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Bi-level model for shared parking decision-making based on parking lot assignment simulation

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Abstract: In order to carry out comprehensive decision-making of multi-class shared parking measures within a region, a bi-level model assisting decision-making is proposed. The upper level selects parkers' average satisfaction and the violation rate during peak hours as indices in object function, and sets probability distribution models describing dynamic parking demand of each site, the feasibility of shared parking scenarios and occupancy requirements during peak hours of each parking lot as restrictions. The simulation model in the lower level sets up rules to assign each parker in the random parking demand series to the proper parking lot. An iterative method is proposed to confirm the state of each parking lot at the start of formal simulations. Besides, two patterns linking initialization and formal simulation are presented to acquire multiple solutions. The results of the numerical examples indicate the effectiveness of the model and solution methods.

Key words: shared parking; decision-making; bi-level model; simulation; iterative method

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The contradiction between supply and demand of parking is apparent in the downtown areas of large cities in China. One of the most important reasons is that not all kinds of parking resources within the region have been applied fully and properly. The relative literature shows that supply potential within the local region usually can be mined through the following four shared parking measures[1-3]: 1) Increasing the site accessory parking spaces; 2) Signing an agreement to share accessory parking lots with adjacent sites; 3) Setting curb parking spaces; 4) Constructing off-street public parking lots under the permit of land planning. These four shared parking measures have been researched individually, but the combined decision-making method of the above measures within the region is seldom explored.

Meanwhile, the above measures should be logically applied. The measure of increasing the site accessory parking spaces is often considered by the site itself, while the execution of other three measures should consider multi-site parking demand. Besides, before accounting for constructing off-street public parking lots, making accessory parking lots shared and setting curb parking spaces should be considered. So the objective of this paper is to formulate a bi-level model to assist the comprehensive decision-making of the second and third shared parking measures, on the premise that every site's accessory parking spaces have been increased.

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1 Bi-Level Decision-Making Model

The goal to implement shared parking measures is not only to relieve the regional contradiction between parking demand and supply, but also to conform to parkers' preferences to increase their satisfaction. The factors affecting the above decision-making include the dynamic features of parking demand attracted by different sites, the preference of parkers for diverse types of parking supply resources, the feasibility of shared parking measures, and so on.

Most of the theoretical studies on dynamic parking demand are in terms of the arrival and departure rate serial of parking cars, or the fluctuation of the real-time space demand serial[4-5]. The above researches mainly employ the time-serial statistical method, concentrating on the correlation of dynamic parking demand. With non-parametric tests[6] and the clustering method, the probability distributions of dynamic parking demand of various types can also be determined.

As for the parking choice preference, Waerden et al.[7-8] concluded the trip purpose, parking duration, walking distance to the destination, and parking fares as key influence factors. Yu et al.[9-10] found that the parking choice is affected by the information acquisition and should be described with random variables. Martens et al.[11] advocated that the development of a minimal but sufficient set of parking lot choice rules required both empirical data and extensive testing. Thompson et al.[12] adopted the economic search principle of expected gain in utility to represent the searching patterns of parkers in congested city centers, concluding that experience in parking searching did not lead to better car parks due to the inherently uncertain nature of the car parking system.

In terms of the feasibility of the shared parking measures, Guo[3] studied the site selection principles of off-street parking lots. Chen et al.[13] concluded the layout conditions of the curb parking spaces. Smith et al.[2, 14] summed up the conditions of making accessory parking facilities shared with each other.

Based on the existing researches, shared parking scenarios should make sure that occupancy of each parking lot be higher than a minimum requirement to realize the high-effective utilization of resources. Meantime, the feasibility of making accessory parking lots available outside, the influence curb parking spaces exert on the traffic, and parking contradiction distribution in the region should also be considered. On the premise of a particular shared parking scenario, a parker will choose a proper parking lot based on the parking lot availability, the real-time remaining number of spaces in each parking lot and his own preference.

Before formulating the model, some assumptions should be made as follows:

1) Suppose that the preference of parkers can be classified in terms of parking duration, and random variables describing parkers' preference in the same class obey the same distribution;

2) Suppose that there are not exclusive parking spaces in the region.

In conclusion, a bi-level model is proposed for the decision-making of shared parking measures. The upper level model is as follows:

$$\max G(h) = \frac{1}{M}\sum_{k=1}^{M} X_k^h - \beta t_{n-1,\alpha/2}\sqrt{\frac{S_{xh}^2(M)}{M}}$$

Let

$$X_k^h = \alpha_1 \frac{1}{n_k}\sum_{i=1}^{n_k} R_i^{hk} - \alpha_2 \frac{P_k^h W}{n_k}$$

$$S_{xh}^2(M) = \sum_{k=1}^{M}\left[\frac{1}{M}\sum_{k=1}^{M} X_k^h - X_k^h\right]^2 / (M-1)$$

$$\text{s. t.} \quad A_\alpha^\tau \sim P(\lambda_\alpha^\tau),\ D_\alpha^\tau \sim P(\beta_\alpha^\tau),\ F^h = 1$$

$$E^h = \frac{1}{M}\sum_{k=1}^{M} E_k^h - \beta t_{n-1,\alpha/2}\sqrt{\frac{S_{eh}^2(M)}{M}} \geqslant E_{\min}$$

Let

$$E_k^h = \min e_j^{hk} \qquad j = 1, 2, \ldots$$

$$S_{eh}^2(M) = \sum_{k=1}^{M}\left[\frac{1}{M}\sum_{k=1}^{M} E_k^h - E_k^h\right]^2 / (M-1)$$

where R_i^{hk} denotes the relative satisfaction of the i-th parker in the k-th random parking demand series on the chosen parking lot under the h-th shared parking scenario; P_k^h denotes the number of violating parkers in the k-th random parking demand series under the h-th shared parking scenario; W denotes the penalty coefficient for parking violation; n_k denotes the total number of parkers in the k-th random parking demand series; M denotes the number of random parking demand series applied during formal simulation period; A_α^τ denotes the arrival rate per unit time of cars attracted to the α-th site during the τ-th hour; λ_α^τ denotes the parameters of the probability distribution models describing A_α^τ; D_α^τ denotes the parking duration of the cars attracted to the α-th site during the τ-th hour; β_α^τ denotes the parameters of the probability distribution model describing D_α^τ; $F^h = 1$ denotes that the h-th shared parking scenario is feasible; e_j^{hk} denotes the occupancy of the j-th parking lot during peak hours while assigning the k-th random parking demand series under the h-th shared parking scenario; $E_{\min}$ denotes the lower limit of parking lots occupancy; α_1, α_2, β denote three weight coefficients, which can be estimated by expert scoring; $t_{n-1,\alpha/2}$ denotes the $100(1-\alpha)\%$ confidence interval; X_k^h, $S_{xh}^2(M)$, E^h, E_k^h, $S_{eh}^2(M)$ function as substitution variables, and their meaning can be referred from the right side of the formulae.

The lower level model is a parking lot assignment simulation model[15], as shown in Fig. 1.

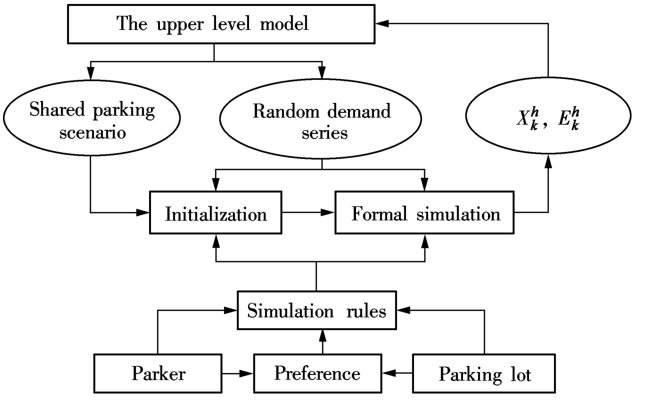

Fig. 1 Lower level of the bi-level model

In the bi-level model, the object function in the upper level mainly embraces two indices such as parkers' average satisfaction and the violation rate during peak hours. Since the initial conditions of the simulation are similar, the weighted results of the above two indices X_k^h ($k = 1, 2, \ldots, M$) can approximately be regarded to obey the same normal distribution independently[16], and one uniform point in the $100(1-\alpha)\%$ confidence interval of X^h is selected as the basis for the decision-making of shared parking scenarios. Similarly, the minimum occupancy of each available parking lots under the h-th shared parking scenario is required in the constraints of the upper level model. Other constraints of the upper level model include the probability distribution model describing the dynamic parking demand characters of each site and the feasibility restrictions of each scenario. The parameters of the probability distribution models can be estimated according to the survey. Considering that the random parking demand series obeying the same probability distribution model may exhibit differences in time serials, other statistical indices can be added to limit the random parking demand series. Besides, the feasibility variable F^h can be determined by experts and local surveys.

The lower level model is composed of four parts, including input variables, basic elements, simulation periods and output variables. Input variables consist of the h-th shared parking scenario and a number of random parking demand series. They are produced based on the constraints of the upper-level model. Output variables include X_k^h and E_k^h. Their calculation results in the lower level are needed by the upper level model. Three basic elements of the simulation model include the parker, parking lot and parkers' preference. Partial attributes of these elements are listed in Tab. 1. According to the assumptions, parkers' preferences can be classified into several types. Each type can be described as

$$P_{ij}^s = U_{ij}^s + r_{ij}^s$$

where P_{ij}^s means the preference to the j-th parking lot of the s-th type of parkers attracted to the i-th site. The meaning of U^s and r^s are listed in Tab. 1. The number of U^s and corresponding r^s depends on the classification of parking duration. The values in U^s and the probability distribution that r^s obeys can be estimated by the survey and statistical analysis. As the shared parking scenarios limit the availability of parking lots, some values in the utility matrix should be revised to zero when considering various scenarios.

Tab. 1 Partial attributes of the simulation elements

Simulation elements	Attributes	Meaning
Parker	ID	The index of the site the parker belongs to
	ARRTM	The parker's arrival time
	PKDU	The parker's parking duration
	SPID	The index of the parking lot the parker chooses
	RLSTIS	The parker's relative satisfaction
Parking lot	ID	The index of the parking lot
	TTNUM	Total number of spaces in the parking lot
	DYNUM	The real-time remaining number of spaces
	LEFTIME	The real-time left time series of the remaining cars in the parking lot
	SLEFTIME	The left time series of the remaining cars in the parking lot at the start of formal simulation
	Eff	The peak hour occupancy
Preference	U^s	The fixed utility matrix of the s-th type of parkers
	r^s	The random preference matrix corresponding to U^s

The simulation rules assigning each parker in the random parking demand series to the proper parking lot are as follows:

1) Update the DYNUM and LEFTIME of each available parking lot according to the ARRTM of the i-th parker. If one element in the LEFTIME of the j-th parking lot is smaller than the ARRTM of the i-th parker, delete the element and add one to the DYNUM of the j-th parking lot.

2) Confirm the selected U^s and r^s according to the PKDU of the i-th parker.

3) Produce random numbers based on the probability distribution model that r^s obeys to, and total utility of each parking lot available to the i-th parker can be acquired by adding the corresponding fixed utility value and random value.

4) Sort the available parking lots descendent according to the total utility, and traverse the DYNUM of parking lots in a sequence.

5) Select the parking lot whose total utility is greater than others when the DYNUM is more than zero, and update its relative attributes. Let SPID of the i-th parker be the ID of the chosen parking lot; let the RLSTIS of the i-th parker be the total utility of the chosen parking lot divided by the maximum total utility of available parking lots; let the DYNUM of the chosen parking lot decrease by one; add one element to the LEFTIME of the chosen parking lot, which usually amounts to the ARRTM plus the PKDU of the i-th parker.

6) If the DYNUM of all available parking lots are equal to zero, the i-th parker selects violation. Thus, let the SPID of the i-th parker be -1 and let its RLSTIS be zero.

The differences between the initialization and formal simulation periods lie in their purpose and process. The aim of initialization is to acquire the initial state of parking lots at the start of the formal simulation while the goal of the latter period is to calculate the value of X_k^h and E_k^h. Besides, the number of attributes needed to be updated during the initialization is less than the formal simulation.

2 Algorithm

As the number of sites and road links within the region is limited, the amount of drafted shared parking scenarios restricted to the constraints of the upper level model is countable. Therefore, the enumeration method can be used in solving this bi-level model by computing the object function value under each shared parking scenario. So the key point is the design of the algorithm used in the simulation.

Suppose that START indicates the start time of formal simulation, and [BEGIN, FINISH] denotes the main period that the dynamic parking cars arrive within a day. Normally, START $\in$ [BEGIN, FINISH]. Considering that the state of each parking lot at the START point will be influenced by the choice of parkers arriving before, an iterative method is proposed, and the detailed steps are as follows:

1) Produce a random parking demand series according to the probability models in the upper level model, and sort parkers in the series in an ascending sequence according to their ARRTM.

2) Assign all the parkers successively according to the assigning simulation rule, during which endow the SLEFTIME of each parking lot with the LEFTIME at the START point.

3) At the FINISH point, delete the elements of the LEFTIME of each parking lot which are smaller than BEGIN plus 24 h, and decrease the remaining elements of the LEFTIME by 24 h.

4) Recycle from the BEGIN point, and keep on assigning the parkers in the same random parking demand series until the process comes to the START point for the second time.

5) Compute the matching degree index β_j of each parking lot as the following formula,

$$\beta_j = \frac{S(\text{LEFTIME}_j,\ \text{SLEFTIME}_j)}{L(\text{LEFTIME}_j,\ \text{SLEFTIME}_j)}$$

where $S(\text{LEFTIME}_j, \text{SLEFTIME}_j)$ means the number of identical elements in LEFTIME and SLFTIME of the j-th parking lot; $L(\text{LEFTIME}_j, \text{SLEFTIME}_j)$ denotes the maximum number of elements in LEFTIME and SLFTIME of the j-th parking lot.

6) Let β denote the minimum matching degrees of all the available parking lots. If β is greater than the lower threshold ε, the LEFTIME and DYNUM of each parking lot can be regarded as the initial state at the start of the formal simulation and the initialization period concludes. Else, switch to step 7).

7) Endow the SLEFTIME of each parking lot with their respective LEFTIME, and assign parkers in the same series from the START point to the FINISH point. Then switch to step 3).

8) After a certain number of iterations, if β is still smaller than ε, it indicates that the initial state of each parking lot is not stable. Then transfer the latest LEFTIME and DYNUM of each parking lot to the formal simulation and initialization concludes.

After initialization, formal simulation will obtain three indices, which are the violation rate, the average relative satisfaction of parkers and the occupancy during peak hours. The calculation of the violation rate and the average relative satisfaction of parkers depend on the update results of the SPID and RLSTIS attributes of parkers in the random parking demand series whose ARRTM is in the interval of the formal simulation period. Meanwhile, the calculation of occupancy not only depends on the PKDU of parkers, but also depends on the LEFTIME attributes of each parking lot at the START point. As the computation of the above three indices is related to the results of initialization, two patterns linking initialization and formal simulation are presented, as shown in Fig. 2. The first pattern is suitable for the unstable initial state of parking lots at the START point, during which only one random parking demand series is input into initialization. Continue the iteration of initialization for several times and use a maximum iteration number as the stopping criterion each time. Therefore, several initial states of each parking lot at the START point are acquired. In the formal simulation period, multi random parking demand series whose ARRTM is in the interval of the formal simulation period are input on the basis of each initial state separately and multi groups of indices are obtained. The second pattern inputs several random parking demand series into the initialization period, and acquires several states of each parking lot, in allusion to which the method of clustering analysis is used to obtain the boundary of standard initial states. Those initial states within the boundary are input into the formal simulation period, only with the sub-set of parkers from their corresponding random parking demand series whose ARRTM are in the interval of the formal simulation period, and several groups of indices are obtained. No matter which pattern is applied, the comparison of multi shared parking scenarios will use the same pattern and random parking demand series.

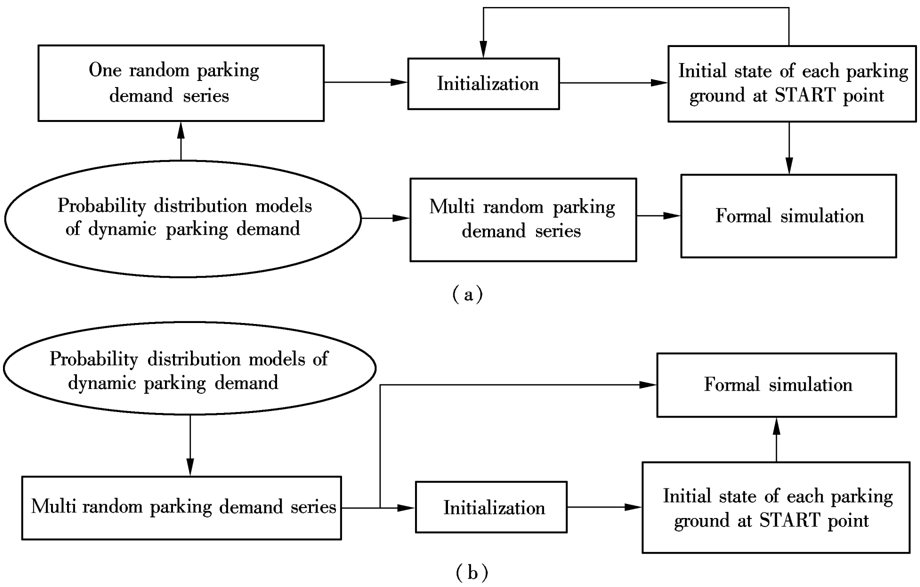

Fig. 2 Two patterns linking initialization and formal simulation. (a) Link pattern one; (b) Link pattern two

3 Numerical Example

The bi-level model and its solution method are applied in a numerical example as shown in Fig. 3. In this region, there are four sites with the accessory parking lots which are not available to the parkers belonging to other sites. These sites are separated by four links, within which public parking space can be disposed. The arrival rate per 2 minutes of cars attracted to park at each site between 8: 00 and 22: 00 obeys the Poisson distribution, and the parking duration of cars arriving in each hour obeys the Gamma distribution. The parameters of each probability distribution model are

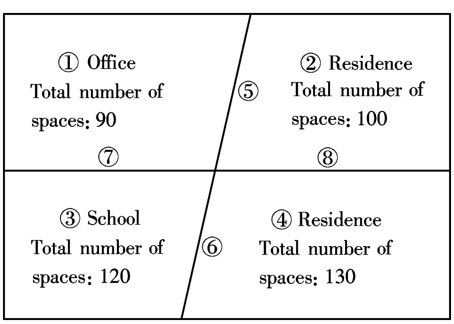

Fig. 3 Numerical example

listed in Tab. 2, which are referred to in the similar surveyed samples. Four feasible shared parking scenarios are drafted after considering the distribution of the parking contradictions, the execution difficulties of signing the shared parking contract between accessory parking lots, room competition between the road traffic and parking demand, as shown in Tab. 3.

Parkers' preference is classified into three types according to parking duration. The first type is that parkers' PKDU is less than 0. 5 h. The second is between 0. 5 h and 2 h while the third is more than 2 h. Three utility matrices $\boldsymbol{U}^s$ and the probability distribution models that their corresponding r^s obeys are listed as follows:

$$\boldsymbol{U}^1 = \begin{bmatrix} 65 & 50 & 50 & 30 & 94 & 80 & 94 & 80 \\ 50 & 65 & 30 & 50 & 94 & 80 & 80 & 94 \\ 50 & 30 & 65 & 50 & 80 & 94 & 94 & 80 \\ 30 & 50 & 50 & 65 & 80 & 94 & 80 & 94 \end{bmatrix}, \quad r^1 \sim U(0,5)$$

$$\boldsymbol{U}^2 = \begin{bmatrix} 85 & 70 & 70 & 60 & 80 & 65 & 80 & 65 \\ 70 & 85 & 60 & 70 & 80 & 65 & 65 & 80 \\ 70 & 60 & 85 & 70 & 65 & 80 & 80 & 65 \\ 60 & 70 & 70 & 85 & 65 & 80 & 65 & 80 \end{bmatrix}, \quad r^2 \sim U(0,10)$$

$$\boldsymbol{U}^3=\begin{bmatrix}94 & 80 & 80 & 70 & 60 & 50 & 60 & 50\\ 80 & 94 & 70 & 80 & 60 & 50 & 50 & 60\\ 80 & 70 & 94 & 80 & 50 & 60 & 60 & 50\\ 70 & 80 & 80 & 94 & 50 & 60 & 50 & 60\end{bmatrix},\quad r^3\sim U(0,5)$$

As for the h-th scenario, when the parking lot j is not available to parkers attracted to site i, $U_{ij}^s=0$.

The period between 9:00 and 12:00 is confirmed as the formal simulation period according to the superimposed dynamic space demand curves. Referring to the relative researches, suppose that $\varepsilon=0.9$, $\alpha_1=0.3$, $\alpha_2=0.7$, $\beta=0.5$, $W=100$, $E_{\min}=30\%$. With Matlab programming, 100 groups of random demand series are input under the first link pattern, and 100 groups of X_k^h and E_k^h are acquired, as shown in Fig. 4.

The values of object function and the expected values of E^h under four shared parking scenarios are as follows: $G(h_1)=0.273$, $E(h_1)=37.38\%$; $G(h_2)=0.271$, $E(h_2)=$

Tab. 2 Probability distribution parameters of dynamic parking demand

Periods	λ_i				α_i				β_i			
	$i=1$	$i=2$	$i=3$	$i=4$	$i=1$	$i=2$	$i=3$	$i=4$	$i=1$	$i=2$	$i=3$	$i=4$
8:00—9:00	1.7	0	2.1	0	3.7	0	3.3	0	78.7	0	80.5	0
9:00—10:00	2.5	0.1	2.5	0.2	2.6	2.9	2.1	3.2	95.7	21.4	105.7	25.4
10:00—11:00	1.7	0.2	1.8	0.5	1.7	4.8	1.5	4.9	121.5	18.4	125.3	19.5
11:00—12:00	1.2	1.2	1	1.3	1.4	33.8	1.5	33.8	98.2	3.2	85.3	3.3
12:00—13:00	0.8	1.1	0.6	1.1	1.1	17.7	1.1	18.7	60.3	4.2	65.4	4.5
13:00—14:00	1.4	0.6	0.9	0.5	1.1	17.9	1.1	17.5	139.5	4.5	130.6	4.8
14:00—15:00	1.8	0.1	0.9	0.2	1.1	17.5	1.1	17.9	98.5	4.2	85.6	5.2
15:00—16:00	1	0.7	0.8	0.5	1.1	265.9	1.1	270.5	67.5	3.7	57.3	3.5
16:00—17:00	0.9	0.8	0.7	0.8	1.1	242.5	1.1	240.3	71.3	3.9	64.5	4.2
17:00—18:00	0.2	1.1	0	1.2	1.2	220.2	0	225.2	118.4	4.1	0	4.1
18:00—19:00	0.4	1.1	0.1	1.2	1.2	192.1	1.2	190.2	98.7	4.3	93.5	4.8
19:00—20:00	0.4	0.2	0.7	0.2	1.1	172.3	1.7	170.2	101.3	4.6	105.2	4.4
20:00—21:00	0	0.2	0	0.2	0	151.6	0	153.3	0	4.9	0	4.5
21:00—22:00	0	0.3	0	0.5	0	128.4	0	122.9	0	5.4	0	5.2
22:00—23:00	0	0.3	0	0.2	0	114.1	0	110.4	0	5.6	0	5.7

Notes: λ_i refers to the parameter of the Poisson distribution of the arrival rate of cars attracted to the i-th site; α_i, β_i refer to the parameters of the Gamma distribution of parking duration of cars attracted to the i-th site.

Tab. 3 Four drafted shared parking scenarios in Fig. 3

Scenario	Shared parking scenario
1	Site ① and Site ② share the accessory parking lots through signing contract; Site ③ and Site ④ share the accessory parking lots through signing contract; Dispose 20 spaces on Link ⑤ and Link ⑥, respectively
2	Site ① and Site ④ share the accessory parking lots through signing contract; Site ② and Site ③ share the accessory parking lots through signing contract; Dispose 20 spaces on Link ⑤ and Link ⑥, respectively
3	Site ① and Site ② share the accessory parking lots through signing contract; Site ③ and Site ④ share the accessory parking lots through signing contract; Dispose 30 spaces on Link ⑦ and Link ⑧, respectively
4	Site ① and Site ④ share the accessory parking lots through signing contract; Site ② and Site ③ share the accessory parking lots through signing contract; Dispose 30 spaces on Link ⑦ and Link ⑧, respectively

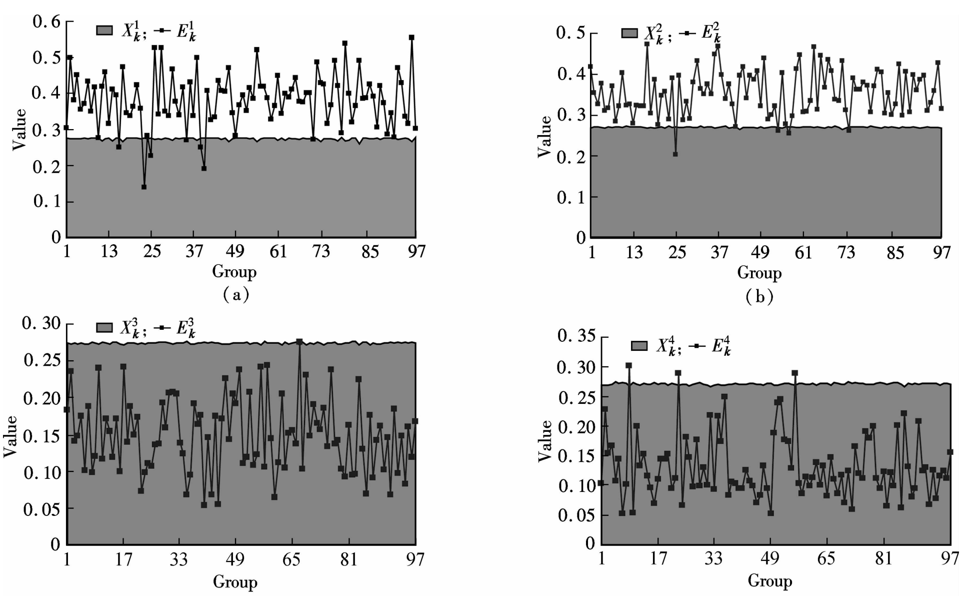

Fig. 4 100 groups of X_k^h and E_k^h under four scenarios. (a) Scenario 1; (b) Scenario 2; (c) Scenario 3; (d) Scenario 4

35.25%; $G(h_3)=0.274$, $E(h_3)=14.63\%$; $G(h_4)=0.271$, $E(h_4)=12.89\%$. The results show that the expected E^h of scenario 3 and scenario 4 are less than $E_{\min}$, which indicates that the minimum occupancy rate under scenario 3 and scenario 4 are too low. Compared with scenario 2, the objective function value of scenario 1 is greater, indicating that the comprehensive effect of scenario 1 is better. So shared parking measures in scenario 1 are chosen.

4 Conclusion

The proposed bi-level model comprehensively considers factors such as parkers' preference, the feasibility of shared parking scenarios, the dynamic distribution of parking demand and the random characteristics of partial factors. In solving the model, the proposed iterative method can be adopted to confirm the state of each parking lot at the start of formal simulation. Besides, two patterns linking initialization and formal simulation are presented to acquire multiple solutions. The results of the numerical examples show that the model and solution methods are effective.

However, the model is only suitable in the situation that there are few parking space specified to individuals. This is not always the case in all local regions. So research on the influence of exclusive space on the parker's choice may lay a foundation for the wider application of the proposed bi-level model. Besides, the preference of parkers to parking lots can further be classified by multi factors according to the local survey data.

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基于停车泊位配置仿真的停车共享措施双层决策模型

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摘要:为了在区域范围内进行多种停车共享措施的综合决策,建立了双层辅助决策模型.上层模型选择停车者平均满意度、高峰时段违章率作为目标函数指标,将各建筑物的动态停车需求概率分布、拟实施共享方案的可行性以及各停车场高峰时段的泊位占有率要求作为约束条件.下层的仿真模型中设置了仿真规则,将随机停车序列中的个体配置到合适的停车设施中.提出了确定正式仿真开始时刻各停车场状态的迭代方法,同时明确了初始化阶段和正式仿真阶段衔接的2种模式.算例结果表明,该模型和求解算法的应用效果良好.

关键词:停车共享;决策;双层模型;仿真;迭代方法

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