Collaborative Optimization for Location-Inventory Problem of Commercial Vehicle Distribution Network

Wanying Peng, Lu Qin *
School of Traffic and Transportation, Beijing Jiaotong University, Beijing, 100044, China
*Corresponding author’s e-mail: lqin@bjtu.edu.cn

Abstract. This paper studies a bi-level programming model addressing the location-inventory problem which can determine the location of distribution centers and the inventory strategy of distribution centers and stores at the same time. In the location-inventory joint decision model, the order quantity is a continuous decision variable associating the upper and lower models and the remaining decision variables are 0-1 variables. In this paper, a branch and bound method is proposed and the SCIP solver is used to solve the bi-level mixed integer non-linear programming problem. The results show that collaborative optimization can save more costs than the one-by-one optimization method and that the optimal solution has better stability under the condition of demand fluctuation and satisfies the optimal allocation of important customers.

1. Introduction
The joint research on the location-inventory problem (LIP) first attracted the attention of Erlebacher et al.[1] in 2000. The research on LIP has continued to increase and systematic solutions to the two major problems have become a research hotspot. There are two main research perspectives on LIP. First, the location-inventory problem is accompanied by routing problems. Saranwong et al.[2] regarded location and inventory sub-problems as cost items in the objective function and routing sub-problems or procurement rules as necessary constraints. Second, a certain influencing factor is incorporated in a specific situation for LIP research. Candas et al.[3] established the LIP model of service parts logistics centers, taking into account the facility allocation restrictions under the requirement of customer-based service levels. Tirkolaee et al.[4] considered the fluctuation of uncertain demands within the interval and designed a location-allocation-inventory model. Wei[5] made bi-level programming with location-inventory decisions as the upper model and customer demands as the lower model to refine the research on influencing factors. Location costs, inventory costs and related influencing factors were fully considered for making location decisions in these studies. Most of them completed location and routing decisions, and some completed inventory decisions.

Regarding the research on commercial vehicle logistics network, Zheng et al.[6] conducted an in-depth study of constraint conditions based on the first research perspective in combination with the characteristics of commercial vehicle transportation. However, the current method has limitations for the commercial vehicle distribution network. First, it fails to describe the characteristics of commercial vehicle logistics accurately. In practice, the location decision of distribution centers is affected by construction costs, the transportation distance and the unit price of transportation. The unit price of transportation is associated with the transportation volume. Assuming that each transportation volume is equal to the order quantity, the unit price of transportation will be higher in the case of a small order quantity when the scale economy of transportation is not reached; otherwise, it will be lower. That is,
the larger the order quantity, the lower the related cost of location decision. However, the related cost of inventory decision first decreases and then increases. The current method involves weak research on the mutual influence and mutual checks and balances between the location problem and the inventory problem.

Second, it fails to solve the inventory problem effectively. How to set up and adjust the inventory strategy of distribution centers and stores will be the next problem faced by enterprises after distribution centers are located and constructed. Both location and inventory problems have been considered in existing researches, however, they focus on the location decision and the study on the inventory problem is mostly limited to the cost perspective and is not in-depth enough.

This paper conducts a study on LIP from the perspective of the check-and-balance relationship between location and inventory decisions of the commercial vehicle distribution network.

2. Cost calculation of commercial vehicle distribution network

2.1. Commercial vehicle distribution network

Alternative distribution centers (DCs) are selected from the demand cities in a three-level commercial vehicle distribution network consisting of one Original Equipment Manufacturer (OEM), m alternative DCs and p stores. The mode of transportation from the main engine plant to the DC and from the DC to the store is railway transportation and short-distance lightering, and road transportation respectively. The two processes are called distribution and delivery. The distribution network is shown in Figure 1.

![Figure 1. Schematic diagram of distribution network](image)

This study includes location and inventory strategies of DCs and the inventory strategy of stores. To facilitate the study of the problem, a basic hypothesis is put forward. That is, the needs of stores are independent of each other and subjected to normal distribution; both DCs and stores implement the (Q, R) inventory strategy; stores follow a single-source procurement mode, that is, only one DC can provide services for them; the order lead time of DCs and stores is fixed without fluctuation; the unit price of transportation of each vehicle is positively correlated with the transportation volume and has a negatively logarithmic relationship with the distance; each order quantity is equal to the transportation volume; and the same order is not considered for partial shipment.

The parameters are given: I is the set of alternative DCs, \( i \in I \); J is the set of stores, \( j \in J \); \( W \) refers to the unit price of commercial vehicles; \( \beta \) is the customer loyalty; \( \mu_i \) and \( \sigma_i \) refer to the average value and standard deviation of daily demands of DC, \( \mu_j \) and \( \sigma_j \) refer to the average value and standard deviation of daily demands of stores, \( \mu_i = \sum_{j \in J} \mu_j Y_{ij} \) and \( \sigma_i^2 = \sum_{j \in J} \sigma_j^2 Y_{ij} \); \( F_i \) refers to fixed costs of alternative DC; \( k_d \) and \( k_s \) are parameters respectively in the function of relationships between the unit price of transportation and the distance and between the same and the transportation volume during distribution and delivery; \( D_d \) and \( D_s \) are the transportation distance in the distribution and delivery stages respectively; \( H_d \) and \( H_s \) are the unit inventory carrying costs of DCs and stores respectively; \( O_d \) and \( O_s \) are the cost of each order of DCs and stores respectively; \( E_d \) and \( E_s \) refer to the emergency
supply cost and the unit product shortage cost of DCs and stores respectively, $E_p = \beta W$; $L_i$ and $L_p$ are the order lead time of DCs and stores respectively; $z$ is the safety factor. $X_i$ indicates whether to use the DC $i$. If yes, it is 1; otherwise it is 0. $Y_j$ indicates whether the store $j$ is served by the DC $i$. If yes, it is 1; otherwise it is 0; $Q_i$ and $Q_j$ are respectively the order quantity of DC $i$ and store $j$.

2.2. Cost structure analysis
Location costs of DCs include their fixed costs and the transportation costs in two stages. Fixed costs:

$$\sum_{i=1}^{n} C_{P_i} = \sum_{i=1}^{n} F_i X_i$$  \hspace{1cm} (1)

A distribution cost function considering both the transportation volume and the distance is proposed here according to the transportation cost function proposed by Li et al.\[7\]:

$$\sum_{i=1}^{n} C_{D_i} = \sum_{i=1}^{n} 360 \mu_i \left[ k_{d,1} + k_{d,2} D_i + k_{d,3} \ln (Q_i + 1) \right]$$  \hspace{1cm} (2)

The calculation of delivery cost is similar to distribution cost, just replace $D_i$ and $Q_i$ in the formula with $D_j$ and $Q_j$.

DCs implement the (Q, R) strategy, that is, continuous check of the inventory. An order is placed when the inventory is reduced to the reorder point $R_i$. Each order quantity is $Q_i$. The safety inventory is $iA_i = z_i L_i$; the reorder point is $R_i = s_i + L_i \mu_i$; and the average shortage in each ordering cycle is $ES_i = -s_i \sqrt{L_i \sigma_i} \left[ 1 - \Phi(z) \right] + \sqrt{L_i \sigma_i} \varphi(z)$, where $\Phi(z)$ and $\varphi(z)$ respectively refer to the value of the distribution function and the probability density of the standard normal distribution when the value is $z$.

Inventory costs of DCs include inventory carrying costs, ordering costs and emergency supply costs. Inventory carrying costs are the product of the unit inventory carrying cost and the average inventory level:

$$\sum_{i=1}^{n} C_{H_i} = \sum_{i=1}^{n} 360 L_i \sigma_i \left( \frac{Q_i}{2} + s_i \right)$$  \hspace{1cm} (3)

Order costs are the product of the unit order cost and the order frequency:

$$\sum_{i=1}^{n} C_{O_i} = \sum_{i=1}^{n} O_i \left( \frac{360 \mu_i}{Q_i} \right)$$  \hspace{1cm} (4)

Emergency supply costs are the product of the unit emergency supply cost, the shortage in the cycle and the number of order cycles:

$$\sum_{i=1}^{n} C_{E_i} = \sum_{i=1}^{n} E_i \left[ ES_i \frac{360 \mu_i}{Q_i} \right]$$  \hspace{1cm} (5)

The cost calculation of the store is similar to that of the DC, simply replace the parameters in the formula with the corresponding parameters of the store.

3. Location-inventory joint decision based on bi-level programming

3.1. Location-inventory joint decision model
From the perspective of DCs and stores, overall consideration is given to network location and inventory optimization problems, and costs corresponding to the two targets are minimized through repeated coordination of location and inventory strategies in this paper. Network location belongs to strategic planning and generally will not change within 5 to 10 years after completion of the facility. Inventory optimization belongs to tactical planning, and the decision-making department adjusts the inventory strategy on an annual or quarterly basis. According to the time limit of decision change, the master of the bi-level programming is the location planning decision-making department, and the slave is the inventory management department.
3.1.1. Upper model.
The upper model provides the optimal location and customer radiation plan for the decision-making
department to minimize the sum of fixed costs, distribution costs and delivery costs.

\[
\min TC_{\text{loc}} = \sum_{i \in I} C_{p_i} + \sum_{j \in J} C_{r_j} + \sum_{j \in J} C_{t_j}
\]

\[
= \sum_{i \in I} F_i X_i + \sum_{j \in J} 360 \mu_i \left[ k_{s_1} + k_{s_2} D_i + k_{s_3} \ln (Q_i + 1) \right] + \sum_{i \in I} \sum_{j \in J} 360 \mu_j \left[ k_{s_1} + k_{s_2} D_j + k_{s_3} \ln (Q_j + 1) \right] y_{ij}
\]

\[
= \sum_{i \in I} F_i X_i + \sum_{j \in J} 360 \mu_i \left[ k_{s_1} + k_{s_2} D_i + k_{s_3} \ln (Q_i + 1) \right] + \sum_{i \in I} \sum_{j \in J} 360 \mu_j \left[ k_{s_1} + k_{s_2} D_j + k_{s_3} \ln (Q_j + 1) \right] y_{ij}
\]

subject to:

\[
\sum_{i \in I} y_{ij} = 1; i \in I, j \in J
\]

\[
\sum_{i \in I} X_i \geq 1; i \in I
\]

\[
y_{ij} - X_i \leq 0; i \in I, j \in J
\]

\[
X_i \in [0,1]; i \in I
\]

\[
y_{ij} \in [0,1]; j \in J
\]

Constraint (7) is a single-source procurement constraint, which means that one store can only be
radiated by one DC; constraint (8) means that at least one DC is selected; constraint (9) means that, if a
DC provides services for stores, it must be kept open; and, constraints (10) and (11) are limits of 0-1
decision variables. The upper model belongs to 0-1 planning, and the decision variables are \( X_i \) and \( Y_{ij} \).

\( Q_i \) and \( Q_j \) are obtained from the lower model.

3.1.2. Lower model.
The lower model provides the optimal inventory strategy for DCs and stores, minimizing their total
inventory costs.

\[
\min TC_{\text{inv}} = C_{p} + C_{o} + C_{k}
\]

\[
= \sum_{i \in I} C_{p_i} + \sum_{j \in J} C_{r_j} + \sum_{i \in I} C_{o_i} + \sum_{j \in J} C_{d_j} + \sum_{j \in J} C_{e_j}
\]

\[
= 360 \times \sum_{i \in I} H_A \left( \frac{Q_i}{2} + s s_i \right) + \sum_{j \in J} H_R \left( \frac{Q_j}{2} + s s_j \right) + \sum_{i \in I} O_A \left( \frac{360 \mu_i}{Q_i} \right)
\]

\[
+ \sum_{j \in J} O_R \left( \frac{360 \mu_j}{Q_j} \right) + \sum_{i \in I} E_d \left( \frac{360 \mu_i}{Q_i} \right) + \sum_{j \in J} E_r \left( \frac{360 \mu_j}{Q_j} \right)
\]

The lower model belongs to unconstrained nonlinear programming, and the decision variables are \( Q_i \) and \( Q_j \). The objective function is a concave function and there is a minimum value. The partial de-

rivatives of \( Q_i \) and \( Q_j \) are calculated respectively. Letting the first derivative be 0, we can obtain the
optimal order quantity:

\[
Q_i = \left[ 2 \mu_i \left( O_i + E_d \left( \frac{360 \mu_i}{Q_i} \right) \right) \right]^{\frac{1}{2}} \left[ 2 \left( O_i + E_d \left( \frac{360 \mu_i}{Q_i} \right) \right) \sum_{j \in J} \mu_j Y_{ij} \right]^{\frac{1}{2}}
\]

\[
Q_j = \left[ 2 \mu_j \left( O_j + E_r \left( \frac{360 \mu_j}{Q_j} \right) \right) \right]^{\frac{1}{2}} \left[ 2 \left( O_j + E_r \left( \frac{360 \mu_j}{Q_j} \right) \right) \sum_{i \in I} \mu_i X_i \right]^{\frac{1}{2}}
\]

3.2. Solving algorithm design
When there are 16 alternative DCs and 31 stores, the model has 512 0-1 variables, 47 integer variables and 590 constraints, involving a large-scale optimization problem. The YALMIP toolbox obtains the solution of the optimization problem by calling an external solver. When the program is designed, a solver is specified or YALMIP calls the applicable solver automatically based on the characteristics of the model[8], which can be used to solve linear programming, integer programming, non-linear programming, mixed programming and bi-level programming and has good optimization and short operation time when solving large-scale problems. In this study, a solving process based on the branch and bound algorithm is designed and the solution is completed by the SCIP (Solving Constraint Integer Programs) solver.

STEP 1: initialization. Set initial $X^0_i, Y^0_j, Q^0_i$ and $Q^0_j$, that is, initial order and location plans. Let $n = 1$ and $d = 1$ ;

STEP 2: calculate the objective function value. Change the set status of each alternative DC one by one with the help of the SCIP solver, that is, let $X^n_i = X^n_i - X^0_i$ and $Y^n_j = Y^n_j - Y^0_j$, and calculate the corresponding $Q^n_i, Q^n_j, TC_{loc}$ and $TC_{inv}$. If the new location and inventory plans are better, that is $TC_{loc} < TC_{loc} - 1$ and $TC_{inv} < TC_{inv} - 1$, let $n = n + 1$ and test the next alternative point; if $TC_{loc} > TC_{loc} - 1$ or $TC_{inv} > TC_{inv} - 1$, that is, the new plans are not better, restore the original settings of $X_i$ and $Y_j$, let $n = n + 1$ and continue to test the next alternative point. If all alternative points have been tested, let $d = d + 1$ and turn to the next step;

STEP 3: convergence judgment. Judge whether the location plan and the inventory plan are repeated respectively, i.e. $X^n = X^{n-1}$, $Y^n = Y^{n-1}$, $Q^n = Q^{n-1}$ and $Q^n = Q^{n-1}$. If yes, modify the initial value and go to STEP 2; if the preset number of inspections has been reached, that is $d = M$ (where $M$ is the preset maximum number of iterations), stop iteration and output the setting plan; otherwise, re-check each road section, let $n = 1$, $d = d + 1$ and go to STEP 2.

4. Case analysis

4.1. Example

One main engine plant of H Automobile Company is located in Chengdu, serving all stores in 31 provinces across China. Values of main parameters are shown in Table 1 and Table 2.

| Alternative DC | $D_i$ (km) | $F_i$ ($10^4$ yuan) | Parameter | Value | Parameter | Value |
|---------------|------------|---------------------|-----------|--------|-----------|--------|
| Yingkou       | 2,388      | 540                 | $W$       | 1,200,000 | $\beta$  | 0.2    |
| Changchun     | 2,736      | 610                 | $H_A$     | 125     | $H_R$     | 167    |
| Harbin        | 3,073      | 598                 | $O_A$     | 100,000  | $O_R$     | 50,000 |
| Dongguan      | 1,644      | 654                 | $E_A$     | 10,000   | $E_R$     | 240,000|
| Foshan        | 1,577      | 685                 | $L_A$     | 15       | $L_R$     | 7      |
| Hefei         | 1,502      | 642                 | $k_{A1}$  | 2,079.127| $k_{RL1}$ | 516.366|
| Guangzhou     | 1,580      | 940                 | $k_{A2}$  | 0.217    | $k_{RL2}$ | 1.006  |
| Beijing       | 1,791      | 1,080               | $k_{A3}$  | -229.830 | $k_{RL3}$ | -5.767 |
| Xuzhou        | 1,543      | 628                 | $k_{A4}$  | 50       | $z$       | 1.64   |
| Xingtao       | 1,420      | 540                 |           |          |           |        |
| Fuzhou        | 2,059      | 646                 |           |          |           |        |
| Shijiazhuang  | 1,506      | 613                 |           |          |           |        |
| Yantai        | 2,055      | 646                 |           |          |           |        |
| Tianjin       | 1,811      | 851                 |           |          |           |        |
| Dezhou        | 1,630      | 563                 |           |          |           |        |
| Chengdu       | 0          | 786                 |           |          |           |        |

The optimization results are shown in Table 3, Table 4 and Table 5.
### Table 3. DC location, allocation and inventory strategy

| Location | $Q_i$ | $R_i$ | $s_i$ | Network distribution plan |
|----------|-------|-------|-------|---------------------------|
| Yingkou  | 935   | 5,877 | 387   | Liaoning, Jilin, Heilongjiang |
| Guangzhou| 629   | 3,099 | 232   | Guangdong, Fujian, Hainan |
| Dezhou   | 1,414 | 10,162| 788   | Shandong, Jiangsu, Hebei, Henan, Anhui, Zhejiang, Beijing, Inner Mongolia, Shanxi, Tianjin, Shanghai |
| Chengdu  | 1,194 | 7,690 | 723   | Hubei, Hunan, Yunnan, Sichuan, Shaanxi, Guizhou, Guangxi, Jiangxi, Xinjiang, Ningxia, Qinghai, Chongqing, Gansu, Tibet |

### Table 4. Store inventory strategy

| Location | $Q_j$ | $R_j$ | $s_j$ |
|----------|-------|-------|-------|
| Liaoning | 1,002 | 908   | 128   |
| Hebei    | 1,490 | 1,221 | 119   |
| Shandong | 856   | 615   | 74    |
| Jilin    | 526   | 545   | 58    |
| Guizhou  | 587   | 546   | 57    |
| Hainan   | 530   | 491   | 479   |
| Jilin    | 479   | 472   | 472   |
| Hebei    | 272   | 265   | 265   |
| Nanjiang | 217   | 217   | 217   |
| Dongqi   | 150   | 150   | 150   |
| Jiangxi  | 157   | 157   | 157   |
| Hebei    | 156   | 156   | 156   |
| Hainan   | 156   | 156   | 156   |
| Anzhen   | 110   | 110   | 110   |
| Shaanxi  | 91    | 91    | 91    |
| Shanxi   | 85    | 85    | 85    |
| Qinghai  | 71    | 71    | 71    |
| Inner Mongolia | 65 | 65 | 65 |
| Shaanxi  | 59    | 59    | 59    |
| Jilin    | 52    | 52    | 52    |
| Hainan   | 46    | 46    | 46    |
| Shaanxi  | 13    | 13    | 13    |
| Anhui    | 10    | 10    | 10    |
| Ningxia  | 7     | 7     | 7     |
| Qinghai  | 5     | 5     | 5     |
| Shaanxi  | 3     | 3     | 3     |
| Inner Mongolia | 1 | 1 | 1 |
| Shaanxi  | 1     | 1     | 1     |
| Anhui    | 1     | 1     | 1     |
| Ningxia  | 1     | 1     | 1     |
| Shaanxi  | 1     | 1     | 1     |
| Inner Mongolia | 1 | 1 | 1 |
| Shaanxi  | 1     | 1     | 1     |
| Anhui    | 1     | 1     | 1     |
| Ningxia  | 1     | 1     | 1     |
| Shaanxi  | 1     | 1     | 1     |

### Table 5. The cost of the optimal solution

| Category            | Costs ($10^4$ yuan) | Percentage |
|---------------------|---------------------|------------|
| Fixed costs         | 2,829               | 1.43%      |
| Distribution costs  | 38,032              | 19.28%     |
| Delivery costs      | 63,601              | 32.33%     |
| Inventory carrying costs of DCs | 18,974 | 9.62% |
| Order costs of DCs  | 1,100               | 0.56%      |
| Emergency supply costs of DCs | 806 | 0.41% |
| Inventory carrying costs of stores | 40,351 | 20.45% |
| Order costs of stores | 7,200               | 3.65%      |
| Customer loss costs of stores | 24,419     | 12.38%    |
| Total               | 197,312             |            |

The total minimum network costs are 1.973 billion yuan, including upper costs 1.045 billion yuan and lower costs 928 million yuan. In comparison with the model of first location and then inventory optimization, the total network costs are reduced by 24.98%, of which the upper costs are saved by 38.89% and the lower costs are increased by 0.87%.

#### 4.2. Parameter sensitivity analysis

##### 4.2.1. Analysis of inventory service level

The inventory service level $\alpha$ indicates the degree of satisfaction of inventory to demand. The safety factor $z$ is the inverse function value of the standard normal cumulative distribution function when the value is $\alpha$. The higher the $\alpha$, the higher the $z$. The inventory service level has the same actual meaning as the safety factor, which is more direct. Costs at different inventory service levels are shown in Figure 2.
The inventory service level is 93% when the upper and lower costs are balanced and 99.9% when the total network costs are minimum. The lower costs drop rapidly as the inventory service level increases, which is due to the substantial reduction of shortage costs. The shortage cost is an important bottleneck that limits cost savings. The reduction of shortage costs will result in great improvement of the total network costs.

4.2.2. Customer loyalty analysis.
Improving customer loyalty is one of the effective measures to reduce shortage costs. Keep $\alpha=95\%$, that is, $z=1.64$. The relationship between customer loyalty and costs is shown in Figure 3.

With the increase of customer loyalty, the upper costs are increased slowly and slightly and the lower costs and the total network costs are reduced greatly. Customer loyalty has a greater impact on lower costs than upper costs.

We will gradually improve customer loyalty to explore the relationship between costs and the inventory service level. With the increase of loyalty, enterprises can ensure balanced upper and lower costs and reduction of the total costs without a high inventory service level. That is, in Figure 3, the junction of upper and lower cost curves moves forward and the total cost curve becomes lower, and the minimum value occurs, as shown in Figure 4 and Figure 5.

When the customer loyalty is greater than 60%, the inventory service level making upper and lower costs balanced declines faster. This means that, to maintain a balance between upper and lower costs of the distribution network, the inventory service level should be kept at 87% or below if stores can keep the customer service level above 60%. This means that the higher the customer loyalty, the lower the requirements for inventory service levels.

4.2.3. Analysis of market demand fluctuations.
When the average demand fluctuates within $\pm50\%$, changes are shown in Table 6.
Table 6. Changes in the optimal plan after fluctuations in the average demand

| Average demand fluctuation | Changes in the optimal solution |
|----------------------------|---------------------------------|
| -50%                       | The DC serving Henan is transferred from Dezhou to Chengdu |
| -25%                       | The DC serving Henan is transferred from Dezhou to Chengdu |
| +25%                       | Same as the original optimal solution |
| +50%                       | Same as the original optimal solution |

The network optimization plan has high stability. The fluctuation of the average demand within a certain range has little impact on the network.

4.2.4. Number of DCs located.

When the number of DCs located increases to 5, 6 and 7, the network location results show that, when 1 to 3 cities are added to the plan with four DCs, customers with the radiation relationship changed include Tibet and Hainan, etc. and the total network costs increase.

At the same time, the increase of the number does not significantly shorten the weighted average distance of the network. The reason is that the model gives priority to improving customers with a long distance after addition of location points. However, customers at remote locations have almost the same distance to each alternative point and small demands, so the weighted average transportation distance is improved little. This indicates that the plan with four DCs has optimized large customers with high demands. If the alternative set remains the same, there is little room for further network optimization.

5. Conclusion

Aiming at the location-inventory joint decision problem of the commercial vehicle distribution network, this paper expresses the connection between location and inventory based on the bi-level programming idea. The location-inventory joint decision model can provide decision-making basis for the main participants in the supply chain at the same time, including location and inventory decisions of DCs and inventory decisions of stores. This paper analyses the inventory service level and customer loyalty from the perspective of cost. To save the total cost of the network, it is necessary to improve customer loyalty as much as possible while adjusting the inventory service level appropriately. The analysis provides cost-saving ideas for automobile companies.

The model idealizes the actual situation. To make the scenario more realistic, consideration will be given subsequently in further research to multiple factors such as facility capacity limitations, multiple categories and collaborative ordering.

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