Journal of Cleaner Production 119 (2016) 223–228

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Low-carbon city logistics distribution network design with resource deployment

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ARTICLE INFO

Article history:
Received 28 April 2013
Received in revised form
12 October 2013
Accepted 6 November 2013
Available online 20 November 2013

Keywords:
Resource deployment
City logistics
Carbon tax
Network planning
Carbon emission

ABSTRACT

The Chinese government has now published its emission reduction goal of carbon dioxide by 2020 and any industrial player is obliged to take effective initiatives to decrease its carbon footprint. For the city logistics distribution system, as a significant energy-consuming and pollutant-emitting sector, energy saving and emission reduction are very meaningful especially for megacities like Beijing. With rational hypotheses and parameter design, meanwhile considering the deployment of low-carbon resources, a novel carbon tax-constrained city logistics distribution network planning model is proposed. The model is a bilinear non-convex mixed integer programming and is reduced to a pure linear mixed integer programming through proper linearization. To verify the effectiveness of the model, an empirical study is conducted on a city logistics operator in Beijing and the popular commercial optimization suite IBM ILOG CPLEX is adopted for optimization purpose. Through analysis of the optimization results and comparison with traditional optimization models, it is found that the proposed model can help the city logistics distribution operator save up to 9.2% of operational cost during a full service cycle, and meanwhile cut down its carbon dioxide discharge by around 54.5% or 2135 metric tons at most.

1. Introduction

Wide consensus has been reached that greenhouse gases (GHG) emissions cause dramatic changes to the earth's climate system. The Chinese Government has declared its carbon emission reduction goal until 2020, when carbon dioxide discharge per unit of GDP growth will be decreased by 40–45% compared to 2005 (State Council Office Announcement, 2009). Increasing environmental consciousness of citizens requires the government to issue more stringent legislations so as to urge firms to take various effective initiatives. Carbon tax is deemed to be one policy of highest market efficiency (Baranzini et al., 2000).

China is expediting its urbanization accompanied with huge inflow of population and energy demands. Urban environment is deteriorating in many cities and they are all facing challenges of unsustainable development (Fei et al., 2013; Christine et al., 2012; Dhakal, 2009). As huge energy consumers and pollutant emitters, cities should play a key role in controlling the world GHG emissions (Granberg and Elander, 2007). In recent years, city logistics distribution sector develops rapidly particularly in large cities in China due to strong supports from all levels of government. Despite its huge roles in promoting local economies, resolving employment and improving city's comprehensive competitiveness (Weika and Shouwen, 2008), its external diseconomy (Kennedy et al., 2010; Susan and Kumar, 2009; Teodor, 2000; Zhe, 2011) has been put in spot light of municipal managers and residents, such as emissions of pollutants, including carbon dioxide, intensive energy and resource consumption, etc.

In this article, we will study how to control carbon emissions from a new perspective of purely operations researches. A bi-level city logistics distribution network is formulated with some high carbon-efficient facilities to be allocated onto various distribution centers. Under the forthcoming carbon tax policy in China, we model the problem with the minimum operational cost as its goal, in which carbon tax cost is also integrated. Due to the medium scale of the problem, we use IBM CPLEX as core solver as the optimization tool. Result analysis shows that the proposed model in this article is very effective in reducing carbon emissions at much lower cost compared to others without effective carbon management. Some policy suggestions and conclusions are given finally.

2. Literature review

Recently, the continuous foggy days and high PM2.5 concentration in Beijing as well as some other regions within China have

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http://dx.doi.org/10.1016/j.jclepro.2013.11.011

drawn worldwide attentions. It still has a long way to fulfill the goal of Green Beijing. City logistics sector, as a fresh pillar industry of Beijing, is receiving great supports from the municipal government of Beijing. However, Beijing is also becoming more congested and highly energy-intensive. Thankfully, the quickly growing public concerns have already become much powerful to push forward the government's legislations of carbon intensity evaluation and reduction (Fei et al., 2013). From perspectives of no matter city logistics operators or city management, most initiatives to reduce carbon reduction are focused on utilization of physical processes. Yet from viewpoint of operations research, quite a few works have paid attentions to operational strategies or tactics which may lead to most part of carbon dioxide. Given environmental constraints or carbon emissions limits, these works redesign their supply chain network strategically or tactically to ensure long-term sustainability of their operations.

Closed-loop supply chain, including forward logistics and reverse logistics network designs, is an option to be considered in designing a more environmental-friendly production or service system (Lieckens and Vandaele, 2007; Özkır and Başlıgil, 2013; Fleischmann et al., 2000; Guide et al., 2003; Schultmann et al., 2006; Pistikopoulos and Hugo, 2005). Sustainable supply chain design is a fresh field in response to integrate economic, environmental and societal decisions at the stage of supply chain design (Frota Neto et al., 2008; Seuring and Muller, 2008). Susan and Kumar (2009) finds that configurations of logistics distribution network have vital influences on its carbon efficiency and intensity. Although some literature does not explicitly refer to green or sustainable supply chains, in their mathematical formulations, environmental impacts of logistics activities have actually been taken into account. For example, Nagurney et al. (2006) formulates a supply chain in which manufacturers can produce homogenous products at various sites with different environmental emissions. Subramanian et al. (2008) introduces a non-linear programming model, incorporating traditional operation planning decisions with environmental considerations.

It could also be found that much limited attentions are also explicitly discussing green or sustainable supply chain designs under carbon emission background. Ramudhin et al. (2010) proposes a supply chain strategic planning model under carbon trading market scheme. Test conducted in a real case within aluminum sector shows that effective carbon management is of great importance in designing firm's sustainable supply chains. Benjaafar et al. (2011) studies the way to associate carbon emission parameters with various decision variables and shows how the traditional models should be modified to consider the cost of carbon dioxide. Their concepts are materialized in a multi-period EOQ model and displays how to control the total cost through simple adjustments to order quantities in each period, meanwhile reduce the carbon emissions tremendously. Chaabane et al. (2013) considers a supply chain design problem under carbon trading scheme. A mixed integer model is established and tested on a small-scale case. Lindo software is used to solve the model. In the above three works, carbon emission is assumed to be linearly proportional to decision variables due to insufficient statistics and difficulties in collecting carbon emission data. No literature is found to study the city logistics network design with consideration of high carbon-efficient resource deployment problem under low-carbon economy. Even some related papers touch on green supply chain network design, verification of their models are oversimplified at small-scale experiments. Furthermore, current studies lack detailed analyses to the actual optimization results of their models and therefore, corresponding suggestions to policy makers or logistics operators are seldom proposed to conclude their studies. In this article, a dual-level city logistics distribution network, made up of logistics centers, distribution centers and retail terminals, is discussed. Not limited to traditional facility location-allocation problems on the network, both the capacity design and low-carbon resource deployment are considered. A more comprehensive non-linear mixed integer programming model is set up. Measures, both at strategic and tactic levels, to be taken by logistics operators to minimize its total operational cost under varying carbon tax rates are addressed. Some suggestions are finally put forward for city planners and industrial players.

3. Problem description and formulation

This section describes the specific problem and its mathematical model. In a city, demands of chain stores or E-businesses are mostly met through city logistics distribution operators. Usually, it is undertaken by the third-party logistics providers (3PLs), which are responsible for goods delivery services from several large retailers. 3PLs collect goods from logistics centers (LCs) located in suburban areas of the city, and then transport them to selected distribution centers (DCs) for further processing procedures (storage, packaging, encoding, cutting, dismantling, combing, loading and unloading, etc), and finally, these goods are distributed to widely distributed sales terminals (STs) of the distribution network. The work flow chart of the 3PLs is described in Fig. 1. Some already-known parameters include locations and goods supplies of LCs, independent demands and locations of numerous STs and candidate sites used for the construction (or leases) of DCs. The objective is to select fixed number of sites for DCs' construction and design their individual throughput. Due to capital expenditure restrictions, only few DCs will be equipped with higher carbon efficient facilities (such as expensive equipment consuming liquid natural gas as fuel or more complex physical structures in design DCs with higher carbon utilization rates). Moreover, like common facility-location problems, we need to decide how much goods from which DCs should be delivered to which STs and to which LCs each DC should to be allocated. Meanwhile, considering the upcoming carbon tax policies in China, which will result in fresh cost pressures to this 3PLs, the cost of carbon emissions should be considered. The final goal is the total operational costs to be minimized.

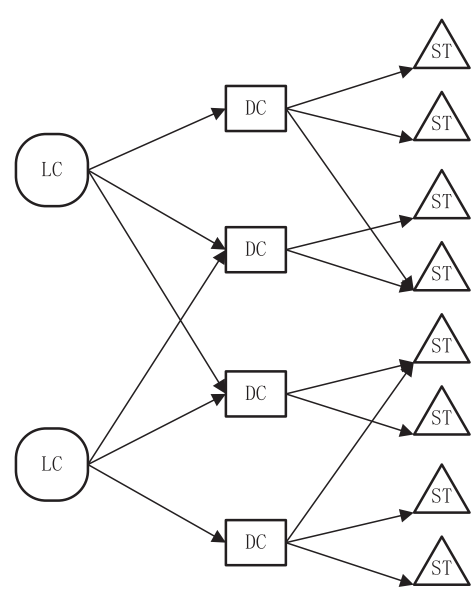

Fig. 1. Work flow chart of the 3PLs

3.1. Assumptions

Before formulating the problem, to meet the real logistics operation situation and meanwhile for the convenience of formulation, the following general assumptions are made:

- The construction costs of DCs are linearly proportional to designed capacities but the unit construction costs are different at different candidate sites.
- Each STs' demand could be met by services from 2 + DCs.
- The delivery costs are linearly proportional to the product of goods quantity and transportation distances even though unit delivery costs for different LCs or DCs are different.
- The carbon emissions are linearly proportional to the product of goods quantity delivered and transportation distances even though unit carbon emissions for the LCs or DCs differs.
- Within every DC, carbon emissions are linearly proportional to the quantity of goods processed there but unit carbon emission within each DC varies.

The first hypothesis is an often-used construction evaluation method in engineering projects. The second one determines the multi-sources of the problem. The assumptions 3 and 4 are similar to literature (Chaabane et al., 2013; Revelle and Eiselt, 2005). Such assumptions are reasonable, as current measurement tools and inspection instruments are not able to tell the functional relations between quantities of carbon emission and cargo freight, distances and other factors. The 5th assumption is also generally satisfied for continuously processing production lines.

3.2. Indices and parameters

i Index for LCs, $i \in I$;
j Index for DCs to be set up in candidate sites, $j \in J$;
k Index for STs, $k \in K$;
TC Total operational cost of the 3PL operator;
D_k Demands of goods for ST k;
d_{ij} Distance from LC i to DC j;
d_{jk} Distance from DC j to ST k;
f_j Unit construction cost for DC j;
v_j Unit processing fee within DC j;
t_j Unit freight for vehicles from DC j;
pe_j Unit carbon emission volume from the all processing procedure within DC j;
te_j Unit carbon emission volume from vehicles from DC j to any STs;
U_i Goods supplying capacity of LC i;
S_i Unit freight for vehicles from LC i;
e_i Unit carbon emission volume from vehicles from LC i to any DCs;
W Number of DCs planned to construct;
V Number of high carbon-efficient resources to be allocated in DCs;
r Percentage of carbon emission reduction in any DCs to which high carbon-efficiency resources are deployed;
a Carbon tax rate;

3.3. Decision variables

X_{ij} Quantity of goods shipped from LC i to DC j;
Z_j 1, if DC j is set up; 0, otherwise
C_j Designed processing capacity in DC j;
P_j 1, if high carbon-efficiency resources are deployed in DC j; 0, otherwise
Y_{jk} Ratio of goods in DC j delivered to ST k;

3.4. Mathematical formulation

3.4.1. Objective function

The objective function of the low-carbon city logistics distribution network design model with resource deployment (the model hereafter) to be minimized is the total operational cost of the 3PL operator, which is given below as

$$\begin{aligned}\min TC = & \left[\sum_j f_j C_j Z_j + \sum_j \sum_k v_j D_k Y_{jk} + \sum_j \sum_k t_j D_k Y_{jk} d_{jk} \right. \\ & \left. + \sum_i \sum_j S_i X_{ij} d_{ij}\right] + a\left[\sum_j (1 - rP_j) pe_j \sum_k D_k Y_{jk} \right. \\ & \left. + \sum_i \sum_j e_i X_{ij} d_{ij} + \sum_j \sum_k te_j D_k Y_{jk} d_{jk}\right]\end{aligned}$$

It mainly consists of two parts. Part 1 represents the total operational cost without consideration of carbon tax cost; Part 2 is the carbon tax cost newly imposed on the operator due to implementation of carbon tax policy. The part 1 is composed of 4 items, namely, the fixed construction cost of DCs, total variable processing cost within DCs, total delivery cost from DCs to STs and total transportation cost from LCs to DCs. Part 2 includes 3 items, representing the carbon cost from processing procedures within DCs, delivery to SLs from DCs and transportation from LCs to DCs respectively.

3.4.2. Constraints

During the optimization process of the model, the following constraints should be satisfied:

$$\sum_j C_j \geq \sum_k D_k \quad \forall j \in J, \forall k \in K \tag{1}$$

$$\sum_i X_{ij} \leq C_j \quad \forall i \in I, \forall j \in J \tag{2}$$

$$\sum_j X_{ij} \leq U_i \quad \forall i \in I, \forall j \in J \tag{3}$$

$$\sum_i \sum_j X_{ij} \leq \sum_j C_j \quad \forall i \in I, \forall j \in J \tag{4}$$

$$\sum_i \sum_j X_{ij} \leq \sum_i U_i \quad \forall i \in I, \forall j \in J \tag{5}$$

$$\sum_k D_k Y_{jk} \leq C_j \quad \forall j \in J, \forall k \in K \tag{6}$$

$$\sum_i \sum_j X_{ij} \geq \sum_k D_k \quad \forall i \in I, \forall j \in J, \forall k \in K \tag{7}$$

$$\sum_i X_{ij} \geq \sum_k D_k Y_{jk} \quad \forall j \in J, \forall k \in K \tag{8}$$

$$Y_{jk} \leq Z_j \quad \forall j \in J, \forall k \in K \tag{9}$$

$$\sum_j Y_{jk} = 1 \quad \forall j \in J, \forall k \in K \tag{10}$$

$$\sum_j Z_j = W \quad \forall j \in J \tag{11}$$

$$P_j \le Z_j \quad \forall j \in J \tag{12}$$

$$\sum_j P_j = V \quad \forall j \in J \tag{13}$$

$$0 \le Y_{jk} \le 1 \quad \forall j \in J, \forall k \in K \tag{14}$$

$$X_{ij} \ge 0 \wedge X_{ij} \in \mathrm{Z} \quad \forall i \in I, \forall j \in J \tag{15}$$

$$Z_j \in \mathrm{B} \quad \forall j \in J \tag{16}$$

$$P_j \in \mathrm{B} \quad \forall j \in J \tag{17}$$

$$C_j \ge 0 \wedge C_j \in \mathrm{Z} \quad \forall j \in J \tag{18}$$

Constraint (1), (2), (4) and (6) are all related to the designed capacities of DCs. They guarantee that the aggressive capacities of all DCs not only meet the total demands from STs altogether, but are also large enough to accommodate all transported goods from LCs; Meanwhile, for any individual DC, its designed capacity should be no less than volume of goods shipped from upstream LCs and total demands from downstream STs served by the DC. Constrain (3) and (5) offer goods supplying ability restrictions for LCs. The 7th and 8th constraints control the balance of material flow on the network. Constraint (9) says that a DC can join in the distribution activities only if it is opened. Constraint (10) and (14) tell us the nature of decision variable, *Y*. It is a real number between 0 and 1. A DC's capacity is fully utilized when $Y = 1$. The 11th and 13th constraints give the number of total DCs to be constructed and total low-carbon resources to be deployed. Constraint (12) requests low-carbon resources could only be arranged onto existing DCs. Nature of some decision variables are further clarified in constraints (15) to (18), which assure the non-negativity of *X* and *C*, integrality of *X* and binary integrality for *Z* plus *P*.

3.4.3. Linearization of formulation

In the model, the item 1 in both part 1 and part 2 deals with product of two decision variables. Through linearization process (Löfberg, 2004) below, it could be reduced to linear so that it is easier to be solved.

For the item 1 in part 1, we use the following logic processing method.

A new integral decision variable, *AC*, will be generated, which is characterized by:

$$AC = \begin{cases} C & \text{if } Z = 1 \\ 0 & \text{if } Z = 0 \end{cases}$$

In this way, the previous product of variables *C* and *Z* turns to one new variable *AC*. Restrictions to *AC* based on *Z* are shown in the set of constraints of the model.

For the item 1 in part 2, the optimal solution can be acquired under the condition below:

$$C_j = \sum_j \sum_k D_k Y_{jk}$$

Therefore, here C_j replaces $\sum_j \sum_k D_k Y_{jk}$. A new non-negative integral variable, *MC* is created, which is characterized by:

$$MC = \begin{cases} (1-r)pe \cdot C & \text{if } P = 1 \\ pe \cdot C & \text{if } P = 0 \end{cases}$$

Similarly, logic restrictions to *MC* based on *P* are displayed in the set of constraints of the model.

Through the above linearization process, the objective function of the model is reduced to a pure mixed integer problem one as follows.

$$Min\left[\sum_j f_j AC_j + \sum_j \sum_k v_j D_k Y_{jk} + \sum_j \sum_k t_j D_k Y_{jk} d_{jk} + \sum_i \sum_j S_i X_{ij} d_{ij}\right] + a\left[\sum_j MC_j + \sum_i \sum_j e_i X_{ij} d_{ij} + \sum_j \sum_k te_j D_k Y_{jk} d_{jk}\right]$$

4. Empirical study

In this section, we will study a real case in Beijing about a 3PL operator, which is responsible for distribution services of fruits, vegetables and water products to totally 86 supermarkets owned by 3 different larger chain retailers, whose location are widely scattered within 2500 square kilometers of the entire city. The local government has established 5 large LCs in suburban areas. After initial investigations, the operator needs to choose 12 sites to build up 12 DCs from total 22 candidate sites. 6 of them will act as low-carbon DCs.

According to previous statistical data, some parameters could be obtained as basic inputs to our model. However, there are no data concerning carbon emissions. Based on preliminary evaluation and experts' experience, we generate these data randomly in normal distribution ranges. Regarding ranges of carbon taxes, we will refer to recently published data by the China's National Development and Reform Commission, namely, the tax rates is in RMB￥0.01 to 0.10 per kg of CO_{2eq} (Yuwei and Shufen, 2011). The descriptive characteristics of some parameters are shown in Table 1 below.

With the above parameters together with location data as inputs of the model, we express it in the modeling tool and solve the model in IBM ILOG CPLEX 12.3. Rich contents are collected and revealed below in figures or tables after being simply processed.

In Fig. 2 below, comparisons between two distinct carbon management measures, i.e., negative or effective carbon management, are made under various carbon tax rates. When carbon tax is imposed on the city logistics distribution system, if the operator still continues its previous operational cost optimization strategy, and omits the potential impact of the new carbon cost, sharp linear rise in its total operational cost will occur, around RMB￥391,683 of carbon cost to bear when carbon tax rate reaches RMB￥0.10 per kg

Table 1
Descriptive characteristics of model's parameters.

Descriptive characteristics	Unit	Sum	Mean	Std	Max.	Min.
D	mt	10,236	119.02	33.88	178	63
U	mt	32,750	6550	1726.5	9090	5212
f	RMB￥/mt	3347.8	152.17	27.61	197.3	106.05
v	RMB￥/mt	283.43	12.88	1.9	15.91	10.1
S	RMB￥/(mt·km)	10.65	2.13	0.01	2.14	2.11
t	RMB￥/(mt·km)	93.29	4.24	0.16	4.49	4.01
Pe	kg CO_{2eq}/mt	7914.2	359.74	158.06	592.26	107.97
e	kg CO_{2eq}/(mt·km)	4.07	0.81	0.08	0.95	0.76
te	kg CO_{2eq}/(mt·km)	27.09	1.23	0.51	1.98	0.43

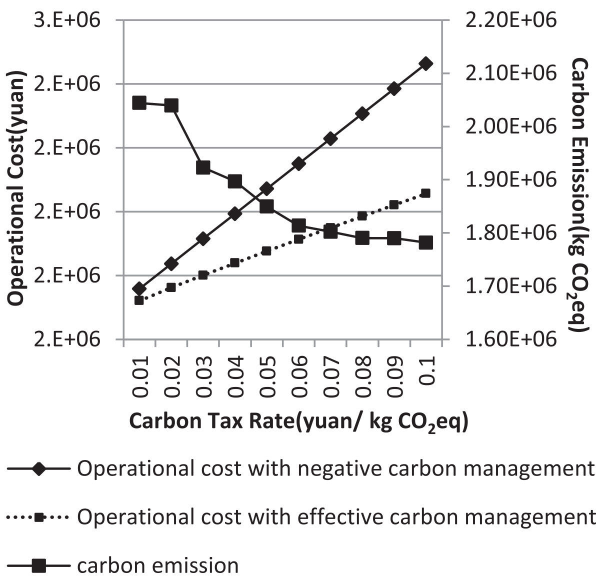

Fig. 2. Cost and carbon emission of the city logistics distribution system with rising carbon tax rates.

of CO_{2eq}, and at the same time, its carbon emission will keep the same as before, at around 3916 tons. If the model proposed in this article is used to re-construct the logistics distribution network, it could also be seen from Fig. 2 that carbon cost will be more under controls and it helps the operator save more and more operational costs when carbon tax goes up steadily. What is more important is that the carbon emission gets effectively managed, declining continually for all the time. For instance, when carbon tax hits its highest RMB ¥ 0.10 per kg of CO_{2eq}, the active carbon management policy with the help of our model can assist the 3PL company cutting down its total operational cost by around RMB ¥ 203,483, meanwhile its carbon emission volume will descend by around 1782 tons, or about 54.5% compared to the negative carbon management. In all, the model is very effective in improving both economic and environmental benefits of the city logistics distribution systems.

Fig. 3 below indicates how the model works to control the fast growth of operational cost due to enforcement of new carbon tax policy. Above all, it is inevitable that carbon cost and total operational cost will go up with carbon tax rate climbing up. But the 3PL operator could adjust its distribution network through changing partial DC nodes, rational low-carbon resource deployments and allocation tactics to partially offset the cost rises. It could be seen from Fig. 3 that during the model optimization process, the biggest cost source, i.e., DCs' construction cost gets well controlled, basically in a slowly decreasing trend. Meanwhile, carbon emission manages to go down sharply. Therefore, even though the other two types of costs are getting higher, the general total operational cost does not go up linearly, which is also the secret why good economic benefits together with environmental friendliness of the logistics distribution system are achieved.

Fig. 4 shows us better what the 3PL operator should mainly do to achieve its total cost goal. Each column in the figure corresponds to a DCs' set and deployments of low-carbon resources. It explicitly tells that with gradually rising carbon taxes, the operator does not need to radically reconstruct its logistics distribution network and the adjustment is much trivial. When carbon tax rate goes up by RMB ¥ 0.01 per kg of CO_{2eq} each time, at most 1 DC's site will vary

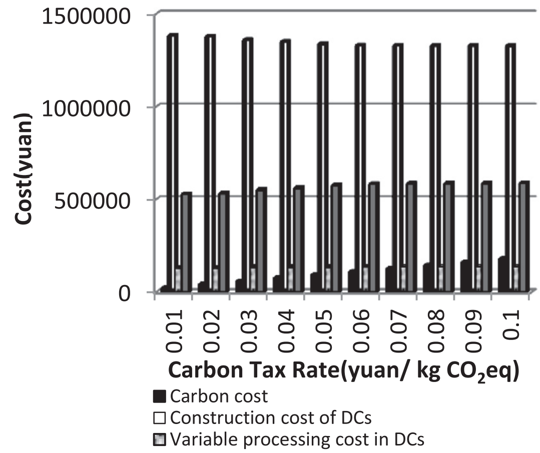

Fig. 3. Cost structure under various carbon tax rates.

and the same situation happens to deployment adjustments of low-carbon resources. It reveals that the network optimization tactics proposed by our model are feasible in the reality, without huge changes to distribution network structure and extra capital expenditures.

We further study such types of minor adjustments on the 3PL's logistics distribution network. It is found that when carbon tax rates changes steadily, including the designed capacities of DCs, STs' allocations to DCs and DCs' allocations to LCs, they all display a relatively stable status. Only slight changes need to be carried out. Furthermore, such changes are all tactical ones, not impacting the total operational structure of the network drastically.

To summarize, we suggest that in China, while the government is actively encouraging the advances of city logistics distribution systems, carbon tax policy could promote the greener and more sustainable development of the sector. However, the carbon tax policy should follow a principle of lower starting point, so as for city

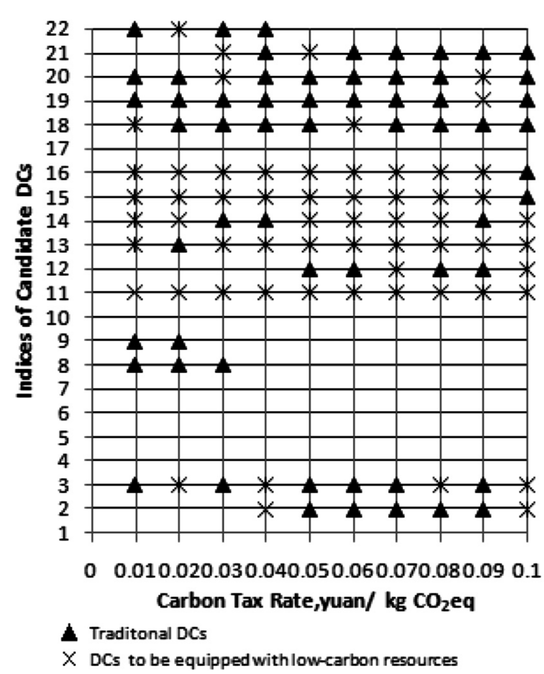

Fig. 4. DCs selection and low-carbon resource deployment under various carbon tax rates.

logistics operators to steadily adjust its network operational mode and rationally arrange their low-carbon resources. Over high carbon taxes from its beginning can hurt the healthy growth of the whole industry. Furthermore, because of expensive costs in land leases and DCs' construction, city policy makers should attract social capitals actively joining into more reasonable land uses and DCs' planning, to help city logistics companies to control their carbon emission. Maybe it is a good policy to return part carbon taxes to better behaving operators to further inspire their carbon reduction enthusiasm. For city logistics distribution operators, they are suggested to pay more attention to their operational carbon efficiency. Proper capital accumulation is necessary for future restructuring their operational network or turning to higher carbon efficiency facilities.

5. Conclusions

In the background of low-carbon economy development mode, this work studies the low-carbon network planning problem for a city logistics distribution system. When carbon tax policy comes into effect in the forthcoming several years, city logistics operator must re-consider its network structure and low-carbon resources deployment. A novel bilinear mixed integer programming model is proposed which combines carbon tax costs, low-carbon resource deployment and common network configurations altogether. Based on analysis of its nature, the model reduces to a linear one. In order to solve it, based on the problem's scale, CPLEX 12.3 is adopted to get the exact solutions of city logistics distribution systems at different carbon tax rates. In a real case, we analyze the experimental results in great details and discuss the tactical changes of the network structure and effects in carbon emission reduction. The result can well manifest the good performance and effectiveness of our model in dealing with the upcoming carbon taxes. Some suggestions are finally given to business operators and also to policy makers.

There are many alternative low-carbon tax policies being implemented or going to be issued in China and around the world. The future research directions include the network operational strategy and tactical adjustment under these policies and comparisons could be made among various low-carbon policies.

Acknowledgment

Beijing philosophy and Social Science Planning Research Fund No. 13JDJGB048

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