Location selection of urban distribution center with a mathematical modeling approach based on the total cost

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ABSTRACT Location selection for urban distribution centers (DCs) is vital in saving distribution cost and reducing the negative externalities arising from freight transportation. Yet increasing level of logistics sprawl in megacity associated with various urban diseases has been creating new challenges for selecting the location of DCs. In this paper, a mathematical model is proposed to enable an efficient and green distribution system by minimizing the total cost, which contains economics cost, environmental cost, and socio-economic cost. The model is a mixed-integer linear programming model and is characterized with quantifying and pricing the multifarious negative externalities. To verify the effectiveness of the model, a case study is conducted. IBM ILOG CPLEX is adopted for optimization purpose. Then a sensitive analysis is provided to investigate the impact of various parameters coefficients on the results. This new method provides a good reference for municipal management department in planning urban DC, and will contribute to promoting urban green development by reducing the negative externalities of distribution operation.

Keywords: Logistics sprawl, Distribution center, Location selection, Negative externalities

I. Introduction

Wide consensus has been reached that the logistics operations are parts of the most significant economic activities nowadays due to its vital function for business to remain competitive [1]. As a key logistics node, distribution centers (DCs) have a pivotal position in the logistics system for the functions of connecting the logistics centers (LCs) and the customers [2]. The location of DCs significantly affects the functioning, efficiency, and the negative externalities for the city, such as fuel consumption, air pollution, congestion, noise pollution and etc. [3, 4]. Notably, the phenomenon of logistics sprawl, i.e. the relocation of logistics facilities away from inner urban areas to suburban areas [5], has received a great level of attention from both academics and policy makers [6-10]. It has contributed to increasing the distribution vehicle’s delivery distance and consequent externalities [5], which has affected the green development of city. Hence, in the background of logistics sprawl, the decision of designing the location of DCs should be shifted from economic-led to the balance between environmental concern and economic factor.

With an ever growing concern about the urban environment, the construction of green logistics system has been proposed by many academicians. Green logistics refers to the management that restrains the harm to the environment and makes full use of the logistics resources in the logistics operation, which follows the alignment between the environmental impacts and economic concern [11]. However, in reality, the cost of negative externalities has not been measured and controlled when planning the DCs, leading that logistics companies neglect to protect the environment in their operation. Hence, to reduce the negative externalities, the external cost of logistics operation should be effectively internalize and paid, which is benefit for designing a more economically green logistics system.

In this paper, we will study how to select the location of DC from the perspective of minimizing the total cost with internalizing the external cost. A bi-level city logistics network is designed, which is combined with LC, DCs, and markets. The logistics company collects goods from LC located in the suburb, and then transports them to DCs by truck for further processing procedures.
(storage, processing, sorting and packing, etc.), and finally delivers those goods to the markets by van. The work flow chart is described in Fig 1. The goal of this study is to select the optimal location of DC with the lowest total cost. A Mixed-integer Linear Programming model that includes economic cost, environmental cost and socio-economic cost is proposed to determine the optimal location, in which the negative externalities are molded and priced. The category of the total cost of distribution operation is shown in Fig 2. In fact, the features considered in the model make it more realistic but more complicated at the same time for the internalization of external cost. However, it provides municipal administration with a more comprehensive tool for planning the DCs to make the city greener.

The rest of paper is organized as follows. In section II, the literatures about DC location selection are reviewed. The problem description, the model formulation and the pricing of negative externalities are proposed in section III. In section IV, a case study is provided to verify this model. Then the sensitivity analysis is conducted in section V. In section VI, the comparison of our method with weighted-sum method is provided. Finally, section VII concludes the paper.

II. Literature review

From the literature, the DCs location selection problem can be considered as a special case of facility location problem (FLP) [12]. Several literatures have been conducted by researchers on FLP. According to the application environment, the existing approach for FLP can be mainly classified into qualitative method and quantitative method [13]. Much of the qualitative methods have studied the FLP under an uncertain environment, that is, the parameters in the problem are difficult to obtain with certainty. For example, the information about capacity of DCs and vehicle, demands of customers are all uncertain. To deal with such situation, fuzzy theory is developed and applied, which is classified as the evaluation method. The criteria that widely used for evaluating the alternatives are economic criteria [14-16], environmental criteria [12, 17], social criteria [12, 15, 17], and technical criteria [18]. Moreover, the algorithms applied for aggregating the evaluating information contain fuzzy TOPSIS [14, 16-18], AHP [16, 19], THOWA operator [12, 20], fuzzy quantified SWOT [15], and etc.. However, when the environment of DCs location selection problem is deterministic and certain, that is, the parameters in the problem are fixed and known
in advance, the quantitative method is more appropriate for the optimal purpose. Quantitative method can be grouped into single objective (SO) and multi-objective (MO) according to the number of objective functions in the mathematical model. Financial indicator is the traditional optimization objective for SO, like literatures [21-23]. Besides, some researchers have developed SO by pursuing maximizing efficiency or responsiveness in their literatures [24, 25]. However, with an ever growing concern for the environment, environmental factor has been simultaneously taken as the objective in many MO literatures [26, 27]. To obtain the Pareto-optimal solution of MO problem, weighting method [28] is usually applied for weighting each objective. But the accuracy of the results is easily influenced by the subjectivity of empowerment. Heuristic algorithms are the most commonly used approach to solve the mathematical model, such as tabu research [29], genetic algorithm [24, 27], particle swarm optimization algorithm [13, 30], imperialist competitive algorithm [31], and etc.. Nevertheless the result calculated by heuristic algorithm is the optimal solution but not the exact solution.

Furthermore, in the objective designed, economical factor is the traditional objective for the optimization of FLP. Many literatures [32-34] conventionally planned with a focus of profit maximization or cost minimization in their mathematical models. Nonetheless, with the global warming, many literatures [30, 35, 36] incorporate carbon emission into their MO mathematical model. However, to the best of our knowledge, there is no integrated model in the literatures that considering economic factor, carbon emission, air pollution and socio-economic factor simultaneously, especially pricing the externalities and internalizing the external cost.

Moreover, with the greater environmental awareness and emphasis on the social responsibility, the study of pricing the negativities of transportation has been conducted by many academics. For example, Emrah et al. [37] built mathematical formulations for various externalities related to different transportation modes to calculate the negative external costs. Jason et al. [38] studied the external cost of top-selling light-duty models in the United States, obtained the result of the averages total external costs per mile. Adrián et al. [39] employed the willingness-to-pay method to assess the external cost of noise in road freight transportation. Patrick et al. [40] analyzed the external cost of electric vehicle in Germany, found that the external costs of electric vehicle and internal combustion engine vehicles do not differ significantly and the external cost of congestion dominate the external costs.

This research is among the first investigation to simultaneously consider economic cost, air pollution cost, carbon tax, and socio-economic cost in mathematical model for the location selection of DC. In which the MO problem was converted into the SO one by pricing the negative externalities of distribution operation. In a sense, we have enriched the mathematical modeling regarding DCs location selection with considering the externalities comprehensively and pricing them.

III. Mathematical Model

A. Problem statement

Fig.1 illustrates a bi-level logistics network including LC, DCs, and markets. The distribution operation is undertaken by a distribution company. Products are aggregated from plants to LC, next transported to the DCs by trucks, finally delivered to markets by vans. To calculate the total cost, various costs generated in the whole distribution operation are considered. First, the cost of renting land and building on the land constitutes the fixed cost. Second, in the process of DCs operation, laborers’ wages, water and electricity fees and garbage disposal fee make up the operating costs. Third, in the transportation and delivery, the driver's salary, fuel cost and vehicle wear cost together constitute the transportation cost. Next, the treatment cost of air pollution emitted by the vehicle is the air pollution cost, and the treatment cost of the greenhouse gasses (GHGs) emitted by the vehicle is the carbon tax. At last, the losses caused by the congestion and noise generated by vehicles makes up the socio-economic cost. In addition, the final goal of this research is to select the optimal DC from the perspective of minimizing the total cost of distribution operation, which is combined with economic costs, environmental costs, and socio-economic cost. Meanwhile, by pricing the externalities and internalizing the external cost, the decision of solving FLP is switched
from economic-led to the balance between economic impact and environmental concern, which are benefit for facilitating the urban green development.

1) Assumption

To facilitate modeling, several assumptions are made as follows:

- This model considers a single product, a single period.
- The demand of all markets is known and deterministic.
- Each market can only be served by one DC.
- The capacity of each DC is predefined and related to the demand of markets.
- The fixed costs and operating cost of DCs are predefined and related to its capacity and the geographic position.
- The transportation cost, air pollution emission, carbon emission, congestion cost and noise pollution are all linearly proportional to the goods quantity and transportation distance.

The assumptions 1-3 are often-used in facility location selection model. The assumptions 4-5 are designed to simplify the model. The assumption 6 is based on the previous works [26], which is necessary and reasonable, as current studies cannot effectively illustrate the function relation between quantities of transportation externalities and products weight and transportation distance.

B. Model formulation

In this section, a mixed-integer linear programming model is proposed for selecting the optimal location of DC. Sets, parameters, and decision variables are given as follows:

1) Sets

\( i \) \hspace{1cm} Set of LCs \( \{1 \ldots i \ldots I \} \)

\( j \) \hspace{1cm} Set of potential DCs \( \{1 \ldots j \ldots J \} \)

\( k \) \hspace{1cm} Set of markets \( \{1 \ldots k \ldots K \} \)

2) Parameters

\( F_j \) \hspace{1cm} Fixed cost for opening DC \( j \)

\( v_j \) \hspace{1cm} Operating cost of DC \( j \)

\( N \) \hspace{1cm} Number of DCs to construct

\( D_k \) \hspace{1cm} Demand of market \( k \)

\( t_{ij} \) \hspace{1cm} Transportation cost to transport a unit of product from LCs to DCs for a unit distance

\( t_{jk} \) \hspace{1cm} Transportation cost to transport a unit of product from DCs to markets for a unit distance

\( d_{ij} \) \hspace{1cm} The distance between LC \( i \) and DC \( j \)

\( d_{jk} \) \hspace{1cm} The distance between DC \( j \) and market \( k \)

\( p^i \) \hspace{1cm} Emission equivalent for released air pollution to transport a unit of product from LC \( i \) to DC \( j \) for a unit distance

\( p^k \) \hspace{1cm} Emission equivalent for released air pollution to transport a unit of product from DC \( j \) to market \( k \) for a unit distance

\( c^i \) \hspace{1cm} Carbon dioxide equivalent for released GHGs to transport a unit of product from LC \( i \) to DC \( j \) for a unit distance

\( c^k \) \hspace{1cm} Carbon dioxide equivalent for released GHGs to transport a unit of product from DC \( j \) to market \( k \) for a unit distance

\( a \) \hspace{1cm} The amount of tax to be paid for one equivalent of air pollution

\( b \) \hspace{1cm} Carbon tax rate

\( s^i \) \hspace{1cm} Socio-economic cost to transport a unit of product from LC \( i \) to DC \( j \) for a unit distance

\( s^k \) \hspace{1cm} Socio-economic cost to transport a unit of product from DC \( j \) to market \( k \) for a unit distance

\( c_a \) \hspace{1cm} Designed processing capacity of DC \( j \)

3) Decision variables

\( X_{ij} \) \hspace{1cm} Quantity of product transported from LC \( i \) to DC \( j \)

\( w_j \) \hspace{1cm} 1, if DC is located and set up at potential candidate \( j \), 0, otherwise
$z_{jk} = 1$, if market $k$ is served by DC $j$, 0, otherwise

4) Objective function

$$\text{Min} \ C = C_{ec} + C_{en} + C_{so}$$

$$C_{ec} = \sum_j F_j w_j + \sum_j v_j w_j + \sum_i \sum_j t_{ij} X_{ij} d_j + \sum_j \sum_k t_{jk} D_k z_{jk} d_j$$

$$C_{en} = a \left( \sum_i \sum_j p^e X_{ij} d_j + \sum_j \sum_k p^h D_k z_{jk} d_j \right) + b \left( \sum_i \sum_j c^e X_{ij} d_j + \sum_j \sum_k c^h D_k z_{jk} d_j \right)$$

$$C_{so} = \sum_i \sum_j s^e X_{ij} d_j + \sum_j \sum_k s^h D_k z_{jk} d_j$$

5) Constraints

$$\sum_i X_{ij} \leq c a_j \quad \forall j,$$  \hspace{1cm} (1)

$$\sum_k D_k \leq \sum_j w_j c a_j \quad \forall j, k$$  \hspace{1cm} (2)

$$\sum_i X_{ij} = \sum_k D_k z_{jk} \quad \forall i, k,$$  \hspace{1cm} (3)

$$z_{jk} \leq w_j \quad \forall j, k,$$  \hspace{1cm} (4)

$$\sum_j w_j = N \quad \forall j$$  \hspace{1cm} (5)

$$\sum_j z_{jk} = 1 \quad \forall k,$$  \hspace{1cm} (6)

$$X_{ij}, D_k \geq 0 \quad \forall i, j, k$$  \hspace{1cm} (7)

$$w_j, z_{jk} \in \{0,1\} \quad \forall j$$  \hspace{1cm} (8)

The objective function minimizes the total cost of the distribution operation, which is the summation of the economic cost $C_{ec}$, the environmental cost $C_{en}$, and the socio-economic cost $C_{so}$. The $C_{ec}$ section is composed of 4 items, namely the fixed cost (rental and construction costs), the operating cost, the transportation cost from LCs to DCs, and the delivery cost from DCs to markets.

The $C_{en}$ section contains two parts. The first part is the air pollution cost generated in the transportation and delivery. The second part is the greenhouse gasses (GHGs) cost generated in the transportation and delivery. The $C_{so}$ section is mainly the congestion cost and noise pollution cost generated in in the transportation and delivery.

The first constraint guarantees that the products transformed from LCs to each DC should be lower or equal to the maximum capacity of the DC. Constraint (2) shows the sum of demand of markets is less or equal to the sum of capacity of the opened DCs. Constraints (3) illustrates that the quantity of products transformed from LCs to DCs is equal to the demand of all markets. Constraint (4) says that a DC can serve for the market only if it is opened. Constraint (5) limits the number of opened DCs to N. Constraint (6) states that a market could only be served by one DC. Constraint (7) illustrates that the amount of products flowed from LCs to DCs and the demand of markets is non-negativity. Constraint (8) shows the binary variables of this mathematical model.

C. Pricing of the negative externalities

Distribution activity produces numerous negative externalities mainly in the freight transportation, which can be classified into two categories. These are environmental impact and socio-economic impact [37]. The environmental impact includes air pollution and GHGs emission whereas the socio-economic impact includes congestion and noise pollution. The negative externalities can affect the quality of the environment, harm human health, and cause the waste of resources. To control them, the external costs of logistics operation should be effectively internalized and paid, which means that the external costs should be included in the company’ private cost [37]. Consequently, decision for selecting the location of DCs should be shifted from economic-led to the balance between environment concern and economic
impact. In this section, we model and price the negative externalities of distribution operation to promote the awareness and cognition of distribution external externalities from the view of economy, preparing for integrating externalities into the total cost. Mathematical formulations for measuring the externalities of distribution operation are discussed below.

1) Air pollution

Generally the main air pollution discharged by the transport vehicles includes particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), and sulfur oxides (SOx). Air pollutants are harmful as their damage to health and environmental. In 2016, the Tax law of the People's Republic of China on environmental protection was promulgated by Chinese government. In which pollution equivalent is designed for calculating the environmental harm and the technical economy of treatment of every air pollutants. The tax for air pollution per equivalent is set as a range value (1.2-12 ¥). We assume that all transport vehicle produce air pollutants in terms of the upper limit of China regulation. The emission function of total air pollutant equivalent (per ton-kilometer) is given by

$$p = \sum_{\alpha=1}^{m} \frac{EF_{\alpha}}{PEV_{\alpha}}$$  \hspace{1cm} (9)

Where $p$ is the total air pollutant equivalent, $\alpha$ is the types of air pollutants, and $m$ is the number of types of air pollutants. Moreover, $EF_{\alpha}$ is the emission factor for $\alpha$ of the transport vehicle. $PEV_{\alpha}$ is the pollution equivalent value of $\alpha$. Therefore, $p_{ij}^c$ and $p_{jk}^c$ can be calculated in terms of $p$.

2) Greenhouse gases

Greenhouse gases (GHGs) are the most common externality studied in the location selection of DCs. The primary GHGs generated in freight transportation are carbon dioxide (CO$_2$), nitrous oxide (N$_2$O), methane (CH$_4$), ozone (O$_3$). The impact of GHGs is mainly the global warming and climate disruption, which are harmful to the ecological equilibrium and human health. Since CO$_2$ dominates the list of GHGs, the impact of other gases can be measured in terms of CO$_2$. Moreover, according to the data released by China national development and reform commission, the price of carbon emission trading is a range value (0.01-0.1 ¥/kg). The total carbon dioxide equivalent of GHGs (per ton-kilometer) emitted by the transport vehicles can be calculated as

$$c = \sum_{\beta=1}^{n} \frac{EF_{\beta}}{CDE_{\beta}}$$  \hspace{1cm} (10)

Where $c$ is the total carbon dioxide equivalent of GHGs, $\beta$ is the type of GHGs, and $n$ is the number of types of GHGs. Moreover, $EF_{\beta}$ is the emission factor for $\beta$ of the transport vehicle. $CDE_{\beta}$ is the carbon dioxide equivalent of $\beta$. Therefore, $c_{ij}^c$ and $c_{jk}^c$ can be calculated in terms of $c$.

3) Congestion

Congestion is a very serious phenomenon in megacity, which causes increased travel times and increased fuel consumption. Therefore, the monetary estimation for congestion can be derived from time loss and increased fuel consumption. In Woensel’s study [41], the time loss cost function and fuel consumption cost function (in ¥/tkm) are calculated respectively by

$$c_i = \frac{t \times g \times P_r \times AFT}{AFT}$$  \hspace{1cm} (11)

$$c_f = \frac{v \times t \times P_f}{k \times AFT}$$  \hspace{1cm} (12)

Where $c_i$ is the external cost of time loss per ton-kilometer caused by congestion, $t$ is the delay travel time per year of the city, $g$ is the regional per capita GDP of unit time, $P_r$ is the proportion of transport vehicles in all vehicles, and $AFT$ is the annual freight turnover of the city. Moreover, $c_f$ is the fuel consumption cost per ton-kilometer caused by congestion,
v is the average speed of vehicles in congestion, \( p_f \) is the price of fuel, \( k \) is the efficiency of fuel.

4) Noise pollution

Noise pollution in distribution operation is mainly generated in the process of vehicle travelling, which can affects people's work and sleep, particularly those around the road. The common way to estimate the external cost of noise pollution is the Protection charge method (PCM). The method looks at the cost of building protection facilities to avoid the noise pollution, such as sound insulation screen. The formula for estimating the monetary values (per ton-kilometer) of noise pollution can be written as

\[
   c_n = \frac{\delta \times L \times p_f}{T_d \times AFT} \tag{13}
\]

Where \( c_n \) is the external cost caused by noise pollution, \( \delta \) is the cost for constructing the noise protection facilities per km, \( L \) is the length of noise protection facilities that should be constructed, and \( T_d \) is the service life of the noise protection facilities.

In sum, the external cost of socio-economic impact per ton-kilometer can be calculated as

\[
   s = c_v + c_f + c_n \tag{14}
\]

Where \( s \) is the external cost of socio-economic impact. Moreover, \( s^{ij} \) and \( s^{jk} \) can be calculated in terms of \( s \).

IV. Case study

In this section, we will apply the model in selecting the optimal location of DC for a distribution company in Beijing, whose business is supplying goods for the supermarkets. The goods are general merchandise, food, beverage, household appliances, clothing, etc., which are all necessary for daily life. As can be seen from Fig 3, the potential location of DCs are denoted by red star and distributed in Chaoyang District and Tongzhou District. There are five potential DCs (A1, A2, A3, A4, and A5). The markets are 20 supermarkets scattered in the urban areas. In addition, in this case there is one LC located in Sanhe, Hebei province, whose responsibility is to aggregate goods from the plants, store and sort, then supply for the DCs and other commodity facilities. Road is the transportation mode in this research. It is noticeable that highway G102 is the major traffic channel for the transportation between LC and DCs. Truck is used to transport goods from LC to DCs. And van is employed for the delivery to the supermarkets. Finally, we need to select the optimal location from the potential DCs to build a new DC.

In this paper, some parameters of the mathematical model have been obtained from the previous statistical date [26, 42], such as, fixed cost, operating cost, and transportation cost. The parameters in regard to the external cost are calculated by formulas (9)-(14). Moreover, in this case, the computation period of this mathematical model is one year. The distances between these facilities (LC, DCs and supermarkets) are calculated by Google Maps. The descriptive characteristics of input parameters have been written in Table I, in which the unit of currency is yuan, and the measure of weight is kilogram.

IBM ILOG CPLEX 12.6.2 is utilized to solve this mathematical model. We have processed the data results and presented them in Fig 4 and Fig 5.
As shown in Fig 4, the total cost of location A2 is minimal and reaches RMB 5,937,748. Therefore, the optimal location of DC is A2. Besides, the rank of A1 is second, whose external cost is lower than A2 due to its closeness to the markets. But since closest to city center, the fixed cost of A1 is the highest of all, leading that its total cost is higher than A2. The total cost of A5 is the highest, although its fixed costs and operating costs is the lowest. The reason for that is A5 is far away from the markets, resulting in high transportation cost and external costs. Moreover, as seen from Fig 3, A1, A2 and A3 are closed to the urban area, while A4 and A5 are located in the suburb area. Hence, we can conclude that building DCs in urban area is better than in suburb area from the perspective of total cost, considering the external cost.

To analysis the cost composition of A2 more clearly, Fig 5 is made. We can see that transportation cost has the largest percentage, reaching 53% of the total cost. Due to the unit transportation cost of truck is lower than van, location near the urban area helps reduce the delivery distance and thus reduce the total cost. Meanwhile, although selecting location in the suburbs can reduce fixed cost and operating costs, increment of transportation cost and external costs is more huge, leading to the increment of the total cost. Therefore, the location of DCs should not be selected in the suburbs. Besides, the sum percentage of fixed cost and operating cost is 32%, which are closely relevant with the geographic position, leading that the location of DCs should not be selected in the urban area for its high land rent. Moreover, the environmental cost and socio-economic cost account for 15% of the total cost, which also play an important role in the location selecting, determining that the location should not be selected in the suburbs for its long delivery distance. Hence, the location should not be selected in the urban and suburb areas. The optimal location for DCs is located at the junction of urban and suburb areas, which is the equilibrium point that deals with the trade-offs...
between economic and environment concern.

V. Sensitivity analysis

In this section, sensitivity analysis is conducted to investigate the impact of various parameters coefficients on the location selection of DCs.

A. Air pollution cost

As given by Environmental protection tax law of the People's Republic of China, the tax for air pollution (TAP) per equivalent is set as a range value, from RMB 1.2 to 12 per equivalent. Based on which the sensitivity analysis of air pollution cost is conducted. The result is provided in Fig 6. The horizontal axis represents the value of TAP. The vertical axis shows the potential locations. For TAP is greater than or equal to RMB 7.9 per equivalent, the optimal location is exchanged from A2 to A1. When TAP hitting the value of RMB 12 per equivalent, the optimal total cost increases by RMB 402,096. By decreasing the TAP, the value of objective function decreases simultaneously. Yet when TAP is less than or equal to RMB 1.8 per equivalent, the optimal location of DC is exchanged from A2 to A3. When TAP hitting the value of RMB 1.2 per equivalent, the optimal total cost decreases by RMB 354,105. Hence, the results illustrate that the mathematical model is sensitive to air pollution tax, which has the practical application value. For example, government departments can determine the location of DCs by adjusting air pollution tax rate. Consequently distribution enterprises should consider air pollution intensively when selecting the location of new DCs. Furthermore, considering air pollution cost in the mathematical model is one of the contributions of this research.

B. Carbon tax

With the global warming, carbon emission has attracted great attention worldly. Carbon trading is carried out in the carbon markets. According to the data released by China national development and reform commission, the price of carbon trading is a range value (0.01-0.1 ¥/kg). To investigate the influence of carbon tax rate (CTR) on the result, sensitivity analysis of CTR is conducted. The result is shown in Fig 7. We can see that the optimal location is always A2, with CTR varying from RMB 0.01 to 0.1 per kg. However, when CTR increasing to RMB 0.1 per kg, the total cost increases by RMB 117,900. When CTR dropping to RMB 0.01 per kg, the total cost decreases by RMB 94,320. Hence, we conclude that the model is relatively insensitive to the carbon tax, even though the variation of carbon tax has some influences on the total cost.

C. Environmental cost

Nowadays electric logistics vehicles are more and more popular in cities, especially in megacity, like...
Beijing, Shanghai. The characteristic of electric logistics vehicles is that there are no air pollution and GHGs emission in the transportation and delivery process. To investigate the variation of optimal location and total cost when all logistics vehicles are replaced by electric vehicles, sensitivity analysis of environmental cost is conducted. In which the air pollution tax coefficient (a) and carbon tax coefficient (b) is set as 0. The results reveal that the optimal location varies from A2 to A3, and the value of objective function decreases by RMB 573,484. Therefore, it can be concluded that the geographic position of the optimal location of DCs should be migrated outward when electric vehicles are widely used in freight transportation.

**D. Capacity**

To cope with the logistics sprawl, some scholars suggested building small logistics facilities in the urban area [5, 43, 44]. There are much more small plots of land in urban area to build small-capacity logistics facilities. So the unit rents are cheaper than big-capacity’s. To verify the economic feasibility of the recommendation, sensitivity analysis of capacity is provided in this section. We designed another two potential DCs A6 and A7, whose capacities are half of the previous candidates. They are all located in urban area, and closer to the supermarkets. The results show that A6 and A7 are selected as the optimal locations, and the total cost is RMB 5,870,159, decreasing by RMB 67,589 compared with A2. Hence, we conclude that the proposal of building small logistics facilities in urban area is economically feasible, which is beneficial for reducing the total cost.

**VI. Comparison with weighted-sum method**

Weight-sum method (WSM) has been used to solve the MO problem of the facility location. We compare our mathematical modeling approach based on the total cost with the method based on WSM. In this case, the MO model based on WSM consists of three objective functions. The first objective function $f_1$ minimizes the direct economic cost which is the combination of economic cost and socio-economic cost. The second objective function $f_2$ minimizes the amount of air pollution generated in the transportation and delivery. The third objective function $f_3$ minimizes the amount of GHGs generated in the transportation and delivery. The mathematical formulations for those objective functions are given below as

$$\min f_i = \sum_j w_j f_{ij} + \sum_j v_j w_j + \sum_j t_j v_j x_j d_j + \sum_j t_j z_{ij} x_{ij}$$

$$\min f_2 = \sum_j \sum_k p_j x_{ij} d_{jk} + \sum_j \sum_k D_k z_{jk} d_{jk}$$

$$\min f_3 = \sum_j \sum_k p_j x_{ij} d_{jk} + \sum_j \sum_k D_k z_{jk} d_{jk}$$

There is no change in Constraints ((1)-(8)).

In weighted-sum method, weights are assigned to each objective function based on the experiences of decision makers. Supposed that $u$ is the set of objective functions ($u = 1, 2, 3$ in this case), $w_u$ presents the weight of objective function $f_u$, and $\sum_{u=1}^3 w_u = 1$. In this case, the weights are assumed as $w_u = (0.4, 0.3, 0.3), u = 1, 2, 3$.

Since the three objective functions have different measuring units, it is necessary to unify the objective functions into the dimensionless when using WSM. In this paper, the normal dimensionless method is applied, which is shown as follows

$$\overline{f_u} = \frac{f_u - f_u^{\min}}{f_u^{\max} - f_u^{\min}}$$

Where $f_u^{\overline{j}}$ is the value of objective function $f_u$ for potential DC $j$ ($j = 1, 2, \cdots, 5$), $\overline{f_u^{\overline{j}}}$ is the dimensionless value of $f_u^{\overline{j}}$, $f_u^{\max}$ is the maximum value of $f_u^{\overline{j}}$ ($j = 1, 2, \cdots, 5$), $f_u^{\min}$ is the minimum value of $f_u^{\overline{j}}$ ($j = 1, 2, \cdots, 5$).
Therefore, a new SO function is constructed based on the MO model above with WSM, which is shown as follows:

$$\min f = \sum_{j=1}^{5} \sum_{u=1}^{3} w_{j,u}f_{j,u}$$  \hspace{1cm} (16)$$

Where $f$ is the dimensionless value of the performance of the potential DCs.

IBM ILOG CPLEX 12.6.2 is utilized to solve the model. We have processed the data results and presented them in Fig 8.

As seen in Fig 8, the optimal location of DC is A1, and the ranking results are generally consistent with that obtained by this paper, excepting that the order of A1 and A2 is switched. However, as shown in Fig 3, A1 is closest to city center, where the fixed cost is too high to build the large capacity DC. Therefore, the result obtained by WSM is not very practical.

Particularly the results calculated with WSM are the dimensionless value, which can only be used for ranking and have no practical reference significance. In our method, the results of the DCs location have definite and specific economic meaning. That is our method cannot only rank the order of the potential DCs but can also give the specific comprehensive economic evaluation of potential DCs for the decision makers. Moreover, we have compared our method with WSM, finding that our method has superiority in providing specific comprehensive economic evaluation of potential DCs for decision makers. In addition, the approach proposed in this paper can be practically applied for planning urban DCs by the municipal management department, which is beneficial for reducing the negative externalities of logistics operation, and conducive to urban green development.

VII. Conclusions

This paper presents a mixed-integer linear programming model for the location selection of DCs by minimizing the total cost, which contains economics cost, environmental cost, and socio-economic cost. We have modeled and priced the negative externalities to promote the awareness and cognition of logistics negative externalities from the perspective of economics. CPLEX is utilized to calculate the exact solution of the model. A case study is provided to verify the effectiveness of the model. Furthermore, a sensitivity analysis is performed to investigate the impacts of various parameters coefficients on the location selection of DCs. The results show that the transportation cost accounts for 53% of the total cost, the environmental cost and socio-economic cost account for 15% of the total cost, leading that the location of DCs should not be selected in suburb for the long delivery distance. The sum percentage of fixed cost and operating cost is 32%, showing that the location of DCs should not be selected in urban for its high land rent. The optimal location for DCs is the junction of urban and suburb areas. Besides, we have observed that the location selection of DCs is sensitive to air pollution cost, environmental cost, and capacity of DCs, but insensitive to carbon tax due to its low trading price. These results can be employed to optimize the DCs layout by adjusting the tax rate of negative externalities. Moreover, we have compared our method with WSM, finding that our method has superiority in providing specific comprehensive economic evaluation of potential DCs for decision makers. In addition, the approach proposed in this paper can be practically applied for planning urban DCs by the municipal management department, which is beneficial for reducing the negative externalities of logistics operation, and conducive to urban green development.

The limitation of this research concerns the simplification of bi-level logistics network, as there is one logistics center and one product in the case. Therefore, the model may be enhanced by conducting research on more comprehensive logistics network, which contains multiple logistics centers and products. Moreover, another direction of the future research is to make the mathematical model more realistic in the consideration of other negative externalities, such as land use and accidents.

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Reference


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