Model for Shared Parking Space Allocation in Residential Areas Considering User Convenience

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Abstract. To effectively manage urban residential parking resources and address the escalating issue of parking difficulties, this paper optimizes a shared parking space allocation model, efficiently utilizing idle parking resources in residential areas. Considering model parameters such as parking supply-demand time windows and supply-demand relationships, the paper establishes a dual-objective model aiming at maximizing platform profit and optimizing user walking distance cost. The feasibility of the model is validated. By prioritizing user walking distance, the allocation results are more optimized than traditional models, indicating that implementing shared parking in urban residential areas not only maximizes the utilization of idle parking spaces but also significantly improves user convenience.

Keywords: shared parking; residential area; space allocation; user convenience

1 Introduction

With the rapid growth of the national economy and the improvement of people's living standards, the number of motor vehicles has surged. According to the Ministry of Public Security's September 2022 statistics, there were 499 million motor vehicle drivers, with 461 million being car drivers, constituting 92.46% of the total [1]. However, the escalating urban parking demand starkly contrasts with the limited parking supply, resulting in a significant gap and widespread parking difficulties. Due to the substantial stock of parking facilities in urban residential areas, many private parking spaces remain unused during the daytime. This situation presents an opportunity for shared parking, utilizing the spatial and temporal distribution differences in parking demand to efficiently share spaces during various time periods. This approach aims to optimize parking resource utilization and address the prevalent issue of parking challenges[2].

In terms of parking space allocation, Shao et al. [3] employed a 0-1 model for parking space allocation, considering time window information for supply and demand. They accounted for potential losses from rejecting user demands and established an integer model focused on maximizing the management platform's profit. Sun Huijun [4] extended this by comprehensively factoring in the cost of renting parking spaces and addressing potential losses from rejecting rentals. Their integer model aimed to maximize the operator's profit. Guo [5] incorporated parking repurchase costs, introduced random constraints for profit maximization, used parking time win-

PMIS 2024, March 15-17, Changsha, People's Republic of China

DOI 10.4108/eai.15-3-2024.2346407

dow constraints for feedback, and optimized parking allocation outcomes. Yang Bo [6] simultaneously considered user walking time costs and operator revenue, introducing time window constraints and designing a timed-type shared parking space allocation 0-1 programming model based on reservation information. Arellano-Verdejo [7], analyzing demand users' parking preferences, designed a model focused on maximizing user benefits by considering walking distance after parking. Zhang Wenhui [8] aimed to minimize walking distance after parking by creating a dual-objective parking allocation model focused on maximizing utilization. They employed a particle swarm multi-objective search algorithm for effective verification.

This paper examines the relationship between the parking duration of demand users and available time windows for parking spaces, considering time window constraints. Simultaneously addressing system benefits and the walking distance of parking demand users, we've developed a calculation method to optimize user convenience. Prioritizing users with the shortest walking distance, our objective is to maximize overall system benefits. This approach ensures a scientifically rational allocation of parking spaces, effectively utilizing resources while maintaining a focus on the quality of parking services for users.

2 Analysis of Shared Parking Space Allocation Model

2.1 Description of shared parking issues

In the vicinity of office and commercial areas, numerous residential areas have surplus parking spaces during the daytime, effectively easing daytime parking challenges in the surrounding regions. Assuming residential areas open their parking spaces to the public, a shared parking management platform aggregates parking space information and availability schedules from residents. Parking demand users submit reservation information and the maximum acceptable walking distance to the platform. Using an assignment problem based on the relationship between user requests and available parking time windows, the management platform establishes a preliminary parking arrangement. Priority is then assigned to users with the shortest walking distance, aiming to maximize system benefits. Through algorithmic optimization, the optimal parking allocation results are provided as feedback to the parking demand users.

2.2 The parking space allocation model established in this study follows the following assumptions:

(1) This paper's shared parking spaces are primarily suitable for parking demand users overflowed from residential areas around commercial and office areas.

(2) This paper does not consider tripartite game relationships within the system; parking demand users and parking space supply users both adhere to the allocation management of the governing authority.

(3) Parking supply and demand strictly adhere to the submitted information, without affecting the normal use of parking spaces.

2.3 Shared parking matching model parameters

Suppose there is a shared parking lot in the research area, Let N represent the set of shared parking spaces provided by parking space providers on a given day, where $N=\{1,2,\cdots,n,\cdots,N\},n\in N$, and n denotes the parking space number. Each parking space n uploads its start time for sharing t_n^{start} and end time for sharing t_n^{end} to the shared parking system, which implies the available sharing period for parking space n as $t_n^{duration}=t_n^{end}-t_n^{start}$. Let M represent the set of parking demand users on the same day, where $M=\{1,2,\cdots,m,\cdots,M\},m\in M$, and m denotes the demand number. The arrival time of parking demand user m at the parking lot is denoted as t_m^{arr}, and the departure time is t_m^{lea}. Consequently, the parking duration for user m is given by $t_m^{duration}=t_m^{lea}-t_m^{arr}$.

As each parking space can only be allocated to one user during the same time period, different parking demand users may have conflicts in their requested time windows. Let i and j represent two parking demand users, where $i,j\in M$. If $(t_i^{arr},t_i^{lea})\cap(t_j^{arr},t_j^{lea})\neq\varnothing$, denoted by $d_{ij}=1$, it means that they cannot be assigned to the same parking space. Conversely, if there is no conflict between the two users, represented by $d_{ij}=0$, it indicates that they can be assigned to the same parking space without overlap.

When the management platform allocates shared parking spaces to parking demand users, each requested parking time must be within the shareable time window and cannot affect the normal use of the parking space provider. The relationship between parking demand user m and parking space n with respect to their time windows is represented by the variable a_{mn}. If $(t_m^{arr},t_m^{lea})\in(t_n^{start},t_n^{end})$, it indicates that parking demand user m falls within the shared time window of parking space n, allowing the manager to allocate parking space n to user m, denoted by $a_{mn}=0$. Conversely, if $(t_m^{arr},t_m^{lea})\notin(t_n^{start},t_n^{end})$, it means that parking space n cannot be used by parking demand user m, and $a_{mn}=1$ is used to represent this scenario.

This paper introduces penalty factor μ, calculated based on the parking duration of each rejected parking demand user, to assess the potential losses incurred by the platform's rejection of users.

Let p represent the income generated when the manager rents out a parking space, and b denote the price paid to the parking space provider for leasing a parking space. We introduce S_n to indicate the availability status of parking space n. When the parking space is available for rent $S_n=1$; otherwise, $S_n=0$. Additionally, we introduce x_{nm} to represent the relationship between parking space n and request m. If parking space n is assigned to meet the demand of user m, $x_{nm}=1$; otherwise, $x_{nm}=0$.

Define q as the walking time cost for parking demand users, representing the conversion of users' travel time into time value. l_p is the walking distance for user m to reach the destination,

V_{walk} is the average walking speed for parking demand users, and L_0 is the acceptable maximum walking distance.

2.4 Building a shared parking space allocation model

Considering income, cost, and potential loss, a profit maximization parking space allocation model is formulated for the parking management platform, as shown in the following formula.

$$\max f_1 = p \cdot \sum_{m=1}^{M} \sum_{n=1}^{N} t_m^{duration} x_{nm} - b \sum_{n=1}^{N} t_n^{duration} S_n - \mu \cdot \sum_{m=1}^{M} t_m^{duration} (1 - x_{nm}) \tag{1}$$

$$\sum_{n=1}^{N} x_{nm} \leqslant 1, m \in M \tag{2}$$

$$x_{ni} + d_{ij} x_{nj} \leqslant 1, i, j \in M; i \neq j; n \in N \tag{3}$$

$$x_{nm} \cdot a_{nm} = 0, n \in N; m \in M \tag{4}$$

In Equation (1), the first term denotes the revenue obtained by the manager, the second term represents the parking space rental cost, and the third term accounts for potential loss. Equation (2) stipulates that a user can be allocated at most one parking space. Equation (3) signifies that when users i and j conflict for the same parking space, they cannot be assigned to that space simultaneously. Equation (4) represents the parking time period uploaded by the user, which should fall within the shareable time period of parking space N.

Creating an optimal objective function for parking users based on walking distance.

$$\min f_2 = q. \sum_{m=1}^{M} \sum_{n=1}^{N} x_{nm} \cdot \frac{l_p}{V_{walk}} \tag{5}$$

Equation (5) denotes the optimal walking distance cost for the user.

$$l_p \leqslant l_0 \tag{6}$$

Equation (6) indicates that the user's walking distance cannot exceed $l_0 = 350m$.

Convert the double objective function of equations (1) and (5) into a single objective function:

$$\begin{aligned} \max f &= \max f_1 - \min f_2 \\ &= \max \left[p \cdot \sum_{m=1}^{M} \sum_{n=1}^{N} t_m^{duration} x_{nm} - b \sum_{n=1}^{N} t_n^{duration} S_n - \mu \cdot \sum_{m=1}^{M} t_m^{duration} (1 - x_{nm}) \right] \\ &\quad - \min \left(q. \sum_{m=1}^{M} \sum_{n=1}^{N} x_{nm} \cdot \frac{l_p}{V_{walk}} \right) \end{aligned} \tag{7}$$

3 Numerical experiments

Selecting a specific region as the target for shared parking, an analysis of the feasibility of implementing shared parking in that area is conducted. The platform operates from 7:00 to 19:00, divided into 48 intervals (T=48), each lasting 15 minutes. Operational hours commence at T=0 and conclude at T=48. The parking fee for demand users is $p = 5$ yuan per interval, parking space cost is $b = 2$ yuan per interval, and the loss coefficient is $\mu = 0.3$ yuan per interval. The walking cost for demand users is q = 35 yuan per hour, and the average walking speed is v = 5 km per hour. Partial berth information is shown in Table 1, where v_i represents the virtualization of the shared time window for berth i.

Table 1. Time window for available parking spaces

Parking space number	Parking space sharing start time	End time of parking space sharing	Shared Time Window
1	8:20	11:10	[6,16]
v_1	14:00	17:30	[28,42]
2	7:10	19:00	[1,48]
3	8:00	17:00	[4,40]
4	7:00	16:30	[0,38]
5	7:30	11:30	[2,18]
v_5	13:50	17:00	[28,40]
6	8:10	17:40	[5,42]
7	9:00	16:00	[8,36]
8	7:30	18:00	[2,44]

Parking demand users should upload available shared time windows and walking distances from the parking lot to their destination to the management platform. Some user reservation information is presented in Table 2.

Table 2. parking demand user reservation information

Parking demand number	Parking demand time window	Walking distance (m)	Parking demand number	Parking demand time window	Walking distance (m)
1	[28,42]	235	16	[24,38]	230
2	[35,39]	205	17	[28,40]	360
3	[10,17]	215	18	[10,36]	230
4	[6,38]	280	19	[2,25]	220
5	[18,40]	275	20	[32,44]	205
6	[0,20]	265	21	[7,16]	260
7	[30,42]	225	22	[28,38]	265
8	[4,34]	365	23	[2,16]	200
9	[22,36]	245	24	[29,42]	240
10	[4,30]	245	25	[6,32]	225
11	[28,40]	360	26	[20,35]	210
12	[8,40]	375	27	[24,38]	230
13	[36,48]	255	28	[28,40]	360
14	[2.8]	220	29	[12,44]	290
15	[6,15]	220	30	[30,40]	245

3.1 Experimental results

In the Python environment, a genetic algorithm was employed to numerically simulate parking space allocation, facilitating the decision-making process. The allocation results of the analysis and evaluation model were then examined. The outcomes for the example section are depicted in Figure 1.

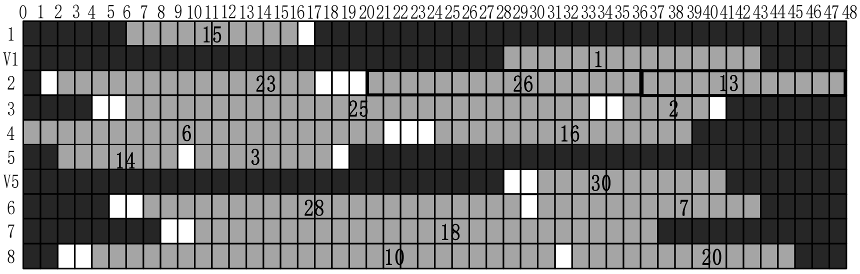

Fig. 1. parking space allocation result

As depicted in the figure and considering the parking demand user information provided in the above table, requests from users 8, 11, 12, and 17 were declined due to the constraint on maximum walking distance for parking. The platform, prioritizing both the walking distance of other users and its own profit, also rejected reservation requests from users 4, 5, 9, and others. Ultimately, allocations were made for requests from users 1, 2, 3, 6, and others. The results demonstrate that the model in this paper fulfills the majority of parking demands, achieving an 88.93% utilization rate of available parking spaces.

3.2 Comparative analysis of experimental models

To validate the model's rationality in this article and assess user convenience, a comparative analysis was carried out against a model neglecting users' walking distance. Only model equation (1) was taken into account, with the remaining parameters set identically. User comparison results are presented in Table 3.

Table 3. Model comparison analysis results

	Traditional model		Model in this article	
Parking space number	Parking demand number	Walking distance (m)	Parking demand number	Walking distance (m)
1	15	220	21	260
V_1	1	235	24	240
2	23、26、13	200、210、255	19、1、13	220、235、255
3	25、2	225、205	4	280
4	6、16	265、230	6、9	265、245
5	14、3	220、215	27	260
V_5	30	245	22	265
6	28、7	200、225	15、5	220、275
7	18	230	18	230
8	10、20	245、205	14、29	220、290
Profit (yuan)	683		657	

As indicated in the table above, in comparison to traditional allocation models, this article prioritizes user walking distance, and the final profit based on platform maximization is consistently high. The comparison results reveal that, for different users assigned to the same berth, the average walking distance of users assigned by the model in this article is lower than that of users assigned by the traditional model, enhancing user convenience.

4 Conclusions

Based on optimal perspectives from both parking demand users and the management platform, this paper establishes a parking space allocation model for residential areas. Using a genetic algorithm for simulation and verification, the model not only ensures the optimal utilization of idle parking resources but also significantly enhances user convenience. This provides a theoretical foundation for the management platform to address urban parking challenges.

However, the parking supply-demand information in the model is predefined and lacks real-time updates for reservation information. Future considerations may involve incorporating real-time arrivals to further quantify user convenience.

Acknowledgment : Fund projects: Basic Research Project of Higher Education Institutions in Liaoning Province: Research Project on Urban Shared Parking Service System Based on Game Model (LJKZ0587); Shenyang Federation of Social Sciences Foundation: Shenyang Public Service Development Strategy Service - Taking the Allocation of Shared Parking Spaces in Residential Areas of Shenyang as an Example Project (SYSK2022-01-063)

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