An Improved Swarm Intelligence Optimizer for Transportation Path Planning of Cold Chain Products

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Abstract. With the development of fresh e-commerce, the problem of cold chain logistics transportation is gradually being studied by relevant researchers. However, there are issues such as high transportation costs and long transportation times in cold chain logistics transportation. This study designed a mathematical model for e-commerce cold chain logistics to address the aforementioned issues. By optimizing the order of distribution points, the model aims to reduce transportation costs and time during the cold chain product distribution process, while also reducing carbon emissions throughout the entire transportation process. On this basis, an improved artificial bee colony algorithm (IABC) was designed, and the selection strategy of the Grey Wolf Optimization (GWO) algorithm and the Artificial Fish Swarm (AFS) algorithm were introduced into the artificial bee colony algorithm, aiming to improve the convergence speed and accuracy of (ABC). Finally, the effectiveness of the algorithm designed in this study was demonstrated through a simulation algorithm.

Keywords: Cold chain logistics, Transportation, Artificial bee colony algorithm, Carbon emissions, Distribution

1 CHALLENGES IN FOOD COLD CHAIN LOGISTICS

1.1 Issue with Traditional Distribution Methods

At present, in the final fulfillment process of food cold chain logistics, cold chai n products such as fresh ice are usually placed in insulated bags or takeaway boxes without any added cooling materials for distribution[1]-[2]. Due to the fact that the ambient temperature of fresh ice food needs to always be maintained within the range of the cold chain logistics temperature range, if the transportation time is too long or the external temperature is high, it is easy to cause problems such as "cold chain detachment" or "pseudo cold chain" during the delivery process of the product, leading to corruption or spoilage [3]. The above issues have led to serious waste in the circulation of cold chain food. Due to the relatively small demand for products by consumers in the B2C e-commerce model, adopting the refrigerated truck direct delivery model will

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cause a sharp increase in the delivery cost of orders and have a significant negative impact on the environment [4]. In the specific process of fulfilling the end of cold chain products, on the one hand, consumers hope to purchase fresh food from e-commerce platforms in a safe and reliable way, replacing traditional channels such as supermarkets or agricultural markets. On the other hand, industry practitioners provide feasible and optimal operational strategies for fresh food through platforms, in order to strike a balance between customer value, product quality, and safety [5].

1.2 Consequences of Inefficient Distribution

Therefore, the joint delivery model of trucks and unmanned aerial vehicles (UAVs) that has emerged in recent years is being attempted by relevant enterprises to be applied in the last mile delivery, in order to solve the problems in the end of line fulfillment process [6]. Although relevant researchers have made efforts to reduce carbon emissions from fuel refrigerated vehicles and shorten delivery times [7-9], there are still problems in the end of contract fulfillment process of B2C fresh ice e-commerce cold chain logistics, such as lagging development of new energy refrigerated vehicles and green energy-saving processes, prominent environmental problems, insufficient Informa ionization and automation of the system, and lack of attention to public attitudes towards delivery methods such as drones [10-11].

1.3 Study Designed a Mathematical Model for E-Commerce Cold Chain Logistics

The development of Cyber Physical Systems (CPS) provides a solution for the full lifecycle management of cold chain products during the last mile delivery process [12]. Therefore, combining CPS technology with the collaborative delivery model of trucks and unmanned aerial vehicles, and designing appropriate equipment and delivery methods to meet the requirements of last mile delivery for cold chain products, is a feasible attempt. The key lies in the low-carbon, energy-saving, and efficient cold chain logistics terminal fulfillment technology for ice fresh e-commerce.

In order to solve the problems in cold chain logistics transportation, this study designed a mathematical model for e-commerce cold chain logistics. By optimizing the order of distribution points, this model considers the transportation cost and time during the cold chain product distribution process, as well as the carbon emissions throughout the entire transportation process. On this basis, an improved artificial bee colony algorithm (IABC) is designed to improve the convergence speed and accuracy of (ABC). At the same time, the IABC algorithm was successfully applied to the established mathematical model and simulated through simulation.

2 REFRIGERATION METHODS AND CHALLENGES IN COLD CHAIN LOGISTICS

2.1 Selection of Refrigeration Method and Refrigeration Time

At present, there are three main refrigeration methods used in distribution equipment for cold chain logistics, including active refrigeration by refrigeration compressors, passive refrigeration using phase change materials for refrigeration or freezing, and mixed refrigeration using phase change materials controlled by refrigeration systems [13]. According to the disclosure of the Cold Chain Logistics Professional Committee, China's cold chain logistics industry produces nearly 300 million foam boxes and nearly 1 billion ice bags every year, which has a serious negative impact on the environment. Therefore, there is an urgent need to improve the refrigeration technology in the fulfillment process of cold chain logistics at the end, in order to form low-carbon emission refrigeration technology. The research on refrigeration technology can be divided into two types, namely the development of refrigeration phase change materials and the selection of refrigeration methods and refrigeration time [14]. The selection of refrigeration method and refrigeration time refers to the rational selection of refrigeration methods and planning of refrigeration time based on factors such as the weight of the delivered goods and the distance of delivery during the delivery process, in order to efficiently and energy-saving complete the delivery work. At present, relevant researchers have conducted research on the development of refrigeration materials for trucks, such as eutectic freezing plates [15]. However, there is still a gap in technical research on the selection of refrigeration methods and refrigeration times for cold chain products such as fresh ice during transportation. It is worth noting that in the process of joint delivery between trucks and UAVs, due to the fact that delivery drones often use batteries to provide energy, the choice of refrigeration method and time for the cargo boxes carried on UAVs is directly related to the working time of UAVs.

2.2 The Cold Chain Logistics Distribution Path Planning Problem

The cold chain logistics distribution path planning problem, as a variant of the traditional Vehicle Routing Problem (VRP), can be divided into two categories according to the different mathematical models established [16]. One type of problem is aimed at minimizing delivery costs, further expanding to multi-objective mathematical models such as improving customer satisfaction and reducing transportation time [17], and ensuring the freshness of products during the delivery process with hard time window constraints, which is closest to traditional VRP. The other type is based on the reality that "sustainable development goals are highly valued by human society", which has led to a separate type of multi-objective mathematical model research, namely the green cold chain logistics distribution problem [18], but there has been no exploration of the relationship between cold chain logistics and social value.

2.3 The Proposal of Establishing a High Fidelity Mathematical Model of the UAV

Through the above research content, it can be found that the refrigeration method and refrigeration time determine the electricity consumption of unmanned aerial vehicles carrying cargo boxes, which directly affects the working time of UAVs. It is important to determine the optimal refrigeration process to balance the contradiction between the sustainability of distribution behavior and quality management; In addition, in the process of monitoring the entire lifecycle of the digital twin model for the fulfillment process of cold chain logistics, the primary issue that needs to be faced is how to accurately locate vehicles and UAVs based on limited sensing equipment, so as to successfully complete the transmission and reception of UAVs; Further, it is necessary to establish a high fidelity mathematical model of the UAV based on its physical performance, in order to carry out three-dimensional flight path planning for the UAV.

3 OPTIMIZER FOR TRANSPORTATION PATH PLANNING OF COLD CHAIN PRODUCTS

3.1 Mathematical Model

This study aims to address technical challenges such as the easy occurrence of "cold chain disconnection" and insufficient environmental protection of existing refrigeration methods in the end of contract fulfillment process of e-commerce cold chain logistics. It attempts to introduce an automated logistics paradigm into the end of contract fulfillment process of cold chain logistics. Based on the joint distribution model of trucks and UAVs, a refined mathematical model of trucks and UAVs is developed to accurately and quantitatively analyze the impact of cold chain logistics on the social level. A multi-objective mathematical model of the joint distribution system is reasonably designed and corresponding algorithms are developed to improve the existing electronic fulfillment technology of ice and fresh products, ensuring that e-commerce enterprises complete the distribution of perishable goods such as high efficiency, low cost, and low-carbon ice and fresh products.

In this study, a multi-objective function model as shown in (1) is established based on the objective functions generated from the objectives of delivery time $f_1(\vec{x})$, delivery cost $f_2(\vec{x})$, and carbon emission cost $f_3(\vec{x})$ as follows.

$$\max f(\vec{x}) = \alpha_1 \times f_1(\vec{x}) + \alpha_2 \times f_2(\vec{x}) + \alpha_3 \times f_3(\vec{x}) \tag{1}$$

Further, constraints are established based on the physical properties (e.g., maximum load constraints, maximum range constraints) of the vehicle and the UAV. First of all, according to the mechanical architecture of the vehicle, sensors, communication modules and the 3D environment in the physical system, a real-time and accurate digital mapping is carried out, and the corresponding geometric Gm, physical Pm, behavioral Bm and rule Rm models are established in the information world. The establishment of the digital twin model in the information-physical system is successfully realized as follows:

$$D_{TM} = \{Gm, Pm, Bm, Rm\} \tag{2}$$

The calculation method for each component of the objective function is as follows:

$$f_1(\vec{x}) = \sum \vec{x}/v \tag{3}$$

where $\vec{x}$ is the distance between two delivery nodes, and v is the speed of the vehicle.

$$f_2(\vec{x}) = C_{ost} \times \sum \vec{x} \tag{4}$$

where C_{ost} is the transportation cost per kilometer of goods.

$$f_2(\vec{x}) = CE \times \sum \vec{x} \tag{5}$$

where CE is the carbon emission cost per kilometer of goods.

3.2 Algorithm Design

Due to the fact that the VRP problem belongs to a typical NP-hard problem, the computation time of the exact algorithm increases exponentially when solving, and it is not suitable for e-commerce models with large-scale consumers such as B2C. With the development of artificial intelligence technology, solving methods such as swarm intelligence and machine learning have been widely applied in various VRP and cold chain logistics distribution path planning problems; Among them, the solution method of swarm intelligence can be specifically divided into two types: posterior based Pareto optimal solution and prior based solution. Both algorithms are inevitably influenced by expert experience, but prior based solutions can weaken the influence of experts by using methods such as Analytic Hierarchy Process. Meanwhile, in order to solve VRP more quickly, a large number of machine learning schemes have been designed. Unlike swarm intelligence algorithms, existing machine learning schemes have certain shortcomings in terms of interpretability of results.

Similar to traditional VRP, the research on the above fulfillment systems aims to improve delivery efficiency or reduce the negative impact of delivery, while ensuring product quality through time window constraints; But without considering the supervision of the entire lifecycle of the cold chain logistics end performance process, it cannot truly ensure the quality of products delivered to customers. In addition, some companies use refrigeration solutions that far exceed the demand for refrigeration to ensure product quality, leading to a contradiction between the sustainability of distribution behavior and quality management. Therefore, it is necessary to further address the issue of monitoring the entire lifecycle of performance at the end of cold chain logistics, in order to prevent the occurrence of "cold chain disconnection" during product delivery. To achieve this, CPS and digital twin technology can be used to construct a virtual real interactive digital twin model for truck and UAV joint delivery fleets, and combined with fresh ice product freshness detection technology to supervise the entire lifecycle of the cold chain logistics terminal fulfillment process.

Fig.1. shows the flowchart of the IABC algorithm designed for this study. We introduce the update strategies of GWO and AFS algorithms into the ABC algorithm, and the improved update strategy is as follows:

Before updating, generate a random number A on the interval [0,1].

If $A \geq 0.5$, then

$$B_{ij}(new) = B_{ij}(old) + \lambda \times \left(B_{ij}(old) - B_{mj}\right) \tag{6}$$

where $B_{ij}(new)$ is the updated individual, and $B_{ij}(old)$ is the individual before the update. B_{mj} is the j-th dimension of the m-th individual, λ is a random number on the interval [-1,1].

If $A < 0.5$, then

$$B_{ij}(new) = B_{ij}(old) + Step \times Rand \tag{7}$$

where $Step$ is the step factor.

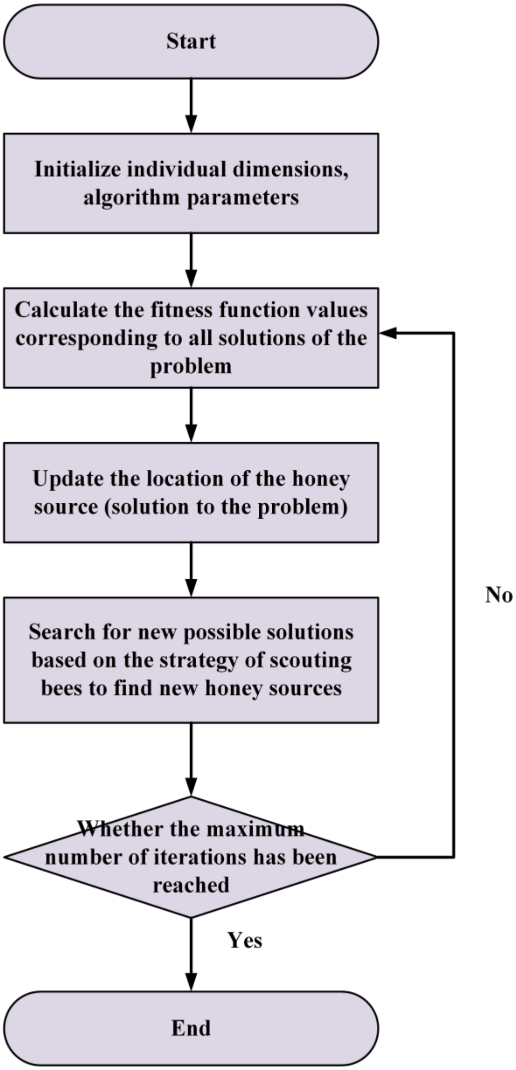


Fig. 1. Algorithm flow chart

3.3 Results Display

In this section, the performance of IABC algorithm as well as path planning results are shown. In the simulation experiment, we set the maximum number of iterations of the algorithm to 600, which means that when the number of iterations exceeds 600, the algorithm will stop running and output results. In addition, to evaluate the robustness of the algorithm, each algorithm was run 20 times.

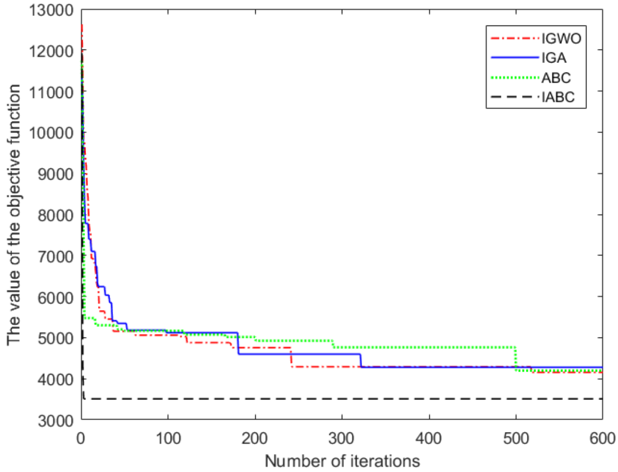


Fig. 2. Iteration curves for the optimal fitness function.

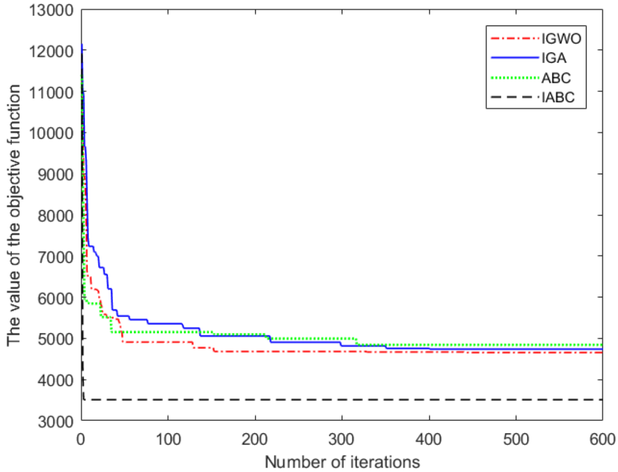


Fig. 3. Iteration curves for the worst fitness function.

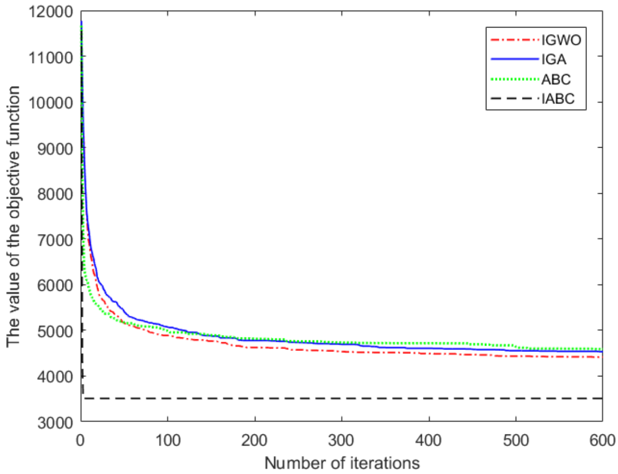
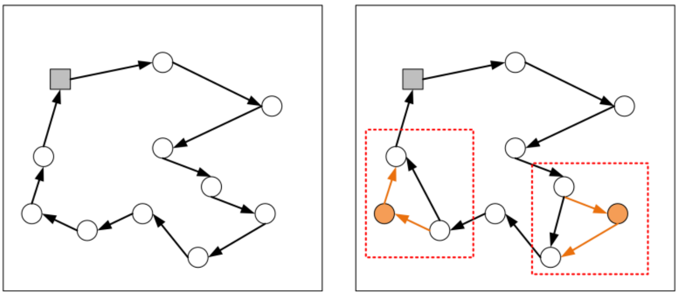


Fig. 4. Iteration curves for the average fitness function.

In order to evaluate the performance of algorithms, several swarm intelligence algorithms were used for comparison. Fig. 2, 3, and 4 respectively show the fitness function curves of the optimal, worst, and average solutions generated during the algorithm operation. The IABC algorithm has the fastest convergence speed and the highest convergence accuracy.



(a) **(b)**

Fig. 5. Path planning results for IABC algorithm.

Fig.5 shows the difference between joint distribution of vehicles and UAVs and distribution schemes that only use vehicles for distribution. World results also show that using joint distribution of vehicles and UAVs results in lower shipping costs and transportation time, as well as lower carbon emissions.

4 CONCLUSIONS

This study focuses on the problem of cold chain logistics transportation. At present, there are problems with high transportation costs and long transportation times in cold chain logistics transportation. This study designed a mathematical model for e-commerce cold chain logistics to address the aforementioned issues. This model aims to reduce transportation costs and time in the distribution process of cold chain products, while also reducing carbon emissions throughout the entire transportation process. On this basis, an improved artificial bee colony algorithm (IABC) was designed, and simulation experiments proved that the improved ABC algorithm has a faster convergence speed and higher convergence accuracy compared to the other three swarm intelligence algorithms. Meanwhile, the experimental results indicate that the use of vehicles combined with drones for delivery can generate less carbon emissions and transportation costs, while also shortening transportation time.

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