

Study on the Location of Cold Chain Distribution Center Considering Scale Effect

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Abstract: People are paying more attention to the freshness of cold chain products when making choices. Establishing cold chain distribution centers can improve the timeliness and service quality of cold chain logistics. Cold chain distribution centers require significant investment, necessitating a more scientific approach to site selection. Furthermore, compared to regular distribution centers, cold chain distribution centers exhibit clear economies of scale, thus necessitating careful consideration of these economies of scale during site selection and construction. The paper analyzes the scale effect of the cold chain distribution center, and constructs a cold chain distribution center location model considering the scale effect. The objective function of the model includes the related costs of the cold chain distribution center location, such as fixed cost, operating cost, transportation cost, loss cost and carbon emission cost, etc., with the minimum total cost as the function objective. Finally, this paper designs a calculation example design. The model calculation example is solved by Lingo software, and the optimal location plan of the cold chain distribution center is obtained. The calculation example results verify the effectiveness of the model.

Keywords: Cold chain, distribution center location, scale effect, mixed 0-1 integer programming.

1. Introduction

Agricultural products, flowers, pharmaceuticals, and chemicals all fall under the category of cold chain products, generating a significant demand for cold chain services. Driven by increasing demand and sustained policy support, the market outlook for cold chain logistics is extremely promising. However, compared to developed countries, there exists a significant gap in the current status of cold chain logistics in China. In developed countries, cold chain transportation rates are currently at 80% to 90%. For instance, Japan's rates exceed 95% for fruits, vegetables, and aquatic products, and are over 90% for meat and poultry, with a 100% circulation rate for cold chain. However, in China, the rates for fruits, vegetables, and meat are only 35%, 57%, and 69% respectively, leaving ample room for improvement. In typical site selection issues for distribution centers, a cost function is usually constructed, but the impact of economies of scale on cost is rarely considered. From an economic perspective, taking economies of scale into account can assist in more accurately calculating costs and help businesses make better site selection decisions.

The cold chain industry in China first emerged in the 1950s. Then, entering the 21st century, China's logistics market for fresh agricultural products in the cold chain continued to expand. Wu Qinggang^[1] outlined the concept of cold chain logistics and conducted a SWOT analysis to study the development environment. He identified issues such as the outdated equipment and systems in China compared to foreign counterparts and proposed directions for advancement, elucidating future development strategies^[1]. Zhou Yanrong^[2] looked back at relevant research on cold chain logistics in foreign countries and believed that China should learn advanced cold chain technologies from developed countries. She also reviewed the development history of cold chain logistics in China and proposed suggestions for promoting the development path of cold chain logistics, including strengthening infrastructure construction, planning the network layout of cold chain logistics nodes, and

building an intelligent cold chain logistics system. In studies related to cold chain quality management, P. Amorim et al.^[3] researched various influencing factors on perishable agricultural products during the distribution process. By establishing a multi-objective planning model, they maximized product freshness while minimizing distribution costs. In the realm of cold chain supply chain management, Chen et al.^[4] developed a cold chain management system applicable to tracking perishable food items. The system utilizes RFID technology and other techniques to track the freshness of perishable food items throughout processes such as storage, transportation, and sales, thereby enhancing consumer satisfaction. In research related to the site selection of cold chain distribution centers, Zou Xiao and Zhang Xiaoning^[5] identified issues with the traditional CFLP model and made improvements. They constructed a new cold chain logistics distribution center site selection model considering time constraints and verified that the improved model achieved optimization. Lu Jingjing^[6] considered carbon costs in the site selection process for cold chain logistics distribution centers, establishing a mathematical model. Through empirical analysis, the effectiveness and feasibility of the model were validated. Furthermore, it was demonstrated that incorporating carbon emission cost considerations can reduce the social costs incurred by distribution centers. M. Hashim et al.^[7] utilized a multi-objective model to study site selection problems for logistics distribution centers in uncertain environments. Uysal^[8] employed grey analysis for site selection, considering the sustainability of warehouses. They comprehensively considered the impact of cold storage on the surrounding environment from the perspective of operating costs, rent, and other cost factors. PL. Abad and V. Aggarwal^[9] established a model from the perspective of logistics nodes with the objective of determining the optimal number of logistics nodes. Then, using the constructed model, they developed a method for constructing logistics network demand points related to logistics nodes and obtained the distribution cost of the network.

In site selection problems, the costs involved in investments are often considered. Cold chain distribution centers require significant investment and exhibit obvious economies of scale. Therefore, some researchers incorporate economies of scale into cost analysis calculations for site selection. Yu Yan^[10] integrated economies of scale theory into distribution center site selection research. They used the Analytic Hierarchy Process (AHP) to outline decision factors in terms of both economic and social benefits, determining specific usage scenarios through calculation. Finally, based on the concept of economies of scale, they proposed a logistics distribution center site selection model that meets the requirements of economies of scale. In the study on the site selection problem of container distribution centers, Dai Minjie^[11] considered a cost function based on economies of scale. By evaluating the degree of conformity between calculation results and actual situations, they decided that the cost function should be a linear function. This function reflects the economies of scale in water transportation, where the total cost increases with the volume of freight but the unit cost decreases with the increase in freight volume.

In summary, there is relatively less research on the site selection of cold chain distribution centers considering economies of scale. However, cold chain distribution centers require more fixed investment costs compared to regular distribution centers, and economies of scale are more pronounced. Therefore, special attention should be paid to economies of scale during site selection and construction. This paper constructs a cold chain distribution center site selection model considering economies of scale from the perspectives of fixed costs, operating costs, transportation costs, loss costs, and carbon emission costs, aiming to find the optimal solution for the model.

2. Model Construction

2.1. Problem Description

In this paper, the concept of scale effect is introduced into the location model of cold chain distribution centers. Under the premise that there are I supply areas upstream and K demand areas downstream, a mixed 0-1 integer programming model is constructed with the goal of minimizing the total cost, which includes fixed cost, operating cost, transportation cost, cargo loss cost, and carbon emission cost. Then, using Lingo software, one or more optimal distribution centers are selected from J candidate cold chain distribution center sites.

Given the need for operational feasibility in the research, the following assumptions are made regarding the cold chain distribution center site selection model considering economies of scale.

(1) The refrigerated truck distribution process includes transportation from the supply location to the distribution center to the demand location, as well as the return trip from the demand location to the distribution center to the supply location.

(2) The refrigerated truck is empty during the return trip.

(3) Only one type of refrigerated vehicle is used during transportation.

(4) The refrigerated truck working between the supply location and the distribution center, and between the distribution center and the demand location, is solely responsible for the transportation of goods between these

locations, and only one truck is available.

(5) The distances between the supply location and the distribution center, and between the distribution center and the demand location, are known.

(6) The unit transportation cost between the supply location and the distribution center, and between the distribution center and the demand location, remains constant and equal.

(7) The vehicle's delivery speed is constant, and any temperature variations during transportation can be ignored.

(8) The distribution center can meet the demand at the demand points

2.2. Parameter Descriptions

The parameters involved in the construction of the model and their respective meanings are shown in Table 1.

Table 1. Parameter Descriptions

| Parameters | Parameter Descriptions |
|---------------|--|
| I | The numbers of supply locations |
| J | The numbers of distribution centers |
| K | The numbers of demand locations |
| Z_j | The throughput capacity of cold chain distribution center |
| M | The maximum supply capacity of supply location |
| N | The demand quantity of demand location |
| D | The number of distribution centers |
| a | The unit transportation cost per unit weight and per unit distance during transportation |
| x_{ij} | The product weight transported from supply location to distribution center |
| x_{jk} | The product weight transported from distribution center to demand location |
| d_{ij} | The transportation distance between supply location and distribution center |
| d_{jk} | The transportation distance between distribution center and demand location |
| μ_j | The unit operating cost |
| ε | The unit cargo damage cost |
| θ | The spoilage reaction rate |
| v | The transportation speed |
| ρ | The fuel consumption per unit distance between two locations |
| ρ_0 | The fuel consumption per unit distance when the refrigerated truck is unloaded |
| e_0 | The carbon dioxide emission coefficient |
| α | The carbon emissions generated by refrigeration per unit weight of goods transported per unit distance |
| c_0 | The carbon tax |

2.3. Model Construction

The cost of scale effect considered in this paper is primarily operational. Typically, as the size of a facility node increases, its unit operational expenses also rise in a nonlinear fashion. Fixed costs are associated with the scale of the cold chain distribution center, with larger scales leading to higher construction costs. Typically, the basic construction cost of a distribution center of a certain size remains constant. The transportation cost component only considers expenses related to road transportation. The transportation expenses of a distribution center are linked to the travel distance between

two locations and the volume of goods transported. Due to the temperature-sensitive nature of cold chain products, longer transportation distances can easily compromise product quality. Therefore, the cost of product loss during distribution is a non-negligible aspect in such scenarios, necessitating the consideration of cargo damage costs in the location selection of cold chain distribution centers. Lastly, we consider carbon emission costs. These costs in this paper are primarily calculated based on carbon dioxide emissions, which are related to both transportation distance and volume. In summary, the location selection model for cold chain distribution centers considering scale effect is as follows.

$$\begin{aligned} \min F = & \sum_j Y_j G_j + \mu_j \sqrt{\sum_{i,j} Y_j x_{ij}} + a Y_j \sum_{i,j,k} (x_{ij} d_{ij} + x_{jk} d_{jk}) \\ & + \varepsilon \sum_{i,j} x_{ij} (1 - e^{-\frac{d_{ij} Y_j}{v}}) + \varepsilon \sum_{j,k} x_{jk} (1 - e^{-\frac{d_{jk} Y_j}{v}}) \\ & + c_0 e_0 \sum_{i,j,k} [\rho(x_{ij}) d_{ij} + \rho(x_{jk}) d_{jk}] \\ & + c_0 \sum_{i,j,k} [\alpha (x_{ij} d_{ij} + x_{jk} d_{jk}) + e_0 \rho_0 (d_{ij} + d_{jk})] \end{aligned} \quad (1)$$

$$\sum_{i,j} x_{ij} = \sum_{j,k} x_{jk} \quad (2)$$

$$\sum_{i,j=1} x_{ij} \leq M \quad (3)$$

$$\sum_{i,j} x_{ij} Y_j \leq Z_j \quad (4)$$

$$\sum_{j,k} x_{jk} \geq N \quad (5)$$

$$\sum_j Y_j \leq D \quad (6)$$

$$x_{ij} \geq 0, x_{jk} \geq 0, i = 1, 2, \dots, I, j = 1, 2, \dots, J, k = 1, 2, \dots, K \quad (7)$$

$$Y_j = \begin{cases} 1, & \text{To establish at location } J \\ 0, & \text{otherwise} \end{cases} \quad (8)$$

Formula (1) represents the objective function. Formula (2) indicates that the weight of the products incoming to the cold chain distribution center is equal to the weight of the products outgoing from it. Formula (3) represents that the weight of products from the supply location to the distribution center is not greater than the maximum supply capacity of the supply location. Formula (4) signifies that the weight of products from the supply location to the distribution center does not exceed the capacity of that particular distribution center. Formula (5) states that the weight of products transported from the distribution center to the demand location is not less than the demand requirement of the demand location. Formula (6) expresses that the total number of selected cold chain distribution centers does not exceed D. Formula (7) specifies that the weight of products during transportation is always a positive number. Formula (8) represents the decision variables.

3. Case Analysis

3.1. Case Figures

The product analyzed in the case of this article is the cold chain product P of L Cold Chain Enterprise. In the case, there are six potential locations for cold chain distribution centers, labeled as J1, J2, J3, J4, J5, and J6. Additionally, there are three upstream supply locations, namely I1, I2, and I3, and four downstream demand locations, K1, K2, K3, and K4. The final selection of distribution centers is limited to no more than three. The specific data and solution process are presented in the following text.

After conducting research and investigation, we have estimated the various numerical values involved in the model. The specific values are presented in Table 2 to Table 7.

Table 2. The Distance from I to J (km)

| | J1 | J2 | J3 | J4 | J5 | J6 |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| I1 | 39 | 35 | 46 | 55 | 64 | 52 |
| I2 | 55 | 42 | 50 | 37 | 48 | 43 |
| I3 | 48 | 58 | 40 | 46 | 55 | 53 |

Table 3. The Distance from J to K (km)

| | K1 | K2 | K3 | K4 |
|-----------|-----------|-----------|-----------|-----------|
| J1 | 32 | 40 | 43 | 45 |
| J2 | 37 | 45 | 32 | 60 |
| J3 | 43 | 40 | 38 | 40 |
| J4 | 38 | 42 | 53 | 46 |
| J5 | 56 | 48 | 62 | 45 |
| J6 | 50 | 33 | 45 | 46 |

Table 4. The Weight of Products Provided by Supply Location(t)

| | I1 | I2 | I3 |
|----------|-----------|-----------|-----------|
| M | 5 | 8 | 12 |

Table 5. The Distance from I to J (km)

| | K1 | K2 | K3 | K4 |
|----------|-----------|-----------|-----------|-----------|
| N | 30 | 40 | 60 | 100 |

Tables 2 and Table 3 present the distances from the supply locations to the distribution centers and from the distribution centers to the demand locations, respectively. Tables 4 and Table 5 provide the maximum supply quantities of the supply locations and the maximum demand quantities of the demand locations, respectively. In addition, the scales of the six potential sites are fixed, with their respective fixed costs and capacities as Table 6.

Table 6. The Fixed Cost and Capacity of Distribution Center

| | J1 | J2 | J3 | J4 | J5 | J6 |
|---------------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| G_j (yuan) | 100,000 | 200,000 | 250,000 | 280,000 | 305,000 | 320,000 |
| Z_j(t) | 5 | 6 | 10 | 12 | 15 | 20 |

In the model, the transportation process only involves refrigerated trucks. The maximum load capacity of these refrigerated trucks is 12 tons.

Besides, based on relevant literature, other parameters related to the model are presented in Table 7.

Table 7. Parameters

| Parameters | Valnes | Parameters | Valnes |
|--------------------------------------|--------|------------------------|--------|
| ρ_0 (t/km) | 0.165 | ρ^* (t/km) | 0.377 |
| m^* | 9 | v (km/h) | 50 |
| a_{ij} 、 a_{jk} (yuan/km · t) | 2 | ε (yuan/t) | 1500 |
| θ | 0.0035 | μ_j (yuan/kg) | 2 |
| c_0 (yuan/tCO ₂) | 20 | e_0 (kg/L) | 2.63 |
| α (g/kg · km) | 0.0066 | | |

3.2. Case Results

By substituting the numerical values of the potential sites into the mixed 0-1 integer programming model considering the scale effect, the transportation weights and various costs were calculated by using Lingo software, resulting in the optimal location selection.

When three points were selected from the six potential sites as cold chain distribution centers. J2, J3, and J6 were chosen, with a minimum total cost of 776,332.1 yuan. With three cold chain distribution centers selected, supply location I1 transported products to distribution centers J2 and J6, supply location I2 transported products to J2 and J6, and supply location I3 transported products to distribution centers J3 and J6. Distribution center J2 only served demand location K4, distribution center J3 served demand locations K1, K2, and K4, and distribution center J6 provided services to all demand locations K1, K2, K3, and K4. From the perspective of costs, the fixed costs of the selected cold chain distribution centers were 200,000 yuan, 250,000 yuan, and 320,000 yuan, respectively. The operating costs were 1,250 yuan. The total transportation costs from supply locations to distribution centers and from distribution centers to demand locations were 4,519.368 yuan. During the entire transportation process, the cargo damage costs were 142.3655 yuan, and the carbon emission costs were 72,783.67 yuan.

4. Conclusion

With the continuous improvement of people's living standards and the gradual shift in consumption concepts, the cold chain logistics industry has experienced rapid growth. The expansion of market demand has brought development opportunities to cold chain logistics, but it has also exposed some issues. To meet the ever-increasing demand, there is still considerable room for improvement in existing infrastructure and system development. To expedite the delivery of cold chain products to their destinations, reduce logistics costs, enhance efficiency, and improve the overall quality of cold chain logistics, it is crucial for cold chain distribution centers to play a pivotal role. Therefore, the research on the location selection of cold chain distribution centers remains highly significant.

This paper primarily explores the impact of scale effects on location-related costs and proposes a model for selecting cold chain distribution centers that considers these effects. Building on existing research, the model takes into account fixed costs, operating costs, transportation costs, cargo damage costs, and carbon emission costs. It also considers the

influence of scale effects on operating costs, employing marginal cost calculations. Finally, the model's effectiveness is demonstrated through a numerical example, making it more aligned with practical location selection needs and enhancing its practical significance.

While this paper focuses on selecting the most suitable location among potential sites based on cost calculations, real-world decision-making involves numerous other factors that are difficult to quantify, such as natural environment, surrounding traffic conditions, and government policies. For simplicity, this paper only selects a few parameters for calculation, which may lack representativeness. Therefore, there are two potential directions for improvement in future research. Firstly, incorporating qualitative research methods to integrate various considerations and leverage the strengths of different research approaches, enriching the content. Secondly, further refining the cost factors or optimizing cost calculation methods to make the research outcomes more representative.

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