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Research Article

Location Optimization of Multidistribution Centers Based on Low-Carbon Constraints

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Location optimization of distribution centers is a systematic and important task in logistics operations. Recently, reducing carbon footprint is becoming one of the decision-making factors in selecting the locations for distribution centers. This paper analyzes the necessity of industrial carbon dioxide emission cost internalization in four aspects and builds a model for multidistribution centers location in effort of reducing carbon footprint that can provide optimized strategy support for decision makers and logistic operators. Numerical examples are presented to illustrate the feasibility and effectiveness of the models.

1. Introduction

Location selection is an important and systematic problem in logistics operations, and it is also a key component of a corporation's strategic management. Optimizations of a distribution center location can improve the center's operational cost and service level, as well as rationalizing the entire logistic systems. This problem has attracted wide attention from managers and scholars over the past years, and there are extensive researches done on this matter. Most of the previous studies focused on location selection based only on the cost of distribution centers, such as fixed cost, transportation cost, and storage cost. Very few of them considered low-carbon footprint factors [1–3]. In an effort of reducing carbon footprint globally, location selection of distribution centers should take the cost of carbon dioxide emission and lowering carbon footprint into account.

Among the few studies of location selection based on carbon footprint, Huang [4] suggested a multibusiness trade of distribution center location selection model that limits carbon footprint without considering the cost of carbon dioxide emission. Yang et al. [5] built a model for carbon tax-constrained capacitated cold chain logistics to mitigate the cost burden resulting from the carbon emission tax; Yang and Lin [6] offered a new model targeting two separate scenarios, carbon trading and carbon tax, and compared the effects of these two mechanisms. These models did not consider the carbon dioxide emission quotas and the cost of carbon dioxide emission simultaneously. This kind of problems will become more and more important with the global low-carbon footprint requirement. To solve this problem, this paper is offering a model that considers not only the cost of carbon footprint emissions but also having emission quotas for each distribution center of a multidistribution center. The rest of the paper is organized as follows: Section 1 explains the indispensability of internalizing carbon emission cost; Section 2 describes a model based on carbon emission quotas in multiple centers of a multidistribution center; Section 3 validates the model and discusses its effectiveness using numerical methods; Section 4 concludes the study.

2. Internalization of Carbon Emission Cost

There are not many research articles about carbon dioxide emission cost because it is difficult to estimate and quantify its cost. For instance, Sadegheih [7] describes a methodology developed for designing an optimal configuration for system transmission planning with carbon emissions costs; Kneifel [8] estimates life-cycle energy savings, carbon emission reduction, and cost effectiveness of energy efficiency

measures in new commercial buildings using an integrated design approach and estimates the implications from a cost on energy-based carbon emissions. The literature on carbon footprint management in supply chain is also very sparse. Some studies focus on the measurement method of carbon emissions in supply chains; Sundarakani et al. [9] examine the carbon footprint across supply chains and thus contribute to the knowledge and practice of green supply chain management; Kannan et al. [10] develop a mixed integer linear model for a carbon footprint based reverse logistics network design; the proposed model aims at minimizing the climate change (specifically, the CO_2 footprint), and it employs reverse logistics activities to recover used products, hence combining the location/transportation decision problem; Piecyk and McKinnon [11] report on research undertaken to determine the baseline trends in logistics and supply chain management and associated environmental effects up to 2020. In this paper, the carbon dioxide emission cost is defined as the financial compensation paid by a corporation for the environment pollutions and damages caused by the carbon dioxide emission during the course of its production processes.

During the time of free carbon emission, it was the entire society which pays for the environment pollutions caused by corporations' production. Corporations were producing carbon dioxide without financial penalties (i.e., the carbon emission cost was considered as an external cost). With the recent global efforts of reducing carbon emission, carbon emission cost needs to be included as a part of the corporations' internal cost to minimize the carbon footprint.

Internalizing carbon emission cost is to quantify the amount of carbon emission as an operational cost in the accounting system. In the era of low-carbon economy, the necessity of internalizing carbon emission cost can be revealed from four perspectives. (i) It can give both pressure and motivations to corporations to reduce their carbon footprint. Without internalizing carbon emission cost, corporations do not have financial motivations to reduce carbon footprint actively. If the carbon emission cost is a part of corporations' internal cost, the balance between carbon footprint and operational revenues will be considered. (ii) Internalizing carbon emission cost is the key problem to maintain corporations' core competences. In reality, different corporations have different carbon emission costs. For 2 enterprises in the same industry, the one that has higher carbon emission cost will be eliminated by the market. This will encourage corporations to include lowering the carbon footprint in their strategic management. (iii) Internalizing carbon emission cost will serve as a catalyst in the process of corporations' development models. Corporations with high carbon footprint emission and high energy consumptions need to develop new technologies to increase its competence, so their production model can be transitioned successfully from resource dependent to technology dependent. (iv) Internalizing carbon emission cost will increase the carbon emission revenue. Carbon trading mechanism is a method to adjust carbon footprint in the market. Carbon trading is actually carbon emission-right trading. Each corporation has a carbon footprint quota, and, during the actual production, corporations that exceeded the quotas would have to purchase quotas from other corporations that had quota surpluses. From the opportunity point of view, the carbon emission quota can be considered as a product, and it will encourage every corporation to emit as little carbon as possible for more profit.

3. Low-Carbon Constraint Model

In this paper, we assume there are m source points, n distribution centers, and p demand points in a 3-level logistic distribution network. The purpose of the research is to solve the following problems: the proper number of distribution centers that does not exceed the given number; the final lowest total cost based on each center's cost and the allocation of customers to distribution centres. In order to build a mathematical model and to find reasonable solutions, we have the following assumptions.

(i) Choose distribution centers that will be built from the candidate distribution centers; the number of the selected distribution centers is bounded. The locations of all candidate available distribution centers are known.

(ii) Every customer's demand is known. The storage capacity of each distribution center is bounded, but it is able to meet customers' demands.

(iii) The flow cost that occurred in each distribution center is known.

(iv) Only a single product's distribution is considered. One distribution center can serve multiple customers, and one customer can be served by multiple distribution centers. There is no product transfer among distribution centers.

(v) From a depot to a distribution center, or from a distribution center to a demand point (customer), only one transportation mode is allowed (i.e., using the same model of vehicle) over the entire system. The unit energy consumptions and road conditions are the same everywhere and are known.

(vi) The equivalent cost of unit mass of carbon dioxide is known.

(vii) The construction cost for each distribution center is the same, so it is not considered in the model, nor the storage cost for each distribution center.

(viii) Only the carbon emission that occurred in the distribution centers' operating processes is considered; the emission that occurred during construction is not included in the total costs.

(ix) Every distribution center's carbon quota is known. The carbon trading mechanism is not considered. Distribution centers can exceed the emission quota but with penalties. The penalty coefficient is known and is constant (i.e., the coefficient does not change with the over-quota amount).

The variables and parameters that will be used in the model are defined as follows:

a_{ij}: transportation rate from the depot i to the distribution center j (\$/t);

b_{jk}: transportation rate from the distribution center j to the demand point k (\$/t);

g_{ij}: energy consumption for unit product transported from the depot i to the distribution center j (L/t);

h_{jk}: energy consumption for unit product transported from the distribution center j to the demand point k (L/t);

d_j: the flow cost for unit product in the distribution center j (\$/t);

f_j: the flow energy consumption for unit product in the distribution center j (L/t);

Q_i: the supply capacity of the depot i (t/year);

R_j: the storage capacity of the distribution j (t/year);

T_k: the yearly demand amount from the demand point k (t/year);

U_j: the carbon dioxide emission quota for the distribution center j (t/year);

M: the maximum number of distribution centers that can be selected;

ε: the carbon dioxide emission coefficient for gasoline (t/L);

μ: the equivalent cost of unit carbon dioxide emission (t/L);

ρ: the penalty coefficient (\$/t);

Z: the total cost (\$);

M, n, p: the numbers of depots, potentially available distribution centers, and demand points, respectively;

X_{ij}: the logistic quantity from the depot i to the distribution center j;

Y_{jk}: the logistic quantity from the distribution center j to the demand point k.

The multidistribution centers location selection model based on low-carbon constraints is as follows:

$$\begin{aligned}\min Z = {} & \sum_{i=1}^{m}\sum_{j=1}^{n}\left(a_{ij}+\mu\varepsilon g_{ij}\right)+\sum_{j=1}^{n}\sum_{k=1}^{p}\left(b_{jk}+\mu\varepsilon h_{jk}\right)Y_{jk} \\ & +\rho\left\{\sum_{j=1}^{n}V_j\max\left[\varepsilon\left(\sum_{i=1}^{m}X_{ij}g_{ij}+\sum_{k=1}^{p}Y_{jk}h_{jk}\right.\right.\right. \\ & \left.\left.\left.+\sum_{i=1}^{m}X_{ij}f_j\right)-U_j,0\right]\right\} \\ & +\sum_{i=1}^{m}\sum_{j=1}^{n}\left(d_j+\mu\varepsilon f_j\right)X_{ij},\end{aligned} \tag{1}$$

such that

$$\sum_{j=1}^{n}X_{ij}\le Q_i,\quad i=1,2,\ldots,m, \tag{2}$$

$$\sum_{i=1}^{m}X_{ij}\le R_jV_j,\quad j=1,2,\ldots,n, \tag{3}$$

$$\sum_{j=1}^{n}Y_{jk}\ge T_k,\quad k=1,2,\ldots,p, \tag{4}$$

$$\sum_{i=1}^{m}X_{ij}=\sum_{k=1}^{p}Y_{jk},\quad j=1,2,\ldots,n, \tag{5}$$

$$\sum_{j=1}^{n}V_j\le M, \tag{6}$$

$$\begin{gathered}X_{ij}\ge 0,\quad Y_{jk}\ge 0,\\ i=1,2,\ldots,m;\quad j=1,2,\ldots,n;\quad k=1,2,\ldots,p,\end{gathered} \tag{7}$$

$$V_j=\begin{cases}1, & \text{if the distribution centre } j \text{ is selected}\\ 0, & \text{otherwise.}\end{cases} \tag{8}$$

In the objective function, the total cost is comprised of four components. The first part is the total cost of transporting products from depots to distribution centers, including transportation cost and the carbon emission cost due to transportation. The second part is the total cost of transporting products from distribution centers to demand points, including transportation cost and the carbon emission cost due to transportation. The third part is the penalty cost of all distribution centers that exceeded carbon emission quotas. In the small brackets, the first term is the energy consumption from all depots to the distribution center j, the second term is the energy consumption from the distribution center j to all demand points, and the third term is the flow energy consumption of the distribution center j. The fourth part is the total cost of products routing through distribution centers, which includes the flow cost and the carbon emission cost due to routing through distribution centers. The flow cost is mainly caused by loading and unloading, handling, and processing products in the distribution centers.

In the constraint conditions, (2) is the supply constraint, which is the total supplied product amount that cannot exceed the depot's total supply capacity; (3) is the storage constraint, which is the total supplied amount from each depot to the distribution center j that cannot exceed the distribution center's total construction storage; (4) is the demand constraint, which is the amount that a distribution center supplies to a demand point that should meet the demand point's needs; (5) is the balance constraint, which controls the amount of products flowing into a distribution center that equals the amount of flowing out of it; (6) is the number constraint, which is the total number of selected distribution centers that cannot exceed M; (7) and (8) are the nonnegative constraint and 0-1 constraint, respectively.

Table 1: Supply capacities and transportation cost rate of depots.

Depot	Supply capacity (t/year)	Transportation cost from depot to distribution centers ($/t)				
		N_1	N_2	N_3	N_4	N_5
E_1	800	140	120	135	120	115
E_2	1000	125	130	110	135	120

Table 2: Energy consumption coefficients from depots to distribution centers.

Depot	Energy consumption coefficients (L/t)				
	N_1	N_2	N_3	N_4	N_5
E_1	18	20	23	16	17
E_2	15	22	18	18	19

Table 3: Demands and transportation costs.

Demand point	Demand (t)	Transportation costs to demand points ($/t)				
		N_1	N_2	N_3	N_4	N_5
P_1	150	60	65	55	70	75
P_2	130	55	70	60	60	50
P_3	200	60	55	70	80	65
P_4	110	75	80	65	50	60
P_5	140	70	55	60	65	75
P_6	100	65	80	65	75	60
P_7	125	50	60	60	65	70
P_8	165	60	65	60	70	60

4. Model Solutions and Numerical Examples

Assume that a corporation plans to build a certain number of distribution centers in district S to extend its product's supply and sales. The corporation has 2 production plants, E_1 and E_2, 8 demand points, and 3 potentially available distribution centers. Considering the cost factor, the newly constructed distribution centers will not exceed 3. Tables 1, 2, 3, 4, and 5 showed conditions and parameters that are used in this model.

This model assumes a single type of vehicle for transportation, a single type of energy (gasoline), and a single transportation mode (road). The carbon dioxide emission factor is given by IPCC2006 as 2.26×10^{-3} t/L [12]. Let the equivalent cost of unit carbon dioxide emission be 90 $/t. The penalty coefficient is 200 $/t when a distribution center exceeds its carbon dioxide emission quota.

From the model description, we have $m = 2$, $n = 5$, $p = 8$, $\varepsilon = 0.00226$, $\mu = 90$, and $\rho = 200$. Combining the given conditions from Tables 1 to 5, numerical results can be obtained by LINGO software, and the results are shown in Figure 1. We can see that $V(N_1) = 1$, $V(N_2) = 0$, $V(N_3) = 1$, $V(N_4) = 0$, and $V(N_5) = 1$. Therefore, the selected three distribution centers are N_1, N_3, and N_5, and they will service 8 demand points. The minimum total cost is $268, 586.3. Z_1 is the penalty cost for all the selected distribution centers due to exceeding the emission constraint. In the numerical program, $S(j)$ represents the amount of carbon dioxide exceeded by the jth distribution center. From Figure 1, one can see that $S(N_3)$ and $S(N_5)$ are both larger than 0, which means the distribution centers N_3 and N_5 both exceeded their carbon dioxide quotas. Z_2 is the total cost of transportation from 2 depots to 3 distribution centers. Z_3 is the total cost of transportation from 3 distribution centers to 8 demand points. Z_4 is the flow cost of the products going through the distribution centers. Tables 6 and 7 showed the optimal plan for each depot and each distribution center, respectively.

Table 4: Energy cost from distribution centers to demand points.

Distribution center	Energy cost from distribution centers to demand points (L/t)							
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
N_1	11	12	10	9	10	10	9	10
N_2	9	7	9	10	11	9	10	11
N_3	11	12	12	11	10	12	11	10
N_4	8	8	9	10	11	9	10	11
N_5	10	11	8	8	9	8	8	9

Table 5: Parameters of distribution centers.

	N_1	N_2	N_3	N_4	N_5
Built capacity (t)	550	600	500	650	700
Unit product's flow cost ($/t)	50	60	55	70	50
Unit product's flow energy consumption ($/t)	5	6	5	7	6
CO_2 emission quota (t/year)	10	9	8	10	9

Table 6: The amount that is supplied to distribution centers (t/year).

	Distribution center N_1	Distribution center N_3	Distribution center N_5
Depot E_1			509.2
Depot E_2	155.8	455	

A comparison study is also provided to compare the results between taking and not taking the low-carbon factor into account. All assumptions remain the same for the ordinary case, and the objective function is

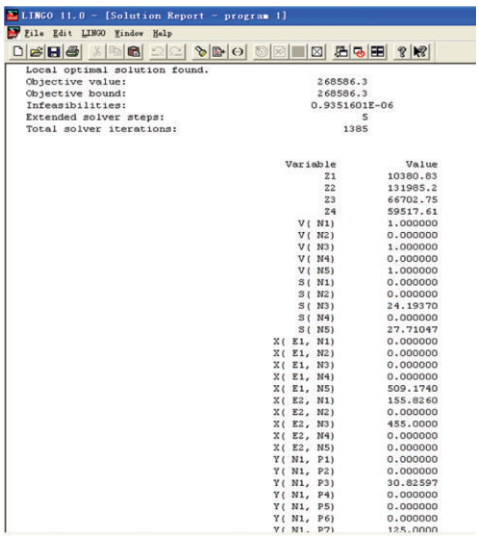
$$\min Z = \sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}X_{ij} + \sum_{j=1}^{n}\sum_{k=1}^{p} b_{jk}Y_{jk} \sum_{i=1}^{m}\sum_{j=1}^{n} d_j X_{ij}. \quad (9)$$

Figure 2 showed the results $V(N_1) = 0$, $V(N_2) = 0$, $V(N_3) = 1$, $V(N_4) = 0$, and $V(N_5) = 1$, which means two distribution centers (N_3 and N_5) are selected for servicing 8 demand points. The minimum total cost is $250,950.

Z_2 is the total cost of transportation from 2 depots to 2 distribution centers, Z_3 is the total cost of transportation from 2 distribution centers to 8 demand points, and Z_4 is the flow cost of the products going through the distribution centers.

Table 7: The amount that is supplied by distribution centers (t/year).

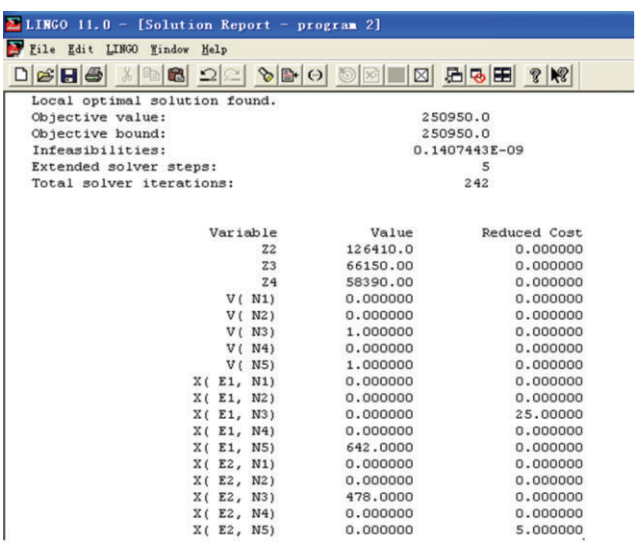
	Demand point P_1	Demand point P_2	Demand point P_3	Demand point P_4	Demand point P_5	Demand point P_6	Demand point P_7	Demand point P_8
Distribution center N_1			30.8				125	
Distribution center N_3	150				140			165
Distribution center N_5		130	169.2	110		100		



```
LINGO 11.0 - [Solution Report - program 1]
File Edit LINGO Window Help
Local optimal solution found.
Objective value:                    268586.3
Objective bound:                    268586.3
Infeasibilities:                 0.9351601E-06
Extended solver steps:                   5
Total solver iterations:              1385

                  Variable           Value
                        Z1        10380.83
                        Z2        131985.2
                        Z3        66702.75
                        Z4        59517.61
                    V( N1)        1.000000
                    V( N2)        0.000000
                    V( N3)        1.000000
                    V( N4)        0.000000
                    V( N5)        1.000000
                    S( N1)        0.000000
                    S( N2)        0.000000
                    S( N3)        24.19370
                    S( N4)        0.000000
                    S( N5)        27.71047
                X( E1, N1)        0.000000
                X( E1, N2)        0.000000
                X( E1, N3)        0.000000
                X( E1, N4)        0.000000
                X( E1, N5)        509.1740
                X( E2, N1)        155.8260
                X( E2, N2)        0.000000
                X( E2, N3)        455.0000
                X( E2, N4)        0.000000
                X( E2, N5)        0.000000
                Y( N1, P1)        0.000000
                Y( N1, P2)        0.000000
                Y( N1, P3)        30.82597
                Y( N1, P4)        0.000000
                Y( N1, P5)        0.000000
                Y( N1, P6)        0.000000
                Y( N1, P7)        125.0000
```

Figure 1: Results of the low-carbon model.



```
LINGO 11.0 - [Solution Report - program 2]
File Edit LINGO Window Help
Local optimal solution found.
Objective value:                    250950.0
Objective bound:                    250950.0
Infeasibilities:                 0.1407443E-09
Extended solver steps:                   5
Total solver iterations:               242

                  Variable           Value        Reduced Cost
                        Z2        126410.0            0.000000
                        Z3        66150.00            0.000000
                        Z4        58390.00            0.000000
                    V( N1)        0.000000            0.000000
                    V( N2)        0.000000            0.000000
                    V( N3)        1.000000            0.000000
                    V( N4)        0.000000            0.000000
                    V( N5)        1.000000            0.000000
                X( E1, N1)        0.000000            0.000000
                X( E1, N2)        0.000000            0.000000
                X( E1, N3)        0.000000            25.00000
                X( E1, N4)        0.000000            0.000000
                X( E1, N5)        642.0000            0.000000
                X( E2, N1)        0.000000            0.000000
                X( E2, N2)        0.000000            0.000000
                X( E2, N3)        478.0000            0.000000
                X( E2, N4)        0.000000            0.000000
                X( E2, N5)        0.000000            5.000000
```

Figure 2: Results of the ordinary model.

From the comparison of the above results, one can see that one more distribution center is selected in the low-carbon model, as compared to the ordinary model that does not consider low-carbon constraint, and the distribution plans are different as well. The total carbon dioxide emission in the low-carbon model is 67.30 t with one more distribution center, and, in the traditional model, the total emission is 68.25 t. Although the difference in carbon emission is small, it will make a significant difference in reality.

5. Conclusion

Distribution center selection is a strategic key component in logistic management. This paper analyzed multidistribution center location selection with low-carbon constraints. The results showed one can reduce the system's global carbon emission by introducing low-carbon component to the model. However, the total cost of the low-carbon model results is higher than the traditional models. If one also considers the construction cost of the distribution centers, the low-carbon model might not be energy efficient and cost efficient. Therefore, in reality, corporations should compare results produced by these two models (traditional and low carbon) to make the best decision for both the development of corporations and the sustainability of the environment. Future research direction should take the carbon tax and carbon trading policy factors into account to advance the low-carbon distribution center selection model.

Acknowledgments

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