Optimization Analysis of Cold Chain Logistics Network Structure Based on Genetic Algorithm

Jun Wan, Chengwu Zheng*
Liaoning Technical University, Xingcheng 125105, Liaoning Province, China
* Corresponding author: chengwvvz99@163.com

ABSTRACT

This paper presents an optimization analysis of the cold chain logistics network structure based on genetic algorithms. Firstly, the theoretical overview of the cold chain logistics network is introduced, including the concept, characteristics, and operation process of cold chain logistics, as well as the functional effects of logistics networks. Then, the structure of the cold chain logistics network is studied, including its composition and link analysis, and the formation mechanism of the cold chain logistics network is discussed. Subsequently, the genetic algorithm and its basic ideas and solution steps are explained in detail, and a genetic algorithm-based optimization model for the layout of cold chain logistics network nodes is constructed. The feasibility and effectiveness of the model are verified through case analysis. Finally, the research results of the paper are summarized, emphasizing the importance of optimizing the structure of the cold chain logistics network to improve operational efficiency. The research findings of this paper are of great significance for promoting the development of the cold chain logistics industry.

Keywords: Genetic Algorithm; Cold chain logistics; Network structure; Optimization analysis

1. INTRODUCTION

With the expansion of global trade and the growth of diversified product demands, the importance of cold chain logistics in modern supply chains is increasing. Cold chain logistics is a special logistics method that involves the transportation and storage of temperature-sensitive and perishable goods. The quality, safety, and shelf life of goods are directly affected by the effectiveness of cold chain logistics. Therefore, optimizing the structure of the cold chain logistics network is a key issue in improving logistics efficiency and reducing operational costs. Traditional design methods for the structure of cold chain logistics networks mainly rely on experience and manual approaches, which are difficult to fully consider factors such as complex transport routes, node layouts, and transport distances. In contrast, genetic algorithms, as an optimization algorithm, have the ability of global search and adaptability search, which can effectively solve the optimization problem of the cold chain logistics network structure. Therefore, in this paper, we will apply genetic algorithms to optimize the structure of the cold chain logistics network to improve operational efficiency and reduce costs. Through case analysis, we will verify the effectiveness and feasibility of the proposed optimization model. Finally, we will summarize the research results of the paper, emphasize the importance of optimizing the structure of the cold chain logistics network in improving the efficiency and quality of cold chain logistics, and provide prospects for future research directions [1].

2. OVERVIEW OF COLD CHAIN LOGISTICS NETWORK THEORY

2.1 Overview of Cold Chain Logistics Network

2.1.1. Concept of Cold Chain Logistics

Cold chain logistics is a specialized logistics method primarily used for the transportation and storage of temperature-sensitive goods to ensure that they are maintained at appropriate temperature conditions throughout the supply chain process, thereby preserving the quality, safety, and shelf life of the goods. Cold chain logistics covers the entire process from production, warehousing, distribution, to sales, and requires the use of specialized refrigeration equipment, transportation vehicles, and temperature monitoring systems. It is widely applied in fields such as food, pharmaceuticals, cosmetics to meet consumer demands for high quality and safety. The scope of service for cold chain logistics is illustrated in Figure 1.

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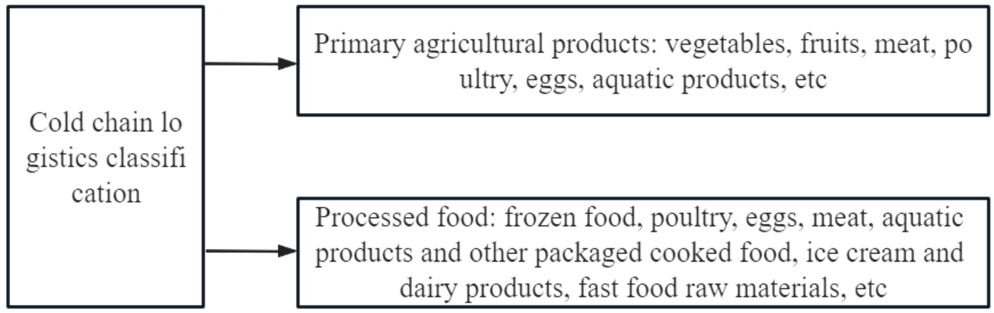

Figure 1. Cold chain logistics classification

Cold chain logistics is of growing importance and is vital for ensuring food safety and the effectiveness of medicines. As global trade grows and consumers continue to seek quality and safety in their goods, cold chain logistics will continue to evolve and innovate to provide more efficient and reliable logistics solutions [2].

2.1.2. Characteristics of cold chain logistics

Cold chain logistics has the following distinctive features:

(1) Temperature control: Cold chain logistics has strict requirements for temperature control. Different goods have different temperature requirements, such as frozen food, fresh agricultural products, pharmaceutical products. Cold chain logistics needs to ensure temperature stability and control throughout the transportation and storage process through refrigeration equipment, refrigerated vehicles, and temperature monitoring systems.

(2) Quality assurance: One of the goals of cold chain logistics is to maintain the quality of goods. Temperature changes and sudden temperature fluctuations during transportation and storage can lead to spoilage, deterioration, and damage to goods. Therefore, effective measures need to be taken in cold chain logistics to maintain freshness, quality, and safety of goods.

(3) Time sensitivity: Goods in cold chain logistics typically have a limited shelf life, making time sensitivity crucial. From production to the hands of consumers, transportation and storage time need to be minimized as much as possible to ensure optimal quality of goods within the limited shelf life.

(4) Diversified transportation modes: Cold chain logistics requires selecting suitable transportation modes based on the characteristics of different goods and transportation distances. It may involve a combination of various transportation modes such as land transportation, sea transportation, and air transportation to meet different transportation needs and distances.

(5) Link coordination: Cold chain logistics involves multiple links, including procurement, production, warehousing, and distribution. Close coordination and cooperation among these links are required to ensure temperature control, smooth information flow, and transportation safety. Only through coordinated operations can efficient cold chain logistics be ensured [3].

These characteristics make cold chain logistics a challenging logistics activity that requires the application of advanced technologies and management methods to ensure the quality, safety, and timeliness of goods.

2.2 Operation flow of cold chain logistics

Cold chain logistics is a comprehensive process that includes freezing processing, frozen storage, refrigerated transportation and distribution, as well as frozen sales. Firstly, cold chain logistics starts with freezing processing, where goods are subjected to freezing processing to lower the temperature and maintain the quality and freshness of the products. Next, frozen goods are stored in cold storage to ensure that they remain in a frozen state for a certain period of time. Then, in the refrigerated transportation and distribution stage, frozen goods are taken out from cold storage and transported and distributed using refrigerated vehicles and special packaging materials to maintain the goods at appropriate temperature conditions and ensure their quality and safety. Finally, in the frozen sales stage, frozen goods are sold to consumers, typically in supermarkets, restaurants, or through e-commerce platforms. During the sales process, the frozen goods need to be kept frozen and displayed and delivered to consumers under suitable temperature conditions.

The entire process requires close coordination and cooperation, the use of professional equipment, and temperature monitoring systems to ensure that the goods remain at suitable frozen conditions throughout the supply chain, ensuring their quality, safety, and freshness [4].

The combination of these four stages forms a cold chain supply chain, and multiple supply chains intertwine to form a complex cold chain logistics network. A typical cold chain supply chain process is illustrated in Figure 2.

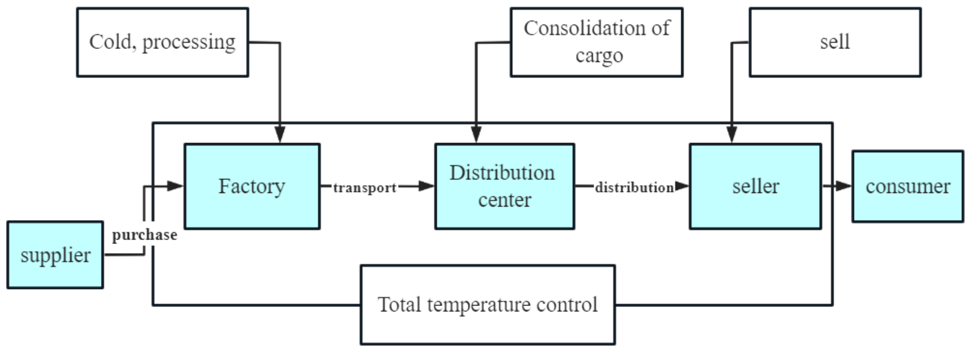

Figure 2. Typical cold chain supply chain process

3. STUDY ON THE STRUCTURE OF COLD CHAIN LOGISTICS NETWORK

3.1 Composition of Cold Chain Logistics Network

The components of a cold chain logistics network include supply chain nodes, transportation equipment and facilities, temperature monitoring and data management systems, compliance and standards, and information and technology support systems is illustrated in Figure 3.

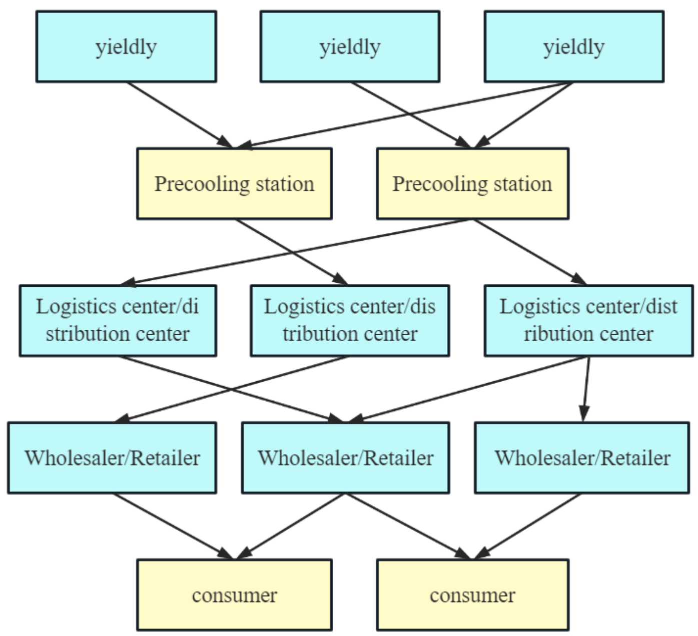

Figure 3. Cold chain logistics network structure

Firstly, supply chain nodes are the core of the cold chain logistics network. They include raw material suppliers, manufacturing and processing factories, warehouses, distribution centers, and sales terminals, forming the flow of logistics from raw materials to end consumers. Secondly, transportation equipment and facilities are essential components of the cold chain logistics network. Refrigerated vehicles, refrigerated ships, refrigerated containers, and cold storage facilities provide necessary transportation and storage conditions to ensure that goods maintain the required temperature throughout the transportation process. Temperature monitoring and data management systems are crucial for ensuring the safety and quality of cold chain logistics. With the help of temperature sensors and monitoring devices, real-time monitoring and recording of temperature data for goods can be achieved to ensure temperature control within the desired range. This data is used for traceability and quality management, supporting continuous improvement in cold chain logistics. Compliance and standards form the basis of the cold chain logistics network. Adhering to food safety regulations, refrigerated transport standards, and cold storage construction norms ensure the safety and quality management of goods during transportation. Information and technology support systems provide the necessary data and information for the cold chain logistics network. Information systems and technological tools such as order management, inventory management, route optimization, and temperature tracking improve the operational efficiency and management level of the cold chain logistics network [5].

3.2 Cold chain logistics network formation mechanism

3.2.1. Cold chain logistics node system dissipation structure analysis

The cold chain logistics node system refers to the composition and interrelation of various nodes in the cold chain logistics network. By analyzing the dissipative structure, we can better understand the operational characteristics and optimization methods of the cold chain logistics node system.

Firstly, the dissipative structure of the cold chain logistics node system is reflected in the flow of information and logistics. Information flow is a crucial part of cold chain logistics, involving the transmission of data related to order management, temperature monitoring, inventory management. Logistics flow includes the procurement, production, storage, and sales of goods. In the node system, these flows of information and logistics are transmitted through the connections and coordination between the nodes. Secondly, the dissipative structure of the cold chain logistics node system is also reflected in the dissipation of resources and energy. Resource dissipation refers to the allocation and utilization of human, material, and information resources required by each node in the system. For example, the node responsible for procurement needs to effectively manage supplier resources and transaction information. Energy dissipation involves temperature control and energy consumption. By using refrigeration equipment and rational energy allocation, the energy consumption during the logistics process can meet the requirements and maintain the appropriate temperature for the goods. Analyzing the dissipative structure of the cold chain logistics node system can help identify and address potential bottlenecks and issues, improving the efficiency and quality management level of the cold chain logistics network. Optimizing the flow of information and logistics between nodes, utilizing resources and energy reasonably, strengthening decision-making and coordination can enhance the resilience and adaptability of the entire cold chain logistics network, better meeting consumers' demands for high-quality cold chain products [6].

3.2.2. Analysis of self-organization of the main system of cold chain logistics operation

The cold chain logistics operational system refers to the various participants responsible for cold chain transportation and storage in the cold chain logistics network, who collaborate in a self-organized manner to achieve efficient operation and high-quality service in cold chain logistics.

Firstly, the self-organization of the cold chain logistics operational system is manifested in the collaborative relationships among the participants. These participants include suppliers, logistics companies, cold storage managers, distributors, and retailers, who work together through cooperation, information sharing, and collaborative decision-making to achieve the goals of the entire cold chain logistics. For example, suppliers provide goods according to order requirements, logistics companies handle transportation and warehousing, and distributors ensure goods are delivered to retailers. The collaboration among these participants forms the foundation of cold chain logistics operations. Secondly, the self-organization of the cold chain logistics operation system is manifested in the flexibility of its organizational structure. In order to meet market demands and changes, the cold chain logistics operation system needs to have a flexible organizational structure. Participants can adjust transportation routes, coordinate transportation capacity resources, and quickly respond to potential issues and challenges based on specific transportation needs and timing changes. This flexibility enables the cold chain logistics operation system to quickly adapt to market changes and demand fluctuations, providing efficient and reliable cold chain logistics services. Furthermore, the self-organization of the cold chain logistics operation system also includes support for information and technology. With advanced information systems and technological tools, participants in cold chain logistics can share real-time information, monitor temperatures, track the location of goods, and achieve accurate information transmission and comprehensive control. These information and technology support systems can enhance the visibility and predictive capabilities of cold chain logistics operations, helping participants make better decisions and adjustments, and improving the efficiency and reliability of the entire cold chain logistics system [7].

4. OPTIMIZATION OF COLD CHAIN LOGISTICS NETWORK NODE LAYOUT BASED ON GENETIC ALGORITHM

4.1 Overview of Genetic Algorithm

Cold chain logistics is a supply chain management system that specializes in handling and managing temperature-sensitive commodities during logistics and transportation. It involves the whole process of commodities from production to consumers, ensuring that commodities always maintain suitable temperature conditions throughout the transportation, storage and delivery process. The principle of genetic algorithm is shown in Figure 4:

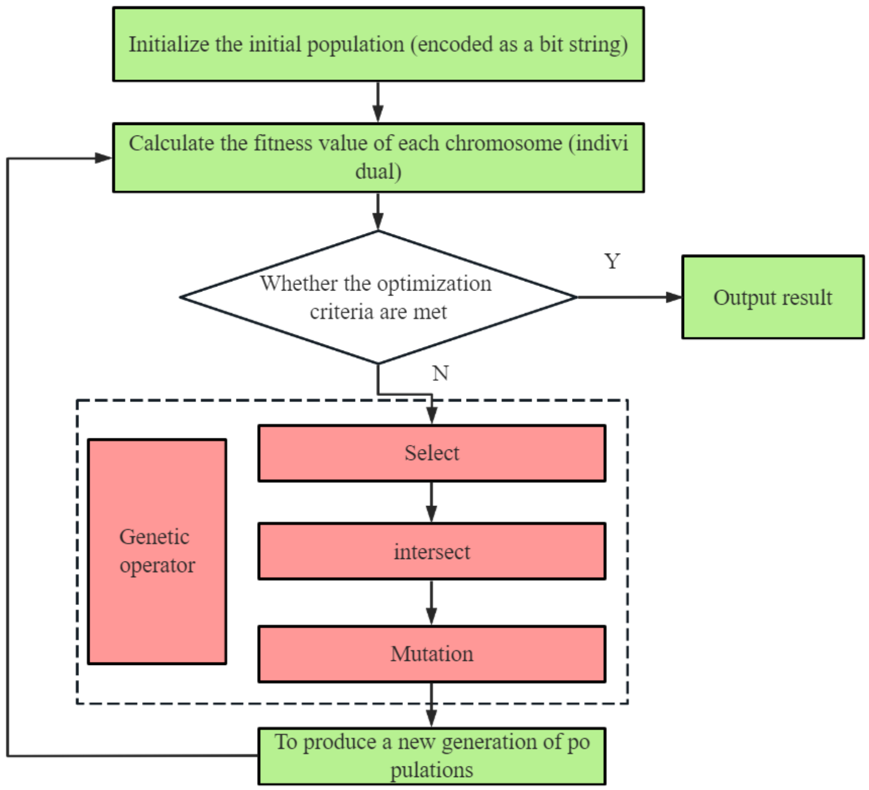

Figure 4. Principle of genetic algorithm

The key objective of cold chain logistics is to maintain the freshness, quality and safety of commodities. This applies mainly to commodities that are perishable, easily deteriorated and particularly sensitive to temperature, such as fresh food, pharmaceuticals, cosmetics and biological products. It requires strict temperature monitoring and control, and the adoption of appropriate measures such as fresh packaging and cold storage equipment, which can ensure that the commodities are not subject to loss or quality deterioration throughout the transportation process.

4.2 Steps for solving the genetic algorithm

Genetic algorithm, as an optimization algorithm, typically involves the following steps:

(1) Initialization: Randomly generate a certain number of individuals as the initial population based on the characteristics of the problem and the requirements of the solution space. Each individual corresponds to a potential solution.

(2) Fitness evaluation: Use a fitness function to assess the quality of each individual. The fitness function measures the objective value or quality of the individual's solution, with higher fitness values indicating better individuals [8].

(3) Selection: Select a certain number of superior individuals as the parents for the next generation population based on their fitness values. Common selection methods include roulette wheel selection and tournament selection.

(4) Crossover: Simulate the exchange of genes through crossover operations. The selected parent individuals undergo a crossover of gene segments with a certain probability, generating new offspring individuals. Crossover operations can increase the diversity and exploratory ability of the population.

(5) Mutation: Randomly mutate certain gene values of the generated offspring individuals with a certain probability. Mutation operations help introduce new combinations of genes, thereby increasing the exploration capability of the search space.

(6) Population update: Merge the offspring individuals generated from selection, crossover, and mutation operations with the parent individuals to form a new population.

(7) Termination check: After each iteration, check if the termination conditions are met. For example, reaching the maximum preset number of iterations, or the fitness reaching a threshold. If the conditions are met, terminate the algorithm; otherwise, return to step 3.

(8) Return the best solution: When the termination conditions are met, select the individual with the highest fitness value as the optimal solution. Depending on the specific problem, return the corresponding optimal solution or solution.

4.3 Example Analysis Study

4.3.1. Example of Genetic Algorithm Analysis

(1) Coding:

In the optimization problem of cold chain logistics network structure, we need to consider the connection methods and path selection between nodes. Genetic algorithms based on binary encoding can be used to represent the network structure. For example, we can encode each node number in the network as binary, and use a binary string to represent the network structure, where each position indicates whether a connection exists. By performing crossover and mutation operations on the genes, the network structure can be gradually optimized. This paper adopts the binary encoding approach for optimizing the layout of the cold chain logistics network, as shown in Figure 5.

Figure 5. Binary code describing chromosomes

(2) Adaptation function:

The fitness function is the evaluation metric for measuring the quality of the network structure. For the optimization of the cold chain logistics network structure, the fitness function can consider factors such as transportation cost, energy consumption, and service quality. For example, the fitness function can be defined as a weighted sum that takes into account these factors comprehensively, with the weights determined by the specific requirements of the problem. By calculating the fitness value of each individual (representing a network structure), its quality can be evaluated. In this model, the fitness values obtained from two consecutive assignment algorithms are embedded in the genetic algorithm for auxiliary solution. The objective function of the first assignment model, as shown in Formula (1), aims to minimize the related operational costs of precooling stations within 90 days [9].

$$MIN\left\{90\sum_{j} Y_j C_j^H \sum_{i} q_i^s X_{ij} + q_{jt} d_{jt} C_{ij} \frac{90}{P_j} \sum_{j} Y_j\right\} \tag{1}$$

where the constraints are shown in Formulas. (2), (3), (4), (5), (6).

$$\sum_{j} Y_j X_{ij} = 1 \tag{2}$$

$$Q_{\min}^P \le \sum_{j} Y_j \le Q_{\max}^P \tag{3}$$

$$d_{ij}X_{ij} \le L_{(i,j)\max} \quad (4)$$

$$0 < \sum_i X_{ij} < \infty \quad (5)$$

$$X_{ij}, Y_j \in (0,1), i \in I, j \in J \quad (6)$$

The objective function of the second assignment model, as shown in Formula (7), primarily involves the assignment of alternative precooling stations to the cold chain logistics distribution centers under the influence of constraint conditions. The objective is to minimize the total logistics cost, including leasing costs, transportation costs, and logistics activity operation costs, in the cold chain logistics distribution centers.

$$MIN\left\{30\sum_j C_t^L Z_T + \sum_t Z_t + \sum_j \left[q_{jt}\frac{90}{P_j}\times(d_{jt}C_{jt} + C_t^s)\right]\right\} \quad (7)$$

The constraints are shown in Formulas. (8), (9), (10), (11), (12), (13) as follows.

$$Q_{\min}^D \le \sum_t Z_t \le Q_{\max}^D \quad (8)$$

$$d_{jt}X_{jt} \le L_{(j,t)\max} \quad (9)$$

$$\sum_t q_{jt} \le Z_t Q_t \quad (10)$$

$$\sum_i q_i^S X_{ij} P_j = \sum_i q_{jt} \quad (11)$$

$$q_{jt} \ge 0 \quad (12)$$

$$X_{jt}, Z_t \in (0,1), j \in J, t \in T \quad (13)$$

(3) Genetic operator parameter setting:

When operating the genetic algorithm, some key parameters need to be set, including the probability of selection operation, crossover operation and mutation operation. For the cold chain logistics network structure optimization problem, these parameters can be set according to the actual situation and resource limitations. For example, the probability of selection operation can be adjusted to make the better solution have higher genetic probability; the probability of crossover operation and mutation operation can be adjusted moderately to maintain the diversity of the population.

4.3.2. Analysis of operation results

For the optimization problem of cold chain logistics network structure, by solving it using genetic algorithms, we can obtain a set of optimized network structures. In the result analysis, we can compare the differences between the initial population and the final optimized results, and evaluate the degree of optimization based on the values of the fitness function. At the same time, we can also analyze the effects of each genetic operator, such as the role of selection in improving the selection process of excellent solutions, the ability of crossover to improve the network structure, and the contribution of mutation in maintaining the population diversity. The MATLAB 7.0 Genetic Algorithm Toolbox is used for the solution, and through multiple parameter adjustments, the average runtime is determined to be 20 minutes, and the average number of generations to reach an approximate optimal solution is 76 generations [10]. Finally, the optimal layout of the nodes in the cold chain logistics network is obtained, as shown in Table 1.

Table 1.Example approximate optimal solutions

Serial number	yieldly	Precooling station	Cold chain logistics distribution center	Pre-cooling station centralized procurement cycle
1	1,3,4,6	IV	A	7
2	5,7,8,9	Il	B	2

5. CONCLUSION

This paper presents an analysis of cold chain logistics network structure optimization based on genetic algorithms. By delving into the characteristics, processes, and network structure of cold chain logistics, a genetic algorithm-based node layout optimization method is proposed. In the case analysis, the feasibility and effectiveness of this method are validated through the application of genetic algorithms. By optimizing the node layout of the cold chain logistics network, operational efficiency can be improved, costs can be reduced, and product quality and service levels can be enhanced. The research findings of this paper are of great significance in promoting the development of the cold chain logistics industry. Optimizing the structure of the cold chain logistics network makes it more efficient, flexible, and reliable, catering to the increasingly complex logistics demands. At the same time, the application of genetic algorithms provides a way for global search and adaptive search in optimizing the cold chain logistics network, offering new ideas and methods for solving practical problems. In summary, the analysis of cold chain logistics network structure optimization based on genetic algorithms can provide effective decision support and reference, guiding the development and practice of the cold chain logistics industry. With the continuous advancement of logistics technology and the abundance of data, the optimization of cold chain logistics network structure is expected to have broader development prospects.

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