

Article

Design of Green Cold Chain Networks for Imported Fresh Agri-Products in Belt and Road Development

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Abstract: The development of Belt and Road has seen a boom of imported fresh agri-products in China. This stimulates the growth of refrigerated transport, which accounts for much more carbon emissions than traditional transport. Designing a sustainable cold chain network is of vital importance from both financial and environmental perspectives. In this research, a multi-objective linear programming model is proposed for green cold chain design for multiple imported fresh agri-products in China to balance between the two competing goals—the total cost and carbon emissions. The effect of the outdoor air temperature on the carbon emissions of transportation and maintaining distribution centers is considered. By applying the ϵ -constraint method, the multi-objective model is solved. Numerical examples derived from the scenario of imported fresh-agri products in China are conducted to shed light on green cold chain design under Belt and Road development.

Keywords: sustainable supply chain design; fresh agri-products; multi-objective programming; carbon emission

1. Introduction

China's Belt and Road Initiative is an economic framework developed to increase connectivity between China and over 100 countries and international organizations based on the ancient Silk Road land and maritime routes [1]. With the development of Belt and Road, the market of imported fresh agri-products has experienced a boom in China, especially for highly perishable products, such as fresh fruit, frozen meat, and frozen seafood. According to the recent report on the dinner consumption trend of China in 2018 [2], the sales of imported fresh agri-products increased more than twofold from 2015 to 2017. Moreover, the Belt and Road development has broadened the scope of countries that are imported from, as well as the variety of imported fresh agri-products. For example, sweet potatoes from Vietnam, mussels from New Zealand, and oranges from Australia were the top three fastest-growing imported products in 2017. The growth of imported agri-products has contributed to an increasing demand for refrigerated transport. The limited shelf lives of the fresh agri-products require the constant maintenance of the prescribed temperature conditions for the storage of goods until products are delivered to their destinations. However, the energy use and carbon emissions associated with refrigerated transportation and storage are tremendous [3]. Consequently, designing a green cold chain network for imported fresh agri-product transportation is of vital importance to the sustainable development of the Belt and Road Initiative.

The cold chain network for imported fresh agri-products in China is characterized by long distances and different climatic conditions. For example, if a customer at the city of Harbin demands a

pitaya from Vietnam, the transportation distance inside China will be around 3516 kilometers from the port of Nanning to the city of Harbin, and the difference of the average temperatures between the two cities is up to 20 degrees centigrade. Due to door openings; product removal/loading; conduction through walls, roofs, and floors of the refrigerated warehouses and vehicles; and length of the journey; the heat transfer between the outside air and refrigerators is highly affected by the outdoor air temperatures [4–7]. Consequently, the outdoor ambient temperature conditions during transportation and storage will change the energy consumption for maintaining the set-point temperature. It will impact the GHG (greenhouse gas) emission and, consequently, affect the design of green cold chains delicately. Meanwhile, the customer preferences for imported fresh agri-products are geographically diversified [2]. The diversified demand for different products from different countries increases the complexity of the transportation progress. Moreover, we are motivated to build a “green” supply chain network, where the environmental indicators in the operations should be considered. Therefore, a trade-off exists between financial targets and environmental objectives [8]. With such concerns, the method of balancing between financial concerns and environmental indicators is a dilemma in the design of green supply chains.

In order to design a green cold chain network for imported fresh agri-products that incorporates the above aspects, a multi-objective linear programming (MOLP) model is developed. The objectives of the model are to minimize the total logistics cost and the total amount of carbon emissions. The model can tackle multiple types of products distributed from different ports to different cities. The GHG emission rate is measured not only as a function of distances but also as a function of the outdoor air temperature conditions. We provide a case for the imported fresh agri-products across China and managerial implications are provided as well.

The rest of the paper is organized as follows. In Section 2, the related literature is reviewed. The research problem is defined and the model is formulated in Section 3. Section 4 illustrates the solution of the proposed model by numerical experiments and the managerial implications are derived. Finally, conclusions are given in Section 5.

2. Literature Review

In the following sections, two streams of related literature are reviewed, namely, (1) green supply chain management and (2) supply chain network design.

(1) Green Supply Chain Management

Green supply chain management (GSCM) has been investigated widely as a major trend in supply chain management [9]. A lot of research work has focused on every process of green supply chain management; for example, the production [10], storage and warehousing [11], logistics, and transportation [12]. The method of measuring the environmental impact is one of the key issues for green supply chain management. Benjafaar et al. [13] and Gallo et al. [14] pointed out that carbon emissions monotonically increase with the travel distance and transportation quality. Recently, some researchers also considered both social and environmental factors as sustainable issues [15,16]. Tozzi et al. [17] analyzed the efficiency of urban distribution processes in a city with strict environmental requirements through information from GPS-based and operation datasets.

In recent years, the green supply chain of fresh food has achieved a lot of attention. Borodin et al. [18] pointed out that the GSCM of food is much more complicated, especially when considering the complex quality control process [19] and the environmental issues [20,21]. Research on the GSCM of food can be classified into three aspects. The first one is from the perspective of food quality control. Panozzo and Cortella [22] described the requirement for temperature-controlled transport vehicles and storage temperatures for perishable food. Yang et al. [23] investigated the pricing and inventory strategies for perishable food based on the quality deterioration model. The second aspect is the measure of sustainability factors. The environmental performance of Thailand’s food supply chains was investigated by Pipatprapa et al. [24]. Gwanpua et al. [25] assessed the carbon

footprint of a fresh chestnut supply chain based on the product quality, energy use, and global warming. Strotmann et al. [26] proposed a participatory concept and provided measures of resource efficiency along the food value chain. Finally, the third aspect is models from strategic- and tactical-level decisions. For this, Bosona et al. [27] combined data mining and the optimization approach to design a local food supply chain. The distribution of fresh food was investigated by Amorim and Almada-Lobo [28]. Wang et al. [29] constructed a green cold chain logistics distribution optimization model.

(2) Supply Chain Network Design

The supply chain network design problem is the strategic decision problem that determines the location, capacity, number, and type of supply chain facilities to achieve specific long-term goals. There are various models to formulate the problem ranging from linear deterministic models [12,30] to nonlinear stochastic ones [31,32]. The most recent studies dealing with the supply chain network design problem can be referred to elsewhere [9,33,34].

Srivastava [35] pointed out that most of the supply chain design problem is for a single economic objective. However, trade-offs among financial and environmental concerns are more practical in designing green supply chain networks. Therefore, a lot of research work has focused on how to handle the multi-objective conflicting problem and propose corresponding solutions and models. One of the widely adopted methods in the literature is multi-objective optimization for its efficiency in modeling and solving. For example, a bi-objective model was proposed by Chaabane et al. [36] for aluminum supply chain network design. Akgul et al. [37] used a multi-objective mixed-integer linear program to formulate the trade-off between the financial and environmental concerns for biofuel supply chain network design. Soysal et al. [8] investigated the design of a beef supply chain using the multi-objective model. In this research, the transportation carbon emission issues involve the road structure, the weight load of vehicles, and many other factors, while the quality of the perishable products is also considered. A three-objective optimization model was proposed by Bortolini et al. [38] to balance between the cost, carbon emissions, and delivery time for fresh food distribution. Other methods used to handle the multi-objective conflicting problem have been proposed by researchers as well. For example, Osvald and Stirn [39] investigated the impact of perishability for the distribution of perishable food, and the overall costs were measured using the linear weighted sum of the distance, time, penalty of delay, and loss of quality. Coskun et al. [40] integrated consumer behavior into the supply chain network design. The goal programming approach is proposed to balance several predefined objectives, including total income and cost, market penalty, green expectation levels of consumers, and lost sales.

In general, the existing findings provide some fundamental elements of our research. However, when taking into account the specific features of the cold supply chain of imported fresh agri-products in the Belt and Road Development, the following work has to be further studied. Firstly, due to the long-range distribution progress, the carbon emission rate during storage and transportation will be different at different places when the outdoor air temperature varies. The question of how to consider the effect of outdoor temperature patterns in the network design is worthy of further study. Secondly, the Belt and Road development has broadened the scope of countries that are imported from, as well as the variety of imported fresh agri-products. The method of designing a model when multiple products are distributed to multiple regions is important. Lastly, balancing between the financial and environmental concerns for the problem of imported fresh agri-products in China must also be focused on. Our research aims to bridge the gaps in the current literature. The contributions of the study can be summarized as the following: (1) we integrate the effect of outdoor air temperature patterns on the emissions into the cold chain network design problem; (2) a multi-objective mixed-integer programming model is formulated for multiple products to be distributed to different regions; and (3) numerical examples derived from scenarios of imported fresh agri-products in China are examined in order to shed light on green cold chain design under the Belt and Road development.

3. Problem Description and Formulation

3.1. Problem Descriptions

The products of our research scope are fresh fruit, frozen meat, and frozen seafood, which are the most favorite imported products in China according to statistical reports [2]. They are all perishable and need to be stored and transported using refrigerated warehouses and vehicles at specific temperatures [3]. For example, the maximum temperature for frozen meat and frozen seafood is $-18\text{ }^{\circ}\text{C}$, and the temperature range for most fresh fruit is $0\text{--}4\text{ }^{\circ}\text{C}$. It is reported that the cold chain of fresh products in China is mainly fulfilled by refrigerated warehouses and trucks, which cost a lot and cause environmental issues [41]. Therefore, our work in designing a cold supply chain network focuses on the complicated land distribution progress in China when products are imported from ports and transported to retailers at target cities. Consequently, a three-tier network involving three types of locations is investigated, as shown in Figure 1 and explained as follows.

The first type of location is the port, which is usually known as the Free Trade Zone for importing fresh agri-products. Various fresh products from different countries are transported or stored at ports. After Customs Clearance, the products will then be transported to the second type of location, namely, DCs (distribution centers). DCs in the cold chain consist of refrigerated warehouses where fresh products can be temporarily stored, removed, and loaded, which is known as cross-docking. Consequently, DCs will incur a financial cost and cause carbon emissions due to the use of energy and operations. The last type of location is the retailers in the target cities, where various demands for the different fresh agri-products should be satisfied. The transportation between locations depends on refrigerated trucks. It is assumed that different products that require different refrigeration temperatures are transported by different vehicles. A distributor is faced with the problem of deciding which places should be selected as distribution centers and how to fulfill the demand of each of the retailers in order to balance between the minimum cost and the carbon emissions. Hereinafter, we use the terms inbound and outbound to represent transportation from ports to DCs and DCs to retailers, respectively.

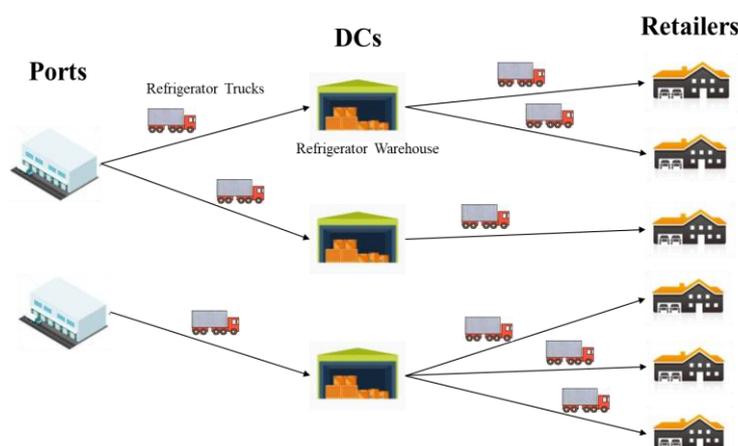


Figure 1. The schematic diagram of a cold chain network for imported fresh agri-products. DCs: distribution centers.

A complete list of parameters and variables is given in Table 1. Preliminary work on assessing emissions is introduced as follows.

Table 1. The definitions of the parameters and variables.

Indices	
$i = 1, \dots, I$	Set of ports
$j = 1, \dots, J$	Set of potential DCs
$k = 1, \dots, K$	Set of retailers
$u = 1, \dots, U$	Set of products
Parameters	
T_i^P	Average annual temperatures of ports
T_j^D	Average annual temperature of DCs
T_k^R	Average annual temperature of cities of retailers
e_{iju}	Unit carbon emission rate of transporting product u from port i to DC j (kg CO ₂ /kg·km)
e_{jku}	Unit carbon emission rate of transporting product u from DC j to retailer k (kg CO ₂ /kg·km)
c_{iju}	Unit cost of transporting product u from port i to DC j (yuan/ kg·km)
c_{jku}	Unit cost of transporting product u from DC j to retailer k (yuan/ kg·km)
d_{ij}	Distance from port i to DC j
d_{jk}	Distance from DC j to retailer k
S_{iu}	Supply of product u of port i
D_{ku}	Demand of product u of retailer j
F_j	Cost of DC j
E_j	Emission of DC j
P_{MIN}	Minimum number of DCs required by the decision-maker
P_{MAX}	Maximum number of DCs required by the decision-maker
M	A large number for modeling
Decision Variables	
Y_j	=1, if DC j is selected (binary decision variable)
X_{iju}	Amount of products u transported from port i to DC j
X_{jku}	Amount of products u transported from DC j to retailer k

(1) Carbon Emissions of Transportation

There is no standard for the assessment of transportation-related carbon emissions. However, a general approach can be observed [5,42]. Accordingly, we consider three factors, namely, distance, outdoor ambient temperature, and the set point of refrigerator temperature regarding different types of products. The most comprehensive data that show the relationship between ambient temperatures, refrigeration temperatures, and vehicular GHG emissions are presented by Wu et al. [7]. It indicates clearly that higher ambient temperatures lead to higher energy consumption and, consequently, increased carbon emissions. Moreover, the set point of the refrigerator temperature has a negative correlation with carbon emissions as well.

In this paper, based on the published experimental data, an expression relating the ambient temperatures to CO₂ emissions is derived. Let e_{iju} denote the unit carbon emission rate in traveling from port i to DC j for product u . Let T_i^P and T_j^D be the average annual temperature of ports and DCs, respectively. Then, the unit carbon emission rate is estimated as $e_{iju} = g((T_i^P + T_j^D)/2)$. Here, the average annual temperature of the two locations is used to estimate the overall temperature condition from port i to DC j . $g(\cdot)$ is a monotonic increasing function with the ambient temperature as well. Similarly, the value of e_{jku} , the unit carbon emission rate for transporting product u from DC j to retailer k , can be determined.

(2) Carbon Emissions of DCs

The carbon emissions of DCs in the cold chain are generated when maintaining refrigerated warehouses where the products are stored, removed, and loaded. Due to door openings; product removal/loading; and the heat conduction through doors, walls, roofs, and floors; the emission rate is positively correlated with the outdoor ambient temperature [4,6]. Consequently, the location of the

DCs will affect the outdoor ambient temperature patterns, as well as the energy use and emissions, accordingly. Meneghetti and Monti [6] conducted research on the sustainable design of refrigerated automated food warehouses. They published the yearly cost, energy consumption, and emissions of warehouses based on reference cases from different locations with different temperature patterns. However, direct and general models to measure carbon emissions of DCs are rare. By combined use of the results and data from references [6,7], an expression for the carbon emission of DCs can be derived. Let T_j^D be the average annual temperature of a potential DC; its carbon emission for a given period (for example, a year), E_j , is estimated as $f(T_j^D)$, where $f(T_j^D)$ is a relationship between the carbon emission and average annual temperature, and can be formulated as a monotonic increasing function with T_j^D .

3.2. Model Development

In order to balance between the financial and environmental indicators, a multi-objective mixed-integer linear program is formulated for the cold chain network design of imported fresh agri-products. The objective of the model is to minimize both the financial cost and the total carbon emissions. The complete model is given as follows and IM is used to denote this initial model.

IM:

$$\min OF_1 = \sum_i \sum_j \sum_u c_{iju} x_{iju} d_{ij} + \sum_j \sum_k \sum_u c_{jku} x_{jku} d_{jk} + \sum_j F_j Y_j \quad (1)$$

$$\min OF_2 = \sum_i \sum_j \sum_u e_{iju} x_{iju} d_{ij} + \sum_i \sum_j \sum_u e_{jku} x_{jku} d_{jk} + \sum_j E_j Y_j \quad (2)$$

s.t.

$$\sum_j x_{iju} \leq S_{iu} \quad \forall i \in S, u \in U \quad (3)$$

$$\sum_j x_{jku} \geq D_{ku} \quad \forall k \in K, u \in U \quad (4)$$

$$\sum_{i=1}^I x_{iju} - \sum_{k=1}^K x_{jku} \geq 0 \quad \forall j \in J, u \in U \quad (5)$$

$$x_{iju} - MY_j \leq 0 \quad \forall i \in I, j \in J, u \in U \quad (6)$$

$$x_{jku} - MY_j \leq 0 \quad \forall j \in J, k \in K \quad (7)$$

$$\sum_j Y_j \geq P_{MIN} \quad \forall j \in J \quad (8)$$

$$\sum_j Y_j \leq P_{MAX} \quad \forall j \in J \quad (9)$$

$$x_{iju}, x_{jku} \geq 0 \quad \forall i \in I, j \in J, k \in K, u \in U \quad (10)$$

$$Y_j = \{0, 1\} \quad \forall j \in J \quad (11)$$

The first objective (OF_1) in Equation (1) is the financial objective which is measured as the total cost including the following three parts: the overall transportation cost from ports to the DCs, the total transportation cost from the DCs to retailers, and the cost for opening and maintaining DCs. The second objective (OF_2) in Equation (2) is the environmental objective and is measured as the total carbon emissions that consist of the following three parts: the total carbon emission for transporting products from ports to the DCs, the overall carbon emission for transporting products from DCs to retailers, and the fixed carbon emissions of DCs for a given time period (for example, a year).

Constraint (3) represents the supply capacity of each product from each port. Constraint (4) ensures that the demand from each retailer is satisfied. Constraint (5) guarantees the outbound flow must be no more than the inbound flow at each DC. Constraints (6) and (7) use a big number, M , to guarantee that only when a potential DC is selected will there be an inbound and outbound logistic

flow associated with the DC. Constraints (8) and (9) ensure that the total number of selected DCs should follow some strategic requirement. Constraints (10) and (11) are for the non-negative and binary decision variables.

3.3. Model Solution

The ε -constraint method is used to solve the MOLP model; detailed principles of the method can be found elsewhere [8,43]. According to the ε -constraint method, the optimization progress of the two objectives is converted into optimizing the first objective (OF_1) while formulating the second objective (OF_2) as an additional constraint. In the CM (Converted Model), the formulation of the first objective (OF_1) and the original Constraints (3)–(11) are in accordance with IM. The second objective (OF_2) is converted into an additional constraint (Constraint (12)). Here, the left-hand side of the additional constraint (Constraint (12)) is equal to Constraint (2). Additionally, the right-hand side value of Equation (12) is ε , which represents the limit on the second objective (carbon emissions).

$$\begin{array}{ll}
 \text{CM:} & \min OF_1 \text{ (1)} \\
 \text{s.t.:} & \text{Constraints (3)–(11);} \\
 & \text{Additional constraint : } OF_2 \leq \varepsilon \qquad (12)
 \end{array}$$

A Pareto frontier that represents the correlation between the two objectives can be accordingly derived as shown in Figure 2. It is obtained by solving CM repeatedly for a set of instances. The initial instance (Instance 0) is generated by solving the objective value of OF_1 according to the CM without the additional constraint (Constraint (12)). Then, using the results, the second objective (OF_2)—carbon emissions of Instance 0—can be calculated and set as the highest value of ε . In order to generate a set of n instances, the value of ε is reduced progressively. Finally, by solving the CM with a set of $n + 1$ instances, the relationship of OF_1 and OF_2 can be obtained step by step; a Pareto frontier can then be obtained.

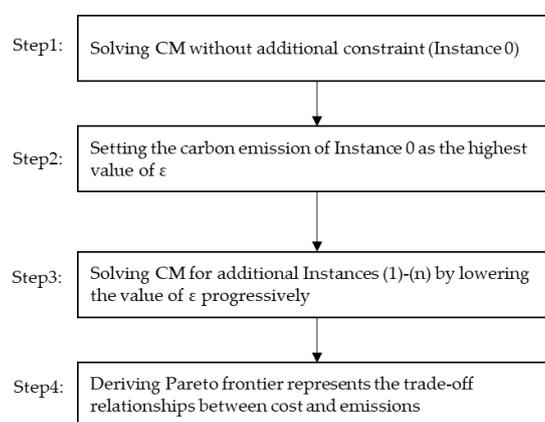


Figure 2. The steps for deriving the Pareto frontier. CM: converted model.

4. Numerical Experiments

4.1. Data Collection

We implement the proposed multi-objective linear programming model using reference examples derived from facts and reports on imported fresh-agri products in China. The overview of the whole network that covers ports, potential DCs, and retailers is presented in Figure 3.

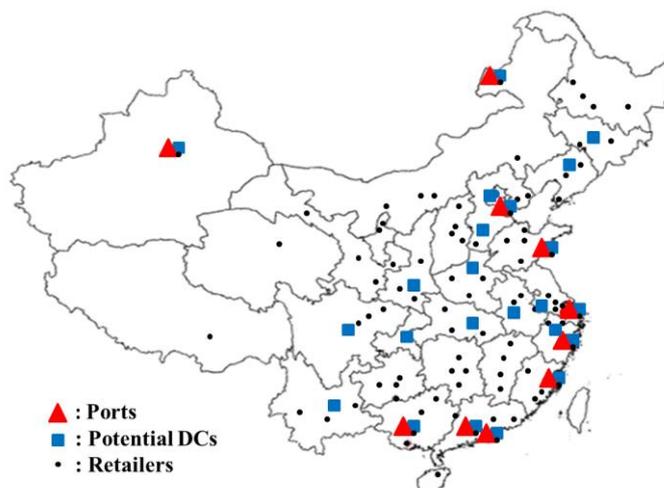


Figure 3. The logistics network of imported fresh agri-products in China.

Ports: As shown in Figure 3, 10 importing ports were selected according to the report by the 21st Century Institute of Economic Research [44]. In particular, under the development of Belt and Road, the port of Nanning in the southeast of China and ports of Urumqi and Manchuria adjacent to Europe were selected due to the increasing demand for products from middle-south Asia and Europe. Detailed information of the ports can be found in Table A1 in Appendix A.

DCs: Twenty-three potential distribution centers were selected from metropolises and capitals of provinces where transport is convenient and the demand is high. Detailed information of the potential distribution centers can be found in Table A2 in Appendix A.

Retailers: One hundred retailers representing cities where the imported fresh agri-products are sold in a large amount (according to the statistics by iresearch) were selected [45]. We list the selected cities in Table A3 in Appendix A.

Temperatures and Distances: We used the average annual temperatures to represent the overall temperature patterns of each city; the data were gathered from websites focusing on the weather in China [46]. As for the distance between two locations, the route distances between them were gathered according to the digital map provided by Baidu [47]. The details are listed in Tables A1–A3 in Appendix A.

Product Types: In the reference case, the most favorite agri-products were considered; these are grouped into two types, namely, fresh fruit and frozen food (such as frozen meat and frozen seafood). The storage temperatures for these two types of products were set as 0 °C and −18 °C, respectively [3,22].

Demand and Supply: The demand of each city and supply of each port are simulated by the following steps. According to demographic information [48], the cities are divided into three categories: big, medium, and small cities. For simplicity and without loss of generality, the demand of each city category is assumed to follow a uniform distribution. The distributions for each type of city are assumed to be $U(4,000,000, 5,000,000)$, $U(2,000,000, 3,000,000)$, and $U(500,000, 1,000,000)$, respectively. By summing all the demands together, the overall supply can be obtained. Then, by splitting the overall supply, the supply of each port can be determined. Here, the published throughput data of each port [49] were used as the weight for splitting the overall supply for each port. The details can be found in Tables A1 and A3 in Appendix A.

Carbon Emission Rate of Freight Transportation: The carbon emissions of transportation are caused by the consumption of fuel/energy [50]. According to the method presented by Defra [51,52], the emission rate e (kg CO₂/kg·km) can be calculated by Equation (13), where L refers to the liters

in fuel per kg·km (L/kg·km) and ε_f represents the fuel conversion factor (kg CO₂/L). Here, we use 2.63 kg CO₂/L for the fuel conversion factor [52].

$$e = L \times \varepsilon_f \quad (13)$$

The other required parameter for the formulation is the liters of fuel per kg·km of refrigerator trucks. Unfortunately, there is no direct data available. To determine this value, two parts of the fuel consumption were distinguished: (1) the fuel consumptions for the load and transport, L^v , and (2) the fuel consumptions for the refrigerator under the vehicle, L^r .

$$L = L^v + L^r \quad (14)$$

Generally speaking, the fuel consumption rates for inbound and outbound transportation are different because the inbound transportation is usually carried out by higher-payload vehicles [53]. Then, the data of fuel consumptions for load and transport published by Reference [5] were used to derive the fuel consumption for inbound and outbound transportation. As shown in Table 2, two types of vehicles—heavy goods vehicles with 24–40 tons and 12–24 tons of gross vehicle mass respectively (HGV-40, HGV-24)—were assumed to be used for inbound transport and outbound transport, respectively. Because the transportation is usually between cities, the vehicles are assumed to be with maximum payload. Then, the fuel consumption rates for the two transportations, L_{ij}^v and L_{jk}^v , are determined as 0.01427 L/ kg·km and 0.01958 L/ kg·km accordingly.

Table 2. The fuel consumption data [5]. HGV-40: heavy goods vehicles with 24–40 tons gross vehicle mass; HGV-24: heavy goods vehicles with 12–24 tons gross vehicle mass.

Vehicle Type	Fuel Consumption: Totally Loaded	Max. Payload
HGV-40	37.1 L/100 km	26 tons
HGV-24	23.5 L/100 km	12 tons

The fuel consumption rate of refrigerators is mainly affected by outdoor ambient temperature patterns and the set point of refrigerator temperatures. According to the model proposed by Reference [7], the fuel consumption of refrigerators is presented in Equation (15).

$$L^r = \frac{L_0^r}{COP} \quad (15)$$

Here, L_0^r is the base value of fuel consumption for a typical refrigerator in a reference scenario. *COP* is the coefficient of performance of refrigerators with respect to the outside ambient temperatures and the refrigeration temperatures. A higher ambient temperature or a lower refrigeration temperature will lead to a smaller COP, resulting in greater energy consumption. Wu et al. [7] also published a variation to the COP with the ambient temperature at the refrigeration temperatures of 0 °C and −18 °C for the typical refrigerator type, Carrier Xarios 600, R410A, as shown in Figure 4. Here, the base fuel consumption per unit weight per unit distance, L_0^r , is 3.6×10^{-6} L/kg·km. Based on the published data and Equation (15), we can derive the fuel consumption rate of a refrigerator at different ambient and refrigeration temperature conditions.

Cost Rate of Freight Transportation: In this research, the variable cost for the product transportation is considered as the fuel cost. Then, the unit cost of the inbound and outbound transportations is calculated by Equation (16), where L refers to the liters of fuel per kg·km (L/ kg·km) and θ_f represents the fuel price (yuan/L). The data of the price is obtained from the website of Oil

Price in China and set to be 6.2 yuan/L [54]. Combined with Equations (14) and (15), the unit costs of the inbound and outbound transportations, c_{iju} and c_{jku} , can be estimated.

$$c = L \times \theta_f \quad (16)$$

Carbon Emission Rate of DCs: The carbon emissions of a DC, E_j , are estimated as $f(T_j^D)$, a monotonically increasing function with respect to the average temperature [4,6]. Few comprehensive datasets exist to show warehouse emissions, while the general relationship between the ambient temperature and emissions will not change (that is, the linear, concave, or convex relationship) [12]. Similarly, with Equation (13), the carbon emission of a warehouse can be formulated as Equation (17). Here, P represents the energy consumed by the warehouse within a given period (for example, a year) and without loss of generality, the energy of the warehouse is provided by electricity. ε_e is the carbon emissions factor for the electrical supply. According to the IEA report [55], the emission factor for China is 0.766 kg CO₂/kWh.

$$E = P \times \varepsilon_e \quad (17)$$

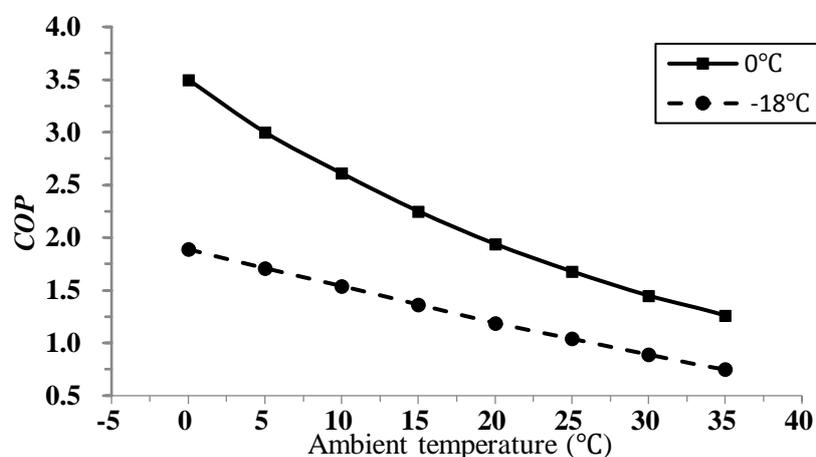


Figure 4. The coefficient of performance (COP) variation with the ambient temperature at two refrigeration temperatures [7]. (Xarios 600, R410A, $v = 21\text{--}70$ km/h).

Meneghetti and Monti [6] investigated the energy consumption of refrigerated warehouses at different places with different ambient temperature patterns. According to the published data by Reference [6], a linear function is used to approximate P as $a(T_j^R) + b$ and the values of a and b are set as 2066.6 and 726,074.5, respectively.

Cost of DCs. The cost of DCs comprises the fixed cost for maintaining DCs and the variable cost for energy use. In reality, the fixed cost can hardly be found; thus, we approximated it as 1,000,000,000 yuan. For the energy cost, we calculated the amount of consumed electricity, P , as a multiple of the electricity price. Through the website of the National Energy Administration, we established that the price is 1.2 yuan/kWh [56].

A summary of the values of the parameters related to the cost and emissions is presented in Table A4 in Appendix A.

4.2. Analysis and Discussion

4.2.1. Solutions of the Two Base Scenarios with a Single Objective

The MOLP model was solved by the Cplex optimization solver. Two base scenarios with a single objective were defined as the lowest cost (LC) and lowest emission (LE). The summary of the results of the LC and LE cases is shown in Table 3 and the overall locations of DCs are presented in Figure 5a,b

respectively. So as to not complicate the figure, the ports and transportation flow through ports to DCs are not shown. Through a quick comparison between LC and LE, the change of cost and emissions can be observed. The items for the cost and emissions are classified into three parts: inbound transportation, outbound transportation, and DC maintenance. The results show that the cost and emission items for inbound transportation and DCs are increasing in the LE case, while that of outbound transportation changes in the opposite way. However, the decreased emission for outbound transportation exceeds the increased amount of the inbound transportation and DCs. Thus, the overall emission of LE is the lowest. This is mainly because the total number of distribution centers under LE is much higher than that under LC. An increase in the DC numbers will shorten the distance from DCs to retailers sharply, which will decrease the correlated outbound transportation costs and emission. The results suggest that a distributed structure of the network is more conducive to reducing carbon emissions.

Table 3. Summary results of two base cases.

	LC (Lowest Cost)	LE (Lowest Emission)
Transportation Cost (Yuan)		
Inbound Transportation	1.25×10^{10}	1.94×10^{10}
Outbound Transportation	2.78×10^{10}	1.74×10^{10}
Cost of DCs	1.10×10^{10}	2.20×10^{10}
Total	5.13×10^{10}	5.88×10^{10}
Carbon emission (kg CO ₂)		
Inbound Transportation	5.19×10^9	7.30×10^9
Outbound Transportation	1.12×10^{10}	7.01×10^9
Emission of DCs	6.37×10^8	1.20×10^9
Total	1.70×10^{10}	1.55×10^{10}
General		
Number of DCs	11	22

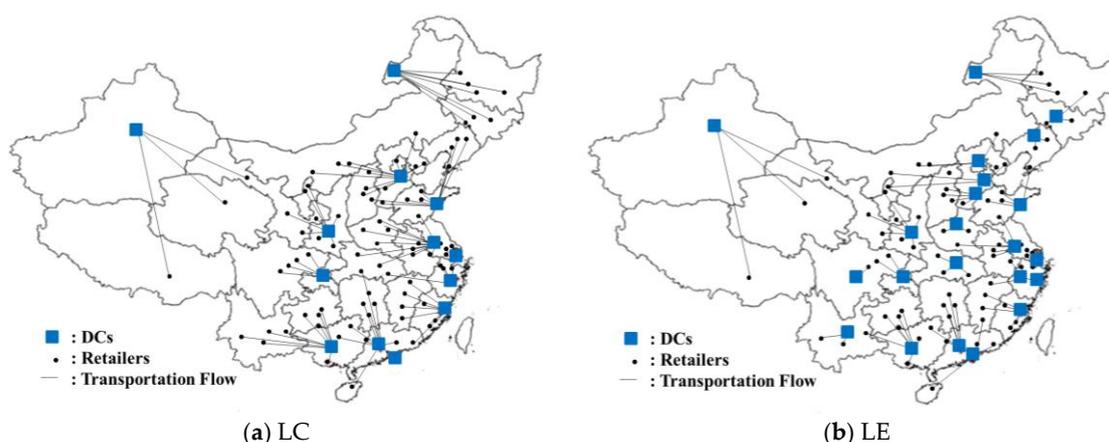


Figure 5. The locations of DCs for the two base cases.

4.2.2. The Trade-Offs between the Two Objectives

In our problem, due to different locations of the DCs, trade-offs occur between the inbound transportation, outbound transportation, and DC maintenance. According to the base cases, 10 additional instances are generated by lowering the ϵ value from the highest emission level (emission of LC) to the lowest one (emission of LE) with an even interval. The trade-off between costs and emissions is shown in the derived Pareto frontier in Figure 6. The ends of the curve denote the cost and emission levels of the two base scenarios. The 10 additional scenarios are present on the curve. The shape of the Pareto frontier clearly shows that it costs more to get on the same portion of emission

reduction. The cost and emission structure of each scenario and the features of their DCs are presented in Figure 7 and Table 4. The findings are as follows:

- (1) The main reason for emission reduction on the cold chain is because of the increase of DC numbers. When more DCs are selected, the distance of outbound transportation will sharply drop. Then, the emission items related to outbound transportation will decrease, which can compensate for the emission increase related to inbound transportation and DC maintenance.
- (2) By carefully comparing the average temperature of each DC as shown in Table 4, we can see that when the number of DCs is increased, the average temperatures of DCs increase accordingly. Meanwhile, when the number of DCs stays equal—for example, in Scenarios 3, 4, and 5—the average temperature declines, which can, in turn, reduce the overall carbon emissions. This explains the decline on the Pareto frontier at the Scenario 3 point. The number of DCs increases at a rate of 2 for Scenarios 1, 2, 3, and the LC scenario. Meanwhile, the number stays stable for Scenario 4. This means that the emission reductions of outbound transportation cannot cover the emission increase caused by opening a DC. Consequently, an emission reduction can be obtained by moving DCs to lower-temperature places, which consequently increases the transportation cost.
- (3) The cost and emissions for inbound transportation and DC maintenance are positively related to the number of DCs, while the effect on outbound transportation is exactly the same in the opposite way. Moreover, the carbon emissions caused by transportation account for the largest share of the total emissions. This provides an important direction for the control of carbon emissions in cold supply chains.

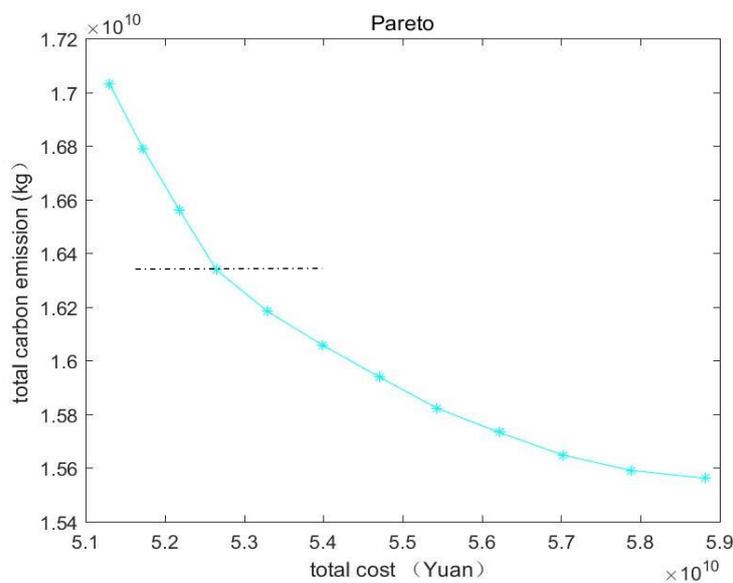


Figure 6. The trade-offs between the total cost and carbon emissions.

Table 4. Number and the average temperature of DCs of each scenario on the Pareto frontier in Figure 6.

Scenarios	LC	1	2	3	4	5	6	7	8	9	10	LE
No. of DCs	11	13	15	17	17	17	18	18	19	20	21	22
Average °C of DCs	7.20	9.03	10.03	11.34	11.01	10.67	12.00	11.58	12.38	13.09	13.88	14.48

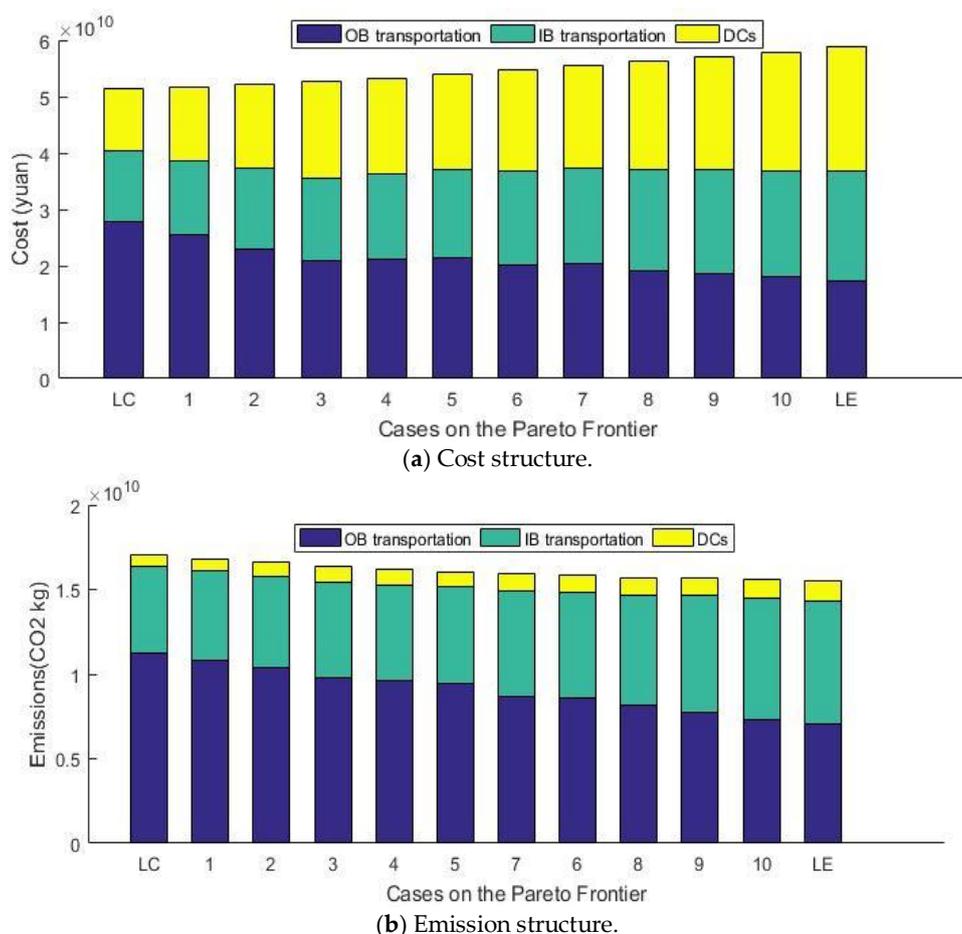


Figure 7. The cost and emission structure of each scenario on the Pareto frontier in Figure 6. IB: inbound; OB: outbound.

5. Conclusions

In this study, we present a MOLP model for the green cold chain design problem for imported fresh agri-products in China. The distinguishing features of the proposed model lie in three aspects: (1) effects of outdoor ambient temperatures on emissions are considered; (2) the model can be applied to multiple highly perishable products required for different set-point temperatures; (3) it can cope with two competing goals—minimizing the total cost and carbon emissions. The model can aid strategic decisions on where distribution centers need to be located and how many of them are needed along with a cold chain, as well as support operational decisions on which route to choose in complicated networks. This model will have important applications in cold chain network design for perishable products under green considerations.

The MOLP model was solved using the ϵ -constraint method and verified by numerical experiments inspired by operating cases of imported fresh agri-products under the development of Belt and Road in China. The Pareto frontier represents the trade-off between the cost and emissions that has been obtained. Managerial insights can be derived from improving sustainability of the cold chain network. For example, how much additional cost would the company like to pay in order to reduce the emission level? Is there a need for the government to provide subsidies for sustainable cold chain design? The results obtained from the numerical analysis indicate that there are two main reasons for carbon emissions in the cold chain. The first one is the number of DCs, which can reduce emissions by shortening the travel distances between DCs and retailers. The average temperatures give another way of reducing emissions by moving DCs to cooler places to save on energy use.

The computational experiments also show that emissions in transportation are a major part of the total emissions. It is appropriate to construct a cold chain with a distributed structure to reduce the transportation emissions. The method of enhancing the energy efficiency during transportation is important for controlling the emission level in green cold chain management.

There are several proposed future research areas that are extensions of the proposed method. Firstly, how to use the day-to-day temperature data instead of the average annual temperature for the decision-making is a direction to investigate in order to improve the precision of the proposed model. Secondly, the market of the imported fresh agri-products will have a lot of uncertainties because of customer preference for new products or market competition. How to design a flexible and sustainable cold chain would be an interesting research area as well. We leave this for future work.

Author Contributions: Y.F. and L.S. conceived the research idea and developed the model. Y.J. implemented and solved the model, while X.H. collected the data and presents the results. All four authors contributed to the writing and revising the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix

Table A1. The supply and temperatures of ports.

Ports	Manzhouli	Urumqi	Qingdao	Tianjin	Ningbo	Shanghai	Fuzhou
AAT (°C)	−1.2	8.4	12.3	13.8	16.6	17.6	21
Supply of Fruit (ton)	8000	10,000	32,000	26,000	52,000	47,000	23,000
Supply of Frozen Product (ton)	18,000	15,000	29,000	20,000	49,000	45,000	24,000
Ports	Guangzhou	Nanning	Shenzhen				
AAT (°C)	21.9	22.3	22.5				
Supply of Fruit (ton)	36,000	18,000	33,000				
Supply of Frozen Product (ton)	32,000	12,000	35,000				

AAT: Average annual temperature; Sources: <http://www.weather.com.cn> [46].

Table A2. The temperature of potential DCs.

Potential DCs	Manzhouli	Changchun	Urumqi	Shenyang	Qingdao	Beijing	Tianjin
AAT (°C)	−1.2	6.6	8.4	8.8	12.3	13.8	13.8
Potential DCs	Shijiazhuang	Kunming	Nanjing	Xi'an	Zhengzhou	Ningbo	Chengdu
AAT (°C)	14.6	15.0	15.1	15.8	16.4	16.6	16.8
Potential DCs	Hefei	Wuhan	Shanghai	Hangzhou	Chongqing	Fuzhou	Guangzhou
AAT (°C)	17.0	17.3	17.6	18.2	19.5	21.0	21.9
Potential DCs	Nanning	Shenzhen					
AAT (°C)	22.3	22.5					

AAT: Average annual temperature; Sources: <http://www.weather.com.cn> [46].

Table A3. The temperatures and demand of retailers.

Retailers	Manzhouli	Jiamusi	Qiqihar	Chifeng	Harbin	Jilin	Daqing
AAT (°C)	−1.2	3.0	3.2	3.5	3.5	3.9	4.2
Demand of Fruit (ton)	2511	2524	1009	2042	1578	1025	2196
Demand of Frozen Product (ton)	1674	1803	1442	1856	3155	1025	1464
Retailers	Hohhot	Siping	Datong	Changchun	Fushun	Jiuquan	Zhangzhou
AAT (°C)	4.3	5.9	6.4	6.6	6.6	6.6	6.7
Demand of Fruit (ton)	1033	2363	2369	3483	1312	2015	1505
Demand of Frozen Product (ton)	1475	1969	1974	3166	1312	1832	1505
Retailers	Baotou	Lhasa	Urumqi	Yinchuan	Anshan	Shizuishan	Shenyang
AAT (°C)	7.2	7.4	8.4	8.5	8.5	8.6	8.8
Demand of Fruit (ton)	2240	1766	1896	2449	1062	1354	2215
Demand of Frozen Product (ton)	1493	1766	1264	3061	1327	1504	3691
Retailers	Pingliang	Yan'an	Taiyuan	Wuhai	Qinhuangdao	Yangquan	Lanzhou
AAT (°C)	9.0	9.1	9.5	9.6	10.0	10.0	10.3
Demand of Fruit (ton)	1959	1122	4036	989	1422	2209	3830
Demand of Frozen Product (ton)	1306	1603	3363	1977	1580	1699	3482
Retailers	Dalian	Tongchuan	Tianshui	Xianyang	Qingdao	Tangshan	Kaifeng
AAT (°C)	10.5	10.6	11.0	11.1	12.3	12.5	12.5
Demand of Fruit (ton)	3020	2513	864	1952	4763	923	1216
Demand of Frozen Product (ton)	3020	1933	1440	1627	3664	1846	1216
Retailers	Dongying	Zibo	Liupanshui	Beijing	Tianjin	Jinan	Handan
AAT (°C)	12.8	13.3	13.5	13.8	13.8	13.8	14.0
Demand of Fruit (ton)	1579	1686	1683	4490	3636	4190	2356
Demand of Frozen Product (ton)	1435	1297	1870	7484	7271	3809	1812
Retailers	Anshun	Zaozhuang	Qijing	Luoyang	Shijiazhuang	Huzhou	Luohe
AAT (°C)	14.0	14.5	14.5	14.5	14.6	14.7	14.7
Demand of Fruit (ton)	1123	1817	1543	1554	1841	3951	2258
Demand of Frozen Product (ton)	1871	1817	1102	1036	3069	3592	1882
Retailers	Kunming	Nanjing	Bengbu	Zunyi	Guiyang	Changzhou	Wuhu
AAT (°C)	15.0	15.1	15.1	15.1	15.3	15.5	15.5
Demand of Fruit (ton)	2971	2494	2064	1216	3934	3991	2297
Demand of Frozen Product (ton)	3301	3563	1474	1216	3278	3070	1641
Retailers	Baoshan	Zhenjiang	Suzhou	Xi'an	Jiaxing	Mianyang	Deyang
AAT (°C)	15.5	15.6	15.7	15.8	15.9	16.0	16.0
Demand of Fruit (ton)	727	4371	3548	5298	2694	822	1735
Demand of Frozen Product (ton)	1212	3362	3225	3784	3367	1643	1446
Retailers	Fuyang	Guangyuan	Xiangtan	Wuxi	Zhengzhou	Huainan	Jiujiang
AAT (°C)	16.0	16.1	16.1	16.2	16.4	16.5	16.5
Demand of Fruit (ton)	1262	1681	1980	4801	2484	2016	1229
Demand of Frozen Product (ton)	1578	1681	1320	3693	3105	1440	1229
Retailers	Ningbo	Chengdu	Yichang	Hefei	Zhuzhou	Huang Shi	Changsha
AAT (°C)	16.6	16.8	16.9	17.0	17.0	17.0	17.2
Demand of Fruit (ton)	10910	10445	1250	1824	1678	1798	11,634
Demand of Frozen Product (ton)	7793	7461	1389	3648	1291	1798	7756
Retailers	Wuhan	Nanchang	Shanghai	Hengyang	Hangzhou	Sanming	Ji'an
AAT (°C)	17.3	17.4	17.6	18.0	18.2	18.2	18.5
Demand of Fruit (ton)	6421	4719	4225	1128	7858	2209	1732
Demand of Frozen Product (ton)	7134	3146	7041	1611	7858	1699	1924
Retailers	Liuzhou	Ganzhou	Guilin	Chongqing	Yuxi	Shantou	Quanzhou
AAT (°C)	18.8	18.8	19.3	19.5	19.8	20.0	20.2
Demand of Fruit (ton)	974	1495	4565	5977	1882	5179	1547
Demand of Frozen Product (ton)	1218	1359	3804	7471	1568	3984	1547
Retailers	Fuzhou	Xiamen	Zhangzhou	Guangzhou	Huizhou	Nanning	Shenzhen
AAT (°C)	21.0	21.0	21.4	21.9	22.0	22.3	22.5
Demand of Fruit (ton)	3108	4938	520	10,641	2256	2775	4490
Demand of Frozen Product (ton)	3453	3292	1039	7601	1880	3469	7483
Retailers	North Sea	Haikou					
AAT (°C)	22.9	24.2					
Demand of Fruit (ton)	2100	1443					
Demand of Frozen Product (ton)	1750	1443					

AAT: Average annual temperature; Sources: <http://www.weather.com.cn> [46], <https://map.baidu.com/> [47].

Table A4. Summary of values or estimations of parameters related to cost and emissions.

Parameters	Values/Estimations	Sources
Fuel conversion factor	2.63 kg CO ₂ /L	https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69568/pb13792-emission-factor-methodologypaper-120706.pdf [52]
Fuel consumption rate for inbound transportation	0.01427 L/kg·km	Kellner and Igl (2015) [5]
Fuel consumption rate for outbound transportation	0.01958 L/kg·km	Kellner and Igl (2015) [5]
Base value of fuel consumption of refrigerators	3.6×10^{-6} L/kg·km	Wu et al. (2013) [7]
Coefficient of performance of refrigerators	Data according to Figure 4	Wu et al. (2013) [7]
Fuel price	6.2 yuan/L [54]	http://youjia.chemcp.com [54]
Emission factor of electricity	0.766 kg CO ₂ /kWh	http://www.iea.org/publications/freepublications/publication/name,32870,en.html [55]
Fixed cost for maintaining DCs	1,000,000,000 yuan	Assumption
Electricity price	1.2 yuan/kWh	http://www.nea.gov.cn/ [56]

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