

Article

Cold Chain Logistics Network Design for Fresh Agricultural Products with Government Subsidy

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Abstract: This paper investigates the cold chain logistics network design in the first mile for fresh agricultural products with government subsidy, involving the capacity, location of cold storage facilities, and transportation from production areas to cold storage facilities after harvest. A bi-level programming model is formulated considering the quality degradation of fresh agricultural products. Based on the proposition and KKT conditions, a solution method is designed for reformulating the bi-level model into a single-level programming model. Numerical experiments are conducted to verify the proposed model. Experimental results show that the solution method efficiently solves the problem of the cold chain logistics network design for fresh agricultural products with subsidy, and sensitivity analysis provides managerial insights for decision-makers.

Keywords: bi-level model; cold chain logistics; fresh agricultural products



Citation: Zhu, H.; Liu, C.; Wu, G.; Gao, Y. Cold Chain Logistics Network Design for Fresh Agricultural Products with Government Subsidy. *Sustainability* **2023**, *15*, 10021. <https://doi.org/10.3390/su151310021>

Academic Editor: Giacomo Falcone

Received: 28 April 2023

Revised: 21 June 2023

Accepted: 22 June 2023

Published: 25 June 2023



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1. Introduction

With the development of the economy and the increase in income, residents' consumption level is rising. Along with upgrading the consumption structure and expanding the consumption scale, people are paying more and more attention to the safety and freshness of food. Fresh agricultural products, such as fruits and vegetables, are perishable foods commonly consumed daily [1]. The quality and performance of fresh agricultural products can be maintained within a specific temperature range by cold chain logistics consisting of precooling treatment, cold storage, transportation, processing, and distribution from the point of origin to the final destination. Moreover, the Internet and E-commerce also have increased the demand for high-quality fresh products, implying that the demand for cold chain logistics is vast and growing [2]. According to the China statistics yearbook data, in 2021, the production volumes of vegetables and fruits in China were 775.5 million and 299.7 million tonnes, respectively.

However, cold chain logistics are still inadequate for fresh agricultural products in China. Only 10–20% of fresh agricultural products are transported through cold chain logistics [3]. In order to meet the demand for the quantity and quality of fresh agricultural products, cold chain logistics in China has been developed quickly in recent years, especially since the “14th Five-Year Plan for Cold Chain Logistics Development” was issued in 2021. Nevertheless, the loss rate of fresh agricultural products in China is 15–30% with a low profit margin of 8%, while the loss rate in developed countries is less than 5% with a high profit margin of 20–30% [4]. Therefore, it is urgent to optimize the design of the cold chain logistics network for fresh agricultural products to reduce the cost of cold chain logistics and ensure the quality of products [5].

To prolong the shelf-life and maintain the quality, fresh agricultural products should be transported and put into cold storage facilities soon after harvest for precooling or storage. Cold storage facilities are critical to reducing post-harvest losses and can be regarded as an important component that should be integrated into the cold chain logistics network from the point of harvest [4]. Note that last-mile logistics represents the final stage of the supply chain concerning the delivery of products to the customer. In contrast, first-mile logistics refers to the first stage of the supply chain, involving collecting products from the origin to the warehouse or distribution center. Accordingly, we investigate cold chain logistics network design from the perspective of the first mile, involving the integration of transportation and cold storage facility location.

Plenty of producers of fresh agricultural products are smallholder farmers located in dispersed positions [6]. Cold chain logistics services for farmers are generally provided by third-party logistics enterprises. Government regulations and financial policies are critical factors in developing a cold chain logistics network, which will encourage enterprises to build cold chain logistics infrastructure. Thus, with this motivation, the optimization of cold chain logistics network design for fresh agricultural products is explored under government regulations.

Many studies have focused on logistics network design, which involves making decisions regarding the number, capacity, and location of facilities, the allocation of products, and transportation in the network [7]. Tadaros and Migdalas [8] conducted a comprehensive review of location-routing problems regarding multi-objective optimization. Schiffer et al. [9] presented an overview of location routing and vehicle routing problems. Additionally, from an integrated perspective, Jalal et al. [10] provided a systematic literature review of integrated problems for logistics network planning from different hierarchical decision levels, i.e., strategic, tactical, and operational levels. Zhang et al. [11] developed a review on reverse logistics network design.

Recently, there has been growing interest in cold chain logistics network design. Han et al. [4] proposed a survey of cold chain logistics for fresh agricultural products and discussed the current status, challenges, and future trends. Leng et al. [12] addressed the location-routing problem for cold chain logistics with a bi-objective model. Fang et al. [13] considered sustainable cold chain networks for imported fresh agricultural products. Singh et al. [14] introduced a cold chain configuration for perishable products formulated as a location-allocation problem. Andoh and Yu [15] explored a two-stage approach for sustainable cold chain logistics planning in the last mile. Leng et al. [16] investigated a low-carbon location-routing problem for cold chain logistics.

The previous research has concentrated on the cold chain logistics network in the last mile. However, few studies attempt to optimize the network design for cold-chain logistics in the first mile. Liang et al. [17] considered a cold chain logistics network for fresh agricultural products, including pre-cooling facility location and transportation from the production area to the pre-cooling facility. The total construction and operation costs are taken as the objective of the proposed model. Liang X. et al. [18] developed a location problem of origin-based cold storage under fresh E-commerce.

Due to the perishable nature of fresh agricultural products, the quality of products degrades seriously during the transportation stage, especially after harvest. Although considerable research has been devoted to the cost of logistics networks, relatively less attention has been paid to the quality degradation of fresh agricultural products. Chen et al. [19] investigated the urban delivery problem of fresh products with total deterioration value. The quality deterioration equations for two types of fresh products were proposed. Furthermore, few researchers have studied cold chain logistics network design, including quality degradation. Rong et al. [20] presented an optimization model for food production and distribution with fresh food quality throughout the supply chain. Similarly, two equations are provided to estimate the quality level of products for zero-order and first-order reactions. Golestani et al. [21] considered a bi-objective location problem for perishable products in the cold supply chain to minimize the total cost and maximize the

quality of products. Thus, we considered the total cost of cold chain logistics and the quality deterioration of fresh agricultural products in the cold chain logistics network.

To strengthen the construction of cold chain logistics infrastructure, the Chinese government has provided subsidies and created financial policies to support cold chain logistics enterprises in recent years. However, these measures rarely considered the impact on the cold chain logistics network of the government subsidy rate. Zhang et al. [22] established a decision-making model of regional cold chain logistics systems through the joint use of government subsidies and carbon emissions trading. Lu et al. [23] optimized a railway cold chain logistics network with freight subsidy.

However, the location of cold storage facilities in logistics network design is a strategic decision with long-term effects, whereas transportation planning and routing problems are tactical/operational decisions. Bi-level programming is widely used for solving the two levels hierarchy decisions making problems [24,25]. Zhang et al. [26] formulated a bi-level programming model of the location problem of distribution centers for urban cold chain logistics.

Therefore, the main contributions of this paper are summarized as follows. First, we investigate the optimization problem of cold chain logistics network design in the first mile with government subsidy, involving the location of cold storage facilities and the transportation of fresh agricultural products from farms to cold storage facilities after harvest. Second, combining strategic decisions and tactical/operational decisions, we present a bi-level programming model, where the objective of the upper level is to minimize the total cost of cold chain logistics, and the objective of the lower level is to maximize the total quality of fresh agricultural products. Third, we reformulate the bi-level programming model into a single-level mathematical model through the proposed proposition and KKT conditions.

The rest of the paper is organized as follows. Section 2 presents a bi-level programming model of cold chain logistics network design for fresh agricultural products with government subsidy. Section 3 designs a solution method. In Section 4, we present the results of numerical experiments. Section 5 concludes the paper.

2. Mathematical Model

We describe the problem as follows. There are two important participants in the cold chain logistics system for fresh agricultural products, the third-party cold chain logistics enterprise as the cold chain logistics service provider and the farmer as the cold chain logistics service user. In the first-mile logistics network, the fresh agricultural products widely dispersed in various production areas have a short shelf life. To reduce the quality loss, fresh agricultural products must be collected from different production areas and transported to cold storage facilities soon after harvest. From the perspective of management levels, the cold chain logistics enterprise is the decision-maker at the strategic decision level, which determines the capacity and location of cold storage facilities by minimizing the total construction and operation cost. The government subsidy is considered for supporting the development of cold storage facilities. In terms of government subsidies, they are related to the capacity and type of cold storage facilities. At the tactical/operational decision level, the decision-maker is the farmer, who selects the logistics service facilities and determines the transportation planning by optimizing the quality value of fresh agricultural products.

2.1. Model Assumptions

To facilitate the modeling, the assumptions are as follows:

- (1) The locations of the production areas and candidate cold storage facilities are predetermined.
- (2) The production capacities of the production areas and the cold storage capacity of each type are predetermined.
- (3) Without loss of generality, we assume that the production capacity of production areas, the capacity of cold storage, and the transportation time are integers.

- (4) All the fresh agricultural products are packaged in vent boxes with a specific capacity for transportation and storage. Here, we use a box as a unit term to measure the amount of fresh agricultural products. Thus, we also assume that the construction, operation, and subsidy costs should be expressed per unit, measured in boxes.
- (5) The distance from the production area and cold storage facility is predetermined.
- (6) For convenience, we define the quality level, service fairness level, and degradation rate of fresh agricultural products as q_0 and α per thousand, respectively, where q_0 and α are integers.
- (7) We only focus on the quality loss of fresh agricultural products and neglect the quantity loss.

2.2. Notations

The notations are stated in Table 1.

Table 1. Notations.

Sets:	
J	set of production areas
I	set of candidate cold storage facilities
L	set of cold storage types
Parameters:	
d_{ji}	distance between production area j and cold storage facility i
p	number of selected cold storage facilities
s_j	production capacity of production area j
C_l	capacity of cold storage with type l
t_{ji}	transportation time from production area j to cold storage facility i
F_l	fixed construction cost per unit for setting up a cold storage facility with type l
O_l	fixed operating cost per unit for maintaining a cold storage facility with type l
V_i	variable operating cost of storage per production unit at cold storage facility i
S_l	subsidy per unit for setting up a cold storage facility with type l
α	degradation rate of fresh agricultural products in the transportation phase per thousand
q_0	initial quality level of fresh agricultural products per thousand
t	transportation time interval
q_t	quality degradation of fresh agricultural products during time t
Q_t	quality level of fresh agricultural products in the logistics network with transportation time interval t
M	large positive constant
Decision variables:	
y_{il}	1, if cold storage facility i is selected to be built 0, otherwise
x_{ji}	amount of fresh agricultural products transported from production area j to cold storage facility i

2.3. Bi-Level Formulation of Cold Chain Logistics Network Design in the First Mile for Fresh Agricultural Products with Government Subsidy

In this section, we begin with a brief description of quality degradation for fresh agricultural products. According to the perishability nature, the quality degradation of fresh agricultural products, e.g., fresh fruits and vegetables, follows the zero-order linear reaction [20]. The quality degradation expression can be written in the following form:

$$q(t) = \alpha t, \quad (1)$$

where $q(t)$ is the quality degradation of fresh agricultural products in the logistics network, t is the transportation time interval and α is the degradation rate.

The quality level of fresh agricultural products can be calculated by the following equation:

$$Q(t) = x(q_0 - \alpha t), \quad (2)$$

where $Q(t)$ is the quality level of fresh agricultural products in the logistics network with transportation time interval t , the amount of fresh agricultural products x , and the degradation rate α .

As mentioned above, there are two levels of decisions in the cold chain logistics network design for fresh agricultural products: strategic decisions and tactical/operational decisions. In order to model the proposed problem, bi-level programming is adopted in this paper. Hence, the strategic decisions level is regarded as the upper level of the mathematical model, whereas the tactical/operational decisions level is recognized as the lower level. As the leader, the decision-maker of the upper level (cold chain logistics enterprise) decides the location and capacity of cold storage facilities under the government subsidy policy through the variables y_{il} . Based on these decisions, the decision-maker (as the follower) of the lower level (customer) reacts and chooses the cold chain logistics service facilities and makes the transportation plan with variables x_{ji} . Then the leader makes the optimal decisions based on the solutions of the follower.

With the assumptions and notations defined in the previous section, the bi-level programming model of cold chain logistics network design in the first mile for fresh agricultural products with government subsidy can be stated as follows.

Upper-level model (UM):

$$\text{minimize } f_1 = \sum_{i \in I} \sum_{l \in L} F_l C_l y_{il} + \sum_{i \in I} \sum_{l \in L} O_l C_l y_{il} + \sum_{i \in I} V_i \sum_{j \in J} x_{ji} - \sum_{i \in I} \sum_{l \in L} S_l C_l y_{il} \quad (3)$$

subject to

$$\sum_{i \in I} \sum_{l \in L} y_{il} \leq p \quad (4)$$

$$\sum_{l \in L} y_{il} \leq 1, i \in I \quad (5)$$

$$\sum_{i \in I} \sum_{l \in L} F_l C_l y_{il} \leq F \quad (6)$$

$$y_{il} \in \{0, 1\}, i \in I, l \in L \quad (7)$$

The upper model's objective function (3) is to minimize the total cost of designing a cold chain logistics network. The first term of the objective function implies the fixed cost for setting up cold storage facilities, while the second and third terms are the fixed and variable operating costs for maintaining cold storage facilities, respectively. The fourth term represents the subsidy for opening cold storage facilities. Constraint (4) means that no more than p cold storage facilities are selected to be built. Constraint (5) imposes that only one type is selected for each open cold storage facility, and no type is selected for non-open cold storage facilities. Constraint (6) guarantees that the total investment of fixed cost for setting up cold storage facilities is no more than F . Constraint (7) is a binary restriction of y_{il} -variables.

Lower level model (LM):

$$\text{maximize } f_2 = \sum_{i \in I} \sum_{j \in J} x_{ji} (q_0 - \alpha t_{ji}) \quad (8)$$

subject to

$$\sum_{i \in I} x_{ji} = s_j, j \in J \quad (9)$$

$$\sum_{j \in J} x_{ji} \leq \sum_{l \in L} y_{il} C_l, i \in I \quad (10)$$

$$x_{ji} \geq 0, x_{ji} \in \mathbb{Z}, j \in J, i \in I \quad (11)$$

The objective function (8) of the lower-level model maximizes the total quality of fresh agricultural products. Constraint (9) stipulates that the total amount of fresh agricultural product from each production site equals its production capacity. Constraint (10) provides two effects: (1) it guarantees that the production capacity of each site is not violated, and (2) it enforces that the fresh agricultural product only can be transported to open cold storage facilities. Constraint (11) defines the domain of decision variables.

3. Solution Method

In this section, we develop a solution method to reformulate the bi-level programming model into a single-level model. The outline of the method is stated as follows: First, we relax the lower level model and prove the equivalence between the lower level and the relaxed problem. Then Karush-Kuhn-Tucker (KKT) conditions and dual theory are used to transform the bi-level optimization problem into a single-level nonlinear programming problem. Finally, we linearize the nonlinear constraints.

For convenience, we denote the relaxed lower level model by relaxed UM when the domain for the x_{ji} variables is replaced by its continuous relaxation, i.e., the integrality of decision variables of the lower level model is relaxed to

$$x_{ji} \geq 0, j \in J, i \in I. \quad (12)$$

In what follows, we state the proposition that the property for the lower-level model.

Proposition 1. *There are integral optimal solutions to the relaxed UM.*

Proof. It is clear that the constraint matrix of relaxed UM is totally unimodular [27]. Moreover, the right-hand side of constraints in the relaxed UM is an integer vector. By Hoffman and Kruskal theorem, we have that polyhedron {Constraints (9), (10) and (12)} is integral. From the model assumptions, it is easily seen that the coefficients of the objective are integers. Hence, we can conclude that the relaxed UM and its dual problem both have optimal integral solutions [28]. Then the result follows. $\square$

Proposition 1 implies that we solve the lower level model by relaxed UM, which relaxes the x_{ji} variables to be continuous. Thus, the solutions do not change.

The dual problem of the relaxed UM is presented in the following:

$$\text{minimize } \sum_{j \in J} s_j u_j + \sum_{i \in I} \left(\sum_{l \in L} y_{il} C_l \right) v_i \quad (13)$$

subject to

$$u_j + v_i \geq q_0 - \alpha t_{ji}, j \in J, i \in I \quad (14)$$

$$u_j \leq URS, j \in J \quad (15)$$

$$v_i \geq 0, i \in I \quad (16)$$

where u_j is the dual variable of Constraint (9), and v_i is the dual variable of Constraint (10).

Since the relaxed UM is linear, its KKT optimality conditions can replace the lower-level model. The bi-level programming problem of cold chain logistics network design for fresh agricultural products is transformed into the following equivalent single-level nonlinear programming problem:

$$\text{minimize } \sum_{i \in I} \sum_{l \in L} F_l C_l y_{il} + \sum_{i \in I} \sum_{l \in L} O_l C_l y_{il} + \sum_{i \in I} V_i \sum_{j \in J} x_{ji} - \sum_{i \in I} \sum_{l \in L} S_l C_l y_{il} \quad (17)$$

subject to

$$\sum_{i \in I} \sum_{l \in L} y_{il} \leq p \quad (18)$$

$$\sum_{l \in L} y_{il} \leq 1, i \in I \quad (19)$$

$$\sum_{i \in I} \sum_{l \in L} F_l C_l y_{il} \leq F \quad (20)$$

$$\sum_{i \in I} x_{ji} = s_j, j \in J \quad (21)$$

$$\sum_{j \in J} x_{ji} \leq \sum_{l \in L} y_{il} C_l, i \in I \quad (22)$$

$$u_j + v_i \geq q_0 - \alpha t_{ji}, j \in J, i \in I \quad (23)$$

$$v_i \left(\sum_{j \in J} x_{ji} - \sum_{l \in L} y_{il} C_l \right) = 0, i \in I \quad (24)$$

$$x_{ji} (u_j + v_i - q_0 + \alpha t_{ji}) = 0, j \in J, i \in I \quad (25)$$

$$y_{il} \in \{0, 1\}, i \in I, l \in L \quad (26)$$

$$x_{ji} \geq 0, j \in J, i \in I \quad (27)$$

$$u_j \leq URS, j \in J \quad (28)$$

$$v_i \geq 0, i \in I \quad (29)$$

In the above formulation, Equation (17) is the objective function of the equivalent single-level nonlinear programming model of cold chain logistics network design for fresh agricultural products. Constraints (18)–(20) and (26) are the constraints of the upper-level model of cold chain logistics network design for fresh agricultural products. Constraints (21), (22) and (27) guarantee the primal feasibility of the relaxed UM. Constraints (23), (28) and (29) provide the dual feasibility of the relaxed UM. Constraints (24) and (25) present the complementary slackness conditions of KKT.

Since the complementary condition in the transformed model is nonlinear, we linearize Equations (24) and (25) in the following. Define δ_i and θ_{ji} as auxiliary binary variables, and let M be a large positive constant.

Therefore, Equation (24) can be replaced by two constraints as follows:

$$v_i \leq M\delta_i, i \in I \quad (30)$$

$$\sum_{l \in L} y_{il} C_l - \sum_{j \in J} x_{ji} \leq M(1 - \delta_i), i \in I \quad (31)$$

Similarly, Equation (25) can be equivalently written as follows:

$$x_{ji} \leq M\theta_{ji}, j \in J, i \in I \quad (32)$$

$$u_j + v_i - (q_0 - \alpha t_{ji}) \leq M(1 - \theta_{ji}), j \in J, i \in I \quad (33)$$

As a result, the final transformed single-level programming model of cold chain logistics network design for fresh agricultural products is provided as follows:

$$\text{Minimize } \sum_{i \in I} \sum_{l \in L} F_l C_l y_{il} + \sum_{i \in I} \sum_{l \in L} O_l C_l y_{il} + \sum_{i \in I} V_i \sum_{j \in J} x_{ji} - \sum_{i \in I} \sum_{l \in L} S_l C_l y_{il} \quad (34)$$

Subject to

$$\sum_{i \in I} \sum_{l \in L} y_{il} \leq p \quad (35)$$

$$\sum_{l \in L} y_{il} \leq 1, i \in I \quad (36)$$

$$\sum_{i \in I} \sum_{l \in L} F_l C_l y_{il} \leq F \quad (37)$$

$$\sum_{i \in I} x_{ji} = s_j, j \in J \quad (38)$$

$$\sum_{j \in J} x_{ji} \leq \sum_{l \in L} y_{il} C_l, i \in I \quad (39)$$

$$u_j + v_i \geq q_0 - \alpha t_{ji}, j \in J, i \in I \quad (40)$$

$$v_i \leq M \delta_i, i \in I \quad (41)$$

$$\sum_{l \in L} y_{il} C_l - \sum_{j \in J} x_{ji} \leq M(1 - \delta_i), i \in I \quad (42)$$

$$x_{ji} \leq M \theta_{ji}, j \in J, i \in I \quad (43)$$

$$u_j + v_i - (q_0 - \alpha t_{ji}) \leq M(1 - \theta_{ji}), j \in J, i \in I \quad (44)$$

$$y_{il} \in \{0, 1\}, i \in I, l \in L \quad (45)$$

$$x_{ji} \geq 0, j \in J, i \in I \quad (46)$$

$$u_j \quad \text{URS}, j \in J \quad (47)$$

$$v_i \geq 0, i \in I \quad (48)$$

4. Numerical Experiments

4.1. Experimental Design

The numerical examples are randomly generated to verify the validity of the proposed model and evaluate the performance of the solution method. The problem dimensions of the cold chain logistics network for fresh agricultural products are determined by the number of production areas, cold storage facilities, and cold storage types. In this section, 20 production areas (P1–P20), six candidate cold storage facilities (S1–S6), and four types of cold storage are conducted in the cold chain logistics network.

Without loss of generality, the locations of the network's production areas and cold storage facilities are randomly generated in the square $[0, 50]^2$, shown in Figure 1. The production capacities of fresh agricultural products in production areas are randomly generated in $[0, 2000]$. Detailed information, such as the distance from production areas (P) to cold storage facilities (S) and the production capacities, is given in Table 2.

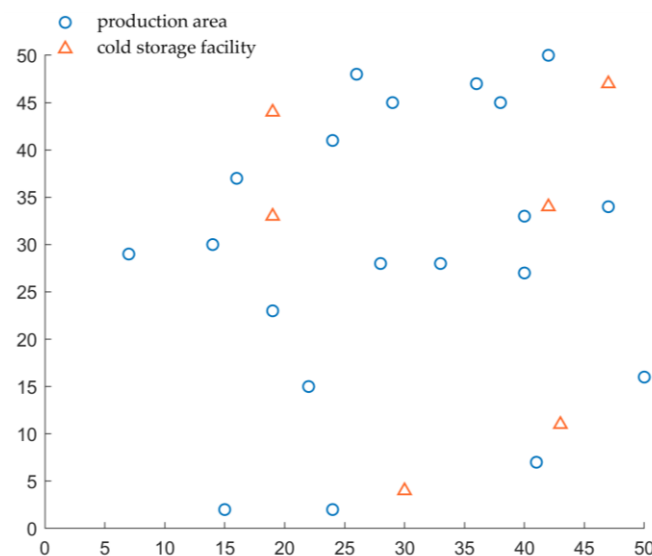


Figure 1. Locations of the production areas and cold storage facilities.

Table 2. Detailed information on the production areas and cold storage facilities.

		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
Distance (km)	S1	30	43	42	18	42	17	24	29	6	10	15	19	8	21	8	19	42	21	24	27
	S2	13	40	55	27	31	11	6	41	24	18	37	9	21	24	33	44	51	37	16	21
	S3	5	27	42	15	20	14	16	28	19	17	28	12	21	11	26	35	37	25	2	7
	S4	23	4	29	23	9	37	39	21	36	37	35	34	41	20	37	40	21	27	22	16
	S5	28	34	31	10	35	22	29	18	9	16	6	22	17	15	5	13	31	10	21	22
	S6	34	11	15	24	23	43	48	14	37	41	31	42	44	24	36	34	6	22	31	25
Capacity (units)		900	1600	1300	1600	300	2000	1700	200	1000	700	1300	500	1200	1300	1200	900	100	1100	900	300

Four types of cold storage are considered in the experiments. Relevant parameters of different types of cold storage are shown in Table 3, where C_l is the capacity of cold storage with type l ; F_l , O_l , and S_l are the fixed cost construction cost, fixed operating cost, and subsidy per unit, respectively; and $l = 1, 2, 3, 4$. Moreover, we set the variable operating cost per unit $V = [0.01 \ 0.03 \ 0.02 \ 0.03 \ 0.02 \ 0.03]$, which is associated with cold storage i . The speed of the pickup vehicle in the first mile is 10 km/h. Let the number of selected cold storage facilities be $p = 3$. According to Chen et al. [8], we take $\alpha = 5$ and $q_0 = 1000$, which means that the degradation rate of fresh agricultural products is 5‰ and the initial quality level is 1000‰ (i.e., 1).

Table 3. Parameters for the construction of cold storage.

	$l = 1$	$l = 2$	$l = 3$	$l = 4$
C_l	1000	5000	6000	9000
F_l	0.9	0.85	0.8	0.8
O_l	0.45	0.4	0.4	0.35
S_l	0.03	0.025	0.02	0.01

4.2. Results and Analysis

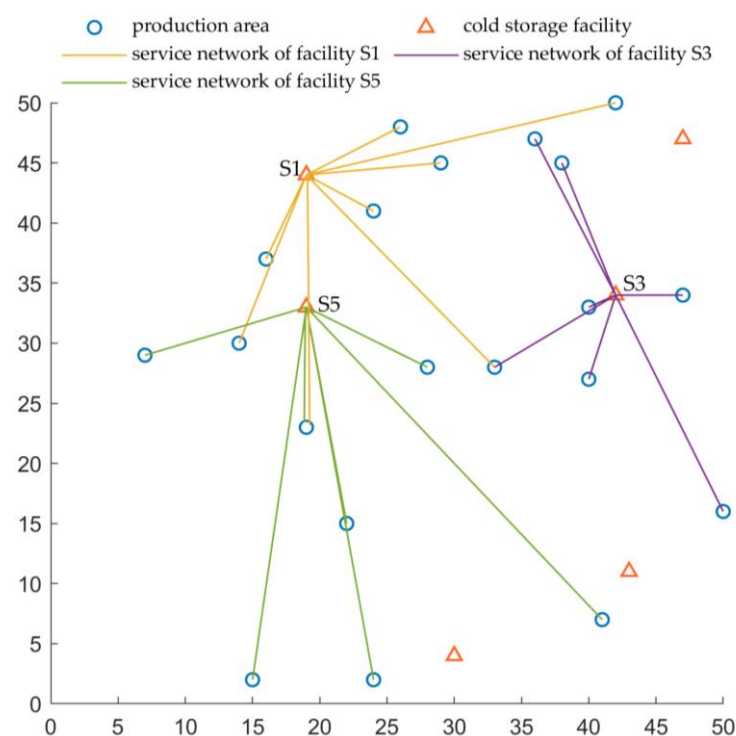
The proposed solution method for the bi-level programming model is conducted with Matlab and Cplex. The numerical experiments are performed on an Intel Core Quad PC with a 3.3 GHz CPU and 8.00 GB RAM. The computational time required to obtain the optimal solution is within seconds.

The optimal solution of the bi-level model of a cold chain logistics network for fresh agricultural products follows. The results of the cold storage facility location selection are stated in Table 4. It implies that cold storage facility S1 is selected with type 4, and S3 and S5 are selected with type 3.

Table 4. Results of the cold storage facility location selection.

	S1	S2	S3	S4	S5	S6
Selection	Y	N	Y	N	Y	N
Type of cold storage (I)	4	-	3	-	3	-

To illustrate the allocation of cold chain logistics service, the allocation results are shown in Figure 2. The detailed transportation plan is given in Table 5. Due to the limitations of cold storage capacity, production areas P14 and P18 are both served by two cold storage facilities. For instance, 300 units of fresh agricultural products from production area P18 are delivered to cold storage S5. Because of the total capacity of cold storage S5, 800 units of fresh agricultural products from P18 are delivered to cold storage S1, which results in higher degradation of fresh agricultural products from production area P18.

**Figure 2.** Results of the cold storage facility allocation.**Table 5.** Results of the transportation plan.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
S1	0	0	0	0	0	0	1700	0	1000	700	1300	0	1200	200	1200	0	0	800	0	0
S3	900	0	0	0	300	2000	0	0	0	0	0	500	0	1100	0	0	0	0	900	300
S5	0	1600	1300	1600	0	0	0	200	0	0	0	0	0	0	0	900	100	300	0	0

The results show that the total cost of the cold chain logistics network is 24,741, the minimum objective value of the upper-level model. The total quality of fresh agricultural products is 19,952, which is the maximum objective value of the lower-level model, and the total initial quality of fresh agricultural products is 20,100. As a result, the average degradation of fresh agricultural products is 7.4%. To our knowledge, the leader would choose cold storage facilities to minimize the total cost by considering the follower's plan. Then the follower reacts and makes the transportation plan regarding the leader's decision. This description implies that the bi-level model applies to solving cold chain logistics network problems. In addition, it is noted that we have achieved a global optimum solution to the problem.

To conduct sensitivity analysis and provide management insights to decision-makers, we focus on two parameters, including the type of cold storage facilities and the subsidy.

The type of cold storage facilities has an impact not only on the total cost but also on the degradation of fresh agricultural products. For this analysis, we investigate a new type of cold storage facility with a larger capacity than that of type 3. Consider that the capacity is 8000, 10,000, 12,000, 14,000, and 16,000, respectively. The optimal results for the cold chain logistics network design are shown in Table 6. This is a game between the leader and the follower. Table 6 shows that with the increase in the cold chain logistics network's total cost, the quality of fresh agricultural products improves with lower degradation. When the capacity of the cold storage facility varies, the leader's decision will change based on the follower's reaction. Then the follower reacts and makes the transportation plan. We can see that the cold chain logistics service level will be improved with more investment in cold storage facilities. Therefore, government subsidies are significant to support the development of cold storage facilities.

Table 6. Results of sensitivity analysis of the cold storage capacity.

	6000	8000	10,000	12,000	14,000	16,000
f_1	24,741	25,334	25,222	24,702	26,974	25,256
f_2	19,951.5	19,955.5	19,935.5	19,930.5	19,955.5	19,916.5

To illustrate the impact of subsidy, all the parameters are kept constant except for the subsidy parameter. We now set the subsidy for the fourth type of cold storage facility as 0, 0.1, 0.2, 0.3, and 0.4. The results are listed in Table 7.

Table 7. Results of sensitivity analysis of the government subsidy.

	0	0.1	0.2	0.3	0.4
f_1	24,831	23,931	23,031	21,754	19,954
f_2	19,951.5	19,951.5	19,951.5	19,955.5	19,955.5

According to the experimental results, the location-allocation strategy for the first three scenarios is identical, which results in an equivalent total quality of fresh agricultural products. As the government subsidy increases, the total costs of the cold chain logistics network decrease. The location-allocation strategy changes when the government subsidy increases from 0.2 to 0.3, which leads to an increase in the total quality of fresh agricultural products due to a higher level of cold chain logistics service and a significant reduction in total costs. Therefore, with the increase of subsidies, the total cost of the cold chain logistics network is reduced, which would improve the cold chain logistics service level for fresh agricultural products. This finding indicates that government subsidies play an important role in encouraging the construction of cold storage facilities.

5. Conclusions

This paper develops a bi-level programming model of the cold chain logistics network for fresh agricultural products in the first mile. From the perspective of management levels, the cold chain logistics enterprise is the leader, while the farmer is the follower. Unlike the traditional location-transportation model, quality degradation and government subsidy are considered. Then we transformed the bi-level model into a nonlinear single-level programming model by KKT conditions. The big M method is adopted to linearize the nonlinear constraints. Numerical experiments are designed to verify the proposed model. Sensitivity analysis is conducted on the model to see the reactions when the type of cold storage and subsidy varies. The findings could not only provide some management insights for the cold chain logistics provider and user but also indicate the importance of subsidies for supporting the development of cold chain logistics.

There are more uncertainties in the real world, such as production capacity and transportation time. Future research will investigate the robust model of the cold chain logistics network for fresh agricultural products. Furthermore, this paper considers that the quality degradation of fresh agricultural products follows the linear zero-order reaction [20]. In practice, the perishability of fresh agricultural products is a complex issue that may be affected by various environmental factors. The future research direction is to investigate an integrated model of the cold chain logistics network for fresh agricultural products with dynamic quality degradation rates.

Author Contributions: Conceptualization, H.Z. and Y.G.; methodology, H.Z., G.W. and C.L.; software, H.Z. and C.L.; validation, H.Z., C.L. and Y.G.; formal analysis, H.Z. and C.L.; investigation, H.Z. and Y.G.; resources, H.Z., Y.G. and G.W.; data curation, H.Z., Y.G. and C.L.; writing—original draft preparation, H.Z. and Y.G.; writing—review and editing, H.Z., C.L., Y.G. and G.W.; visualization, H.Z. and C.L.; supervision, H.Z.; project administration, H.Z.; funding acquisition, H.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Humanities and Social Sciences Foundation of the Ministry of Education in China (grant number 17YJC630238, H.Z.).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data have been included in the paper.

Acknowledgments: The authors would like to thank the editor and the reviewers for their constructive suggestions and kind help.

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

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