/s	418489.6	394822.6
Total construction cost/Yuan	671600	923500
Objective function value	545044.8	659161.3
The number of shared bike parking spots	28	35

Table 5: Number of optimized parking spots and corresponding shared bikes.

Parking spot	1	2	3	4	5	6	7	8	9	10
Number of shared bikes	37	7	60	37	75	51	102	26	6	27
Parking spot	11	12	13	14	15	16	17	18	19	20
Number of shared bikes	27	61	163	3	3	37	68	78	82	68
Parking spot	21	22	23	24	25	26	27	28		
Number of shared bikes	34	34	17	17	40	44	40	88		

Table 6: The optimization result when k takes different values.

Parameter	Total travel time/s	Total construction cost/Yuan	The number of shared bike parking spots
$k = 0.1$	483624	644300	24
$k = 0.2$	445960	651900	27
$k = 0.3$	445855	651900	27
$k = 0.4$	436092	656700	26
$k = 0.5$	418490	671600	28
$k = 0.6$	409266	682000	30
$k = 0.7$	409266	682000	30
$k = 0.8$	401180	703900	32
$k = 0.9$	401180	703900	32

planning and layout of optimized parking spots are shown in Figure 5.

This paper also analyzes the influence of the weight k value in the model on the layout optimization results, as shown in Table 6. The results show that the value of k determines the impact of the total travel time and construction cost on the objective function, so the corresponding optimization results are quite different. When $k = 0.1$, the optimized parking point is 24; when $k = 0.9$, the optimized parking point is 32.

5. Conclusions

(1) Considering the influence of the functionality of campus buildings on the demand of bike sharing, the layout rules of the bike-sharing parking spot are proposed.

(2) In view of the optimization of the campus bike-sharing parking spot layout, a model of campus bike-sharing parking spot planning is established with the total travel time of the user and the total construction cost as the optimization goal.

(3) The rationality of the model is verified by using Nanjing University of Science and Technology as the research case study. The user's travel time is reduced by 6.0%, the total construction cost is reduced by 27.3%, and it has a certain reference value for the operation management of bike-sharing on campus.

The results also show that considering different factors will have a greater impact on the optimization results. There are many factors that affect the layout of campus bike-sharing parking spots. In the subsequent research work, the planning of shared bicycle parking spots under multiobjective and multiconstraint conditions can be considered to further improve the model.

Data Availability

On request, the data supporting the results of this study can be provided by the author of the article.

Conflicts of Interest

The authors affirm that there are no conflicts of interest.

Acknowledgments

This research was supported by "the Fundamental Research Funds for the Central Universities" (Nos. 30920010010 and 30919011290).

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