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Cold Chain Logistics Distribution Network Planning Subjected to Cost Constraints

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Abstract

In order to reduce the loss in the circulation of agricultural products, and to reduce the total cost, this article minimizes the operation cost by establishing an objective function when designing the cold chain logistics distribution network. Considering the characteristics of the cold chain products, this paper regards construction cost of network nodes, transportation cost and damage cost as the main factors in establishing an objective function. As the cold chain logistics is correlated to the demand of service time, this article comes up with a concept of "service radius", which transformed the transportation time between logistics nodes into the service radius of logistic nodes. The model is verified through a series of constraint conditions to express the relationship between the various decision variables. An example is given in the end, which demonstrates the application of this model in a vegetable firm distribution logistics network planning. The final computation results illustrated that the model is effective.

Keywords: *Cold chain logistics; distribution; network planning; service radius*

1. Introduction

In recent years, with the improvement of people's living standard, the demands for fresh food and fresh agricultural products have increased quickly, food safety has attracted great attention. Cold chain logistics plays a more and more important role in the circulation of agricultural products. As the development of cold chain logistics is able to reduce the deterioration of food in the process of circulation, which eventually reduces the circulation costs and stimulates sales. However, China's cold-chain logistics has not formed an integrated system compared with those in the developed countries. Cold chain logistics in China lacks effective integration in the system, therefore, the logistics efficiency is low.

At present, scholars studying the cold-chain logistics network mainly focus on three aspects. The first aspect is on the macro analysis of the present status of cold chain logistics network. Through analyzing the current situation of fresh food chain in Chinese supermarkets, He and Zhang (2011) [1] summarized that there are three cold chain logistics network models in China, namely the individual, regional and cross-regional cold-chain logistics networks. Following the same classification of the cold chain logistics, Gong and Liang (2006) [2] analyzed three models respectively. They concluded that there is no smooth links between the upstream and downstream of the cold chain logistics for the intermediates, therefore, regional agricultural logistics distribution system has not been completed yet and a comprehensive distribution center is needed. The second aspect is the location problem for cold chain logistics. For example, Li &Ma (2003) [3], Wang *et al.*, (2008) [4] and Pan (2013) [8] established the mathematical models to analyzed the distribution center location problems. Zhang (2012) [5], Li (2012) [6] and Zheng *et al.*, (2009) [7] used the comprehensive evaluation method to evaluate the cold chain logistics distribution center location. The third aspect is the optimization

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problem of cold chain logistics distribution path, such as Huang (2012) [9], Liu (2011) [10] and Shi (2013) [11] respectively optimized the food cold chain logistics inventory, transportation, warehousing, distribution problems, *etc.*, Song (2010) [12], Qi (2011) [13] and Peng (2008) [14] optimized stochastic vehicle routing problem by used heuristic algorithm.

Based on the above analysis, there is more research analyzing the cold chain logistics in China and abroad, while less attention is paid to the analysis of the overall cold chain logistics distribution network planning. The cold-chain logistics network has various structures because of the dissimilarity of product characteristics and demand. Particularly in China, the cold-chain logistics network covers larger area than other countries, and the cold-chain logistics network is a hierarchical network system. How to optimize the hierarchical logistics network is very important and difficult for enterprise. In this paper, minimizing the total operating cost is set as the objective function. By applying the concept of "service radius", which constrained the distribution time between logistics nodes within the “service radius", this paper figures out the relationships between decision variables. At last, a case study is used to verify the effectiveness of the model.

2. Problem Description

It is supposed that there is a firm (***O***) supplies fresh products for *N* consumers(***C***). In order to guarantee the freshness of the food when arrival, the firm needs to arrange the cold chain logistics distribution network properly. The perishable goods are transported via *J* distribution centers (***DC***) and *K* cold storage (***CS***) to the end customers. The network is shown in Figure 1:

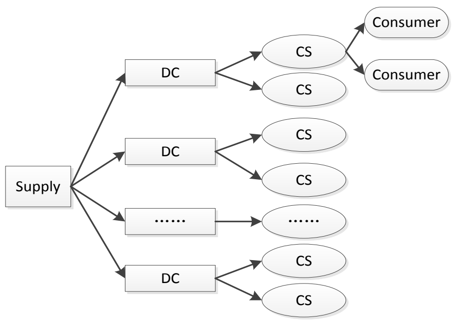

Figure 1. Cold Chain Logistics Distribution Network

The efficiency of cold chain logistics depends on the network of logistics nodes. In the distribution network, each mother node serves more than one sub-node, but each sub-node is served only by one mother node.

The total cost is the sum of the operation costs and the damage cost. In addition, the operation costs are the cost among distribution center (DC) and cold storage (CS) and customers.

3. Mathematical Model

In order to optimize the operation of the cold chain logistics distribution network, this article minimize the total operation cost which is composed of logistics nodes construction cost and transportation cost. Due to the character of the perishable products, damage costs of the products are also considered during the journey. The damage cost of cold chain logistics mainly contains two aspects: On the one hand, goods be damaged as a result of long transport time; On the other hand, the hot air sneaking into the cold storage will change the interior temperature and eventually deteriorate the products in the process of loading and unloading of goods. At the same time, in order to guarantee the quality of perishable products, this paper adds up the service time to make sure the goods are delivered on certain time range. The service time referring to the distance between two logistics nodes is denoted as "service radius". Therefore, distance between logistics nodes is converted to the service radius of logistics nodes. In the following model, the distance from the supply point to the distribution center is marked as the radius of the service center $\boldsymbol{R^D}$. Similarly, the distance between the distribution center and the cold storage is marked as $\boldsymbol{R^S}$, and the distance between the cold storage and the consumers is $\boldsymbol{R^C}$.

3.1. Model Assumption

(1)Only one supplier deliveries one type of product.

(2)Supply node, distribution center, demand points are scattered in different areas of the city.

(3)The number of required distribution center for distribution network is known.

(4)The fixed costs of establishing and managing distribution center are known.

(5)One supplier's goods are distributed by only one distribution center to the customers.

(6)One distribution center's goods are distributed by only one cold storage to the customers.

(7)The total demand is less than what the suppliers can offer.

(8)The demand for each distribution center and cold storage is certainty and remains relatively stable for a period.

3.2. Model Establishment

Parameter setting:

J : The number of the alternative distribution center, $J = \{1,2,..., J\}$;

K : The number of the alternative cold storage, $K = \{1,2,..., K\}$;

q_n : The demand quantity of each consumer;

Decision-making variables:

$$Z_k = \begin{cases} 1, \ if \ \ the \ \ CS_k \ \ was \ \ selected \\ 0, \ \ \ \ \ \ \ \ \ \ otherwise \end{cases}$$

$$X_{jk} = \begin{cases} 1, \ if \ \ the \ \ DC_j \ \ directly \ \ \sup plies \ \ CS_k \\ 0, \ \ \ \ \ \ \ \ \ \ otherwise \end{cases}$$

$$X_{kn} = \begin{cases} 1, \ if \ \ the \ \ CS_k \ \ directly \ \ \sup plies \ \ C_n \\ 0, \ \ \ \ \ \ \ \ \ \ otherwise \end{cases}$$

Table 1. Notation

Parameter	*Meaning*	*Parameter*	*Meaning*
F_j	The fixed costs of establishing a distribution center	Q_{jk}	The shipment quantity from distribution center *j* to cold storage *k*
F_k	The fixed costs of establishing a cold storage	Q_{kn}	The shipment quantity of from cold storage *k* to customer
ω_j	The coefficient of variable cost per unit for establishing a distribution center	S_j	The distance from firm *O* to distribution center *j*

ω_k	The coefficient of variable cost per unit for establishing a cold storage	S_{jk}	The distance from distribution center *j* to cold storage *k*
W_j	The throughput of $\boldsymbol{DC_j}$	P	The unit price of the product
W_k	The throughput of $\boldsymbol{CS_k}$	θ_1	The percentage of damage in the process of transportation
C_j	The unit transportation cost from firm *O* to distribution center *j*	θ_2	The percentage of damage in the process of loading and unloading operations
C_{jk}	The unit transportation cost from distribution center *j* to cold storage *k*	R^D	The service radius from firm to distribution center
C_{kn}	The unit transportation cost from cold storage *k* to customers	R^S	The service radius from distribution center to cold storage
Q_j	The volume of $\boldsymbol{DC_j}$	R^C	The service radius from cold storage to customers

Objective function:

$$\min \quad f = \sum_{j=1}^{J} F_j Z_j + \sum_{j=1}^{J} \omega_j (W_j)^{\theta} + \sum_{k=1}^{K} F_k Z_k + \sum_{k=1}^{K} \omega_k (W_k)^{\theta} + \sum_{j=1}^{J} Z_j C_j Q_j S_j$$
$$+ \sum_{j=1}^{J}\sum_{k=1}^{K} X_{jk} C_{jk} Q_{jk} S_{jk} + \sum_{k=1}^{K}\sum_{n=1}^{N} X_{kn} C_{kn} Q_{kn} \tag{1}$$
$$+ P\sum_{j=1}^{J}\sum_{k=1}^{K} [\theta_1 (R^D + R^S + R^C) + \theta_2 (Q_j + Q_{jk} + Q_{kn})]$$

s.t.

$$W_j = \sum_{k=1}^{K} X_{jk} \times W_k \tag{1-1}$$
$$\sum_{k=1}^{K} X_{jk} \le Z_j \times k \tag{1-6}$$
$$W_k = \sum_{n=1}^{N} X_{kn} \times q_n \tag{1-2}$$
$$\sum_{n=1}^{N} X_{kn} \le Z_k \times n \tag{1-7}$$
$$Q_j = W_j \tag{1-3}$$
$$Z_j \times S_j \le R^D \tag{1-8}$$
$$Q_{jk} = X_{jk} \times W_k \tag{1-4}$$
$$X_{jk} \times S_{jk} \le R^S \tag{1-9}$$
$$Q_{kn} = X_{kn} \times q_n \tag{1-5}$$
$$X_{kn} \times S_{kn} \le R^C \tag{1-10}$$

The objective function (1) minimizes the total cost, which is the sum of the construction cost, transportation cost and damage cost. In particular, the network nodes' construction costs include the fixed cost and variable cost. The network node fixed cost is composed of the opportunity cost, staff costs and other management cost. In addition, the network node's variable cost depends on the throughput, and transportation costs include the costs among firm, distribution center and customer.

Eq. (1-1)to(1-5) indicated the linear relationship of each node between throughput and demand. Eq. (1-6) gives the relation between ***DC*** location decision variables and ***CS***'s father node decision variables; Eq. (1-7) gives the relation between ***CS*** location decision variables and ***C***'s mother node decision variables. Eq. (1-8) to (1-10) demonstrated the service radius restriction of ***DC***, ***CS***, and ***C*** respectively.

4. Numerical Example

In this paper, the distribution work of a vegetable firm in the Shanghai Pudong New Area is used as an example. Figure 2 is the administrative division map of Shanghai, where the vegetable firm supplies vegetables. To fulfill the demand, the vegetable firm plans to establish some distribution centers and corresponding cold storages. In order that distribution network cover the whole city, now plans four potential locations of distribution centers include Nanhui, Downtown, Jiading and Songjiang. The potential locations of cold storage need to be selected from 9 cold storage nodes (C1 to C9 in the map).The question is how to plan and optimize the cold chain logistics distribution network in order to minimize the total operating cost under the current constraints.

Figure 2. Location of Network Nodes

Through field trips, it is known that the mentioned vegetable firm currently has one supply point (Pudong, marked as O) and 9 demand areas. The detailed demands of each area and their distances to Pudong are shown in Table 2. The related distances from the firm to each distribution center and to cold storage are shown in Table 3 and Table 4. These service radius and operation costs are obtained from historical data which are shown in Table 5.

Table 2. The Regional Demand Quantity (ton) and Distance to Pudong (km)

Demand point	*Quantity Demand*	*The distance with the supplier*
C1	43	66
C2	29	68
C3	43	48
C4	80	40
C5	110	35
C6	76	36
C7	59	60
C8	63	62
C9	97	42

Table 3. The Distance from Firm *O* to Distribution Center *j* (km)

Primary distribution center	*Distance of from Primary distribution*

	center to supply node
DC1	32
DC2	34
DC3	60
DC4	66

Table 4. The Distance from Distribution Center j to Cold Storage k (km)

RS/C	*DC*			
	DC1	DC2	DC3	DC4
RS1/C1	86	38	28	15
RS2/C2	72	48	53	14
RS3/C3	48	38	54	25
RS4/C4	0	56	84	72
RS5/C5	58	0	28	35
RS6/C6	67	20	26	48
RS7/C7	84	28	0	40
RS8/C8	73	35	38	0
RS9/C9	58	15	33	20

Table 5. The Service Radius and Coefficient of Operation Cost

Symbol	*Meaning*	*Value*	*Unit*
R^D	The service radius from firm to distribution center	70	km
R^S	The service radius from distribution center to cold storage	35	km
R^C	The service radius from cold storage to customers	8	km
C_j	The unit transportation cost from firm *O* to distribution center *j*	0.03	Yuan/ton·km
C_{jk}	The unit transportation cost from distribution center *j* to cold storage *k*	0.08	Yuan/ton·km
F_j	The fixed costs of establishing a distribution center	207,000	Yuan
F_k	The fixed costs of establishing a cold storage	38,000	Yuan
ω_j	The coefficient of variable cost per unit for establishing a distribution center	810	Yuan/ton
ω_k	The coefficient of variable cost per unit for establishing a cold storage	0.4	Yuan/ton
P	The unit price of the product	2000	Yuan/ton
θ_1	The percentage of damage in the process of transportation	0.1%	
θ_2	The percentage of damage in the process of loading and unloading operations	0.05%	

In this example, the coefficients of fixed costs and variable cost per unit are the same for each distribution center and cold storage, the unit transportation costs of each path is the same too. Moreover, each cold storage can only serve its local area.

According to the data, the objective function of this logistics network can be defined as follows:

J:Collection of distribution center ***j***, $j \in J$, $j=1,2,3,4$;

K:Collection of refrigerator ***k***, $k \in K$, $k=1,2,3,\ldots,9$;

N:Collection of consumption area ***n***, $n \in N$, $n=1,2,3,\ldots,9$.

Decision-making variables:

$$Z_j = \begin{cases} 1, & if \quad the \quad DC_j \quad was \quad selected \\ 0, & otherwise \end{cases} \quad ,j=1,2,3,4;$$

$$Z_k = \begin{cases} 1, if \quad the \quad CS_k \quad was \quad selected \\ 0, \quad otherwise \end{cases}, k=1,2,3,\ldots,9;$$

$$X_{jk} = \begin{cases} 1, if \quad the \quad DC_j \quad directly \quad sup\ plies \quad CS_k \\ 0, \quad otherwise \end{cases}, j=1,2,3,4;k=1,2,3,\ldots,9;$$

According to the Table 4 and the function (1), the objective function of the cold chain logistics distribution network is shown as follows:

$$\begin{aligned} \min \quad f = {} & 20700 \sum_{j=1}^{4} Z_j + 810 \sum_{j=1}^{4} (W_j)^{\frac{1}{2}} + 38000 \sum_{k=1}^{9} Z_k + 0.4 \sum_{k=1}^{9} (W_k)^{\frac{1}{2}} \\ & + 0.03 \sum_{j=1}^{4} Z_j Q_j S_j + 0.08 \sum_{j=1}^{4} \sum_{k=1}^{9} X_{jk} Q_{jk} S_{jk} \\ & + 4.068 \sum_{j=1}^{4} \sum_{k=1}^{9} (Q_j + Q_{jk} + Q_{kn}) \quad \left(\theta = \frac{1}{2} \right) \end{aligned} \quad (2)$$

s.t.

$$W_j = \sum_{k=1}^{9} X_{jk} \times W_k \quad (2\text{-}1) \qquad \sum_{k=1}^{9} X_{jk} \le Z_j \times 9 \quad (2\text{-}6)$$

$$W_k = \sum_{n=1}^{9} X_{kn} \times q_n \quad (2\text{-}2) \qquad \sum_{n=1}^{9} X_{kn} \le Z_k \times 9 \quad (2\text{-}7)$$

$$Q_j = Wj \quad (2\text{-}3) \qquad Z_j \times S_j \le 70 \quad (2\text{-}8)$$

$$Q_{jk} = X_{jk} \times W_k \quad (2\text{-}4) \qquad X_{jk} \times S_{jk} \le 35 \quad (2\text{-}9)$$

$$Q_{kn} = X_{kn} \times q_n \quad (2\text{-}5) \qquad X_{kn} \times S_{kn} \le 8 \quad (2\text{-}10)$$

The above model is solved by Lingo, and the results demonstrated three distribution centers were selected as the main logistics network nodes (showed in Figure 3). The corresponding service areas of each distribution center were showed in Table 6 and Table 7. According to the results, the distribution center Nanhui supplies Fengxian and Minhang, Jiading directly supplies Baoshan and downtown, and Songjiang directly supplies Qingpu and Jinshan.

Figure 3. The Distribution Network

Table 6. The Choice of Network Nodes

Type	*Node*	*City*	*Selected*
O	*O*	Pudong	
DC	*DC1*	Nanhui	Y
	DC2	Downtown	N

	DC3	Jiading	Y
	DC4	Songjiang	Y
C	*C1*	Qingpu	Y
	C2	Jinshan	Y
	C3	Fengxian	Y
	C4	Nanhui	N
	C5	Downtown	Y
	C6	Baoshan	Y
	C7	Jiading	N
	C8	Songjiang	N
	C9	Minhang	Y

Table 7. The Service Scope of Network Nodes

O/DC	*Service area*
Pudong *(O)*	Nanhui*(DC1)*, Jiading (*DC2)*, Songjiang *(DC3)*
Nanhui(*DC1*)	Fengxian*(C3)*,Minhang*(C9)*
Jiading(*DC2*)	Downtown*(C5)*, Baoshan*(C6)*
Songjiang(*DC3*)	Qingpu*(C1)*, Jinshan*(C2)*

The reasons for selecting Nanhui, Jiading and Songjiang as the distribution centers are mainly the geographical concern. These three areas are rural area where the surrounding lands are cheaper to build the logistics facilities. Moreover, building the distribution center in or near the downtown is against the development blueprint of Shanghai City. Finally, there are a large number of residential districts around these three points, where demand for fresh products is high. And due to these three points away from downtown, it is convenient for supplier to transport without traffic jam. Therefore, the three regions are considered to be the cold chain distribution centers.

5. Conclusion

This paper analyzes the cold chain logistics distribution network planning which is subjected to cost constraints, and establishes a cold chain logistics distribution network model by minimizing the total operation cost. The model is verified through a vegetable firm case in which series of constraint conditions are used to represent the relationship between the various decision variables. The verification results demonstrated the proposed model is capable and effective to solve the distribution problem. Moreover, makes a network planning for Shanghai vegetable logistic distribution, and through some actual survey data and calculation proves the model is effective.

From the theoretical perspective, the solution of this research is to convert the transportation constraints into the service radius, which takes account of the characteristics of the cold chain goods. The proposed method is able to be applied to other regular supply chain network plans, which do not have such strict requirement of the time. In the practical application, this research provides insights about the importance of the site selecting.

However, this study has some limitations. The proposed model is the basic version which includes single supplier, one product type and cost concern. In the practice, cold chain providers need to offer various products in the same time, which is more complex and the proposed model should be adapted. Moreover, though freezer can assist keeping the cold chain goods fresh, the time would still be a big concern. Therefore, in the future work, this model needs to add more objectives into consideration.

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