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Research Papers - Modelling the dynamic one-way car sharing system

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Abstract

The one-way car sharing scheme allows users to return a rented car to any designated spot, which may be different from the origin station. The existing studies mainly focus on the vehicle relocation problem in order to deal with the travel demand fluctuation over time and demand imbalance in space. However, the strategic plan for the station deployment and its capacity design for the one-way car sharing have not been well studied, especially when taking the vehicle relocation into consideration. To solve the car-sharing station location and capacity problem, this paper developed a Mixed-integer Non-linear Programming (MINLP) model. Firstly, the relocation operation and relocation cost are taken into consideration to address the imbalance between demand and availability of vehicles in different time steps, which is a key part in car sharing dispatch. Secondly, the flexible travel demand based on the different time steps are taken as the inputs to the dynamic optimization model. Thirdly, the elastic service rate is constructed using the ratio of car sharing utility and private car utility. An illustrative example is constructed to demonstrate the effectiveness of the model and to draw insights on policy implications to promote car sharing.

Keywords: One-way car sharing; Relocation; Station Location; Dynamic travel demand

1. Introduction

Traffic congestion and traffic-related air pollution are regarded as the two main traffic issues in the urbanization process due to the quick growth of private cars (Beckmann, 2013; Shekarrizfard et al., 2016). The increasing car ownership imposes great pressure on parking in urban areas. Hence, reducing the adoption of private cars may be an effective measure to alleviate traffic congestion, reduce traffic-related air pollutions and save land resources. Car sharing was first proposed and adopted in the 1940s, which aimed to save travel cost when the oil price rose. A representative example is the “Sefage” in Zurich, Switzerland in 1948 (Correia and Antunes, 2012). It is a non-governmental club consisting of citizens who were willing to share vehicles with less payment. This earliest sharing mode was only limitedly used by a small number of club members. Car sharing started to become popular in Europe and USA in the 1980s (Jorge et al., 2015). By October 2012, there had been 27 counties operating car sharing with around 1,788,000 members and over 43,550 vehicles (Susan and Cohen, 2013). In recent years, car sharing is becoming more attractive due to its high speed and comfort level. Kaspi et al. (2014) pointed out that car sharing can be a bridging mode in between private cars and public transportation. The shared car has a higher utilization rate than the private car and causes less air pollution, especially when using an Electric Vehicle

(EV) (Jorge et al., 2015; herbawi et al., 2016). Besides, low price and flexible car-return stations encourage citizens to choose car sharing.

Car sharing can be divided into two categories: round-way and one-way, based on the operation mode (Shaheen et al., 2015; Boyacı et al., 2017). Traditional car rental company provides round-way car sharing services, in which the vehicle should be returned to the original rental station and is charged on daily rates. One-way car sharing allows users to return the vehicle to any designated spot, and is usually charged based on a combination cost of time in minutes and distance. Hence, one-way car sharing can attract more potential users like commuters. Regarding the service mode, most car renting demand can be met in the round-way car sharing scheme. However, due to the dynamic demand from hour to hour, the one-way car sharing scheme cannot provide service for all potential users when the parking vehicles are not enough. Moreover, round-way car sharing operators usually select a small number of hubs (e.g. airport) to store a large amount of vehicles. Whereas in the one-way car sharing companies tend to deploy more stations with less vehicles in an urban area to reduce the walking distances for potential customers. Due to the significant improvement in customer convenience, one-way car sharing is witnessing its popularity with new companies (e.g., Car2go, GoGet and Hertz 24/7) quickly emerging all over the world. In the early stage, the operation companies are currently focusing on market penetration to attract more potential users, yet with challenges from planning to operation.

The first challenge comes from the operation side. Taking the commuting as an example, commuters need to drive to companies but cannot return sharing cars to original rental stations in a short time. Hence, operators need to spend more money and time on relocation operation. Considering the imbalance between the demand and the availability of vehicles, the relocation problem should be studied in the one-way car sharing (Bruglieri et al., 2017). Jorge et al. (2014, 2015) developed a minute-by-minute relocation operational model to reduce the vehicle imbalances across the stations. In 2014, Bruglieri et al. established a Mixed Integer Linear Programming (MILP) model to solve the macroscopic inter zone relocation problem and microscopic inter zone relocation problem of EV sharing. To optimize the EV sharing problem, Weikl and Bogenberger (2015a, 2015b) proposed a practice-ready relocation model for free-floating car sharing systems based on the case in Munich, Germany. In 2017, Boyacı et al. developed an integrated framework to optimize operational decisions related to vehicle and relocation personnel relocation decisions considering both the inter-relocation cost and intra-relocation cost.

Another challenge in one-way car sharing lies in the demand loss when there are not enough parking cars in spots. To maximize the total profit, operators need to weight the relocation cost and the car sharing income (Nair and Miller-Hooks, 2011; Boldrini et al., 2016). Nourinejad and Roorda (2014) introduced a dynamic model to maximize the total profit by servicing partial car sharing demand rather than all the demand. Jorge et al. (2015) developed a Mixed-integer Non-linear Programming (MINLP) based on elastic pricing to strike a balance between demand and supply at each station. In this model, the travel demand is assumed to drop with the car sharing price. The optimal dynamic pricing is obtained when no relocation is needed.

We consider a one-way car sharing operator who intends to enter the market by deploying car-sharing stations in a region. The operator aims to maximize the total profit by optimizing the long term resource allocation (the car sharing station location and the total number of cars) as well as the short term operation strategies (car relocation and dynamic pricing). On the other hand, customers' demand is influenced by the travel cost (sharing fee) and car availability. This paper aims to provide a mathematical model to solve the station location and capacity determination of one-way car sharing problem. The main contributions of the paper are:

- It is an innovative one-way car sharing method, which considers the relocation operation and relocation cost in the optimization procedure;
- It is based on the dynamic travel demand, where the travel demand between different traffic zones fluctuate over time;
- The flexible service rate is proposed, which is constructed using the ratio of car sharing utility and private car utility.

The remainder of this paper is organized as follows. In Section 2, the dynamic one-way car sharing model is introduced. Section 3 presents the case of simple traffic network including the flexible travel demand and travel time. And the optimized model is solved through the solver of MINOS in AMPL. In Section 4, policy implications of the one-way car sharing scheme are investigated. Conclusions are drawn in Section 5.

2. Model formulation

2.1. Assumptions

This model is established to optimize the one-way car sharing scheme. The following assumptions are made to formulate this problem:

- Customers do not need to return sharing cars to the original stations;
- Not all the travel demand should be satisfied and the elastic service rate is constructed using the ratio of car sharing utility and private car utility;
- The relocation operation must be taken when the actual number of vehicles is lower than the demand in the next time step in each station;
- The travel demand is dynamic in different time steps.

2.2. Variable definitions

The decision variables used in our model are as follows:

$P_{i,j}^{t}$	Proportion of covered car sharing service from station i to station j in time step t
$N_{i,j}^{t}$	Number of sharing cars relocation from station i to station j in time step t
S_i	Number of parking spots in station i
V_i^t	Number of sharing cars in station i at the beginning of time step t
X_i	Binary decision variable that equals 1 if the station in station i is open, and 0 otherwise

The input parameters used in our model are as follows:

c_d	Depreciation cost of one vehicle (the sharing car and private car) per day
c_m	Cost of maintaining one vehicle (the sharing-car and private car) per day
$c_{p^{pc}}$	Parking charge of one vehicle (private car) per trip
c_p	Parking charge of one spot (car sharing) per day
c_w	Cost of walking (car sharing) per trip
i	Origin station, $i \in J$, $i \neq j$
j	Destination station, $j \in J$, $i \neq j$
J	Set of stations
M	A large positive value
r	Charge rate of car sharing per time step
r_o	Cost rate of oil consumption per time step
r_r	Cost rate of relocation per time step
$q_{i,j}^t$	Travel demand between the OD pair (i, j) in the step time t .
$tr_{i,j}^t$	Relocation travel time, in time steps, from station i to station j departing at time t
$tt_{i,j}^t$	Travel time, in time steps, from station i to station j departing at time t
T	Set of time steps
α	Coefficient influencing the value of potential proportion

The auxiliary variables used in our model are follows:

$P_{i,j}^{t,cs}$	Potential proportion of travelers taking car sharing between the OD pair (i, j) in the step time t
$U_{i,j}^{t,cs}$	Utility of car sharing between the OD pair (i, j) in the step time t
$U_{i,j}^{t,pc}$	Utility of private cars between the OD pair (i, j) in the step time t

2.3. Dynamic model

$$Max\ \theta = \left\{ \sum_{t \in T} \sum_{i,j \in J} \left[P_{i,j}^t \cdot q_{i,j}^t \cdot \left(r - r_o \right) \cdot tt_{i,j}^t \right] - \sum_{t \in T} \sum_{i,j \in J} \left[N_{i,j}^t \cdot r_r \cdot tr_{i,j}^t \right] - (c_m + c_d) \cdot \sum_{i \in J} V_i^1 - c_p \cdot \sum_{i \in J} S_i \right\} \quad (1)$$

Subject to:

$$V_i^t - \sum_{j \in J} q_{i,j}^t \cdot P_{i,j}^t - \sum_{j \in J} N_{i,j}^t + \sum_{j \in J} q_{j,i}^{t+1-\lceil tt_{i,j}^t \rceil} \cdot P_{j,i}^{t+1-\lceil tt_{i,j}^t \rceil} + \sum_{j \in J} N_{j,i}^{t+1-\lceil tr_{i,j}^t \rceil} \geq \sum_{j \in J} q_{i,j}^{t+1} \cdot P_{i,j}^{t+1} + \sum_{j \in J} N_{i,j}^{t+1} \quad \forall i \in J \quad \forall t \in T \tag{2}$$

$$V_i^t \geq \sum_{j \in J} \left(q_{i,j}^t \cdot P_{i,j}^t + N_{i,j}^t \right) \quad \forall i \in J \quad \forall t \in T \tag{3}$$

$$X_i \leq S_i \leq M \cdot X_i \quad \forall i \in J \tag{4}$$

$$S_i \geq V_i^t \quad \forall i \in J \tag{5}$$

$$P_{i,j}^{t,cs} = \frac{e^{\alpha \cdot U_{i,j}^{t,cs}}}{e^{\alpha \cdot U_{i,j}^{t,cs}} + e^{U_{i,j}^{t,pc}}} \quad \forall i, j \in J \quad \forall t \in T \tag{6}$$

$$U_{i,j}^{t,cs} = -tt_{i,j}^t \cdot r - c_w \quad \forall i, j \in J \quad \forall t \in T \tag{7}$$

$$U_{i,j}^{t,pc} = -tt_{i,j}^t \cdot r_o - c_{p^{pc}} - c_m - c_d \quad \forall i, j \in J \quad \forall t \in T \tag{8}$$

$$P_{i,j}^{t,cs} \geq P_{i,j}^t \quad \forall i, j \in J \quad \forall t \in T \tag{9}$$

$$P_{i,j}^t \geq 0 \quad \forall i, j \in J \quad \forall t \in T \tag{10}$$

$$V_i^t \geq 0 \quad \forall i \in J \quad \forall t \in T \tag{11}$$

$$X_i \in \{0,1\} \quad \forall i \in J \tag{12}$$

The objective function (1) is to maximize the operating profit, which consists of operating incomes, relocation costs, vehicle depreciation and maintaining costs, and parking station rent costs.

The model comprises 11 sets of constraints. Constraint (2) defines the minimum number of sharing cars in station i in the time step t. It is the balance of the number of existing cars at the beginning of time step t, the number of renting cars leaving station i in time step t, the number of relocating cars leaving station i in time step t, the number of renting cars entering station i between time steps t and $t+1$, the number of relocating cars entering station i between time steps t and $t+1$, the number of renting cars leaving station i in time step $t+1$, and number of relocating cars entering station i in time step $t+1$. Constraint (3) ensures that the number of sharing cars is larger than the sum of the satisfied car sharing demand and the relocating sharing cars leaving at each station. Constraint (4) and (5) define the relationship between the station and its spots. Constraint (6) defines the potential proportion of car sharing travel demand when providing the car sharing service. Constraints (7) and (8) define the utility function of sharing car and private car, respectively. Constraint (9) ensures that the potential car sharing travel demand is larger than the satisfied travel demand. Constraints (10)-(12) specify the domain of decision variables.

3. Numerical studies

3.1. Study data

According to the survey, input parameters are given. Figure 1 shows the travel cost and cost rates.

Table 1: The inputs of travel cost and cost rates

Parameters	c_d	c_m	$c_{p^{pc}}$	c_p	c_w	r	r_o	r_r	α
Values	4	4	10	25	1	160	10	7	1

As shown in Table 1, the unit of travel cost of c_d, c_m, $c_{p^{pc}}$ and c_p is Yuan/day·vehicle, the unit of c_w is Yuan/trip, and the unit of r, r_o and r_r is Yuan/time step.

Then, a simple traffic network with 4 zones and 3 time steps is given. Figure 1 demonstrates the traffic network with the travel time shown along the link. Suppose that the shortest travel time is used and it is fixed in different time steps.

Figure 1: The traffic network

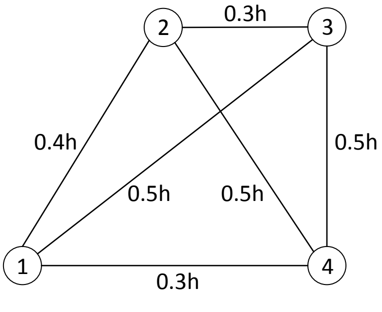


Table 2 shows the detailed information, which includes the OD demand data in each time step, the travel time and relocation travel time. In this case study, both of the travel time and relocation travel time are equal to the shortest travel time. We can see that the travel demand in the same OD pair at different time steps could be different, which incurs demand/supply imbalance.

Table 2: The inputs of travel cost and cost rates

t	i	j	$q_{i,j}^{t}$	$tt_{i,j}^{t}$	$tr_{i,j}^{t}$
1	1	2	40	0.5	0.5
	1	3	20	0.4	0.4

	1	4	30	0.3	0.3
	2	1	3	0.5	0.5
	2	3	5	0.3	0.3
	2	4	8	0.2	0.2
	3	1	2	0.4	0.4
	3	2	10	0.3	0.3
	3	4	30	0.5	0.5
	4	1	20	0.3	0.3
	4	2	10	0.5	0.5
	4	3	15	0.5	0.5
2	1	2	30	0.5	0.5
	1	3	18	0.4	0.4
	1	4	24	0.3	0.3
	2	1	3	0.5	0.5
	2	3	4	0.3	0.3
	2	4	6	0.2	0.2
	3	1	1	0.4	0.4
	3	2	8	0.3	0.3
	3	4	25	0.5	0.5
	4	1	18	0.3	0.3
	4	2	8	0.5	0.5
	4	3	12	0.5	0.5
3	1	2	60	0.5	0.5
	1	3	30	0.4	0.4
	1	4	35	0.3	0.3
	2	1	5	0.5	0.5
	2	3	8	0.3	0.3
	2	4	10	0.2	0.2
	3	1	2	0.4	0.4
	3	2	15	0.3	0.3
	3	4	40	0.5	0.5
	4	1	30	0.3	0.3
	4	2	15	0.5	0.5
	4	3	20	0.5	0.5

3.2. Model solving

The optimized model is run in an i7 processor @ 2.4 GHz, 8.00 Gb RAM computer under a Windows 7 64 bit operation system using Ampl, and the solver of MINOS is used to solve the MINLP model.

3.3. Results

After 97 iterations, the optimized result was obtained as shown in Tables 3.

Table 3: The study result 1

t	i	j	$q_{i,j}^t$	$tt_{i,j}^t$	$tr_{i,j}^t$	$P_{i,j}^t$	$N_{i,j}^t$	$P_{i,j}^{t,cs}$	$U_{i,j}^{t,cs}$	$U_{i,j}^{t,pc}$
1	1	2	40	0.5	0.5	0.73	0	0.73	-11	-47
	1	3	20	0.4	0.4	1.00	0	1.00	-9	-46
	1	4	30	0.3	0.3	1.00	0	1.00	-7	-45
	2	1	3	0.5	0.5	0.73	0	0.73	-11	-47
	2	3	5	0.3	0.3	1.00	0	1.00	-7	-45
	2	4	8	0.2	0.2	0.98	0	1.00	-5	-44
	3	1	2	0.4	0.4	1.00	0	1.00	-9	-46
	3	2	10	0.3	0.3	1.00	0	1.00	-7	-45
	3	4	30	0.5	0.5	0.73	0	0.73	-11	-47
	4	1	20	0.3	0.3	1.00	0	1.00	-7	-45
	4	2	10	0.5	0.5	0.73	0	0.73	-11	-47
	4	3	15	0.5	0.5	0.73	0	0.73	-11	-47
2	1	2	30	0.5	0.5	0.73	0	0.73	-11	-47
	1	3	18	0.4	0.4	1.00	0	1.00	-9	-46
	1	4	24	0.3	0.3	1.00	0	1.00	-7	-45
	2	1	3	0.5	0.5	0.73	10	0.73	-11	-47
	2	3	4	0.3	0.3	1.00	0	1.00	-7	-45
	2	4	6	0.2	0.2	0.97	0	1.00	-5	-44
	3	1	1	0.4	0.4	1.00	4	1.00	-9	-46
	3	2	8	0.3	0.3	1.00	0	1.00	-7	-45
	3	4	25	0.5	0.5	0.73	0	0.73	-11	-47
	4	1	18	0.3	0.3	1.00	16	1.00	-7	-45
	4	2	8	0.5	0.5	0.73	0	0.73	-11	-47
	4	3	12	0.5	0.5	0.73	0	0.73	-11	-47

3	1	2	60	0.5	0.5	0.73	0	0.73	-11	-47
	1	3	30	0.4	0.4	1.00	0	1.00	-9	-46
	1	4	35	0.3	0.3	0.93	0	1.00	-7	-45
	2	1	5	0.5	0.5	0.73	0	0.73	-11	-47
	2	3	8	0.3	0.3	1.00	0	1.00	-7	-45
	2	4	10	0.2	0.2	1.00	0	1.00	-5	-44
	3	1	2	0.4	0.4	1.00	0	1.00	-9	-46
	3	2	15	0.3	0.3	0.15	0	1.00	-7	-45
	3	4	40	0.5	0.5	0.73	0	0.73	-11	-47
	4	1	30	0.3	0.3	0.76	0	1.00	-7	-45
	4	2	15	0.5	0.5	0.73	0	0.73	-11	-47
	4	3	20	0.5	0.5	0.73	0	0.73	-11	-47

The proportion is no less than the ratios of utility functions’ exponents according to Constraint (6). For the relocation, there are three relocation operations in this optimization. The relocation occurs at the second time trip from zone 2 to zone 4, from zone 3 to zone 1, and from zone 4 to zone 1.

Furthermore, the number of sharing cars, the number of parking spots and state of stations are shown in Table 4 and Table 5.

Table 4: Number of available cars in each station

i	t	V_i^t
1	1	119
2	1	15
3	1	34
4	1	38
1	2	119
2	2	22
3	2	34
4	2	48
1	3	105
2	3	22
3	3	34
4	3	48

Table 5: Station location and capacity

i	S_i	X_i
1	119	1
2	22	1
3	34	1
4	28	1

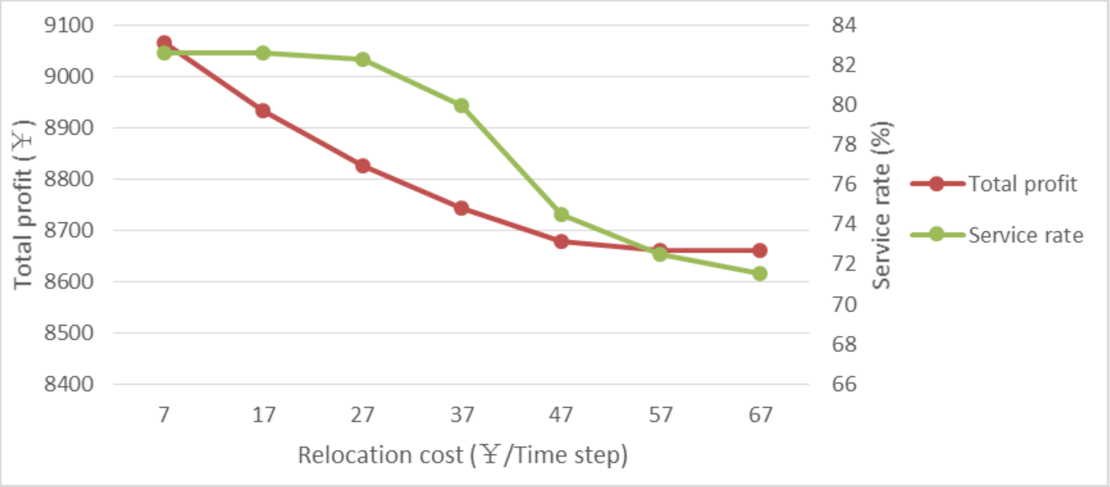
The number of sharing cars in each station in each time step is given in Table 4. In the first time step, V_1^1, V_2^1 and V_3^1 refer to the initial vehicle deployment before the system operation. In Table 5, the number of parking spots in each station and state of each station are obtained. S_1, S_2, S_3 and S_4 define the number of parking spots which are 119, 22, 34 and 28, respectively.

4. Policy implications

4.1. Relocation problem

In the case study discussed in Section 3, the relocation cost is equal to ￥7 per time step. To understand how the relocation cost influences the car sharing scheme, the cost is increased from 7 to 67 (other input parameters are fixed). When the relocation cost is equal to 67, the relocation operation is not needed any more. Figure 2 indicates the result of relocation cost's sensitivity analysis.

Figure 2: The total profit and service rate based on relocation cost



The relocation cost and total profit are negatively correlated. When the relocation cost increases from ￥7 to ￥67 per time step, the total profit reduces from ￥9064 to ￥8661. Also, there is a negative correlation between the relocation cost and service rate. When the relocation cost increases from ￥7 to ￥67 per time step, the service rate reduces to 82.60%

from 72.54%. It indicates that the operator can service less travel demand when the operation cost becomes higher.

Table 6 lists the optimized results, which includes the number of vehicles arranged at the beginning of the first time step, the number of parking spots in each zone and the relocation operation.

Table 6: The optimized results based on car sharing pricing

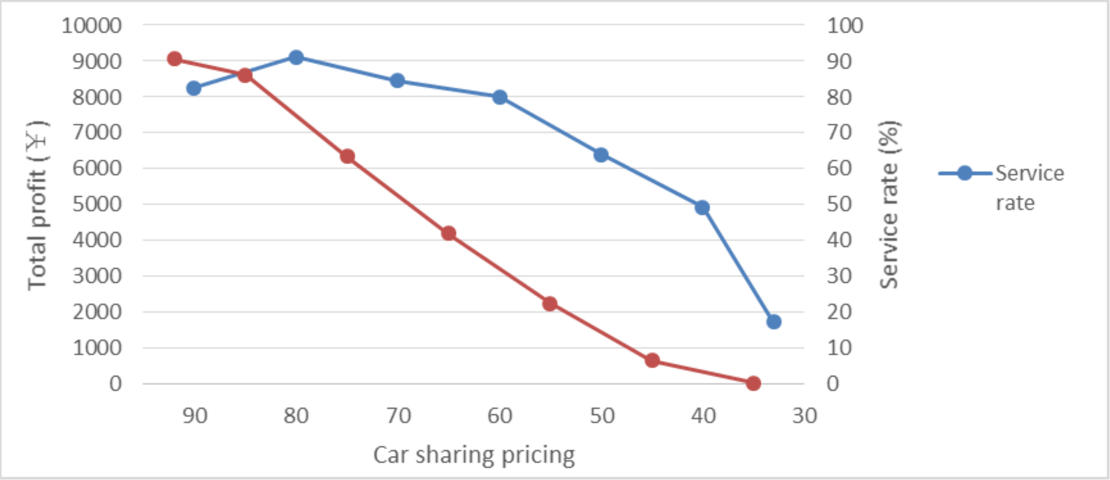
Relocation Pricing	Number of arranged cars				Number of parking spots				Relocation operation			
	Z1	Z2	Z3	Z4	Z1	Z2	Z3	Z4	*t*	*i*	*j*	No.
7	119	15	34	39	119	22	34	49	2	2	1	10
									2	3	1	4
									2	4	1	16
17	119	23	42	55	119	23	42	55	2	2	1	10
									2	3	1	4
									2	4	1	16
27	119	23	42	55	119	23	42	55	2	2	1	9
									2	3	1	3
									2	4	1	16
37	118	15	34	39	118	15	34	48	2	2	1	3
									2	3	1	3
									2	4	1	15
47	109	13	34	39	109	13	34	39	2	4	1	6
57	103	13	34	39	103	13	34	39	--	--	--	--

As shown in Table 6, when the relocation cost is larger, the relocation operation becomes reduced. Besides, the number of arranged cars and number of parking spots is reduced. The numerical results can prove that the operator will reduce the operation cost when the relocation cost increases.

4.2. Car sharing pricing problem

Car sharing pricing is a key factor which affects the customers' travel demand, the operators' incomes and the total profit. When other input parameters are fixed, we tested 7 values of car sharing prices from ￥90 per time step to ￥33 per time step. When the value reaches 33, the service rate is equal to 0. Figure 3 demonstrates the result of car sharing pricing's sensitivity analysis.

Figure 3: The total profit and service rate based on car sharing pricing



As shown in Figure 3, the car sharing pricing and total profit are positively correlated. When the car sharing pricing decreases to ￥33 from ￥90 per time step , the total profit becomes 0 from the maximum value of ￥9064. Also, there is a positive correlation between the car sharing pricing and service rate. The service rate decreases with the decreasing of the car sharing price, which indicates the operator will cut down services when its income drops.

Table 7: The optimized results based on car sharing pricing

CS Fee	Number of arranged cars				Number of parking spots				Relocation operation			
	Z1	Z2	Z3	Z4	Z1	Z2	Z3	Z4	*t*	*i*	*j*	No.
90	119	15	34	39	119	22	34	49	2	2	1	10
									2	3	1	4
									2	4	1	16
80	119	23	42	55	119	23	42	55	1	2	1	7
									1	4	1	10
									2	2	1	10
									2	4	1	17
70	97	23	42	45	97	23	42	45	1	2	1	7
									2	2	1	10
									2	4	1	7
60	90	16	42	45	90	12	42	45	2	4	2	3
									2	4	1	3
50	60	13	34	38	60	13	34	38	2	3	1	3
40	22	13	32	55	22	13	32	55	--	--	--	--
33	3	3	15	15	3	3	15	15	--	--	--	--

As shown in Table 7, when the number of sharing cars decreases, the relocation operation is also reduced. Besides, the number of arranged cars and number of parking spots is reduced as well. For the operator, they need to reduce the service rate when the prospective income and profit are smaller.

To promote car sharing applications, the key car sharing pricing should be found out. In this case, ￥90 per time step is a critical value with which the maximum total profit is reached. Then, for car sharing operators, reducing service rate can help to cut down the loss of opportunity benefit.

5. Conclusion

This paper addressed the one-way car sharing location and capacity problem. To solve the siting and sizing problem, this paper focuses on the following issues. (i) The relocation operation and relocation cost are taken into consideration when optimizing the one-way car sharing scheme. (ii) The flexible travel demand is taken as the inputs when establishing the MINLP optimized model. (iii) In this model, the elastic service rate is proposed which is based on the utility functions of taking car sharing and private car.

The major findings based on our case study are discussed below. Firstly, for the relocation problem, the relocation cost and total profit, as well as the relocation cost and service rate are obvious negatively correlated, respectively. Also, there is a negative correlation between the relocation cost and operation cost including the number of arranged cars and the number of parking spots. Secondly, for the car sharing pricing problem, the car sharing pricing and total profit, as well as the car sharing pricing and the service rate are positively correlated, respectively. Also, there is a positive correlation between the car sharing pricing and operation cost including the number of arranged cars and the number of parking spots.

Although this paper has studied the one-way car sharing system, there are still some issues needing to be explored further. The solver of MINOS in AMPL is taken to solve the model. To solve a large-scale network design problem, establishing an efficient algorithm is necessary. Such an enhancement should be addressed in future studies.

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