Research on layout optimization of express parcel transportation network distribution center based on node operation process

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Abstract. Through refining the ability of distribution center node and combining the national political factors, this paper proposes an improved P-median model, which considers the constraints of the import operation scale, export operation scale and intermediate operation capability of each candidate distribution center node and mandatory nodes. Finally, this paper takes a large express logistics enterprise parcel transportation network as an example to analyse the optimization result of case and parameter sensitivity of node service scope. We find that the optimized layout of the distribution center breaks the administrative division constraint, realizes the nearest transit of parcel, fully considers the scale of each operation of the node, and meets the requirements of mid-to-long term development trend of the parcel express transportation network, which has reference significance for the development of the parcel transportation business and the research on site selection model.

1. Introduction

In recent years, China’s express delivery business has continued to develop. Under the influence of logistics demand in various industries, the competition of domestic express logistics enterprises has become increasingly fierce. However, the layout of the existing parcel transportation network distribution center is difficult to support the rapid development of express delivery business, which is reflected in the following aspects: (1) Some provinces use the provincial capital as a network hub connecting the whole country, but they are not the geographic center of the province and cannot meet the growing needs of express delivery parcels. (2) In some areas, the capacity of distribution center is limited, and the future development need is difficult to meet. (3) In some provinces, there are few channels for parcel distribution, hence the pressure of the express network parcel flow will gather in the provincial capital in the peak season. (4) The distribution level of some distribution centers is not clear. In the northwest, northeast, southwest and other regions, there is a lack of transit hubs to serve remote areas.

In order to improve the transportation efficiency of express logistics industry, seize the central market, and better meet the customer’s small batch size, multi-category and time-sensitive distribution requirements, logistics enterprises need to optimize the layout of the parcel transportation network in addition to improving staff productivity and infrastructure construction.

The parcel transportation network distribution center is also called the transshipment center and the
processing center. It refers to the production operation unit responsible for parcel sorting, shipping and transfer operations in the parcel transportation network, which constitutes the node of the parcel transportation network\cite{1}.

The layout optimization of the distribution center of the parcel express transportation network belongs to the location problem. In the existing research, experts and scholars have carried out sufficient and in-depth research on site selection theory, which has played a good guiding role in production operations\cite{2}. Specifically, in foreign countries, literature\cite{3} has reviewed the research of hierarchical location model; literature\cite{4-5} proposed a hospital location model based on capacity limitation; literature\cite{6-8} proposed hierarchical selection models with capacity limitation. Domestically, Wu Xing et al\cite{9} built a railway logistics center hierarchical location model with the goal of maximizing total demand and minimizing logistics transportation costs; Liu Qiang et al\cite{10} proposed the two-level planning model of regional integrated transportation hub layout; Li Daikun\cite{11} classified the transportation hubs, and then used the median model to optimize the layout of each level of hubs; Li Tingting et al\cite{12} optimized the layout of regional passenger hubs using a hierarchical location model; Ding Jinxue et al\cite{13} optimized and analyzed the layout of China’s transportation hubs.

In summary, the current research on the construction of location model mainly considers the node capacity limitation and the demand stratification. According to the actual production situation, which plays a guiding role of the model construction, the current research mainly has two problems. First, most studies only consider the overall operational capability of the candidate nodes but ignore the differences between distribution centers in the import and export capabilities which may have an impact on the selection of the distribution centers; second, the analysis and constraints on the factors influencing the selection of the distribution center ignore the fact that the political factors will have a decisive influence on the choice of the distribution centers.

In view of the limitations of the current research, this paper proposes an improved optimization model of distribution center, which refines the operational capabilities of the alternative distribution centers and their associated relationships, fully considers the import operations scale, the export operations scale and the constraints of intermediate operations of each candidate node, and also integrates political factors in order to provide decision-making reference for the layout optimization of the parcel express transportation network and the construction of the relevant location model.

2. Analysis of Factors Affecting Site Selection of Distribution Center

In the parcel express transportation network, the distribution center is the node of each transportation line. Other aspects of parcel delivery, except transportation, including loading, unloading, sorting, distribution, and sending, occur most at the distribution center. Therefore, the distribution center is an important part of the entire express transportation network, and the rationality of its layout determines the transportation efficiency of the entire parcel transportation system. The selection of the parcel express delivery center needs to start from the internal operations of each candidate node, refine the operation capability, and pay attention to the import and export operation scale and intermediate operation processing capability of each candidate node.

The import operation means that the distribution center receives parcels shipped from various places. The export operation means that the distribution center sends the sorted parcels to their destinations. The scale of import and export operations is mainly affected by the number of goods stacks, the handling capacity of goods stacks and the efficiency of the operators. The intermediate operation means that the distribution center sorts the imported parcels, and performs the corresponding operations such as circulation, classification, and collection of the parcels according to the destination. The operation process of the parcel express distribution center is shown in Figure1.
Figure 1. The summary operation process of parcel express transportation network distribution center

The scale of import and export operations reflects the parcel transportation demand of the distribution center in the express transportation network, that is, if the demand reaches a certain standard, the candidate node should be selected as the distribution center. The intermediate operation capacity limits the total operation of the distribution center. If only one overall capability value is used for constraint, the data with smaller import and export operations will become the constraint value, so that other capabilities may have surplus, which in turn causes waste of a large amount of transportation resources. This paper fully considers the difference in the scale of the import and export of alternative nodes, and constrains the import scale and export scale of the alternative nodes separately. Specifically, this paper calculates the import and export scale of each candidate node separately and stipulates the scale standard of import and export operations.

In addition, the location of the distribution center should be conducive to the delivery and transportation of the parcels in the choice of the express delivery network distribution center, so the administrative center or traffic center should be selected as much as possible\textsuperscript{[14]}. Therefore, it is necessary to set some mandatory distribution centers according to the political status and economic scale of the alternative distribution center. Furthermore, for some remote areas, the parcel transportation volume is relatively small and the coverage is vast, so it is also necessary to set some mandatory distribution centers in order to balance the transportation network and increase the accessibility of the transportation network.

In summary, the layout optimization problem of the parcel express delivery network distribution center studied in this paper is a mixed integer linear programming problem with minimum weighted distance for full network demand transportation, which takes into account the scale of the import operations, the scale of export operations, the constraints of intermediate operations of each candidate node, and the constraints of political factors. In this problem, the distance matrix between each candidate node, the coverage service distance of each node, the minimum number of distribution centers that can cover all the requirements, the mandatory distribution centers, the import and export volume of the candidate nodes, and the total business volume are all known.

3. Improved parcel express delivery network distribution center layout optimization model

3.1. Model hypothesis
(1) The number of the distribution center is known and unchanged.
(2) The size and structure of the parcel express transportation network is stable, and the parameters related to nodes and arcs are known.
(3) The mandatory node information limited by political conditions is known.

3.2. Related symbol definition
The collections are defined as follows: set \( V \) be a collection of distribution centers, indexed by \( i, j \); set \( Z_j \) be a collection of mandatory distribution centers, in general, provincial capitals and municipalities are mandatory distribution centers.

The parameters are defined as follows: set \( P \) as the selection number of distribution centers; \( d_{ij} \) as the transportation distance between nodes; \( D_j \) as node coverage service distance; \( h_i \) as the total amount of transportation at the hub node, also the demand weight of the hub node; \( o_i \) as node’s export volume;
$d_i$ as node’s import volume; $C_j$ as import operation scale standard; $C_z$ as total operation scale standard (export operation volume add import operation volume); $C_3$ as operation capacity of the distribution center; $M$ as a positive integer large enough.

The decision variables are defined as follows: $x_j$ --- whether $j$ is selected as the distribution center, if it is, the value is 1, otherwise is 0; $y_{ij}$ --- whether node $i$ is served by node $j$, if it is, the value is 1, otherwise is 0.

3.3. Improved parcel express delivery network distribution center layout optimization model

$$\min \sum_{i \in V} \sum_{j \in V} h_i d_i y_{ij}$$

s.t.

$$\sum_{j \in V} x_j = P$$  

$$\sum_{j \in V} y_{ij} = 1 \quad \forall i \in V$$  

$$y_{ij} - x_j \leq 0 \quad \forall i \in V, j \in V$$  

$$\sum_{j \in V} y_{ij} o_i - Mx_j \leq C_1 \quad \forall j \in V$$  

$$\sum_{j \in V} y_{ij} (o_i + d_i) - Mx_j \leq C_2 \quad \forall j \in V$$  

$$d_j \leq D_j + M \cdot (1 - y_{ij}) \quad \forall i, j \in V$$  

$$x_j \geq z_j \quad \forall j \in V$$  

$$x_j, y_{ij} \in \{0, 1\} \quad \forall i \in V, j \in V$$

Among them, formula (1) is the objective function that minimizes the total transportation distance for demand weighting; formula (2) is a limit on the number of choices for the express parcel transportation network distribution center; formula (3) represents that for demand node $i$, it can only be served by one distribution center $j$; formula (4) is a logical constraint, which means that if the demand point $i$ is served by the distribution center $j$, the candidate distribution center $j$ must be selected; formula (5) is a logical constraint, that is, if the import scale of candidate node reaches $C_i$, it must be set as the distribution center; formula (6) is a logical constraint, that is, the sum of import and export scale of the candidate node reaches $C_z$, it must be set as the distribution center; formula (7) is the intermediate operational ability constraint of the distribution center; formula (8) is the node coverage constraint; formula (9) is a mandatory node constraint; formula (10) is a decision variable 0-1 constraint.

3.4. Model solving

The model is a 0-1 mixed integer linear programming model. It can be concluded from the model that if $V$ contains $n$ values, the whole model has $(n+n^2)$ decision variables and $(2n^2+5n+1)$ constraint expressions. So it can be seen that the solution scale of the model is $O(n^2)$, that is, as $n$ increases, the problem solving complexity changes as the number of square polynomials.

ILOG CPLEX software has significant advantages in solving such problems. It embeds various precise algorithms such as Branch and Bound, Lagrangian Relaxation and Column Generation. The most suitable algorithm is determined according to the complexity of the problem, the efficiency of the solution and the quality of the solution [15]. Based on the above analysis, this paper uses CPLEX optimization software to solve the problem. In addition, this paper writes VBA code to sort out the running results of CPLEX, and obtains the optimized distribution center layout plan.
4. Case study
This paper takes a large express logistics enterprise express parcel delivery network as an example. The large express logistics enterprise parcel express delivery network now contains 338 parcel nodes. In order to break the influence of the regional administrative division on the layout plan, all the nodes are both the distribution center candidate nodes and the service demand nodes, so that the demand parcel of each node can be transferred nearby. The distance matrix between 338 nodes and the OD parcel volume matrix between nodes are known.

In order to speed up the efficiency of parcel transportation, the service distance interval is determined to be \([300, 350]\) km according to the current next day delivery business of the large express logistics enterprise. Combining the differences in natural geography conditions in China, the service distance of each node is divided into the eastern, central and western regions according to the location of the nodes. The service distance of nodes in the eastern region is appropriately reduced and the service distance of the western node is expanded according to the situation that the eastern region has developed economy and high demand, and the western region is sparsely populated and the parcel amount is small.

The scale of import and export operations and the restriction of intermediate operation capacity are shown in Table 1. The provincial capitals and municipalities directly under the Central Government are designated as the mandatory distribution centers. Under the coverage mode of 150/300/600 km, the basic coverage set model can be used to obtain the minimum number of distribution centers, which is 85.

Table 1. Import and export operation scale and intermediate operation capability of each node

| Import volume | Total business volume (sum of import volume and export volume) | The intermediate operation capacity |
|---------------|---------------------------------------------------------------|-----------------------------------|
| 20 (ten thousand pieces) | 35 (ten thousand pieces) | 120 (ten thousand pieces) |

4.1. Solution result
In the Windows7 operating environment, this paper uses the optimization software CPLEX to solve the model, each run time is less than 4s, then uses Excel software to write the VBA code to sort out the calculation results. The layout plan of the express delivery network distribution center under the coverage distance mode of 150/300/600 km is shown in Table 2. Table 2 only shows part of the layout and coverage plan of the distribution center.

Table 2. Optimization result of layout plan of distribution center under the coverage distance mode of 150/300/600 km

| No. | Distribution Center | Service City                                                                 |
|-----|---------------------|-------------------------------------------------------------------------------|
| 1   | Jingdezhen          | Jingdezhen                                                                   |
| 2   | Lanzhou             | Lanzhou, Baiyin, Jinchang, Tianshui, Wuwei, Dingxi, Pingliang, Linxia, Guyuan |
| 3   | Beijing             | Beijing, Langfang                                                            |
| 4   | Tianjin             | Tianjin, Zhangzhou, Tangshan                                                 |
| 5   | Chaoyang            | Chaoyang, Qinhuangdao, Chengde, Chifeng, Jinzhou, Fuxin, Huludao              |
| 6   | Zhangjiakou         | Zhangjiakou                                                                  |
| ... | ...                 | ...                                                                          |
| 85  | Haixi State         | Haixi State, Guoluo State                                                     |

According to all the data in Table 2, the layout of the 85 distribution center is shown in Figure 2. The node name is not marked in the figure due to too many nodes.
4.2. Result analysis

At present, the large express logistics enterprise has set up 75 distribution centers, and implements the processing mode of “Relatively concentrated exports and stratification of imports”. This model has planned 85 distribution center nodes and their specific coverage plans for the large express logistics enterprise package transportation network. Compared with the existing parcel transportation network, the optimized distribution center layout plan changes greatly. Take the two provinces of Henan and Hubei as examples, as can be seen from Table 3, Table 4 and Figure 3, the city which is underlined means that the city served is a non-provincial city.

Table 3. The layout plan of distribution center in Henan and Hubei provinces before optimization

| Province | Distribution Center | Service City | The Number of Service City |
|----------|---------------------|--------------|---------------------------|
| Henan    | Zhengzhou           | Zhengzhou, Shangqiu, Anyang, Hebi, Jiaozuo, Kaifeng, Luoyang, Luode, Pingdingshan, Fuyang, Xinxiang, Xuchang, Zhoukou, Sanmenxia | 14 |
|          | Xinyang             | Xinyang, Nanyang, Zhumadian, Wuhan, Ezhou, Huanggang, Huangshi, Suizhou, Xianning, Xiaogan, Jingmen, Jingzhou, Yichang, Enshi | 3 |
| Hubei    | Wuhan               | Xiangyang, Fuyang, Shiyan | 2 |

Table 4. The layout plan of distribution center in Henan and Hubei provinces after optimization

| Province | Distribution Center | Service City | The number of Service City |
|----------|---------------------|--------------|---------------------------|
| Henan    | Zhengzhou           | Zhengzhou, Handan, Kaifeng, Anyang, Hebi, Xinxiang, Xuchang, Zhumadian, Luoyang, Jincheng (Shanxi), Yuncheng (Shanxi), Changzhi (Shanxi), Pingdingshan, Jiaozuo, Sanmenxia, Nanyang | 8 |
|          | Luoyang             | Shangqiu, Bengbu (Anhui), Huaihai (Anhui), Fuyang (Anhui), Jining (Shandong), Heze (Shandong), Fuyang, Luoe, Zhoukou, Bozhou (Anhui) | 10 |
|          | Shangqiu            |               |                           |
Figure 3. The layout plan of distribution center in Henan provinces after optimization

As can be seen from Table 3, Table 4 and Figure 3:

(1)The service targets of some distribution centers in Henan and Hubei provinces are not limited to the demand points in the province. Take Shangqiu City as an example, it is located in the handover area of Henan, Fujian and Shandong provinces, so it undertakes a large number of tasks outside the province because of its relatively important hub status. In the same way, Luoyang and Wuhan also undertake the demand for some nodes in Shanxi Province and Henan Province. The node layout is more uniform, and it is more in line with the actual road network construction needs. It verifies the effectiveness of the planning principle of breaking the administrative division and realizes the nearest transit of parcel delivery.

(2)In the optimized layout plan of the distribution centers of Henan and Hubei provinces, some service cities of Zhengzhou and Wuhan were transferred to non-provincial-capital distribution centers such as Luoyang, Shangqiu and Jingmen, which effectively reduces the pressure on the transfer operations of provincial capitals and also prevents the parcel flow from accumulating excessively in the provincial center. The optimized layout plan effectively solved the problem of imbalance in the amount of parcels of distribution centers in some provinces.

In addition, the optimized layout’s level is more distinct and the positioning is clearer. The optimized layout appropriately increases the transit hubs to remote areas such as the southwest and northwest, which enhances the efficiency of parcel express distribution in the case of poor transportation conditions in remote areas. The corresponding optimized layout is shown in Table 5.

Table 5. The layout plan of distribution center in some southwest and northwestern provinces

| Province | Distribution Center | Service City |
|----------|---------------------|--------------|
| Yunnan   | Kunming             | Kunming, Qujing, Chuxiong, Yuxi, Wenshan, Qianxinan, Honghe |
|          | Dali                | Dali, Baoshan, Dehong, Lijiang, Nujiang |
|          | Puer                | Pu’er, Linyi, Xishuangbanna |
| Xinjiang | Karamay             | Karamay, Altay, Bozhou, Tacheng, Yili |
In summary, the optimized parcel delivery network layout is more reasonable, which will provide decision-making reference for further transportation route planning of the large express logistics enterprise.

4.3. Node coverage sensitivity analysis

In response to the call of the country’s “Rise of Central China” strategy, the state has clearly emphasized the optimization of transportation resource allocation, and required the acceleration of the construction of railway networks in the central provinces and the improvement of the transportation capacity of the highway trunk lines. With the further improvement of the transportation network and road network structure, the timeliness of parcel transportation will inevitably be greatly improved. In this paper, the coverage parameters of the nodes are further considered. The coverage distance of the nodes in the central provinces is adjusted from 300km to 150km, which is consistent with that in the east. The model is solved again and the solution results are shown in Table 6.

| Hub Coverage Distance (km) | Number of Distribution Center | Objective Function Value (km) |
|---------------------------|------------------------------|-------------------------------|
| East 150, Central 300, West 600 | 85 | 2,514,958,620 |
| East 150, Central 150, West 600 | 124 | 1,814,880,930 |

According to the result of re-solving, the layout plan of the optimized distribution center under the coverage distance mode of 150/150/600 km is shown in Fig.4. Since the number of distribution centers is too large, the node name is not marked in the figure.

Figure 4. The layout plan diagram of 124 distribution centers

Combining Table 6 and Figure 4, the number of distribution centers has increased from 85 to 124. The re-solving layout plan increases a certain number of distribution centers especially in the central provinces. This is in line with the gradual improvement of the transportation network in the central region, and the trend that the demand for parcel transportation is increasing and the demand for the number of distribution centers is further increasing. However, the objective function value, that is, the demand-weighted transportation distance, is reduced by nearly 30%. This is because the increase of the distribution center makes the distribution center of the entire parcel express transportation network
more densely distributed, and the accessibility between nodes is further increased, thereby the demand weighted distance decreases. This also shows that the coverage distance of the node has a direct impact on the layout of the parcel express delivery network distribution center.

With the development of China’s economic level and the further improvement of the structure of the parcel express transportation network, especially with the implementation of the strategy of “Rise of Central China”, the demand for parcel transportation and distribution centers will increase day by day. The layout of parcel express transportation network needs to have certain forward-looking and moderately ahead of the development of the corresponding business. By comparison, it can be obtained that the optimization plan under the coverage distance mode of 150km in the east, 150km in the middle and 600km in the west can provide important decision-making reference for the long-term planning of the parcel express transportation network.

5. Conclusion
This paper analyzes the process and impact mechanism of the distribution center operation, innovatively decomposes the scale of the import and export operations of the nodes, constrains the logistics capability of the nodes from the aspects of import volume, export volume and intermediate operation capacity, integrates the political factors, and proposes an improved distribution center layout optimization model in the optimization problem of the parcel transportation network node. Then this paper takes a large express delivery logistics enterprise parcel express transportation network as an example. According to the service distance mode of 150km in the east, 300km in the middle and 600km in the west, 85 layout centers and their coverage plans are solved. Compared with the existing package express delivery network distribution center layout, the optimized layout fully considers the various operational capabilities of the node, breaks the administrative division limit, realizes the nearest transit of parcel delivery, and appropriately increases the distribution center to remote areas. The optimization plan enhances accessibility of the entire parcel express delivery network, which also verifies the feasibility of the model proposed in this paper. Finally, this paper further considers the node coverage distance sensitivity and obtains the layout and coverage optimization plan of the 124 distribution centers of the parcel express transportation network, which satisfies the trend of the increasing volume of parcels and the increasing demand for distribution centers, increases the forward-looking nature of the package express delivery network layout, and also provides a decision-making reference for the medium and long-term planning of the parcel express transportation network.

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