Two-stage Optimization of Low Carbon Logistics Distribution Network Considering Carbon-Tax Constraint

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Keywords: Two-stage Optimization, Low Carbon, Carbon-Tax

Abstract: This paper studies the optimization of urban express distribution network based on low carbon perspective. Considering carbon tax, this paper established the distribution hub selection, vehicle scheduling and demand matching and routing model to minimize the total cost in two stages. Finally, this paper used case data to verify the two-stage model, which has a certain realistic value for express enterprises.

1. Introduction

With the global warming, the environment is under tremendous pressure and the problem of greenhouse gas emission has been closely watched. Energy-saving and environmental protection issues such as low-carbon economy and green logistics have gradually become the hotspots of research. In 2007, Jiang studied carbon emission problem, which showed that research on transportation tools can effectively reduce carbon dioxide emissions and optimizing vehicle routing can reduce fuel consumption [1].

In 2011, Ren proposed that rational selection of transportation tools and routing optimization can reduce carbon dioxide emissions [2]. In 2012, Qiu conducted a literature review on low-carbon logistics, which showed that the essence of low-carbon logistics is to optimize transportation scheduling, which can reduce carbon emissions [3]. However, the existing research adopts a single-stage model, which is not only easy for calculation. Therefore, considering carbon emissions, this paper establishes a two-stage network optimization model, and optimizes the network of an express enterprise.

2. Two-stage optimization model considering carbon tax constraints

This paper is faced with a multi-layer express network consisting of a single primary hub, multiple secondary distribution hubs and multiple third distribution points. The total cost consists of the following parts: transportation cost and carbon tax cost from the first hub to each second hub, the distribution cost from the second hub to third hub, construction fixed cost and carbon tax cost of the second hub.

2.1 Model hypothesis

(1) The alternative 2nd hub has a capacity limit. If the 2nd hub is selected, the fixed cost and carbon tax cost are known. The transportation and distribution costs are all linear functions.

(2) The total inflow should be equal to the total outflow [4].

(3) Vehicles have maximum load limit, regardless of the demand point for delivery time.

(4) Only one 2nd hub can be assigned to each 3rd hub, and the demand for each 3rd hub can be satisfied.

(5) At least one 3rd hub is on one route, and delivery vehicle is a single and closed-loop trip [5].

(6) There are a variety of vehicle types to choose from the 1st hub to each 2nd hub.

2.2 Calculation method of carbon tax

Carbon emissions are due to direct and indirect carbon dioxide emissions from various energy consumption and substances in logistics activities [6]. This paper mainly considers the carbon dioxide emissions in the transportation stage and estimates the fuel consumed by vehicles. The fuel consumption of vehicles is not only related to distance but also cargo load. The carbon coefficient is e_0 determined by the type of fuel [7]. There is a linear relationship between fuel consumption ρ and on-board cargo X. If total weight of vehicles is divided in two parts: Q_0(vehicle weight) and X(load weight). We can assume the maximum load is Q, fuel consumption per meter at full load is ρ^*, and that at no load is ρ_0.

$$\rho(X) = \alpha(Q_0 + X) + b \tag{1}$$

$$\rho^*(X) = \alpha(Q_0 + X) + b \tag{2}$$

Therefore, (1) and (2) can be rewritten as

$$\rho(X) = \rho_0 + \frac{(\rho^* - \rho_0)}{Q} X \tag{3}$$

(5) represents a linear relationship between fuel consumption and cargo load, the emission cost is:

$$e(x_{ij}) = c_0 e_0 \rho(x_{ij}) d_{ij} \tag{4}$$

2.3 Model Construction

Considering carbon tax, the modeling of hub selection, vehicle scheduling and demand matching was established in first stage. Then, the routing model with lowest cost is established in second stage.

2.3.1 Hub Selection, Vehicle Scheduling & Demand Matching Model

The express network consists of one 1st hub, j 2nd hub, and k 3rd hub. The vehicle type from 1st to 2nd hub is a ($\mathrm{a} \in \mathrm{T}$, T: the collection of transport vehicles). The distance from 1st hub to j 2nd hub is $\mathrm{d_j}$. The max-capacity and construction fixed cost of 2nd hub is $\mathrm{v_j}$ and $\mathrm{d_j}$, carbon tax of 2nd hub is $\mathrm{R_j}$, and the demand for 3rd hub is $\mathrm{b_k}$. The max-load capacity of the ath type vehicle is $\mathrm{Q_a}$, the unit cost is $\mathrm{c_a}$, and carbon tax is $\mathrm{e_a}$. The delivery cost from 2nd hub to 3rd hub is $\mathrm{h_{jk}}$. Define continuous variable $\mathrm{x_{1j}^a}$, 0-1 variable $\mathrm{y_{jk}}$, and 0-1variable $\mathrm{z_j}$. $\mathrm{x_{1j}^a}$ indicates cargo from 1st hub to j 2nd hub by a vehicle; $\mathrm{y_{jk}} = 1$ means 3rd hub is served by 2nd hub, $\mathrm{z_j} = 1$ means j 2nd hub, otherwise is 0.

$$\mathrm{MIN} = \sum_{a=1}^{t} \sum_{j=1}^{n} e^a (x_{1j} z_j) + \sum_{j=1}^{n} \sum_{a=1}^{t} c_a x_{1j}^a d_j + \sum_{j=1}^{n} \sum_{k=1}^{p} h_{jk} y_{jk} + \sum_{j=1}^{n} g_j z_j + \sum_{j=1}^{n} R_j z_j \tag{5}$$

s.t.

$$\sum_{j=1}^{n} y_{jk} = 1, \ \ k \in P \tag{6}$$

$$\sum_{a=1}^{t} x_{1j}^a = \sum_{k=1}^{p} b_k y_{jk}, \ \ j \in M \tag{7}$$

$$\sum_{a=1}^{t} x_{1j}^a \le v_j z_j, \ \ j \in M \tag{8}$$

$$\sum_{k=1}^{p} b_k y_{jk} \le v_j z_j, \ \ j \in M \tag{9}$$

$$x_{1j}^a \le Q_a, \ \ j \in M \tag{10}$$

$$y_{jk} \in \{0,1\}, \ \ j \in M, k \in P \tag{11}$$

$$z_j \in \{0,1\}, \ \ j \in M \tag{12}$$

$$x_{1j}^a \ge Q_a, \ \ j \in M \tag{13}$$

(5) indicates that objective function of multi-layer express network system is the lowest total cost. (7) ensures the selected 2nd hub balances the inflow and outflow; (8) and (9) are for the capacity limitation, only the opened 2nd hub is required, and cargo flow cannot exceed limit;

2.3.2 Distribution Routing Optimization Model

The model at this stage is based on first stage, i,j are nodes ($i,j \in N$, N: the collection of nodes, and 1~N: the number of elements). If the label is 0, it indicates 2nd hub, and rests are represented as 3rd hub; C_{ij} indicates distance of i,j, X_{ijk} is a 0-1variable, indicating the node is on k trip, if it is adjacent, its value is 1, otherwise is 0; Y_{ik} is a 0-1 variable, if the vehicle k serves the node i, the value is 1, otherwise is 0; w_j is the cargo demand of node j; Z is the maximum load of vehicle; $U_{ik}$is for the elimination of constraint vector on k trip, indicating the order in which nodes are accessed in k trip.

$$MIN = \sum_k \sum_i \sum_j C_{ij} X_{ijk} \tag{14}$$

s.t.

$$\sum_k \sum_i X_{ijk} = 1, \; i,j \in N \tag{15}$$

$$\sum_k X_{ijk} = Y_{ik}, \; j \in N \tag{16}$$

$$\sum_j w_j \sum_i X_{ijk} \leq Z \tag{17}$$

$$\sum_i X_{ijk} = 0, \; j \in N \tag{18}$$

$$U_{ik} - U_{jk} + NX_{ijk}, \; i,j \in N \tag{19}$$

$$X_{ijk} \in \{0,1\}, \; i,j \in N \tag{20}$$

$$y_{ik} \in \{0,1\}, \; j \in N \tag{21}$$

$$U_{ik} \geq 0, \; j \in N \tag{22}$$

(14) is the objective function indicating sum of distribution costs of all delivery vehicles. (15) ensures each 3rd hub can be served by only one 2nd hub; (16) can ensure that two 0-1 variables are equal;

3. Case Study

In order to verify rationality of the method, this paper used data of an express enterprise to optimize the express network, and obtains optimal network optimization, and carries out sensitivity analysis.

3.1 Parameter Setting

Table 1. Distance between 1st hub &2nd hub

Number	(km)	Number	(km)
1	12.31	5	13.38
2	12.09	6	12.86
3	5.14	7	11.33
4	5.96	8	10.72

Table 2. Capacity, Fixed & Carbon costs of 2nd hub

	1	2	3	4	5	6	7	8
Fixed cost	70	70	70	70	55	55	55	70
Capacity	4	4	4	4	3	3	3	4
Carbon-Tax	30	30	30	30	25	25	25	30

Table 3. Distance between 2nd hub and 3rd hub

(km)	2nd hub 1	2nd hub 2	2nd hub 3	2nd hub 4	2nd hub 5	2nd hub 6	2nd hub 7	2nd hub 8
3rd hub 1	4.03	7.05	13.67	6.44	19.2	1.87	14.37	8.58
3rd hub 2	3.93	6.75	18.62	10.11	20.81	5.18	15.44	9.17
3rd hub 3	13.42	15.17	5.99	9.80	21.3	10.28	18.50	15.12
3rd hub 4	5.87	7.91	10.54	4.46	17.71	4.39	13.59	8.54
3rd hub 5	0.84	3.31	16.62	7.16	17.28	5.89	12.09	5.62
3rd hub 6	2.21	1.09	16.01	6.06	15.07	7.59	9.85	3.36
3rd hub 7	4.37	4.70	11.66	2.08	14.32	6.82	9.82	4.68
3rd hub 8	17.84	17.45	5.91	11.65	14.19	18.11	14.48	15.71
3rd hub 9	3.89	0.80	15.87	5.84	13.39	9.02	8.09	1.66
3rd hub 10	5.63	3.10	14.41	4.69	11.39	10.16	6.28	0.95
3rd hub 11	6.96	5.75	11.10	1.99	11.44	9.76	7.31	4.35
3rd hub 12	8.93	8.20	8.60	2.52	11.70	10.62	8.56	0.83
3rd hub 13	8.62	5.74	15.03	6.39	8.36	13.08	3.29	3.33
3rd hub 14	11.15	9.29	12.10	6.63	6.86	14.67	4.53	7.04
3rd hub 15	13.28	10.61	15.91	9.97	3.63	17.48	2.06	8.09
3rd hub 16	14.82	12.92	11.42	9.21	6.52	17.64	7.07	10.71
3rd hub 17	10.40	11.10	5.40	5.00	16.05	9.73	12.91	10.46
3rd hub 18	7.95	10.28	10.38	6.91	20.27	4.34	15.86	10.97
3rd hub 19	3.44	5.50	12.60	4.43	17.17	4.18	12.70	6.56
3rd hub 20	3.82	2.28	14.13	4.06	13.17	8.48	7.97	1.94

Table 4. The demand of 3rd hub

Number	Demand	Number	Demand
1	0.72	11	0.27
2	0.93	12	0.67
3	1.45	13	0.64
4	1.24	14	0.33
5	1.49	15	1.25
6	0.88	16	1.25
7	1.38	17	0.91
8	0.37	18	0.12
9	0.91	19	0.74
10	0.55	20	0.46

Table 5. Parameters of vehicles

Name	Type 1	Type 2	Type 3	Type 4
e_0(kg/l)	2.61	2.61	2.61	0
Q_a(t)	2.5	2	1.5	1.8
c_a(yuan/km)	7.12	4.93	2.64	1.91
ρ^*(l/km)	3.1	2.4	2	Null
ρ_0(l/km)	1.5	1.2	1	Null

3.2 Problem Solving

This section will solve the mixed integer programming model proposed in previous section. We set the unit carbon fee $c_0 = 0.5$ (yuan/kg), the results are in the Table 6. The optimal solution in first stage is the cost upper bound for second stage. Through routing optimizing, the amounts of vehicles are reduced, and distribution cost is lower than that in first stage.

Table 6. Results in First Stage

Selected Hub	Controlling 3rd hub	Transportation Plan
2nd hub 1	1, 2, 5, 18, 19	Type 1 for 0.5 t, Type 2 for 2 t, Type 3 for 1.5 t
2nd hub 2	6, 9, 10, 13, 20	Type 2 for 1.94 t, Type 3 for 1.5 t
2nd hub 3	3, 8, 16, 17	Type 1 for 0.48 t, Type 2 for 2 t, Type 3 for 1.5 t
2nd hub 4	4, 7, 11, 12, 14	Type 1 for 0.39 t, Type 2 for 2 t, Type 3 for 1.5 t
2nd hub 5	15	Type 3 for 1.25 t

Table 7. Distance matrix of 2nd hub 1

(km)	2nd h1	3rd h1	3rd h2	3rd h5	3rd h18	3rd h19
2nd h1	0	4.03	3.93	0.84	7.95	3.44
3rd h1	4.03	0	5.10	4.61	4.21	2.13
3rd h2	3.93	5.10	0	3.50	9.13	6.10
3rd h5	0.84	4.61	3.50	0	8.65	4.11
3rd h18	7.95	4.21	9.13	8.65	0	4.82
3rd h19	3.44	2.13	6.10	4.11	4.82	0

Table 8. Distance matrix of 2nd hub 2

(km)	2nd h 2	3rd h 6	3rd h 9	3rd h10	3rd h13	3rd h 20
2nd h2	0	1.09	0.80	3.10	5.74	2.28
3rd h6	1.09	0	1.70	3.71	6.66	2.32
3rd h9	0.80	1.70	0	2.29	5.02	1.81
3rd h10	3.10	3.71	2.29	0	3.03	1.96
3rd h13	5.74	6.66	5.02	3.03	0	4.92
3rd h20	2.28	2.32	1.81	1.96	4.92	0

Table 9. Distance matrix of 2nd hub 3

(km)	2nd h3	3rd h3	3rd h8	3rd h16	3rd h17
2nd h3	0	5.99	5.91	11.42	5.40
3rd h3	5.99	0	11.65	15.36	5.37
3rd h8	5.91	11.65	0	7.89	8.79
3rd h16	11.42	15.36	7.89	0	10.21
3rd h17	5.40	5.37	8.79	10.21	0

Table 10. Distance matrix of 2nd hub 4

(km)	2nd h4	3rd h4	3rd h7	3rd h11	3rd h12	3rd h14
2nd h4	0	4.46	2.08	1.99	2.52	6.63
3rd h4	4.46	0	3.89	6.37	6.51	11.11
3rd h7	2.08	3.89	0	3.03	4.47	7.92
3rd h11	1.99	6.37	3.03	0	2.45	4.85
3rd h12	2.52	6.51	4.47	2.45	0	4.91
3rd h14	6.63	11.11	7.92	4.85	4.91	0

Table 11. Result in Second Stage

Name	Distribution Plan
2nd h1	2nd h1→3rd h2→2nd h1, 2nd h1→3rd h5→2nd h1, 2nd h1→3rd h19→3rd h1→3rd h18→2nd h1
2nd h2	2nd h2→3rd h6→2nd h2, 2nd h2→3rd h9→2nd h2, 2nd h2→3rd h20→3rd h10→3rd h13→2nd h2
2nd h3	2nd h3→3rd h3→2nd h3, 2nd h3→3rd h17→2nd h3, 2nd h3→3rd h8→3rd h16→2nd h3
2nd h4	2nd h4→3rd h4→2nd h4, 2nd h4→3rd h7→2nd h4, 2nd h4→3rd h11→3rd h12→3rd h14→2nd h4
2nd h5	2nd h5→3rd h15→2nd h5

3.3 Model improvement

In order to explore the impact of carbon tax, this section sets $c_0 = 0, 3.5$ and recalculates results. When $c_0 = 0$, the change of solution is small, which is because the impact in carbon tax on total cost is much less than that on fixed construction costs and transportation and distribution costs. However, when the carbon tax price $c_0 = 3.5$ the impact on total cost is far greater than that on other costs, and results has produced significant changes.

Table 12. Comparison of the Result

Original Plan	Changed Plan	Original Partitioning Plan	Changed Partitioning Plan
2nd hub 1	2nd hub 1	1, 2, 5, 18, 19	1, 2, 5, 19
2nd hub 2	2nd hub 2	6, 9, 10, 13, 20	4, 6, 9, 20
2nd hub 3	2nd hub 3	3, 8, 3, 16, 17	3, 8, 16, 17
2nd hub 4	2nd hub 4	4, 7, 11, 12, 14	7, 10, 11, 12, 13, 1, 18
2nd hub 5	2nd hub 7	3, 15	3, 15

We can find from the sensitivity analysis that when the price has a greater impact on the total cost than the original cost, the hub with higher fixed cost and larger capacity can be selected.

What's more, we want to verify the model effectiveness by comparing distribution costs calculated in two stages. After the second-stage, the costs of each distribution center have decreased, which proved the necessity of the second-stage routing model.

Table 13. Comparison of distribution costs

Name	Original distribution cost in first stage	Distribution cost after the second first stage	Reduction ratio (%)
2nd hub 1	77.13	52.09	32.46
2nd hub 2	49.70	35.89	27.79
2nd hub 3	109.71	99.21	9.57
2nd hub 4	67.54	62.42	7.58
2nd hub 5	13.87	13.87	0

4. Conclusion

The purpose of the paper is to optimize the problem of location, allocation and routing optimization for the multi-layer express network from a low-carbon perspective. This paper proposes a two-stage model to separate the two main processes of allocation and routing optimization. Although this paper has obtained some results, there are still many directions for improvement. There are certain limitations on the consideration of the low-carbon factors. The calculation method of carbon tax can be more reasonable, and the effect of network optimization with larger data scale needs further study.

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