

LOCATION OF URBAN LOGISTICS DISTRIBUTION CENTERS CONSIDERING CARGO TRANSPORTATION SERVICES OF A PUBLIC TRANSPORTATION SYSTEM

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Highlights:

- a method for the ULDCLPPTS is proposed;
- several collaborative distribution scenarios using one or several bus lines are explored;
- 2 mixed-integer linear programming models are established to address different collaborative distribution modes;
- the impact of different bus lines on the location of distribution centers, collaborative distribution and truck carbon emissions are showed.

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Abstract. Urban logistics distribution accounts for a large proportion of CO₂ emissions generated by urban transportation. Reducing CO₂ emissions in the process of logistics distribution is one of the urgent urban problems to be solved. This article investigates the location of urban logistics distribution centers considering cargo transportation services of a public transportation system. Considering one or several bus lines for representing a public transportation system, several collaborative distribution scenarios are studied, and 2 mixed integer linear programming models are established to explore the impact of the public transportation system on the location of distribution centers in urban logistics. Numerical experiments show the influence of different bus lines on the location of distribution centers, collaborative distribution and truck carbon emissions in Dalian (China). In any case, the possibility of establishing distribution centers in blocks 5 and 42 of Dalian is very high. When bus lines are used, the highest bus line utilization can reach 47.83%, and the CO₂ emission can be reduced by up to 36.3%. In terms of different bus lines, line 2002 is more suitable to participate in the collaborative distribution in Dalian compared with other bus lines.

Keywords: distribution center, urban logistics, collaborative distribution, carbon emission, public transportation system.

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Notations

- CBD – central business district;
 DCLP – distribution center location problem;
 OD – origin–destination;
 ULDCLPPTS – urban logistics DCLP considering the use of a public transportation system.

1. Introduction

Global warming caused by greenhouse gases has attracted wide attention worldwide (Mohammed *et al.* 2019). In 2019, the concentration of CO₂ in the global atmosphere increased by 46% compared with that before industrialization, reaching 409.8 ppm (Lindsey 2025). The develop-

ment of transportation industry is an important reason for the increase of CO₂ emissions, accounting for more than 20% of the total global emissions (Chen *et al.* 2021). Among them, a large proportion of CO₂ emissions and other environmental pollutants come from production activities related to urban transportation (Zhang *et al.* 2018). Urban transportation accounts for 40% of the total CO₂ emissions from road transportation (Gota *et al.* 2015) and 70% of the total emissions of other pollutants (EC 2007). Urban logistics distribution is an important part of urban transportation, and unreasonable planning of urban logistics distribution is an important cause of unnecessary congestion and greenhouse gas emissions (Savelsbergh, Van Woensel 2016).

The current urban logistics distribution system has brought many negative impacts on economy, environment and society. CO₂ emissions generated by urban logistics distribution account for 25% of CO₂ emissions from urban transportation. Reducing CO₂ emissions in the process of logistics distribution is one of the urgent urban problems to be addressed. The current urban logistics distribution is mainly based on road transportation, where trucks are mainly used for urban logistics distribution. The fuel used by most trucks in urban logistics distribution activities is diesel, which causes more serious pollution than gasoline (Li *et al.* 2020). The researches on CO₂ emission reduction in the field of trucks have begun to increase in recent years, including measurement of CO₂ emissions of trucks (Elhedhli, Merrick 2012; Demir *et al.* 2014; Guerrero de la Peña *et al.* 2020) and CO₂ emission reduction of heavy trucks (Díaz-Ramírez *et al.* 2017; Giuliano *et al.* 2021). Other studies are trying to find solutions to make urban logistics distribution more sustainable, including the design of urban logistics distribution networks (Yang *et al.* 2012; Guo *et al.* 2017), optimization of low-carbon logistics distribution path (Zhang *et al.* 2019; Su, Fan 2020; Tang *et al.* 2021), and location and evaluation of logistics centers (Correia *et al.* 2012; Zhang *et al.* 2021; Mepparambath *et al.* 2021). This article combines current trends to study the collaborative transportation problem using public transportation systems and trucks in the urban logistics industry.

The use of public transportation systems for cargo transportation services may be a solution to improve urban air quality (Zhao *et al.* 2018). As the backbone of urban transportation, public transportation system has been greatly developed in terms of energy conservation and emission reduction under the promotion of national incentive measures (Logan *et al.* 2020; Liu *et al.* 2021, 2022). It has become a future trend to use perfect and low-cost public transportation system to assist urban logistics transportation (Savelsbergh, Van Woensel 2016). The concept of using public transportation systems to transport cargoes has been put forward for a long time (Nash 1982), and gradually covers many aspects such as buses, subways and trams (Masson *et al.* 2017; Dampier, Marinov 2015; Fatnassi *et al.* 2015).

The collaborative distribution mode using urban public transportation systems and trucks still reflects a new concept of urban logistics development, which has the characteristics of low-carbon, economy and convenience (Cochrane *et al.* 2017). Compared with traditional logistics distribution, the integration of cargo transportation using trucks with public transportation systems can potentially reduce the operating costs of trucks, and increase the utilization of public transportation systems, while reducing CO₂ emissions of trucks (Ghilas *et al.* 2016a, 2016b). The average waiting time for cargoes in the logistics system can also be greatly reduced through the joint optimization of the utilization of public transportation systems and trucks (Zhen *et al.* 2020). In addition, with the increase of urbanization rate, the urban public transportation system is becoming larger and larger. From 2015 to 2020, China's urban bus ownership increased from 562000 to 704000 (MOT 2021).

Previous studies on collaborative distribution of urban logistics are more limited to a single public transport line, without considering the internal optimization of the scheduled line (Kikuta *et al.* 2012; Dampier, Marinov 2015), or the research problem is limited to vehicle routing problem with transshipment or centralized delivery, without considering the selection of transshipment points (Ghilas *et al.* 2016a, 2016b; Masson *et al.* 2014, 2017). The location of distribution centers plays an important role in urban logistics and undertakes the important task of optimizing urban logistics network. The location of distribution centers can have an impact on the total operating cost of an enterprise up to 50% (Rikalović *et al.* 2018). There are no studies carried out on collaborative distribution of urban logistics combined with the DCLP. To fill this research gap, this article investigates the ULDCLPPTS, which is a novel DCLP.

The main contributions and works of this article are as follows:

- this article investigates the location of distribution centers considering the impact of a public transportation system (i.e., the ULDCLPPTS), where one or several bus lines are used to represent a public transportation system, and several collaborative distribution scenarios are devised;
- 2 mixed integer linear programming models are proposed to formulate the ULDCLPPTS under different situations;
- numerical experiments show that the public transportation system can have a big impact on the location of distribution centers in urban logistics, as well as reducing CO₂ emissions of trucks.

The rest of this article is organized as follows:

- current Section 1 – introduction;
- Section 2 gives literature review;
- in Section 3, notation, assumptions and problem description are provided for the ULDCLPPTS;
- in Section 4, 2 mixed integer linear programming models are established for the ULDCLPPTS;
- Section 5 provides numerical experiments;
- finally, a summary is given in Section 6.

2. Literature review

This article aims to study the ULDCLPPTS, which is a novel DCLP, belonging to the location problem. The location problem was 1st proposed by Alfred Weber (Brandeau, Chiu 1989). After decades, it has been widely used in many fields such as transportation, logistics and medical treatment (Owen, Daskin 1998; Melo *et al.* 2009; Ahmadi-Javid *et al.* 2017). Here this article mainly review the related studies on the DCLP.

Many scholars have studied the DCLP in view of the competitive relationship between distribution centers. According to the existing distribution centers, Sun & Gao (2002) established a competitive location mode to provide decision support for effective location for a new distribution center. On the basis of analysing the characteristics of logistics distribution centers, Gao *et al.* (2007) proposed

a competitive logistics distribution center location model. Both of them aim to obtain the largest market share, and construct nonlinear programming problems to study. Sheng & Wang (2014), Drezner *et al.* (2015) and Beresnev & Melnikov (2018) studied the DCLP under the competitive conditions, following the framework of leaders and followers. Sheng & Wang (2014) considered the carbon emissions and costs of many links and established a logistics distribution center location model under monopoly conditions. Drezner *et al.* (2015) optimized the follower's problem and the leader's problem using a branch and bound algorithm and a taboo search algorithm, respectively, to obtain the optimal location results. Beresnev & Melnikov (2018) proposed an optimistic bi-level mixed integer programming and used a branch and bound algorithm to solve the upper bound of the problem.

With the deepening of the concept of sustainable development, low-carbon emissions have gradually become an important factor affecting the DCLP. In order to reduce the total cost of carbon emissions, Yang & Lu (2014) established a hierarchical distribution center location model with different carbon emission policies. Zhao & Yang (2014) constructed a bi-objective integer programming model considering CO₂ emission and logistics cost from the perspective of local government to locate urban logistics centers. Considering uncertain demand, Lin *et al.* (2020) adopted the stochastic programming theory to establish a location model aiming at the lowest total cost, including carbon emission cost. Zhang *et al.* (2021) established a bi-level programming model for the DCLP, in which the upper level problem aims to establish a reasonable carbon emission policy to minimize the total social cost of the logistics system. Wang *et al.* (2024) considered the constraints of demand and time windows, combined with the influence of carbon emissions, and established an environmental cold chain logistics distribution center location model.

Many scholars have studied the DCLP based on fuzzy theory. Yang *et al.* (2007) established a chance constrained programming model to study DCLP in fuzzy environments and investigated some properties of the model. Hashim *et al.* (2014) studied the DCLP in fuzzy environment by multi-objective optimization of the 3-level supply chain architecture composed of manufacturer, distribution center and customer. Awasthi *et al.* (2011) proposed a multi-criteria decision-making method under uncertainty with the help of fuzzy theory, and then quantified the value of selected criteria for urban distribution center location. Wang *et al.* (2014) incorporated the historical evaluation accuracy mechanism into the fuzzy environment, and established a multi-criteria decision-making model based on the decision maker's credibility for logistics center location.

In addition, Agrebi *et al.* (2015) reviewed the DCLP for 2 major categories of problems: uncertain environment and certain environment. Hu (2011) and Gutjahr & Dzubur (2016) established a bi-level programming model to seek the optimal location of distribution centers, taking into account customer interest needs. Agrebi *et al.* (2016) also proposed a decision method based on ELECTRE I, which verifies the selected location by conducting both consistency

and inconsistency tests simultaneously. Sopha *et al.* (2016) proposed a 2-stage urban distribution center location method, which includes spatial analysis and multi-objective mixed integer linear programming. Yan *et al.* (2022) considered the dynamism of customer demand and established a multi-stage dynamic location model to solve the DCLP by introducing transfer costs between adjacent stages. Pan *et al.* (2022) proposed an intelligent evolutionary algorithm called Rafflesia optimization algorithm to solve the DCLP, and compared it with 7 meta-heuristic algorithms. Wu *et al.* (2022) considered uncertain demand, improved the clustering algorithm, and combined it with the center-of-gravity method to propose a 2-stage model to solve DCLP.

The previous studies on the DCLP are adequate, however there are no studies carried out on the DCLP considering the use of a public transportation system. This article proposes the ULDCLPPTS, which addresses the location of distribution centers considering buses and trucks for collaborative distribution, as well as reducing CO₂ emissions of trucks.

3. Notation, assumptions and problem description

3.1. Distribution demands, truck types and a public transportation system

This article aims to investigate the location of distribution centers in urban logistics, by considering the use of a public transportation system. Namely, trucks and public transportation system are used together for collaborative distribution. For simplicity, one or several bus lines are used to represent the public transportation system in this article.

As will be shown in numerical experiments, case studies in a port city are considered. For the convenience of research, the city is divided into several blocks based on the main road network and administrative divisions, and each block is marked with a different number, with the population of each block corresponding to its logistics demand. Assuming that distribution demands are transported from the port (and/or the railway station) to each block, where the port and the railway station are supply nodes, and each block is the demand node, as shown in Figure 1. Traditional urban logistics distribution takes trucks as the main transportation mode. Depending on the quantity of cargoes and transportation environment, different types of trucks are often used for transportation to reduce operating costs. In urban logistics, heavy trucks mainly undertake mass transportation tasks between large logistics warehouses and ports (Demir *et al.* 2014). Generally, heavy trucks are not allowed to access to CBDs, where compact trucks are used to optimize logistics operations within the city (Szymczyk, Kadłubek 2019). For the last-mile delivery, logistics companies often set up their own fleet of minivans for transportation due to the quantity of cargoes and physical characteristics of vehicles (Janjevic *et al.* 2021). Therefore, in this study, different types of trucks are used between different logistics distribution nodes, as shown in Figure 1. There have been studies on transporting cargoes by bus (Ghi-

las *et al.* 2016a, 2016b; Masson *et al.* 2017). For bus lines, it is assumed that the storage space of each considered bus is enough to meet the daily distribution demand. Each customer's needs are loaded into a single rolling container, which is then loaded into a specific area of the bus. The number of containers allowed on a bus is small, and the maximum number of containers that can be unloaded simultaneously at the station is limited, which is assumed to be ten (Masson *et al.* 2017). Furthermore, when using bus lines for cargo transportation, it is assumed that cargoes can only be loaded and unloaded at the starting station and the ending station of each considered bus line. Therefore, there will not be a significant impact on passengers or other aspects. This article studies from the planning perspective, because the bus freight volume is small and the frequency of buses is very high, so the impact of timetable is not considered.

3.2. Distribution modes and transportation cost

As shown in Figure 1, the logistics distribution processes from the port (or railway station) to each block can be classified into 2 scenarios on whether integration and transshipment must be carried out through distribution centers. Figure 1a shows 2 distribution modes (1 and 2) that are transferred through distribution centers, while Figure 1b expands on the distribution mode 3 that does not pass through distribution centers.

In the traditional distribution mode, cargoes are usually transported from factories or ports to distribution cent-

ers for transshipment, and then transported to another distribution center or directly transported to each store or block. Following Yaman (2009), Demir *et al.* (2014), Szymczyk & Kadłubek (2019), Janjevic *et al.* (2021), Rodríguez *et al.* (2022), heavy trucks are used to transport between the port (or the railway station) and distribution centers, trucks are used to transport among distribution centers, and minivans are used to transport between distribution centers and blocks (i.e., distribution mode 1 shown in Figure 1). Due to the limited use of heavy trucks, this study assumes that heavy trucks only serve transportation between the port (or the railway station) and distribution centers within 10 km from the port or railway station, and heavy trucks are not allowed to CBDs. When considering bus lines, 2 additional distribution modes are introduced on whether cargoes should be routed via a distribution center. When distribution centers are required, the distribution mode is called distribution mode 2, otherwise it is called distribution mode 3, as shown in Figure 1.

The port and the railway station are regarded as 2 super supply nodes in this article. Next, the transportation paths and associated costs for 3 different distribution modes (Figure 1) with respect to OD pairs are introduced. By using the transportation path for any OD pair, Figure 1 can be described as Figure 2.

Based on distribution mode 1, for any OD pair (i, j) ($\forall (i, j) \in Q$), cargoes are transported from origin i to destination j routed via 2 distribution centers k and m , and its transportation path can be expressed as follows:

$$i \rightarrow k \rightarrow m \rightarrow j, \tag{1}$$

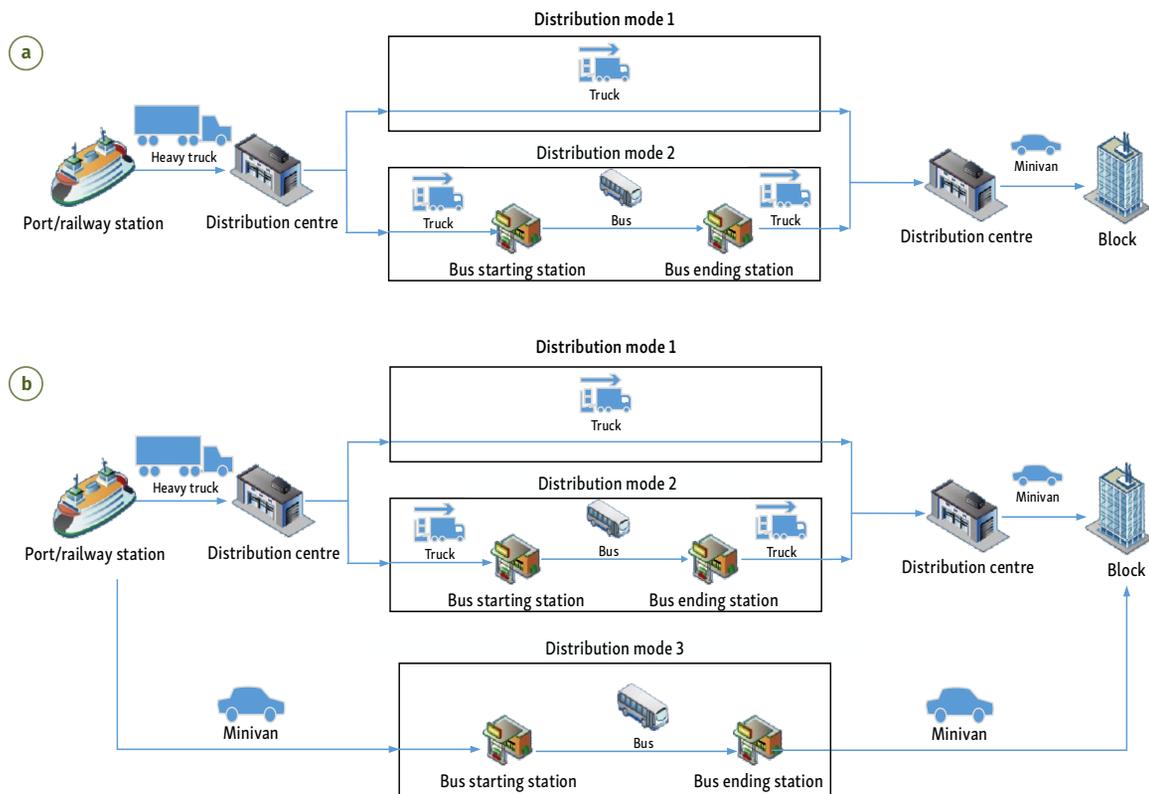


Figure 1. Distribution modes in 2 scenarios: (a) – using distribution modes 1 and 2; (b) – using distribution modes 1, 2, and 3

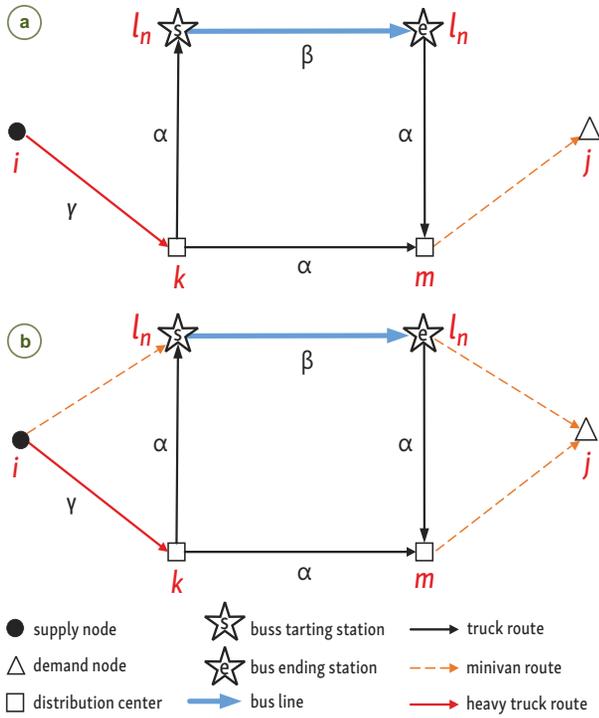


Figure 2. Simplified distribution modes in 2 scenarios

where: heavy trucks are used between origin i and distribution center k , trucks are used between distribution centers k and m , and minivans are used between distribution center m and destination j .

When bus line l is used, transportation paths associated with distribution modes 2 and 3 can be expressed as follows:

$$i \rightarrow k \rightarrow l_h \rightarrow l_n \rightarrow m \rightarrow j; \quad (2)$$

$$i \rightarrow l_h \rightarrow l_n \rightarrow j, \quad (3)$$

where: l_h , l_n represent the starting station and the ending station of bus line l , respectively.

For the transportation cost, this article considers transportation distance and transportation discount factors of different trucks. Let D_{ik} represent the transportation cost between nodes i and k . Let C_{ijkm}^1 , C_{ijkml}^2 and C_{ijl}^3 represent the transportation cost of 3 transportation paths associated with distribution modes 1, 2 and 3, respectively. Namely:

$$C_{ijkm}^1 = \gamma \cdot D_{ik} + \alpha \cdot D_{km} + D_{mj}; \quad (4)$$

$$C_{ijkml}^2 = \gamma \cdot D_{ik} + \alpha \cdot (D_{kl_h} + D_{l_n, m}) + D_{mj} + \beta; \quad (5)$$

$$C_{ijl}^3 = D_{il_h} + D_{l_n, j} + \beta, \quad (6)$$

where: α , γ represent the transportation discount factor for transporting cargoes between distribution centers and between the port (or railway station) and distribution centers ($\gamma < \alpha$); β is a fixed unit price when any bus line is used.

3.3. Fuel consumption and CO₂ emission calculation

The collaborative distribution of buses and trucks is of great significance in reducing the CO₂ emissions of trucks,

so this sub-section aims to provide a basis for calculating the CO₂ emissions of trucks. For CO₂ emission calculation, a comprehensive fuel consumption model is adopted through comparative analysis, following Bektaş & Laporte (2011). Generally, the speed of trucks during logistics distribution is between 40...80 km/h (He, Li 2018). Following Mei (2020), it is assumed that the truck speed equals 60 km/h. Following Bektaş & Laporte (2011), fuel consumption F_{ij} when transporting between nodes i and j , can be estimated as follows:

$$F_{ij} \approx \frac{P_t \cdot \left(\frac{D_{ij}}{v_{ij}} \right)}{q} \approx \frac{\alpha_{ij} \cdot (w^m + f_{ij}^m) \cdot D_{ij} + \beta^m \cdot v_{ij}^2 \cdot D_{ij}}{q}, \quad (7)$$

where: P_t represents the truck traction power; v_{ij} represents the running speed of the truck on link $\langle i, j \rangle$ with distance D_{ij} ; q represents the calorific value of the fuel; w^m represents the dead weight of m type truck; f_{ij}^m represents the load of m type truck on link $\langle i, j \rangle$; the maximum load of different types of truck is expressed by Q^m , $f_{ij}^m \leq Q^m$; α_{ij} , β^m are 2 parameters.

Then the CO₂ emission E_{ij} on link $\langle i, j \rangle$ can be calculated as follows:

$$E_{ij} = \varepsilon \cdot F_{ij}, \quad (8)$$

where: ε represents the fuel emission factor.

Following Bektaş & Laporte (2011), He & Li (2018), truck type related parameters involved in Equations (7) and (8) are shown in Table 1.

Table 1. Truck type related parameters

Truck type	w^m [kg]	Q^m [kg]	α_{ij}	β^m	q [J/L]	ε [kg/L]
Minivan	5000	9000	0.10	2.71	$3.3 \cdot 10^7$	2.62
Truck	9000	15000	0.10	3.61	$3.3 \cdot 10^7$	2.62
Heavy truck	15000	25000	0.10	5.80	$3.3 \cdot 10^7$	2.62

4. Model development

In this section, 2 mixed integer linear programming models (Models A and B) are established to formulate the UL-DCLPPTS for the 2 scenarios shown in Figures 1 and 2. Among them, Model A corresponds to Figure 1 and considers distribution modes 1 and 2, while Model B corresponds to Figure 2 and further considers distribution mode 3. Within Models A and B, the optimal bus lines should be determined for transportation paths associated with distribution modes 2 and 3. Some notations need to be defined to more intuitively formulate the UL-DCLPPTS. The main sets, parameters and decision variables used in this article are shown in Table 2.

Next, Sub-sections 4.1 and 4.2 show the objective functions and related constraints of Model A and Model B with different distribution modes, respectively.

Table 2. Sets, parameters and decision variables used in this article

Sets:	
\mathcal{N}	set of supply nodes
\mathcal{DN}	set of demand nodes
\mathcal{H}	set of bus lines
\mathcal{Q}	set of OD pairs
Parameters:	
q_{ij}	demand between supply node i and demand node $j \forall (i, j) \in \mathcal{Q}$
Decision variables:	
Z_k	a binary variable that equals 1 if node k is a distribution center, and 0 otherwise
Z_{ik}	a binary variable that equals 1 if supply node i is assigned to distribution center k , and 0 otherwise
Z_{jm}	a binary variable that equals 1 if demand node j is assigned to distribution center m , and 0 otherwise
x_{ijkm}	fraction of demand from supply node i to demand node j , routed via distribution center k and m successively, without using bus on the way
y_{ijkml}	fraction of demand from supply node i to demand node j , routed via distribution center k and m successively, with using bus line l on the way
y_{ijl}	fraction of demand from supply node i to demand node j by bus line l without passing through distribution center

4.1. Model A

The ULDCLPPTS with distribution modes 1 and 2 as shown in Figure 1a can be formulated by the following mixed integer linear programming model (denoted by Model A):

$$\min \sum_{i,j \in \mathcal{Q}} \sum_{k \in \mathcal{DN}} \sum_{m \in \mathcal{DN}} \sum_{l \in \mathcal{H}} q_{ij} \times (C_{ijkm}^1 \cdot x_{ijkm} + C_{ijkml}^2 \cdot y_{ijkml}) \tag{9}$$

subject to:

$$\sum_{k \in \mathcal{DN}} Z_k = p; \tag{10}$$

$$\sum_{m \in \mathcal{DN}} x_{ijkm} \leq Z_k, \forall (i, j) \in \mathcal{Q}, \forall k \in \mathcal{DN}; \tag{11}$$

$$\sum_{k \in \mathcal{DN}} x_{ijkm} \leq Z_m, \forall (i, j) \in \mathcal{Q}, \forall m \in \mathcal{DN}; \tag{12}$$

$$\sum_{m \in \mathcal{DN}} \sum_{l \in \mathcal{H}} y_{ijkml} \leq Z_k, \forall (i, j) \in \mathcal{Q}, \forall k \in \mathcal{DN}; \tag{13}$$

$$\sum_{k \in \mathcal{DN}} \sum_{l \in \mathcal{H}} y_{ijkml} \leq Z_m, \forall (i, j) \in \mathcal{Q}, \forall m \in \mathcal{DN}; \tag{14}$$

$$\sum_{k \in \mathcal{DN}} \sum_{m \in \mathcal{DN}} x_{ijkm} + \sum_{k \in \mathcal{DN}} \sum_{m \in \mathcal{DN}} \sum_{l \in \mathcal{H}} y_{ijkml} = 1, \forall (i, j) \in \mathcal{Q}; \tag{15}$$

$$x_{ijkm} \cdot D_{im} \leq 10, \forall (i, j) \in \mathcal{Q}, \forall k, m \in \mathcal{DN}; \tag{16}$$

$$y_{ijkml} \cdot D_{im} \leq 10, \forall (i, j) \in \mathcal{Q}, \forall l \in \mathcal{H}, \forall k, m \in \mathcal{DN}; \tag{17}$$

$$Z_k \in \{0, 1\}, \forall k \in \mathcal{DN}; \tag{18}$$

$$x_{ijkm} \geq 0, \forall (i, j) \in \mathcal{Q}, \forall k, m \in \mathcal{DN}; \tag{19}$$

$$y_{ijkml} \geq 0, \forall (i, j) \in \mathcal{Q}, \forall l \in \mathcal{H}, \forall k, m \in \mathcal{DN}. \tag{20}$$

The Objective Function (9) is to minimize the total cost of 2 distribution modes when several bus lines are used. Constraint (10) ensures that p distribution centers should

be established. Constraints (11) and (12) ensure that cargoes must be transferred through the distribution center when using distribution mode 1. Constraints (13) and (14) ensure that cargoes must be transferred through the distribution center when using distribution mode 2. Constraints (15) mean that cargoes distribution must be carried out in one of 2 modes. Constraints (16) and (17) mean that heavy trucks only serve distribution centers within 10 km of the port (or the railway station). Constraints (18)–(20) are the domain of residual decision variables.

4.2. Model B

By further considering distribution mode 3, the ULDCLPPTS can be formulated by the following mixed integer linear programming model (denoted by Model B):

$$\min \sum_{i,j \in \mathcal{Q}} \sum_{k \in \mathcal{DN}} \sum_{m \in \mathcal{DN}} \sum_{l \in \mathcal{H}} q_{ij} \times (C_{ijkm}^1 \cdot x_{ijkm} + C_{ijkml}^2 \cdot y_{ijkml} + C_{ijl}^3 \cdot y_{ijl}) \tag{21}$$

subject to:

Constraints (10)–(14), (16)–(20);

$$\sum_{k \in \mathcal{DN}} \sum_{m \in \mathcal{DN}} x_{ijkm} + \sum_{k \in \mathcal{DN}} \sum_{m \in \mathcal{DN}} \sum_{l \in \mathcal{H}} y_{ijkml} + \sum_{l \in \mathcal{H}} y_{ijl} = 1, \forall (i, j) \in \mathcal{Q}; \tag{22}$$

$$y_{ijl} \geq 0, \forall (i, j) \in \mathcal{Q}, \forall l \in \mathcal{H}. \tag{23}$$

The Objective Function (21) is to minimize the total cost of 3 distribution modes when several bus lines are used. Similar to Constraints (15), Constraints (22) means that cargoes distribution between any OD pair can only be carried out in one of distribution modes 1, 2, or 3. Constraints (23) are the domain of residual decision variables. In addition, Model B also ensures the number of distribution centers established, the service scope of heavy trucks, and the

fact that cargoes must be transferred through distribution centers when using distribution modes 1 and 2.

To enhance the comprehensiveness of our model, we have taken into account three additional factors based on Models A and B: the time value of using buses and trucks to transport goods, the fixed construction costs of different locations, and the use of new energy vehicles. These factors are presented in Appendices A, B, and C, respectively.

5. Numerical experiments

In this section, Dalian (China) is taken as an example for numerical experiments. Based on the main road network and administrative division of Dalian, Figure 3 shows the relevant data of 46 blocks, 6 bus lines and distribution network of Dalian. With 46 blocks as demand nodes, and their logistics demand is converted proportionally according to the population data of each block. For simplicity, 10 of 46 demand nodes are selected as candidate distribution centers, as shown in Figure 3. For the number of distribution centers to be established, this article mainly considers $p = 4$, and similar results can be obtained when considering different values of p . For bus lines representing a public transportation system, 6 realistic bus lines are selected, i.e., bus lines 1, 2, 6, 10, 1105 and 2002, which basically cover the whole city of Dalian. The distribution network is mainly composed of the shortest road transportation path from Dalian North Railway Station and Dalian Port to each demand node and between demand nodes.

As shown in Figure 2 and Equations (1)–(3), this article considers 3 different distribution modes when investigating ULDCLPPTS. In Figure 3, 6 bus lines are used to represent a public transportation system, and for each bus line, loading and unloading can only be done at the starting station and the ending station. When cargoes are transported from Dalian Port or Dalian North Railway Station to various blocks, one of 3 distribution modes needs to be selected for transportation. Taking line 2002 as an example, due to its long route, the bus fare is relatively lower compared with the truck transportation cost between logistics distribution centers. In theory, mode 2 or mode 3 is more preferred for transporting goods to the 5 blocks near the ending station of line 2002, rather than mode 1. Of course, the specific choice needs to be calculated. The selection of distribution mode between 46 blocks in Dalian and Dalian North Railway Station (or Dalian Port) and the location of logistics distribution center need to be determined by model optimization results. 2 models are solved by *IBM ILOG CPLEX Optimization Studio* (<https://www.ibm.com/products/ilog-cplex-optimization-studio>), which runs on a 3.7 GHz Dual-Core desktop PC with Windows 7 operating system and 4GB of RAM. The optimality gap of *IBM ILOG CPLEX Optimization Studio* is set as 0.001, and 2 models can be efficiently solved by *IBM ILOG CPLEX Optimization Studio* within 1s.

Next, the distribution center location results using different models are presented in Sub-section 5.1. Sub-section 5.2 shows the impact of different bus lines on distribu-

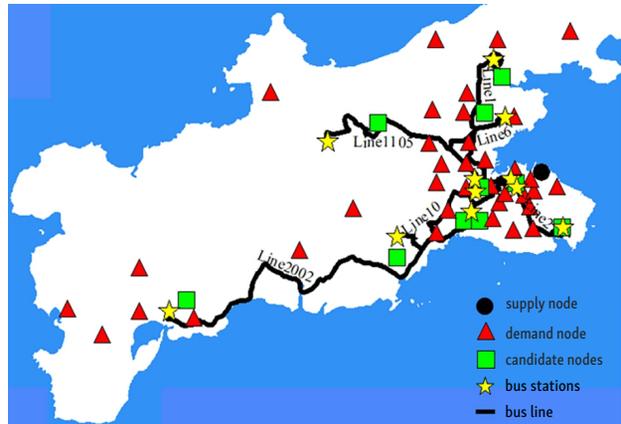


Figure 3. Distribution of demand nodes and bus lines in Dalian

tion center location. The utilization of bus lines is shown in Sub-section 5.3. Finally, Sub-section 5.4 shows the impact of bus lines on CO₂ emissions.

5.1. Distribution center location results using different models

In this sub-section, based on Models A and B, the distribution center location results are shown by considering the different values of α , γ and β . Since $\gamma < \alpha$, following Corey *et al.* (2022), in order to show the model results under different transportation discount factors as comprehensively as possible, let $\alpha = 0.5, 0.7, 0.9$, $\gamma = 0.2, 0.4, 0.5, 0.7$. In order to demonstrate the impact of fixed unit price within a certain range on 2 models and price it reasonably, following Liu & Ceder (2015), let $\beta = 2, 8, 14, 20$. A hub probability is introduced for each node, which is defined as the frequency of this node to be selected as a distribution center. Figures 4 and 5 show results by considering one bus line and several bus lines, respectively. When considering one bus line in Figure 4, each of 6 bus lines is used for calculating the hub probability of each node. When considering several bus lines in Figure 5, 6 bus lines are used together for calculating the hub probability of each node. For simple presentation, Model A with one bus line and 6 bus lines are represented as Case I and Case III, respectively, and Model B with one bus line and 6 bus lines are represented as Case II and Case IV, respectively.

When one bus line is used, as shown in Figure 4, in Cases I and II, blocks 5 and 42 have high hub probabilities for establishing distribution centers. When only distribution modes 1 and 2 are adopted (i.e., Model A or Case I), as shown in Figure 4a, the hub probabilities at blocks 8, 14 and 29 are low. After the introduction of distribution mode 3 (i.e., Model B or Case II), as shown in Figure 4b, the hub probabilities at blocks 8 and 17 decrease accordingly, while block 14 becomes more suitable for establishing a distribution center.

When 6 bus lines are used together, as shown in Figure 5, in Cases III and IV, blocks 5, 17, 30 and 42 have high hub probabilities for establishing distribution centers, sim-

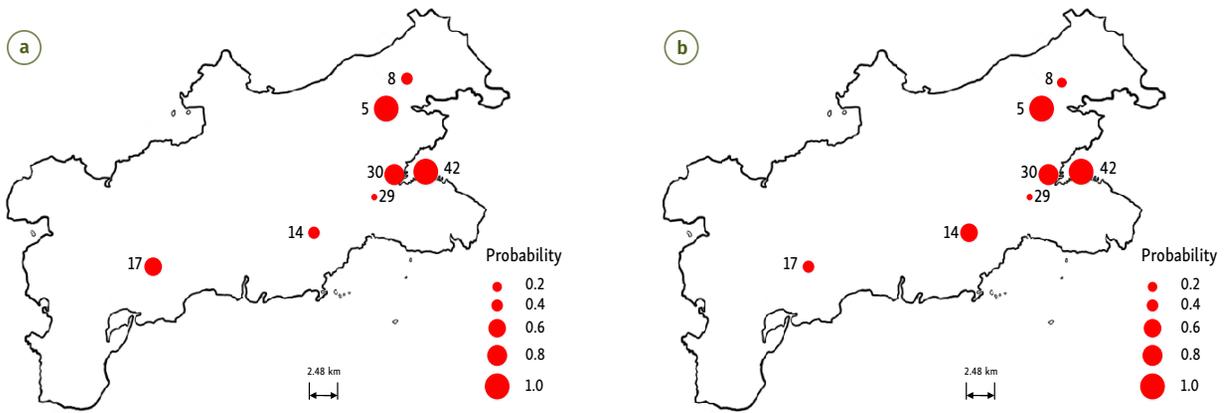


Figure 4. By considering one bus line, hub probabilities at different locations for: (a) – Model A; (b) – Model B

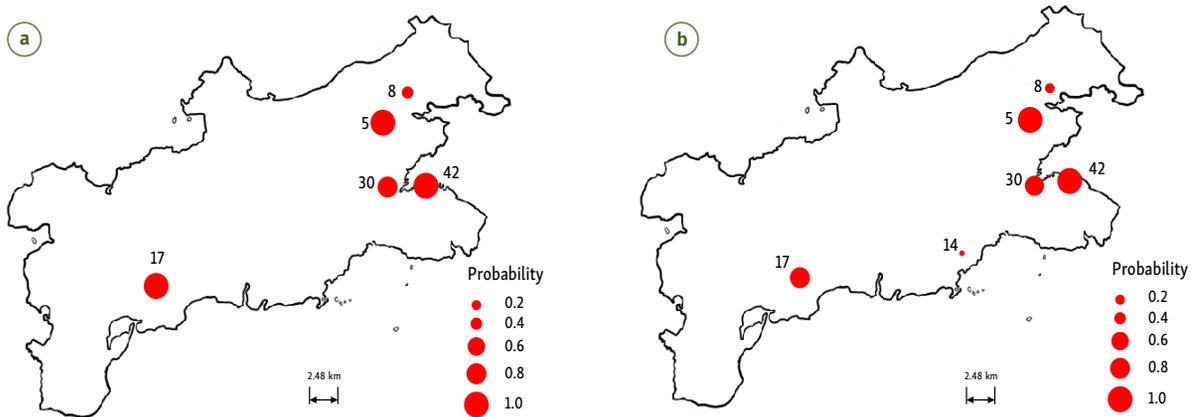


Figure 5. By considering several bus lines, hub probabilities at different locations for: (a) – Model A; (b) – Model B

ilar to the results in Case I shown in Figure 4a. Different from Figure 4, hub probabilities are more concentrated at certain nodes in Cases III and IV, i.e., there are more nodes whose hub probability equals 0, as shown in Figure 5.

5.2. Impact of different bus lines on distribution center location

In this sub-section, the impact of different bus lines on the location of distribution centers is shown in 4 cases (i.e., Cases I...IV), as mentioned above. Next the results of using bus lines for cargo transportation in different cases are presented.

The results for Case I are shown in Figure 6, where only bus lines 1, 6, 10 and 2002 are selected respectively for collaborative distribution with trucks. As shown in Figure 6, blocks 5 and 42 have high hub probabilities when bus line 1, 6, 10 or 2002 is used. For other nodes, they may have different hub probabilities when different bus line is used. For example, block 14 has a relatively high hub probability when bus line 1, 6 or 10 used, while its hub probability equals 0 when bus line 2002 is used.

Next, the results for Case II are shown in Figure 7, where all considered 6 bus lines are selected, respectively. Similar to Figure 6, blocks 5 and 42 have high hub probabilities. Similarly, for other nodes, they may have different hub probabilities when different bus line is used. Take block 17

for instance. When bus line 2002 is used, block 17 has a relatively high hub probability, while its hub probability becomes lower when bus line 1, 2, 6 or 10 is used, and its hub probability equals 0 when bus line 1105 is used.

For Case III, as shown in Figure 8, 2 bus lines (i.e., bus lines 1 and 2002) are selected for cargo transportation under different situations. In this case, blocks 5, 17 and 42 have high hub probabilities, and blocks 8 and 30 have relatively lower hub probabilities. Similarly, for Case IV, as shown in Figure 9, blocks 5, 17, 30 and 42 have high hub probabilities. When 5 bus lines (i.e., bus lines 1, 2, 10, 1105 and 2002) are used for cargo transportation, as shown in Figure 9e, these 4 blocks are always selected as distribution centers, i.e., their hub probabilities equal 1.

Whether using only one bus line or several bus lines together, blocks 5 and 42 have a high probability of establishing distribution centers. In addition, when using only one bus line, block 14 has a greater advantage than block 17. When several bus lines are used, the result is completely the opposite. It is almost impossible to establish a distribution center in block 14. At this time, line 2002 will definitely be used to participate in collaborative distribution, leading to a significant increase in the hub status of block 17. Therefore, logistics distribution companies should invest and layout in blocks 5, 42, and 17 as early as possible to achieve collaborative distribution of buses and trucks.

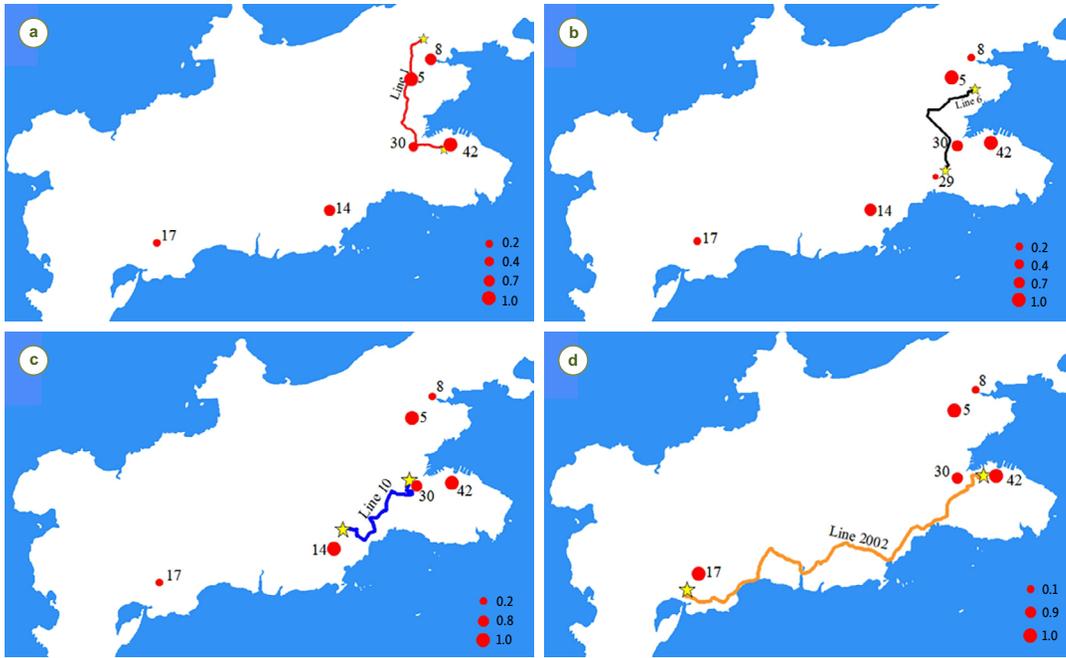


Figure 6. The hub probability results for Case I when bus lines are used:

(a) – bus line 1; (b) – bus line 6; (c) – bus line 10; (d) – bus line 2002

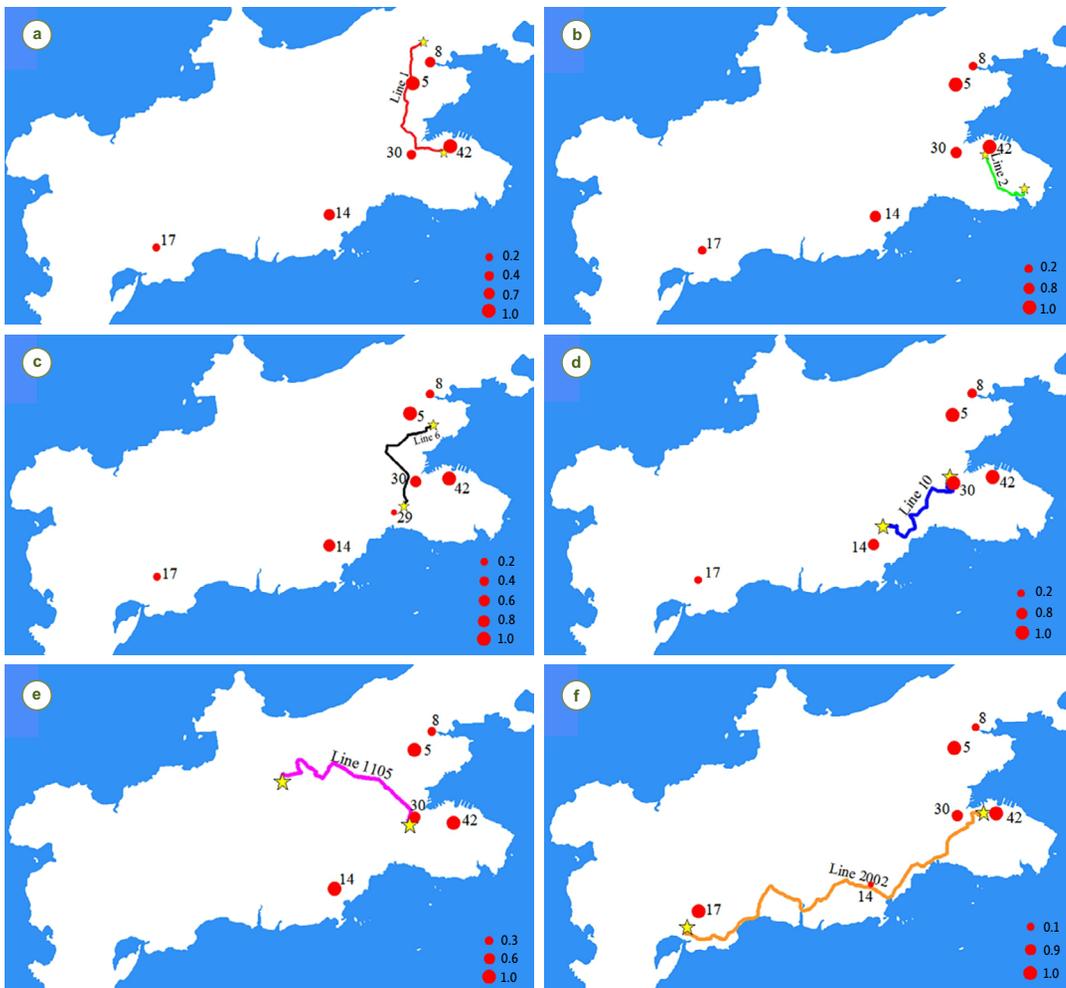


Figure 7. The hub probability results for Case II when different bus lines are used:

(a) – bus line 1; (b) – bus line 2; (c) – bus line 6; (d) – bus line 10; (e) – bus line 1105; (f) – bus line 2002

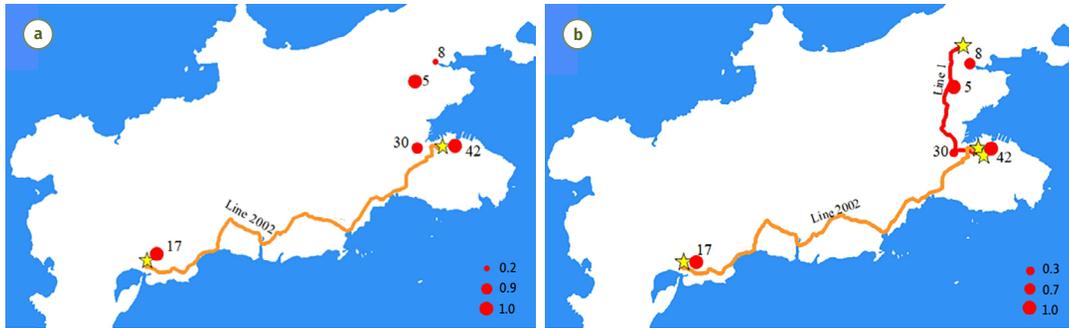


Figure 8. The hub probability results for Case III when different bus lines are used:

(a) – bus line 2002; (b) – bus lines 1 and 2002

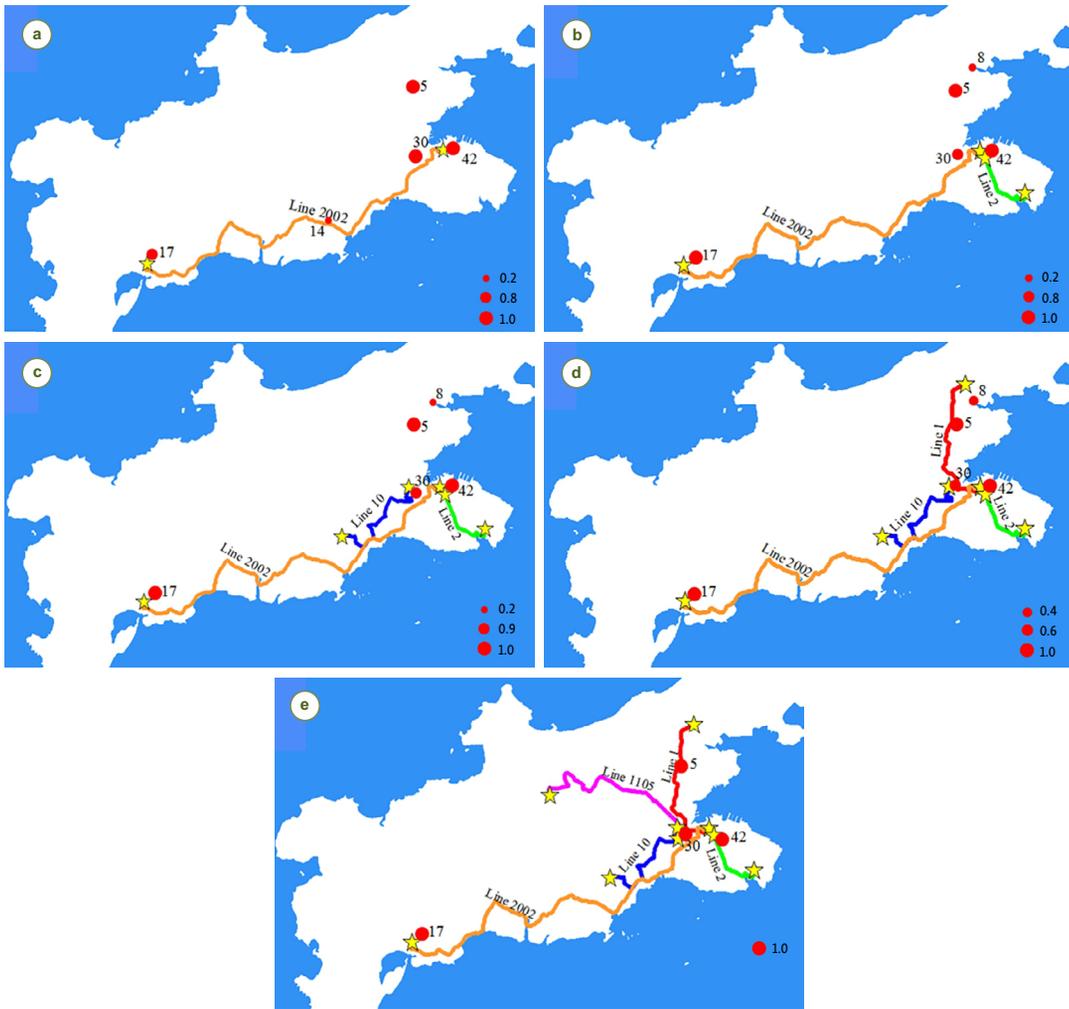


Figure 9. The hub probability results for Case IV when different bus lines are used:

(a) – bus line 2002; (b) – bus lines 2 and 2002; (c) – bus lines 2, 10 and 2002;

(d) – bus lines 1, 2, 10 and 2002; (e) – bus lines 1, 2, 10, 1105 and 2002

5.3. Bus line utilization

This sub-section shows the utilization of bus lines for Cases III and IV. The bus line utilization is defined as the proportion of OD pairs, whose cargoes are transported via bus lines.

Figure 10 shows the bus line utilization in collaborative distribution under different values of α for Case III. The bus

line utilization decreases with the increase of β . When $2 < \beta < 8$, this trend is more obvious. When $\beta > 8$, the overall trend tends to be flat, especially when $\alpha = 0.7$ and $\alpha = 0.9$. In addition, the bus line utilization increases with the increase of γ . This trend is more obvious when the value of β is small (e.g., $\beta = 2$), and slows down with the increase of γ . In Case III, the bus line utilization is up to 39.13%, where $\alpha = 0.5$, $\gamma = 0.4$, $\beta = 2$, as shown in Figure 10a.

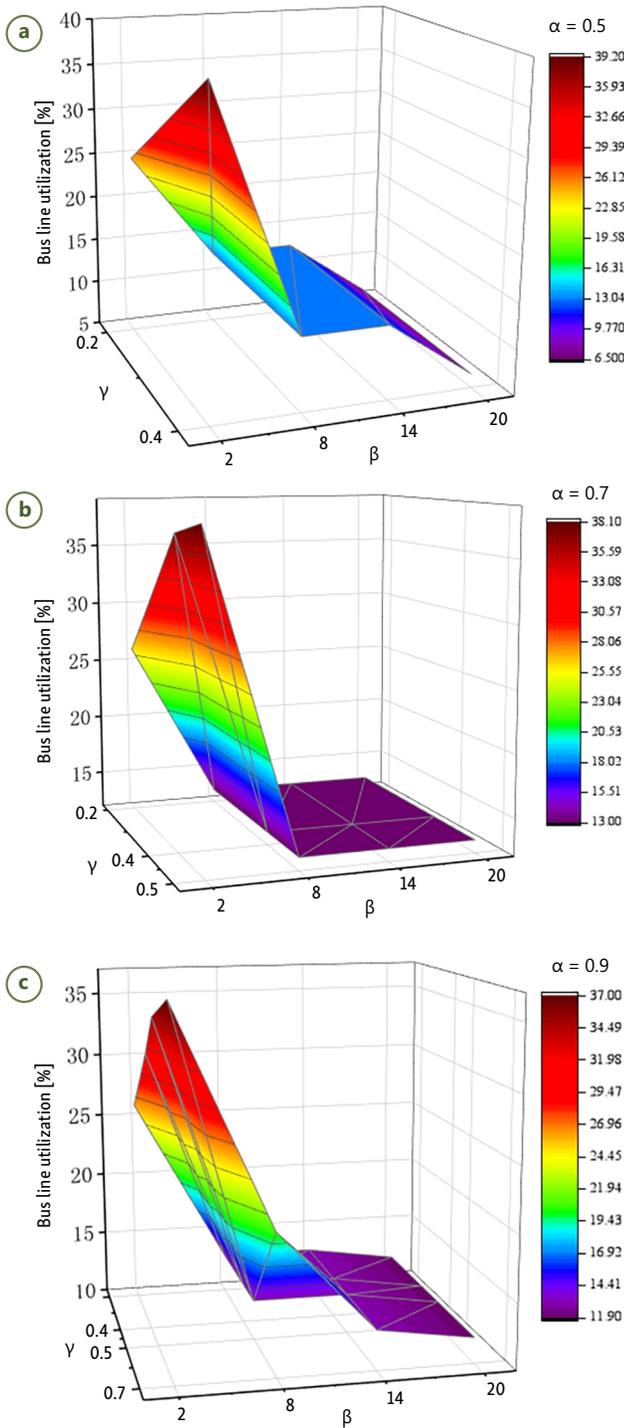


Figure 10. The bus line utilization under different values of α for Cases III

Figure 11 shows the bus line utilization under different values of α for Case IV. The change of bus line utilization with β is basically the same as that of Case III, but the change with γ is slightly different. Although it also increases with the increase of γ , and the change is more obvious when $\beta = 2$, the utilization increases more significantly with the increase of γ . The maximum utilization of Case IV is up to 47.83%, as shown in Figure 11c.

Figure 10 and Figure 11 show a similar phenomenon that the bus line utilization in collaborative distribution decreases with the increase of β . At the same time, the bus

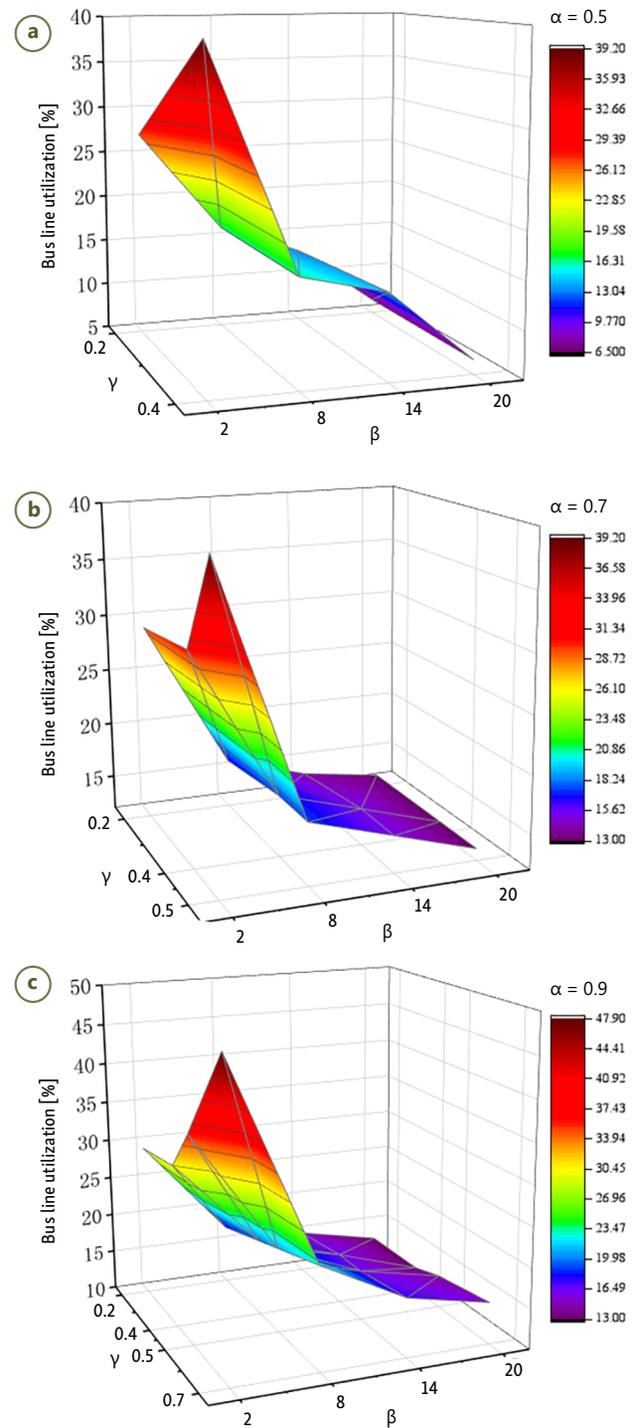


Figure 11. The bus line utilization under different values of α for Cases IV

line utilization increases with the increase of γ , but this is more obvious only when the β value is small. In addition, under the same β value, compared with Case III, Case IV where the 3 distribution modes are used together, the bus line utilization is generally higher. That is, the choice of distribution mode also has a great impact on improving the bus line utilization. Therefore, logistics distribution companies should conduct reasonable pricing with bus companies, and adopt appropriate distribution modes in order to make use of buses for collaborative distribution as much as possible.

5.4. The impact of bus lines on CO₂ emissions

This sub-section shows the total CO₂ emissions of trucks for Cases III and IV to reflect the impact of using bus lines on reducing CO₂ emissions in Dalian.

Figure 12 shows the total CO₂ emissions under different values of α for Case III. The total CO₂ emission increases with the increase of β . When $2 < \beta < 8$, this trend is more obvious, and when $\beta > 8$, the growth trend slows down. In addition, the total CO₂ emission decreases with the increase of γ . When $\alpha = 0.5$ and $\alpha = 0.7$, this trend is only reflected in $\beta = 2$ and slows down with the increase of γ .

When $\alpha = 0.9$ and $\beta > 8$, the total CO₂ emission 1st remains stable and then decreases sharply with the increase of γ . As shown in Figure 11a, when $\alpha = 0.5$, $\gamma = 0.4$ and $\beta = 2$, the total CO₂ emission of trucks in Case III is the lowest, 768.9 kg, which is 28.1% lower than that without bus lines.

Figure 13 shows the total CO₂ emissions under different values of α for Case IV. The change of total CO₂ emission with β is basically the same as that of Case III, but the change with γ is slightly different. When the value of β is small, the overall trend of total CO₂ emission also decreases with the increase of γ . However, when $\alpha = 0.9$ and $\beta = 20$, the total CO₂ emission shows a trend of 1st increasing

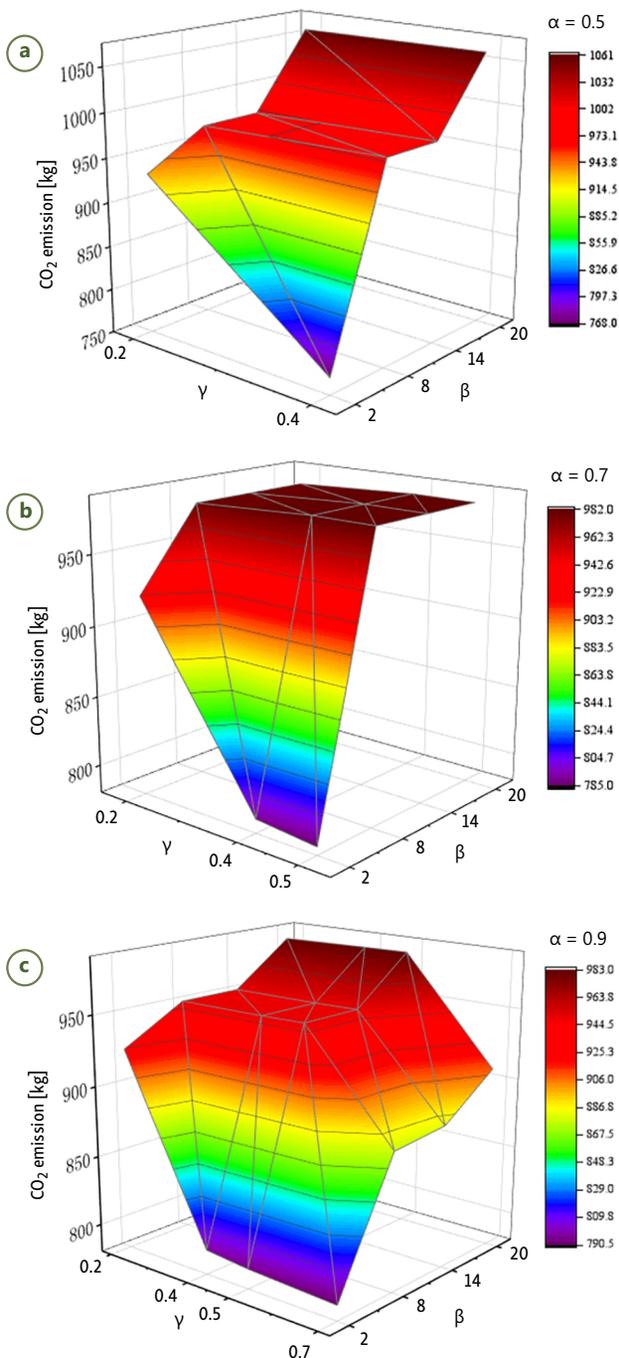


Figure 12. Total CO₂ emissions of trucks under different values of α for Case III

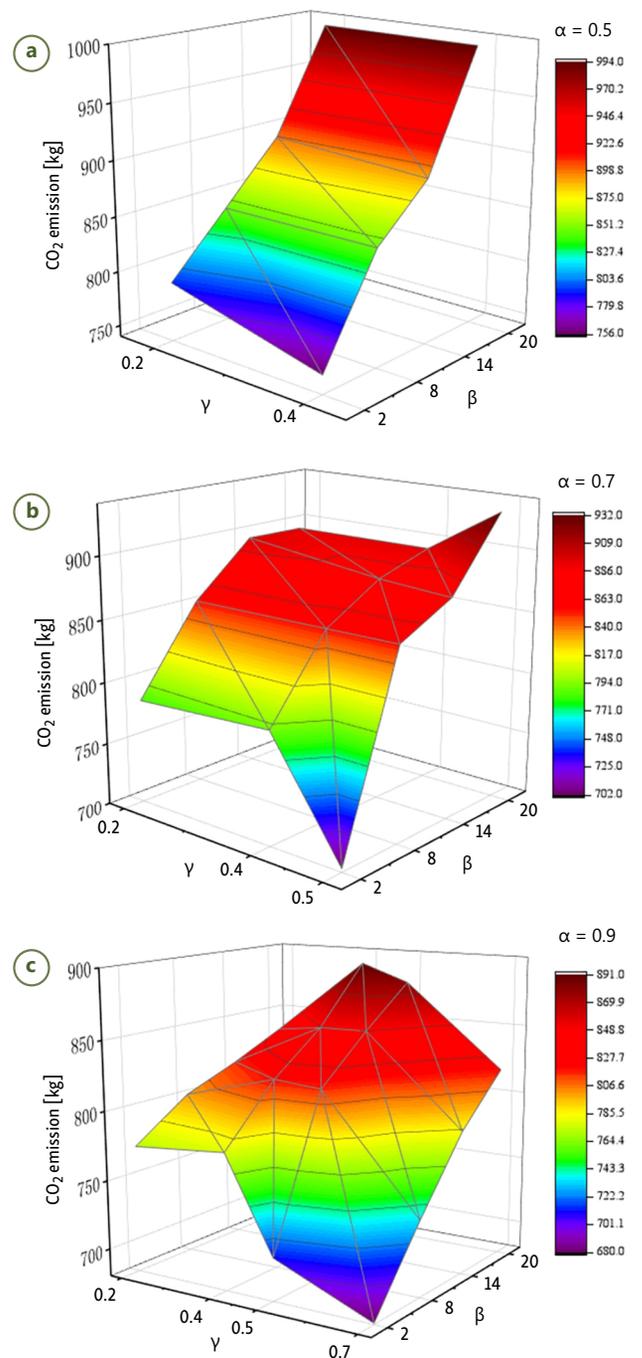


Figure 13. Total CO₂ emissions of trucks under different values of α for Case IV

and then decreasing with the increase of γ . These changes are closely related to the bus lines used. As shown in Figure 13c, when $\alpha = 0.9$, $\gamma = 0.7$ and $\beta = 2$, the total CO₂ emission of trucks in Case IV is the lowest, 680.9 kg, which is 36.3% lower than that without bus lines.

Bus lines play an extremely important role in the distribution center location, collaborative distribution and carbon emission reduction, especially line 2002. Line 2002 not only has a long driving distance, but also the starting station is close to Dalian Port. More importantly, the starting and ending stations are located in the area with relatively dense demand distribution.

6. Conclusions and future studies

This article introduces the influence of using bus lines for urban logistics distribution into the DCLP (i.e., the ULD-CLPPTS) and discusses the influence of public transportation system on the location of distribution centers in urban logistics, as well as reducing CO₂ emissions of trucks. Considering different distribution scenarios and modes, 2 mixed integer linear programming models are proposed to solve the ULDCLPPTS.

The numerical results show in any case, the possibility of establishing distribution centers in blocks 5 and 42 of Dalian is very high. When several bus lines are used, block 17 is also a good choice to establish a distribution center. When bus lines are used, the maximum bus line utilization can reach 47.83%, and the CO₂ emission can be reduced by up to 36.3%. At this time, 5 bus lines (i.e., bus lines 1, 2, 10, 1105 and 2002) are used for cargo transportation, and distribution modes 1, 2, and 3 are used simultaneously.

In terms of different bus lines, line 2002 is more suitable to participate in the collaborative distribution in Dalian compared with other bus lines. Line 2002 can not only adapt to various distribution scenarios, but also bear a high utilization, and can greatly reduce the carbon emission of trucks in the process of urban logistics distribution. When line 2002 is used for collaborative distribution, in addition to blocks 5 and 42, blocks 17 and 30 are more likely to be selected to establish distribution centers.

It should be pointed out that the research on the location of distribution centers in this article does not do too much research on the construction cost of specific locations and the use of new energy technologies such as electric trucks. In the future, the DCLP with fixed cost and the urban logistics distribution problem considering the use of electric trucks can be expanded by further refining fixed construction costs and new energy technologies.

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Author contributions

Qian Wang and Jianfeng Zheng conceived the study and were responsible for the design and development of the data analysis.

Huibin Liu and Yao Wang were responsible for data collection and analysis.

Qian Wang wrote the 1st draft of the article.

Qian Wang and Xia Li revised the article.

Appendix A

Based on Models A and B, the time value of using buses and trucks to transport goods is further considered. A few new notations are introduced. Let S represent the value of the cargoes themselves and δ represent the depreciation rate of the cargoes. Let v_{ij}^B represent the running speed of the bus on link $\langle i, j \rangle$ with distance D_{ij} . Following Shen *et al.* (2023), $S = 569$ CNY/kg, $\delta = 0.043\%$, and $v_{ij}^B = 25$ km/h. Let t_{ij} represent the transportation time of the truck on link $\langle i, j \rangle$, and t_{ij}^B represent the transportation time of the bus on link $\langle i, j \rangle$. Let t_{ijkml}^1 , t_{ijkml}^2 and t_{ijl}^3 represent the transportation time of 3 transportation paths associated with distribution modes 1, 2 and 3, respectively. Namely:

$$t_{ijkml}^1 = t_{ik} + t_{km} + t_{mj}; \quad (24)$$

$$t_{ijkml}^2 = t_{ik} + t_{kl_h} + t_{l_h l_n}^B + t_{l_n m} + t_{mj}; \quad (25)$$

$$t_{ijl}^3 = t_{il_h} + t_{l_n j} + t_{l_h l_n}^B; \quad (26)$$

$$t_{ij} = \frac{D_{ij}}{v_{ij}}; \quad (27)$$

$$t_{ij}^B = \frac{D_{ij}}{v_{ij}^B}. \quad (28)$$

Model A can be extended to the following mixed integer linear programming model (denoted by Model C):

$$\begin{aligned} \min & \sum_{i,j \in \mathcal{Q}} \sum_{k \in \mathcal{DN}} \sum_{m \in \mathcal{DN}} \sum_{l \in \mathcal{H}} q_{ij} \times \\ & \left(\delta \cdot S \cdot \left(t_{ijkml}^1 \cdot x_{ijkml} + t_{ijkml}^2 \cdot y_{ijkml} \right) + \right. \\ & \left. \left(C_{ijkml}^1 \cdot x_{ijkml} + C_{ijkml}^2 \cdot y_{ijkml} \right) \right) \end{aligned} \quad (29)$$

subject to:

Constraints (10)–(20):

$$\begin{aligned} & \sum_{k \in \mathcal{DN}} \sum_{m \in \mathcal{DN}} \sum_{l \in \mathcal{H}} \left(t_{ijkml}^1 \cdot x_{ijkml} + t_{ijkml}^2 \cdot y_{ijkml} \right) \leq T_{\max}, \\ & \forall (i, j) \in \mathcal{Q}. \end{aligned} \quad (30)$$

The Objective Function (29) is to minimize the transportation and time costs of 2 distribution modes when using several bus lines. Constraints (30) mean that the transportation time between any OD pair (i, j) cannot exceed T_{\max} .

Considering the time value, in Case III (i.e., Model C), blocks 5, 17 and 42 are definitely chosen to establish distribution centers. In addition, block 30 has a high probability, while the probability of blocks 8 and 14 is relatively low. Line 2002 is inevitably used to participate in collaborative distribution. If a distribution center is established in block 30, line 6 will inevitably participate in collaborative distribution. Secondly, there is a high probability that line 1 will also be used.

Similarly, Model B can be extended to the following mixed integer linear programming model (denoted by Model D):

$$\min \sum_{i,j \in \mathcal{Q}} \sum_{k \in \mathcal{D}\mathcal{N}} \sum_{m \in \mathcal{D}\mathcal{N}} \sum_{l \in \mathcal{H}} q_{ij} \times (\delta \cdot S \cdot (t_{ijkm}^1 \cdot x_{ijkm} + t_{ijkml}^2 \cdot y_{ijkml} + t_{ijl}^3 \cdot y_{ijl})) + (C_{ijkm}^1 \cdot x_{ijkm} + C_{ijkml}^2 \cdot y_{ijkml} + C_{ijl}^3 \cdot y_{ijl}) \quad (31)$$

subject to:

Constraints (10)–(14), (16)–(20), (22), (23);

$$\sum_{k \in \mathcal{D}\mathcal{N}} \sum_{m \in \mathcal{D}\mathcal{N}} \sum_{l \in \mathcal{H}} (t_{ijkm}^1 \cdot x_{ijkm} + t_{ijkml}^2 \cdot y_{ijkml} + t_{ijl}^3 \cdot y_{ijl}) \leq T_{\max}, \quad \forall (i, j) \in \mathcal{Q}. \quad (32)$$

The objective function (31) is to minimize the transportation and time costs of 3 distribution modes when using several bus lines. The meaning of constraints (32) is the same as constraints (30).

The location results and bus line utilization are exactly the same as the results of Model C. Due to the influence of time value, distribution mode 3 is not used.

Appendix B

Based on Models A and B, let F_k represent the fixed construction costs of different locations. Model A can be extended to the following mixed integer linear programming model (denoted by Model E):

$$\min \sum_{i,j \in \mathcal{Q}} \sum_{k \in \mathcal{D}\mathcal{N}} \sum_{m \in \mathcal{D}\mathcal{N}} \sum_{l \in \mathcal{H}} q_{ij} \times (C_{ijkm}^1 \cdot x_{ijkm} + C_{ijkml}^2 \cdot y_{ijkml}) + \sum_{k \in \mathcal{D}\mathcal{N}} F_k \cdot Z_k \quad (33)$$

subject to:

Constraints (11)–(20).

The Objective Function (33) is to minimize the transportation costs and fixed construction costs of 2 distribution modes when using several bus lines.

Considering fixed construction costs in Case III (i.e., Model E), there is an opportunity to establish distribution centers in blocks 5, 8, 17 and 42. Due to its excellent geographical location and low fixed construction costs, the distribution center is definitely established in block 42. Due

to their proximity, only one distribution center was established in blocks 5 and 8, and the fixed cost of establishing a distribution center in block 8 is lower than that in block 5. The higher the value of γ , the more likely block 8 is to build a distribution center, and when $\beta = 2$, block 8 will definitely be chosen. When block 8 is selected, line 1 participates in collaborative distribution. When block 5 is selected, no bus lines are used for collaborative distribution. When α , γ and β are relatively small, block 17 has the opportunity to establish a distribution center. At this time, blocks 8 and 42 will also be selected, and lines 1 and 2002 will participate in the distribution simultaneously.

Similarly, Model B can be extended to the following mixed integer linear programming model (denoted by Model F):

$$\min \sum_{i,j \in \mathcal{Q}} \sum_{k \in \mathcal{D}\mathcal{N}} \sum_{m \in \mathcal{D}\mathcal{N}} \sum_{l \in \mathcal{H}} q_{ij} \times (C_{ijkm}^1 \cdot x_{ijkm} + C_{ijkml}^2 \cdot y_{ijkml} + C_{ijl}^3 \cdot y_{ijl}) + \sum_{k \in \mathcal{D}\mathcal{N}} F_k \cdot Z_k \quad (34)$$

subject to:

Constraints (11)–(14), (16)–(20).

The objective function (34) is to minimize the transportation costs and fixed construction costs of 3 distribution modes when using several bus lines.

Considering fixed construction costs in Case IV (i.e., model F), only blocks 5, 8, 42 are likely to build distribution centers, and the situation for blocks 5 and 8 is similar to that for model E. Block 42 is definitely chosen to build a distribution center, and line 2002 will also participate in collaborative distribution in any case.

Appendix C

Based on Models A and B, the use of new energy vehicles is further considered. In Models A and B, the transportation cost of trucks is assumed to be proportional to the transportation distance. After the introduction of new energy vehicles, the transportation cost of trucks needs to be further considered in combination with the electricity consumption cost per km and the fuel consumption cost per km. Let σ represent the ratio of the 2. According to the calorific value conversion method, 1 kW-h electricity consumption equals 0.1161 L fuel consumption. The value of σ can be obtained. Let C_{ijkm}^{e1} , C_{ijkml}^{e2} and C_{ijl}^{e3} respectively represent the transportation cost of 3 transportation paths associated with distribution modes 1, 2 and 3 when using new energy vehicles. Namely:

$$C_{ijkm}^{e1} = \sigma \cdot (\gamma \cdot D_{ik} + \alpha \cdot D_{km} + D_{mj}); \quad (35)$$

$$C_{ijkml}^{e2} = \sigma \cdot (\gamma \cdot D_{ik} + \alpha \cdot (D_{klh} + D_{l_n m}) + D_{mj}) + \beta; \quad (36)$$

$$C_{ijl}^{e3} = \sigma \cdot (D_{il_h} + D_{l_n j}) + \beta. \quad (37)$$

Model A can be extended to the following mixed integer linear programming model (denoted by Model G):

$$\min \sum_{i,j \in Q} \sum_{k \in \mathcal{D}^N} \sum_{m \in \mathcal{D}^N} \sum_{l \in \mathcal{H}} q_{ij} \times (C_{ijkm}^{e1} \cdot x_{ijkm} + C_{ijkml}^{e2} \cdot y_{ijkml}) \quad (38)$$

subject to:

Constraints (10)–(20).

The Objective Function (38) is to minimize the total cost of 2 distribution modes when using new energy vehicles and several bus lines.

Similarly, Model B can be extended to the following mixed integer linear programming model (denoted by Model H):

$$\min \sum_{i,j \in Q} \sum_{k \in \mathcal{D}^N} \sum_{m \in \mathcal{D}^N} \sum_{l \in \mathcal{H}} q_{ij} \times (C_{ijkm}^{e1} \cdot x_{ijkm} + C_{ijkml}^{e2} \cdot y_{ijkml} + C_{ijl}^{e3} \cdot y_{ijl}) \quad (39)$$

subject to:

Constraints (10)–(14), (16)–(20), (22), (23).

The Objective Function (39) is to minimize the total cost of 3 distribution modes when using new energy vehicles and several bus lines.

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