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Inventory Policy for Electric Vehicle Battery Swapping Stations in Beijing

Guowei Hua[12], Yueyue Liu[1], Yadong Xu[1*]

[1] School of Economics and Management, Beijing Jiaotong University, Beijing, 100044, China
[2] National Academy of Economic Security, Beijing Jiaotong University, Beijing 100044, China

yadongxu@bjtu.edu.cn (Corresponding author)

Abstract. Aiming at tackling the inventory problems caused by the insufficient power supply in Beijing, the difficulty of matching supply and demand, and the high volatility of demand, this paper proposes a novel inventory policy for Beijing's battery swapping stations under a certain level of service. As Beijing is actively promoting the standardization of battery swapping stations, batteries can be shared among battery swapping stations belonging to different enterprises, which lays a solid foundation for lateral transshipment between battery swapping stations in Beijing. Based on demand forecasting, lateral transshipment is incorporated into the traditional inventory management model, and a novel inventory management model for Beijing's battery swapping stations is constructed. The results show that (1) based on the widest network of battery swapping stations in China and the large number of transferable batteries, lateral transshipment can help to reduce the inventory cost of battery swapping stations and facilitate economic efficiency; (2) transshipment quantity is negatively correlated with the congestion index and positively correlated with the out-of-stock cost; (3) transshipment cost imposes the greatest influence on the total cost of battery swapping stations under the lateral transshipment mode. This study breaks the traditional independent operation mode of Beijing's battery swapping stations by introducing the concept of sharing in the context of Beijing's active promotion of the standardization of battery swapping stations. In addition, it provides new methods for inventory management in Beijing's battery swapping stations.

Keywords: Beijing’s Battery Swapping Station, Inventory Management, Lateral Transshipment, Electric Vehicles

1. Introduction

With the high-quality development of China's economy, environmental protection has become a key point and a new breakthrough point for China's economic development (Xu et al, 2022). Under the guidance of the ‘Carbon Peaking and Carbon Neutrality Goals’, electrification of vehicles has become the future development direction of the automotive industry (Feng & Lu, 2021). As the essential infrastructure, the construction of battery charging and swapping stations is the pivotal point in the development of the automotive industry. Considering the advantages of battery swapping stations in terms of grid stability, economic returns, organization, and management, battery swapping stations have gradually become the trend of future development. How to solve the inventory problem of battery swapping stations has also been given top priority when talking about the development of battery swapping stations and electric vehicles (Sun et al, 2014; Tian et al, 2014).

Along with the popularization of electric vehicles, Beijing's battery swapping business is booming. Between January 2020 and July 2021, the number of battery swapping stations in Beijing grew from 126 to 221, an increase of 74.5%. However, the flourishing development of Beijing's battery swapping business has also brought about some practical problems:(1) the large amount of centralized power demand generated by Beijing's battery swapping stations poses a great threat to the security of Beijing’s power grid; (2) the decentralized demand and centralized supply of the battery swapping business in Beijing make it difficult to match supply and demand completely; (3) Due to the frequent movement of people in Beijing, the spatial and temporal distribution of electric vehicles is unstable, and as a result, the demand is highly volatile. Considering the power grid security in Beijing, it is unreasonable to blindly expand the supply of batteries. Therefore, the government needs to find a new "supply source" for batteries in addition to the charging network. With Beijing's efforts to promote the standardization of battery swapping stations, batteries can be shared among battery swapping stations belonging to different enterprises, which lays a solid foundation for lateral transshipment between battery swapping stations in Beijing.

Based on the realistic problems facing by Beijing, the main research questions of this paper are as follows: (1) Compared to the common mode, is lateral transshipment more suitable for the actual situation in Beijing? (2) What are the factors affecting transshipment quantity? (3) How can the inventory of battery swapping stations be managed with lateral transshipment?

In this paper, lateral transshipment is incorporated as an effective method to tackle the problems of Beijing's battery swapping stations. Before studying the inventory management strategy, the battery demand of Beijing's battery swapping stations is first predicted. Considering the influence of factors such as the performance of electric vehicles and the distribution of demand in Beijing, a model for forecasting the demand for batteries in Beijing is constructed. On the basis of demand forecasting, this paper introduces lateral transshipment into the traditional inventory management model and constructs an inventory strategy with lateral transshipment applicable to Beijing. To better match the situation in Beijing, the Beijing congestion index is introduced into the model to measure the transshipment cost. Finally, the actual data from Beijing is applied to examine the validity of the constructed model and conduct further analysis accordingly.

By analysing the results, it is concluded that (1) lateral transshipment can not only help settle the problems of power grid security and the mismatch between supply and demand in Beijing but also help to reduce the total cost of Beijing's battery swapping stations and improve the economic efficiency; (2) transshipment quantity decreases when the congestion index rises, while transshipment quantity increases when the out-of-stock cost rises. The study of the factors affecting the transshipment quantity points out the direction of how the government takes advantage of the lateral transshipment to the fullest; (3) the transshipment cost is the most important factor affecting the total cost. To reduce the cost of battery swapping stations and improve economic efficiency, the government should manage it in various ways, such as through the construction of battery swapping network and the adjustment of transportation mode.

This strategy breaks the traditional independent operation mode of Beijing's battery swapping stations and introduces the concept of sharing. In addition, by combining the inventory management of battery swapping stations with the construction of smart transportation, it constructs a novel inventory management strategy for Beijing's battery swapping stations with lateral transshipment. The strategy reduces the risk of power grid security and the risk of stock-out, decreases the dead stock, and promotes supply-demand matching through lateral transshipment. The strategy provides a new approach for battery inventory management in Beijing's battery swapping stations.

2. Literature Review

Under the guidance of the ‘Carbon Peaking and Carbon Neutrality Goals’, Beijing's electric vehicles are booming. However, the imperfections of the supporting infrastructure, represented by the battery swapping stations, are becoming increasingly obvious. Among them, the match between supply and demand has become the most prominent problem, which can be solved by increasing inventory and transportation replenishment. Thus, it requires optimized allocation of batteries in the battery swapping stations. This part can be mainly divided into two aspects: battery inventory management and lateral transshipment.

Most studies involving battery inventory in battery swapping stations managed the inventory from the perspectives of demand or supply. Based on the study of the demand for batteries, with the goal of maximizing economic efficiency--maximized the utility and economic return of the service, a research identified that there is a trade-off between the number of stations and the amount of batteries equipped in each station (Wu et al, 2022). Battery swapping stations could be aggregated and dispatched by the grid operator for demand-side resource regulation. An optimization model was developed by incorporating electric vehicles demand uncertainty through a distributed robust optimization (DRO) method. (Zhang et al, 2023) Developing battery strategies from the demand perspective could maximize the satisfaction of demand, but the degree of satisfaction was still limited by the production capacity. Charging capacity constraints were also an important factor affecting the inventory of battery swapping stations(Jin et al, 2018).Constrained by the supply capacity of the grid, the battery inventory strategy for the battery swapping station introduced spare capacity from building-specific transformers and rooftop PV to better satisfy the demand(Zhang et al, 2023).Based on the power supply capacity constraints and environmental protection needs, a joint optimal scheduling model including wind power generation plan, battery swapping demand, battery charging and discharging, and vehicle routing problem (VRP) was established(Jing et al, 2018).

Inventory lateral transshipment is a significant aspect of inventory management and an integral part of the supply chain management. Lateral transshipment mainly refers to the deployment of goods between warehouses to cope with out-of-stock problem. (Feng et al, 2023). Researches on lateral transshipment has mainly focused on emergency inventory and shared inventory at the enterprise level. In the aftermath of a disaster, obtaining and meeting blood requirements was critical to prevent further loss of life. Strategies including back-up recapitulation, lateral transshipment, buffer storage and transfusion had been developed to improve coordination between the different echelons of the network and to reduce blood shortages within the system(Nahofti et al, 2021).Considering the uncertainty of the quantity and occurrence of emergency demand, a no-dispatch newsboy model was developed for the disaster relief supply chain, and in turn, a subsidized cooperation strategy and pro-social sales strategy were designed to mitigate expiration losses in the emergency perishable goods inventory system(Meng et al, 2021)

In addition, inventory management under ordinary circumstances was also studied in lateral transshipment. A multi-product, multi-warehouse model was proposed to select the optimal inventory review strategy for Group B items in the ABC analysis, and it was found that lateral transshipment could be used to minimize inventory management problems and to support industry in emergency situations(Keshavarz & Pasandideh, 2022).A simulation model was developed to evaluate inventory and distribution decisions such as lateral transshipment in a multi-product network.Discrete event simulation was developed in Python to investigate the support of managers' decision-making process through different lateral transshipment algorithms(Kundu & Rossini, 2023).In order to solve the problem of balanced scheduling of apparel inventory between outlets that allowed lateral transshipment, the relaxation and fixation (R & F) method was proposed on the basis of mixed integer linear programming (MILP) models(Wang et al, 2023).

Through summarizing and analyzing, it is found that the majority of existing inventory management strategies were developed from the perspective of supply and demand, and cost management was carried out by changing the charging or ordering strategy of batteries. Meanwhile, lateral transshipment, as an important means of inventory management, was mostly applied to emergency logistics. There were few studies on the lateral transshipment used in general commodities in common scenarios, among which there were even fewer on the lateral transshipment of batteries between battery swapping stations. Therefore, this paper applies lateral transshipment to the battery inventory management strategy of battery swapping stations. In this new demand forecasting model, factors with Beijing's characteristics are fully considered. Based on demand forecasting, the ordinary transportation mode is compared to the lateral transshipment mode, and as a result, the new battery inventory management strategy with lateral transshipment for Beijing's battery swapping stations is identified. Finally, the data from battery swapping stations in Chaoyang District in Beijing are used for calculation and analysis to validate the effectiveness of the strategy. In addition, we find the factors affecting the transshipment quantity under the lateral transshipment mode and the factors affecting the total cost of Beijing's battery swapping stations. This study is conducive to improving the efficiency of inventory management and reducing the cost of Beijing's battery swapping stations. Moreover, it provides a new research perspective for battery inventory management in Beijing's battery swapping stations.

3. Model Development

3.1. Demand Forecasting Model

Referring to the method of exsting research, this paper considers the owning rate of electric vehicles, the proportion of electric vehicles adopting the battery-swapping mode, the expected driving range, and the battery demand of electric vehicles (Gao et al, 2013). Note that the battery demand of electric vehicles is replaced by the proportion of the expected daily driving range to electric vehicle's driving range.

Construct a forecasting model R for the daily battery demand:

$$R = \alpha \times N \times \gamma \times \frac{L_f}{L_i}.$$

R denotes the daily battery demand. α represents the owning rate of electric vehicles, and $\alpha =$ The population in the region / Total population. N denotes the number of electric vehicles in the region. γ represents the proportion of electric vehicles adopting the battery-swapping mode. L_f represents kilometers driven per day, and L_i denotes the range of electric vehicles.

As the main travel mode of Beijing residents is commuting to work, kilometers driven per day is measured by the average commuting distance in the central region in Beijing, as reported in the 2022 Annual Report on Commuting Characteristics in Beijing, $L_f = 13.2$ kilometers.

In summary, the forecasting model of daily battery demand is as follows:

$$R = \alpha \times N \times \gamma \times \frac{13.2}{L_i}.$$

3.2. Inventory Management Model

3.2.1. Hypothesis

(1) There is 1 centralized charging station and N small battery swapping stations. Batteries are distributed to each battery swapping station from the centralized charging station (Xu, 2022);

(2) Each battery swapping station takes a periodic inventory checking strategy, with regular inventory checks and timely replenishment (Wei et al, 2022);

(3) The number of batteries transshipped between battery swapping stations is uncertain and is determined primarily by the stock-outs at transshipping-in battery swapping stations and inventory levels at transshipping-out battery swapping stations. Multiple transshipment can be made between battery swapping stations as long as the inventory levels allow for it (Liao et al, 2020);

(4) The unit cost is the same for each battery swapping station;

(5) Prohibit transportation between the centralized charging station and each battery swapping stations once the batteries have been transported to each battery swapping station (Bassey et al, 2022);

(6) Service level is measured as the ratio of stock-outs to total demand, and the service level is less than or equal to a set lowest service level (Karimi et al, 2022).

3.2.2. Nomenclature

Variables used in the model are shown in the Table 1:

Table 1: The variables in the model

Variables	**Description**
N	A collection of battery swapping stations
α	Number of batteries in one shipment
Q_i	Demand for battery swapping station *i*
S_i	Basic inventory level of battery swapping station *i*
x_{ji}	Number of batteries shipped from station *j* to station *i*
z_i	Number of stock-outs in battery swapping stations *i*
D_{ji}	Distance from battery swapping station *i* to station *j*
d_i	Distance from centralized charging station to battery swapping station *i*
n_i	Times of order from battery swapping station *i*
C_1	Inventory cost
C_2	Transshipment cost
C_3	Ordering costs
C_4	Out-of-stock cost
μ	Beijing traffic congestion index
θ_i	Service level of battery swapping station *i*
θ_e	Minimum acceptable level of service level
X_{ij}/X_{ji}	The subscript *ij* denotes from battery swapping station *i* to station *j*
	The subscript *ji* denotes from battery swapping station *j* to station *i*

3.2.3. Cost components under the lateral transshipment mode

The total cost under the lateral transshipment mode mainly includes the ordering cost, transshipment cost, transportation cost from the centralized charging station to the battery swapping stations, inventory cost and out-of-stock cost.

(1) Ordering cost = The cost of a single order × The number of orders:

$$\sum_{i\in N} C_3 \times n_i.$$

(2) Transshipment cost

The demand for batteries is affected by travelling demand, so lateral transshipment generally occurs during peak traffic hours. At this time, congestion in Beijing is more critical, and congestion will seriously affect the transportation speed, leading to an increase in the transshipment cost. Transshipment cost = The congestion index × Distance × Transshipment quantity × Unit transshipment cost. Considering that the car needs to return after transshipping batteries from one battery swapping station to another, the transshipment cost needs to be multiplied by 2. In summary, the transshipment cost is:

$$\sum_{i,j\in N} 2 \times \mu \times D_{ji} \times C_2 \times x_{ji.}.$$

(3) Out-of-stock cost: refers to the cost associated with shortage, Out-of-stock cost = Out-of-stock quantity × Unit out-of-stock cost:

$$\sum_{i\in N} C_4 \times z_i.$$

(4) Transportation cost

Transportation cost from centralized charging station to battery swapping stations = Distance × Transportation quantity × Times of transportation ×Unit transportation cost. Considering that the car needs to return after transporting batteries from the centralized charging station to battery swapping stations, the transportation cost needs to be multiplied by 2. In summary, the transportation cost from the centralized charging station to battery swapping stations is:

$$\sum_{i\in N} 2 \times d_i \times \alpha \times C_2 \times n_i.$$

(5) Inventory costs

Number of batteries in the battery swapping station= Number of batteries ordered + Number of batteries transshipped in − Number of batteries sold (demand)− Number of batteries transshipped out. In summary, the inventory cost is:

$$\sum_{i,j\in N} C_1 \times \left[\alpha n_i + \sum_{i,j\in N} x_{ji} - Q_i - \sum_{i,j\in N} x_{ij}\right].$$

(6) Total cost

$$\begin{aligned} \mathrm{TC} = {} & \sum_{i,j\in N} C_1 \times \left[\alpha n_i + \sum_{i,j\in N} x_{ji} - Q_i - \sum_{i,j\in N} x_{ij}\right]. \\ & + \sum_{j\in N} 2 \times \mu \times D_{ji} \times C_2 \times x_{ji}. \\ & + \sum_{i\in N} C_3 \times n_i + \sum_{i\in N} C_4 \times z_i. \\ & + \sum_{i\in N} 2 \times d_i \times \alpha \times C_2 \times n_i. \end{aligned}$$

3.2.4. Constraints

(1) Transshipment distance constraints

The distance from *i* to *j* is equal to the distance from *j* to *i*:

$$D_{ij} = D_{ji.}.$$

Once the batteries ordered in advance have been sent out, no further ordering to the centralized charging station is allowed, and only transshipment between the battery swapping stations exists.

(2) Transshipment quantity constraints

The transshipment quantity should be greater than or equal to the number of batteries that can be transshipped (the number of remaining batteries) at the transshipping-out battery swapping stations. The number of batteries that can be transshipped at the transshipping-out battery swapping stations = Quantity of purchased batteries − Demand for battery. The transshipment quantity should be less than or equal to the number of out-of-stock batteries at transshipping-in battery swapping stations. The number of out-of-stock batteries at the transferring-in battery swapping stations = Demand for battery − Quantity of purchased batteries:

$$\begin{cases} x_{ji} \geq n_j\alpha_j - Q_j \\ x_{ji} \leq Q_i - n_i\alpha_i \\ x_{ij} \geq 0 \\ x_{ij} = 0\,, i = j \end{cases}.$$

(3) Out-of-stock condition constraints

The supply of batteries must be greater than the demand for batteries:

$$\sum_{i\in N} \alpha \times n_i \geq Q_i.$$

(4) Service level constraints

The service level of the battery swapping stations = Out-of-stock quantity / Battery demand:

$$\vartheta_i = 1 - \frac{z_i}{R_i}.$$

The service level of the battery swapping stations should be greater than or equal to the lowest acceptable level of service:

$$\theta_i \geq \theta_e.$$

3.2.5. Model solving

Total cost modelling considering lateral transshipment:

$$\mathrm{TC} = \sum_{i,j\in N} C_1 \times \left[\alpha n_i + \sum_{i,j\in N} x_{ji} - Q_i - \sum_{i,j\in N} x_{ij}\right].$$

$$+ \sum_{j\in N} 2 \times \mu \times D_{ji} \times C_2 \times x_{ji}.$$

$$+ \sum_{i\in N} C_3 \times n_i + \sum_{i\in N} C_4 \times z_i.$$

$$+ \sum_{i\in N} 2 \times d_i \times \alpha \times C_2 \times n_i.$$

Constraints:

$$D_{ij} = D_{ji}.$$

$$\sum_{i \in N} \alpha \times n_i \geq Q_i.$$

$$\begin{cases} x_{ji} \geq n_j \alpha_j - Q_j \\ x_{ji} \leq Q_i - n_i \alpha_i \\ x_{ij} \geq 0 \\ x_{ij} = 0, \quad i = j \end{cases}.$$

$$\theta_i \leq \theta_e.$$

The optimal solution for the number of batteries transhipped can be obtained:

$$x_{ij}^* = E_{R_i}\left[E_{R_j}\left(x_{ij} \middle| R_i\right)\right].$$

$$x_{ij}^* = \int_{r_i=0}^{\alpha_i} F_i(r_i)\left[1 - F_i\left(\alpha_i + \alpha_j - r_i\right)\right] dr_i.$$

$$n \neq j, n \in N.$$

$$D_{in} < D_{ij}.$$

$$D_{ij} \leq D_{im}.$$

$$m \in N$$

As $S_i = \alpha + x_{ji} - z_i$, the optimal solution of S_i is

$$S_i = \alpha_i + \int_{r_i=0}^{\alpha_i} F_i(r_i)\left[1 - F_i(\alpha_i + \alpha_j - r_i)\right] dr_i + R_i - \alpha_i$$

$$+ \int_{r_i=0}^{\alpha_i} F(r_i) dr_i - \int_{r_j=0}^{\alpha_j} F(r_j) dr_j - \int_{d_i=\alpha_i}^{\alpha_i+\alpha_j} F(r_i) F(\alpha_i + \alpha_j - r_i) dr_i$$

4. Results and Discussion

4.1. Relevant Data in Beijing

There are 400,400 private electric vehicles in Beijing in 2022, according to data from the New Beijing Newspaper[1]. According to the data published by CEC Data, the resident population of each district in Beijing is shown in Table 2. Based on the situation of electric vehicles and population in Beijing, the number of electric vehicles in each district in Beijing is calculated: The number of electric vehicles = The total number of electric vehicles in Beijing × Resident population of each district / Total population. Assume that the current operation of battery swapping stations in Chaoyang District in Beijing is as follows:

Table 2: Resident Population and Weights

District	Resident Population (10,000)	Weighting	Number of Electric Vehicles
Haidian district	312.4	0.20	86053
Changping district	226.7	0.14	62343

[1] https://gov.sohu.com/a/617712012_121124480

Chaoyang district	334.2	0.21	94818
Tongzhou district	184.3	0.12	50553
Fengtai district	201.2	0.13	55472
Shunyi district	132.5	0.08	36379

For example, Azera has a battery capacity of 100 kWh and a range of approximately 625 kilometers[2]. The utilization rate of battery swapping stations of electric vehicles is 30%[3]. Taking Chaoyang District as an example, substituting the data into the model to calculate demand, we find that the demand is 135 units/day. Combined with the usual daily demand of the 13 battery swapping stations in Chaoyang District, the data in Table 4-1 and the demand forecasting model, the battery demand of the 13 battery swapping stations is shown in Table 3.

Table 3: Battery Demand for 13 Battery Swapping Stations

Battery Swapping Station	**Quantity Demand**	**Battery Swapping Station**	**Quantity Demand**
Sunny 100 Battery Swapping Station	12	Sinopec Chaoying Battery Swapping Station	5
Shuangqiao Electronic City Battery Swapping Station	9	Kam Lung Cultural and Creative Park Battery Swapping Station	10
Lishuiqiao Battery Swapping station	32	Jiuxianqiao Battery Swapping station	10
New Energy Battery Swapping Station	10	Langham Building Battery Swappinge Station	9
Jiangzhuang Lake Battery Swapping station	5	Tatsuen Merchants Center Battery Swapping Station	12
Chaoyang Park Battery Swapping Station	8	Daliushu Energy Chain Station Battery Swapping Station	4
Elite Dream Valley Power Battery Swapping Station	9		

Based on the actual spatial locations of 13 battery swapping stations in Chaoyang District in Beijing, the distance between battery swapping stations is measured. The locations of centralized charging stations and battery swapping stations can be observed from the map of Beijing. The distribution of their locations is shown in Table 4.

[2] https://www.nio.cn/configurator/ES6

[3] Gao Ciwei,Wu Xi,Xue Fei, et al. Demand planning for electric vehicle battery packs under power switching mode[J]. Grid Technology, 2013, 37(7):9.

Table 4: Locations of the 13 Battery Swapping Stations

Position	**Name**	**Longitude**	**Latitude**
Centralized Charging Station	Azure Charging Station	116.38	39.89
Battery Swapping Station 1	Sunny 100 Battery Swapping Station	116.57	39.76
Battery Swapping Station 2	Shuangqiao Electronic City Battery Swapping Station	116.58	39.91
Battery Swapping Station 3	Lishuiqiao Battery Swapping Station	116.31	39.99
Battery Swapping Station 4	New Energy Battery Swapping Station	116.41	40.06
Battery Swapping Station 5	Jiangzhuang Lake Battery Swapping Station	116.44	40.00
Battery Swapping Station 6	Chaoyang Park Battery Swapping Station	116.48	39.95
Battery Swapping Station 7	Elite Dream Valley Battery Swapping Station	116.52	39.90
Battery Swapping Station 8	Sinopec Chaoyang Battery Swapping Station	116.50	39.87
Battery Swapping Station 9	Kam Lung Cultural and Creative Park Battery Swapping Station	116.56	39.86
Battery Swapping Station 10	Jiuxianqiao Battery Swapping Station n	116.33	39.85
Battery Swapping Station 11	Langham Building Battery Swapping Station	116.60	39.92
Battery Swapping Station 12	Tatsuen Merchants Center Battery Swapping Station	116.60	39.90
Battery Swapping Station 13	Daliushu Energy Chain Station Battery Swapping Station	116.52	39.88

Table 5: Supply of 13 Battery Swapping Stations

Battery Swapping Station	**Quantity Demand**	**Supply**
Sunny 100 Battery Swapping Station	12	11
Shuangqiao Electronic City Battery Swapping Station	9	11
Lishuiqiao Battery Swapping Station	32	11
New Energy Battery Swapping Station	10	11
Jiangzhuang Lake Battery Swapping Station	5	11
Chaoyang Park Battery Swapping Station	8	11
Elite Dream Valley Battery Swapping Station	9	11
Sinopec Chaoying Battery Swapping Station	5	11
Kam Lung Cultural and Creative Park Battery	10	11

Swapping Station		
Jiuxianqiao Battery Swapping Station	10	11
Langham Building Battery Swapping Station	9	11
Tatsuen Merchants Center Battery Swapping Station	12	11
Daliushu Energy Chain Station Battery Swapping Station	4	11

Other relevant values are set as follows: the unit inventory cost (C_1) is ¥22 (Unit inventory cost = (Area of the battery swapping station[4] × Land rent[5] + Labor cost[6] + Operation cost[7]) / 30), and the transportation cost between stations (C_2) is ¥3.2[8]. The cost of one order (C_3) is ¥100[9], and the number of orders (n) is 1. The unit out-of-stock cost (C_4) is ¥160 (Unit out-of-stock cost = Price of electricity at the battery swapping stations[10] × Battery capacity[11] + Service fee[12]). According to the statistics of Azalea's battery swapping stations, the highest demand points are 9, 10, 13 and 14 o'clock[13]. The average congestion index of the four points is 1.8[14].

4.2. Calculations

It can be seen from the results that after the centralized charging station distributes the batteries to the battery swapping stations, it is not necessarily able to meet the demand of each battery swapping station. At this time, some battery swapping stations will be out of stock. To meet the demand of each battery swapping station as much as possible, the battery is transferred by means of lateral transshipment.

Substituting the above data, you can determine the stock-out and stock-in situations of the battery swapping stations. The results are shown in the following table.

4 https://www.yoojia.com/ask/17-11777756404011010580.html

5 Beijing Chaoyang District Land Rent from WUBA

6 http://wap.hunt007.com/employer/viewInvite/6688067/28411475_1.htm

7 LIU Qing. Revenue analysis of pure electric cab battery swapping operation mode[J]. Research on Automobile Industry,2022(03):41-45.

8 Refer to Beijing Cargo Data

9 Xu Linlin. Research on the inventory-distribution problem of electric vehicle battery operators under the battery swapping mode[D]. North China Electric Power University (Beijing), 2022.

10 The average price of electricity at the peak time at the battery swapping stations in Beijing Chaoyang District in the Azalea App.

11 https://gov.sohu.com/a/617712012_121124480

12 Service charge of the battery swapping stations in Beijing Chaoyang District in Azalea APP

13 the number of swapped batteries in battery swapping stations in the Azera App

14 https://jiaotong.baidu.com/congestion/city/urbanrealtime/

Table 6: Out-of-stock and Inventory at 13 Battery Swapping Stations

Battery Swapping Stations	**Shortage**	**Battery Swapping Stations**	**Inventory**
Sunny 100 Battery Swapping Station	1	Shuangqiao Electronic City Battery Swapping Station	2
LishuiqiaoBattery Swapping Station	21	Jiangzhuang Lake Battery Swapping Station	6
Tatsuen Merchants Center Battery Swapping Station	1	Sinopec Chaoying Battery Swapping Station	6
		Daliushu Energy Chain Station Battery Swapping Station	7
		New Energy Battery Swapping Station	1
		Chaoyang Park Battery Swapping Station	3
		Elite Dream Valley Battery Swapping Station	2
		Kam Lung Cultural and Creative Park Battery Swapping Station	1
		Jiuxianqiao Battery Swapping Station	1
		Langham Building Battery Swapping Station	2

The above table indicates that the Sunshine 100 Battery Swapping Station, Lishuiqiao Battery Swapping Station, and Cinnabar Park Merchants Center Battery Swapping Stations are out of stock by 1, 21, and 1, respectively. The rest of battery swapping stations are in stock. Therefore, it is considered to tranship batteries between battery swapping stations to coordinate the battery inventory. However, it should be noted that if the transshipment cost is greater than the out-of-stock cost, the station will give up lateral transshipment. The battery transshipment situations are shown in the Table 7.

Table 7: Battery Transshipment

Transhipping-in Battery Swapping Stations	**Transhipping-out Battery Swapping Stations**	**Quantity of Transhipment**
Sunny 100 Battery Swapping Station	Shuangqiao Electronic City Battery Swapping Station	1
Tatsuen Merchants Center Battery Swapping Station	Daliushu Energy Chain Station Battery Swapping Station	1
Lishuiqiao Battery Swapping Station	Jiangzhuang Lake Battery Swapping Station	6
	Jiuxianqiao Battery Swapping Station	1

Substituting the data into the calculation, the total cost is ¥14523.84. Based on the calculation model for the basic inventory level, $S_i = \alpha + x_{ji} + z_i$, the basic inventory level of each battery swapping station in Chaoyang District in Beijing can be obtained. The results are shown in Table 8.

Table 8: Basic Battery Inventory

Battery Swapping Station	**Basic Inventory Level**	**Battery Swapping Station**	**Basic Inventory Level**
Sunny 100 Battery Swapping Station	12	Sinopec Chaoying Battery Swapping Station	5
Shuangqiao Electronic CityBattery Swapping Station	9	Kam Lung Cultural and Creative Park Battery Swapping Station	10
Lishuiqiao Battery Swapping Station	32	Jiuxianqiao Battery Swapping Station	10
New Energy Battery Swapping Station	10	Langham Building Power Battery Swapping Station	9
Jiangzhuang Lake Battery Swapping Station	5	Tatsuen Merchants Center Battery Swapping Station	12
Chaoyang Park Battery Swapping Station	8	Daliushu Energy Chain Station Battery Swapping Station	4
Elite Dream Valley Battery Swapping Station	9		

4.3. Comparison to Ordinary Transportation Mode

The main difference between the lateral transshipment mode and the ordinary transportation mode is that there is no lateral transshipment between battery swapping stations. Therefore, compared to the cost components of the lateral transshipment mode, the cost components of the ordinary transportation mode lack the transshipment cost between battery swapping stations but have increased out-of-stock cost and inventory cost.

Substituting the above data of Beijing, we can calculate that the total cost of the ordinary transportation mode is ¥14814. The cost of the lateral transshipment mode is smaller. Thus, the lateral transshipment mode is more suitable for the situation in Beijing.

4.4. Further Analysis

The transshipment quantity between the battery swapping stations in the current scenario is small, and the lateral transshipment is not fully utilized. Therefore, the factors affecting the quantity of lateral transshipment are investigated. The results of the study are shown in Table 9. When the congestion index rises, the transshipment cost rises with it, resulting in the transshipment cost being greater than the out-of-stock cost and the quantity of transshipment decreasing; when the out-of-stock cost rises, the transshipment cost is gradually lower than the out-of-stock cost, leading to the transshipment quantity increasing.

Table 9: Impact of Congestion Index and Out-of-stock Cost on the Transshipment Quantity

Congestion Index	Quantity of Transshipment	Out-of-stock Cost	Quantity of Transshipment
1	12	130	2
1.2	12	145	9
1.4	9	160	9
1.6	9	175	9
1.8	8	190	23
2	2	205	23

4.5. Sensitivity Analysis

To conduct a more in-depth study on the factors affecting the total cost of the battery swapping stations, we conduct a sensitivity analysis on the transshipment cost, inventory cost, ordering cost, and out-of-stock cost. Sensitivity coefficient = Percentage of change in the target value / Percentage of change in the reference value, which indicates the magnitude of the effect of the independent variable on the dependent variable. The results are shown in the Table 10.

Table 10: Sensitivity Analysis Results

Transportation Cost	Transshipment Cost	Inventory Cost	Out-of-stock Cost	Ordering Cost
0.315	0.779	0.033	0.154	0.090

Analysis of the results reveals that the transshipment cost is the factor that has the greatest impact on the total cost. Since the peak demand for transshipment at Beijing's battery swapping stations coincides with the peak traffic period in Beijing, there is a long congestion time when transshipment is performed. At the same time, the density of the battery swapping stations in Beijing is low, and the distance between stations is long. Both of these factors contribute to the high transshipment cost of battery swapping stations in Beijing.

5. Conclusion

In this paper, based on the prediction of demand for batteries in Beijing, we construct an inventory management strategy considering lateral transshipment and analyse it with the actual data of Beijing to obtain the following conclusions:

1. The lateral transshipment is incorporated into the traditional inventory management model, and a novel inventory management strategy for battery swapping stations applicable to Beijing is proposed. The inventory management strategy with lateral transshipment proposed in this paper is conducive to reducing the risk of power grid security, lowering the risk of out-of-stock, reducing the backlog of inventory, and promoting the matching of supply and demand. In addition, it provides a new method and new idea for the inventory management of batteries in Beijing's battery swapping stations.

2. It is found that the transshipment quantity has a negative correlation with the congestion index and a positive correlation with the out-of-stock cost. The study of the factors affecting the transshipment quantity at the battery swapping stations points out the direction of how the government can give full play to the lateral transshipment. To take advantage of lateral transshipment to the fullest, the government can manage it through congestion relief and other means.

3. Through the sensitivity analysis, it is found that the transshipment cost is the most important factor affecting the total cost. To further improve the economic efficiency of battery swapping stations and reduce costs, the government can manage in various ways, such as constructing a battery swapping network and adjusting the transportation mode.

However, there are still some deficiencies. Data in this paper are not comprehensive and precise enough, and the model is not accurate. With the deepening of subsequent researches, I believe that the shortcomings will be consistently remedied and corrected.

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