International Journal for Housing Science and Its Applications
Publish August 10, 2025. Volume 46, Issue 4 Pages 271-283

https://doi.org/10.70517/ijhsa46422

Research on optimization and performance improvement of cross-border e-commerce logistics network based on quantum annealing algorithm in digital economy environment

Shuxin Wei[1,*]
[1] Guangdong University of Science and Technology, Dongguan, Guangdong, 523083, China
Corresponding authors: (e-mail: weishuxin@gdust.edu.cn).

Abstract Under the background of rapid development of digital economy, cross-border e-commerce has become an important engine of global trade, and the efficiency of its logistics network directly affects customer satisfaction and enterprise cost control. Aiming at the multi-objective optimization of cross-border e-commerce logistics network, this study innovatively introduces the quantum annealing algorithm, which breaks through the local optimal limitation of the traditional algorithm through the quantum tunneling effect and the superposition state characteristic, and constructs a multi-objective optimization model focusing on the logistics cost, time value and customer satisfaction. The study takes the overseas warehouse mode maritime logistics network as the object, and quantifies the multiple cost items such as storage, transportation, tax and fee through the mechanism of task decomposition and resource synergy. In the simulation example, the network robustness is verified by destruction resistance simulation. Under random attack, the network connectivity drops to 49.29% (node attack) and 56.55% (edge attack) when the node deletion ratio reaches 50%. In the deliberate attack, the improved maximum node mediator attack maintains a connectivity rate of 43.10% at a deletion ratio of 20%, which is better than the 20.79% of the traditional strategy and the 11.04% of the node-degree attack, indicating that the optimized network possesses a strong anti-interference capability. The quantum annealing algorithm has an optimal solution ratio of 79.23% in large-scale problems, which is significantly higher than the 56.19% of the genetic algorithm and the 50.18% of the heuristic algorithm, and the average number of solutions is 27.3, which is also ahead of similar algorithms. Although the CPU running time is slightly higher than that of the genetic algorithm, its global search ability and the quality of the solution have a significant advantage. This study provides support for the intelligent optimization of cross-border e-commerce logistics network and helps enterprises to reduce cost and increase efficiency and sustainable development.

Index Terms quantum annealing algorithm, cross-border e-commerce, logistics network optimization, quantum tunneling effect

I. Introduction

With the gradual development of e-commerce, online transactions, online shopping and other services are becoming more and more convenient. Under economic globalization and China's “One Belt, One Road” development policy, e-commerce gradually involves cross-border business, and many countries strongly support the development of cross-border e-commerce, and a number of related policies have been enacted, laying the foundation for the rapid development of cross-border e-commerce [1]-[3]. Nowadays, it is in the era of digital economy, which breaks the geographical barriers and makes it easier for merchants to enter the global market [4]. Through the Internet and digital technology, not only does it increase the exposure of cross-border e-commerce enterprises, but cross-border e-commerce enterprises also have direct access to the global consumer market and consumer data, and customize their marketing strategies in response to changes in the market [5], [6]. In addition, the digital economy environment expands the cross-border e-commerce business model, realizes the globalization of sales and exchanges, provides more efficient supply chain management, and makes cross-border e-commerce more competitive [7], [8]. However, in terms of logistics, on the one hand, because cross-border e-commerce trading platforms will regularly carry out shopping promotions, so there will be a surge of large quantities of goods within a short period of time, which puts higher requirements on the efficiency of warehouse scheduling, and the traditional logistics network is insufficiently supervised, which puts enormous pressure on the entire logistics network [9]-[11].

Meanwhile, the carbon emission of cross-border e-commerce logistics and transportation increases gradually with the rise of the order volume, while the traditional logistics network ignores the carbon cost, which exceeds the merchant's budget [12]. On the other hand, since cross-border e-commerce platforms have to have a corresponding logistics network for cross-border transportation of goods after they are sold, consumers are demanding more and more efficiency in cross-border logistics, but the current logistics network has a long time limit for transporting goods, high cost, weak infrastructure, complicated customs clearance procedures, and lack of dynamic response, which seriously restricts the further development of the industry [13]-[16]. Therefore, the optimization and efficiency improvement of cross-border e-commerce logistics network has also gradually become a mainstream issue.

Under ideal circumstances, a good cross-border e-commerce logistics network can bring higher value to enterprises, reduce costs, and improve service standards for consumers. Most optimization problems of logistics networks are conducted with the goal of minimizing cost, and a small number of studies include maximizing consumer service, but there is a certain conflict between the two, as consumer service level is reflected in responsiveness and reliability [17], [18]. In order to ensure higher consumer service quality, some intermediate steps can be added (e.g., adding some distribution centers), but this will inevitably increase the cost expenses of the firms [19], [20]. At the same time, it is also possible to reduce the costs through low-priced distribution channels and cheap transportation methods, but this will have a great impact on the consumer service. Therefore, scholars have proposed several algorithm-supported optimization schemes for logistics networks, but the current optimization techniques have problems to be optimized, such as low computational efficiency in the quantum limit and quantum encryption compliance [21], [22].

In this study, quantum annealing algorithm is introduced into the field of cross-border e-commerce logistics network optimization, aiming to break through the limit of local optimization and realize the efficient allocation of global resources through the advantage of quantum computing. The article is based on the logic of “logistics network modeling - parameter analysis - algorithm adaptation”. Firstly, taking the overseas warehouse mode maritime logistics network as the research object, the cross-border logistics tasks are decomposed into the sub-task sequences of hub warehouse and overseas warehouse through structural mapping and problem abstraction, and the resource selection mechanism under multi-party collaboration is clarified. Further, a mathematical model is constructed to quantify the key objective functions such as logistics cost, time value and total time, covering multiple cost items such as storage, transportation, tax, etc., and forming a multi-objective optimization framework by combining time constraints and customer satisfaction. Finally, the quantum annealing algorithm is introduced to solve the high-dimensional search problem in combinatorial optimization through quantum tunneling effect and superposition state characteristics, and maps the logistics resource allocation problem into the Hamiltonian of the Ising model. The quantum annealing algorithm is able to transform the combinatorial optimization of sub-task candidate resources into the base state search of quantum bits, so as to dynamically balance the multi-objective conflicts of cost, time and satisfaction in the process of quantum annealing, and ultimately to realize the fast approximation of the global optimal solution.

II. Multi-objective optimization model construction and solution for cross-border e-commerce logistics network

II. A. Cross-border e-commerce overseas warehouse model maritime logistics network

II. A. 1) Description of the problem

Figure 1 shows the network structure of cross-border transaction by sea transportation in overseas warehouse mode.

In the ocean transportation process, we set the number of overseas warehouses to be certain, the number of domestic sellers and the number of foreign buyers to be random, and sellers and buyers can only choose any one overseas warehouse at the same time. Since the transportation cost from sellers to domestic hubs and the transportation cost from overseas warehouses to customers are negligible relative to the cost of ocean transportation, without loss of generality, the contents of the dotted box in Fig. 1 are used as the research object of the cross-border transaction network structure of overseas warehouse mode.

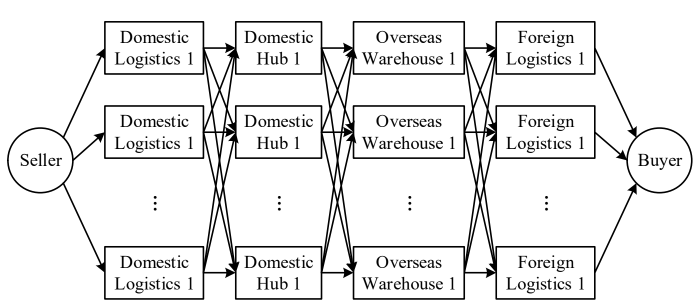

Figure 1: Structure of warehouse model for cross-border maritime transactions

In the overseas warehouse mode cross-border transaction network model shown in Figure 1, third-party logistics is generally required to complete the transportation from domestic to foreign countries, while the overseas warehouse can be obtained through self-built warehouses or through leasing, and usually the logistics from the overseas warehouse to the customer is also completed by the foreign third-party logistics, and thus the whole process of cross-border transactions is accomplished by the logistics of multiple parties working together. Therefore, we map this process of multi-party collaboration into the problem of optimal allocation of logistics resources across organizational boundaries. In this logistics operation process, the service core enterprises need to collaborate and share the logistics resources in the global scope due to their own resource constraints to accomplish the logistics tasks together. We map the logistics process in the dotted box in Figure 1 into the structure of the cross-border e-commerce maritime logistics network operation in overseas warehouse mode shown in Figure 2.

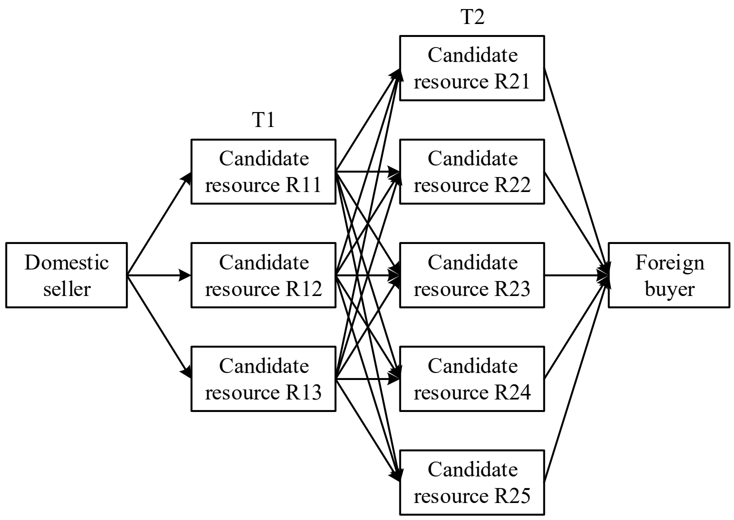

Figure 2: The operation structure of the logistics network in the warehouse model

In the whole transaction process, cross-border e-commerce enterprises can decompose the logistics task T into multiple sub-task sequences T_i according to certain rules based on customer demand. Divide the whole task into T_1 and T_2 tasks, where sub-task T_i denotes that there are 3 candidate hub warehouse resources, sub-task T_2 denotes that there are 5 candidate overseas warehouse resources, and each sub-task T_i has k_i candidate resources, the first j candidate resource of the i sub-task is denoted as $R_{ij}, i \in \{1,2,.....I\}, j \in \{1,2,...,k_i\}$, thus constituting a network of overseas warehouse mode operation structure under the ocean transportation mode driven by subtasks T_i and sharing of various resources R_{ij} among logistics alliance enterprises, with the number of subtasks T_1, the candidate resources of hub warehouses $k_i = 3$ the number of subtasks T_2, and candidate resource $k_i = 5$ for overseas warehouse. For different candidate logistics resources, there are differences in service cost, customer satisfaction, and goods return service, etc. Resource allocation is to obtain the optimal resource combination by evaluating the combined resources.

II. A. 2) Parameter definitions

The parameters of the operational structure model of the logistics network for the overseas warehouse model of Fig. 2 are defined as follows:

T : logistics task;

T_i : logistics task subsequence, $i \in \{1,2,.....I\}$;

R_{ij} : the j th candidate resource for the i th subtask, $i \in \{1,2,...,I\}, j \in \{1,2,...,k_i\}$;

T_1 : this paper refers to the domestic third-party logistics sub-task for hub warehouse;

T_2 : this paper refers to foreign third-party logistics subtasks, for overseas warehouses;

C_{ij} : the cost of using the j th candidate resource for the i th subtask, in dollars per cubic meter;

P_a : is the total amount of ocean freight per shipment, in cubic meters;

η : The cost of overseas warehouse storage per day in USD/day/cubic meter;

t_j : the time of overseas warehouse storage, calculated by day, $j \in \{1,2,...,N\}$;

P_j : the volume of goods stored in the overseas warehouse on the j th day, in cubic meters, $j \in \{1,2,...,N\}$;

X : the average daily volume of goods shipped from the overseas warehouse, in cubic meters per day;

C_j : storage fee cost for the j th overseas warehouse, $C_j = P_j t_j \eta$, in dollars;

C_{mn} : headway cost cost from the m th hub warehouse to the n th overseas warehouse;

C_{nw} : total warehousing cost cost of the n th overseas warehouse;

$f(C)$: total cost objective function;

C_p : total customer program cost;

$f(S)$: satisfaction objective function;

S_p : customer program satisfaction;

S_{ij} : denotes the satisfaction evaluation after task i selects the j th resource to execute;

H_{ij} : is the decision variable, $H_{ij} \in \{0,1\}$, $H_{ij} = 1$ means that the i th sub-task selects the candidate resource R_{ij} , and $H_{ij} = 0$ means that the i th sub-task does not select the candidate resource R_{ij} .

II. B.Function analysis

Based on the above structural characteristics and task decomposition logic of the logistics network in overseas warehouse mode, the cost and efficiency parameters of each link need to be further quantified to support the construction of the mathematical model. In this section, the complex logistics resource allocation problem is transformed into a multi-objective optimization task by defining key variables and functional relationships.

II. B. 1) Logistics cost function

The logistics cost mainly considers the development and operation cost of bonded warehouse, enterprise operation cost, warehousing cost, transportation cost, tax of products and other additional costs such as port fee.

According to the parameters, assumptions and the actual situation, the number from 1 to n is the bonded warehouse that the enterprise has at present, and n+1 to m is the alternative location of the bonded warehouse that can be newly developed, then the cost of opening and closing the bonded warehouse and the fixed operating costs are calculated as shown in formula (1).

$$C_1 = \sum_{j=n+1}^{m} X_j \cdot u_j - \sum_{j=1}^{n} (1 - X_j) \cdot v_j + \sum_{j \in J} X_j \cdot a_j, 1 \le n < m \tag{1}$$

Enterprise operating cost refers to the labor cost and other resources spent by the enterprise to maintain the operation of the logistics network, which is directly proportional to the number of products, and the larger the volume of goods, the higher the operating cost. Then the calculation of enterprise operation cost is shown in formula (2).

$$C_2 = \sum_{h \in H} a_0 \cdot Q_h \tag{2}$$

Warehousing costs include the cost of warehousing products in domestic warehouses and bonded warehouses, and different warehouses have different unit warehousing costs. Unit warehousing costs must be warehousing costs related to time and the number of products, the decision variable Y is 1 when the product is valid, indicating that the use of the warehouse for warehousing, incurring costs are included in the cost of warehousing. Which each (batch) of products in a bonded warehouse within the period of exemption from paying storage costs, more than the period of exemption from paying storage costs per unit. Warehousing costs are calculated as shown in the formula (3), where the formula at the end of the upper right corner of the "+" that the results of the calculation in parentheses for the positive value of the validity of the parentheses if the negative value is taken as zero.

$$\begin{aligned} C_3 = & \sum_{h \in H} \sum_{k \in K} Y_{hik} \cdot Q_h \cdot w_{hk} \cdot t_{3hk} \\ & + \sum_{h \in H} \sum_{j \in J} Y_{hijk} \cdot Q_h \cdot w_{hj} \cdot (t_{1hj} - T_j)^+ \end{aligned} \tag{3}$$

Transportation costs include the road transportation costs for the three paths from the port to the bonded warehouse, from the bonded warehouse to the domestic warehouse, and from the port to the domestic warehouse, with different unit transportation costs for different segments. When the unit transportation cost is certain, the road transportation cost is related to the transportation distance and the number of products, and the product is valid when the decision variable Y is 1, which means that the transportation is carried out through this section of the path, and the costs incurred are included in the transportation cost. Then the transportation cost is calculated as shown in equation (4).

$$\begin{aligned} C_4 = &\sum_{h\in H}\sum_{i\in I}\sum_{j\in J} Y_{hijk}\cdot C_{hij}\cdot D_{ij}\cdot Q_h \\ &+\sum_{h\in H}\sum_{j\in J}\sum_{k\in K} Y_{hijk}\cdot C_{hk}\cdot D_{jk}\cdot Q_h \\ &+\sum_{h\in H}\sum_{i\in I}\sum_{k\in K} Y_{hik}\cdot C_{hk}\cdot D_{ik}\cdot Q_h \end{aligned} \tag{4}$$

Taxes and charges on imported products mainly include customs duties and value-added tax, with different tax rates for different products. The value of the products is generally based on the purchase contract signed for the imported products, and the taxes and charges to be paid are calculated by multiplying the value of the products by the tax rate. The total tax is then calculated as shown in formula (5).

$$C_s = \sum_{h\in H} s_{1h}\cdot P_h + \sum_{h\in H} s_{2h}\cdot P_h \tag{5}$$

The storage and loading and unloading of cross-border transportation products after their arrival in Hong Kong will generate additional costs such as port charges, plus bank charges, insurance premiums, etc., for each batch of orders, which can be regarded as directly proportional to the number of products according to the average value of the calculation. The total surcharge is then calculated as shown in formula (6).

$$C_6 = \sum_{h\in H} e_h\cdot Q_h \tag{6}$$

II. B. 2) Time value function

Imported fresh products need to pay taxes and fees when customs clearance, so the tax payment time is different between customs clearance from bonded area and customs clearance from port. Transportation from the port direct customs clearance, the need to pay taxes and fees on the same day, while transportation through the bonded warehouse is to pay taxes and fees when out of the bonded warehouse, delayed payment of taxes in addition to alleviate the pressure on the enterprise's capital, but also save the tax in the limited time difference in the interest or investment income, so with the time saved times multiplied by the need to pay taxes and fees and then multiplied by the rate of interest or rate of return can be obtained from the value of time. Therefore, the time value function is calculated as shown in formula (7).

$$P_1 = \sum_{h\in H}\sum_{i\in I}\sum_{j\in J} Y_{hijk}\cdot C_5\cdot (t_{0hij}+t_{1hj}+t_{2hj}-t_{1hi})\cdot \gamma / 365 \tag{7}$$

II. B. 3) Functions of time

For a numbered arbitrary h a (lot) of products facing a business customer, the contract has agreed on a pickup or delivery time, so it is assumed that the total time duration is equal to that specified time frame. The decision variable Y is valid when it is 1, indicating that the path through the segment. The total length of the product transported through the bonded warehouse is the port to the bonded warehouse transportation time + bonded warehouse storage time + bonded warehouse clearance time + bonded warehouse to the domestic warehouse transportation time, the total length of the product transported directly from the port customs clearance to the domestic warehouse is the port customs clearance time + port to the domestic warehouse transportation time + domestic warehouse storage time. The total duration of the product is calculated as shown in formula (8).

$$T_h = Y_{hijk}(t_{0hij}+t_{1hjk}+t_{2hj}+t_{3hjk}) + Y_{hik}(t_{1hi}+t_{2hk}+t_{3hk}) = t_h \tag{8}$$

Equations (9)-(13) show the calculation of product transportation time and storage time. Transportation time is calculated by dividing the distance by the average road transportation speed. The storage time is calculated by subtracting the customs clearance time and transportation time from the total length (specified time limit).

$$t_{0hij} = D_{ij} / V \tag{9}$$

$$t_{3hjk} = D_{jk} / V \tag{10}$$

$$t_{2hk} = D_{ik} / V \tag{11}$$

$$t_{1hj} = t_h - t_{0hj} - t_{2hj} - t_{3hjk} \tag{12}$$

$$t_{3hk} = t_h - t_{1hi} - t_{2hk} \tag{13}$$

II. C.Quantum annealing algorithm

After clarifying the mathematical model of logistics cost, time value and total duration, it becomes crucial to efficiently solve this multi-constraint, high-dimensional combinatorial optimization problem. The quantum annealing algorithm provides a new technical path for the exploration of the global optimal solution by virtue of its quantum tunneling and parallel search characteristics.

Quantum annealing, similar to simulated annealing, is inspired by the physical annealing process to find the optimal state of a system by simulating the process of heating and then slowly cooling a substance. Analog annealing is a thermally assisted jump by controlling the change of temperature parameters to determine the probability of transitioning from the current state to a higher energy state. In quantum annealing, on the other hand, quantum tunneling is the key to crossing the energy barrier. Quantum annealing effectively avoids local minima (local optima of the optimization problem) through the quantum tunneling effect, allowing the system to pass directly through the energy barriers instead of having to "crawl over" them, which is especially important when dealing with complex optimization problems with multiple local minima, and theoretically can reach the global minimum of energy (the optimization problem) at the end of the adiabatic evolution. The global minimum of the energy (the global optimum of the optimization problem) is reached at the end of the adiabatic evolution.

QA can be viewed as a subclass of AQC, where the Hamiltonian type of H_f is fixed and is not guaranteed to be adiabatic, but is subject to the same adiabatic conditions. The simplest form of quantum annealing is shown below:

$$H(t) = A(t)\left[\sum_i \sigma_i^x\right] + B(t)\left[\sum_i h_i\sigma_i^z + \sum_{i<j} J_{ij}\sigma_i^z\sigma_j^z\right] \tag{14}$$

The σ_i^x and σ_i^z are the bubble-X and bubble-Y spin matrices of the i th quantum bit with two completely random possible states (e.g., 0 vs. 1, ±1), respectively. Whereas the initial Hamiltonian H_i is replaced with a simple quantum state convenient for computation, the problem Hamiltonian is formulated using a two-dimensional Ising model, h_i is the energy offset acting on the σ_i^z of the bubbly-Z spin matrix, and J_{ij} is the strength of the couplings between the different quantum bits. By modulating the energy offset h_i and the coupling strength J_{ij} it is possible to realize the application of the optimization problem encoding to the quantum annealing algorithm. The ground state of the two-dimensional Ising model is found to be NP-Hard, and the Hamiltonian quantity described by Eq. (14) is sufficient to construct many combinatorial optimization problems.

At the algorithmic level, the Hamiltonian function of the quantum annealing algorithm can also be expressed in the following form:

$$H = H_P + I(t)H_D \tag{15}$$

where H_P is the Ising model Hamiltonian function of the problem and H_D is the introduced external cross field. The Γ is the coefficient controlling the strength of the cross field, which is time-dependent and acts similarly to the temperature of analog annealing, and is capable of inducing the collapse of a quantum bit from a superposition state to a classical state of 0 or 1.

The biggest advantage of quantum annealing over simulated annealing is that quantum annealing algorithms, by exploiting the properties of quantum randomness and quantum rise and fall, can with some probability jump over high-energy barriers, jump out of the local optimum, and better explore the search space. However, this advantage is limited to crossing those high and thin energy potential barriers, because the escape probability of quantum annealing depends not only on the height ΔH_p of the potential barrier, but also on the width w of the potential barrier, as shown in equation (16).

$$P_{Escape} = \exp\left(-\frac{\sqrt{\Delta H_P}\,w}{\Gamma(t)}\right) \tag{16}$$

In addition, quantum annealing can take advantage of the properties of quantum superposition and entanglement to realize parallel operation, and consider multiple possible solutions at the same time when searching the solution space, which makes quantum annealing more efficient in dealing with large-scale problems. The basic flow of the quantum annealing algorithm is shown in Fig. 3, with different schemes varying in details.

III. Simulation optimization and performance evaluation of cross-border e-commerce logistics network based on quantum annealing

In Chapter 2, this study constructs a multi-objective optimization model of cross-border e-commerce logistics network based on quantum annealing algorithm, and clarifies the dynamic equilibrium mechanism between logistics cost, time value and customer satisfaction through mathematical modeling. In order to further verify the effectiveness of the model and the potential of the algorithm for practical application, this chapter will focus on simulation experiments and performance evaluation, specifically including the validation of the optimization effect of the quantum annealing algorithm in distribution center siting, the analysis of the destruction resistance of the distribution network, as well as the comparison of the comprehensive performance with the genetic algorithm and the heuristic algorithm, so as to provide empirical support for the global optimization and efficiency enhancement of the cross-border e-commerce logistics network.

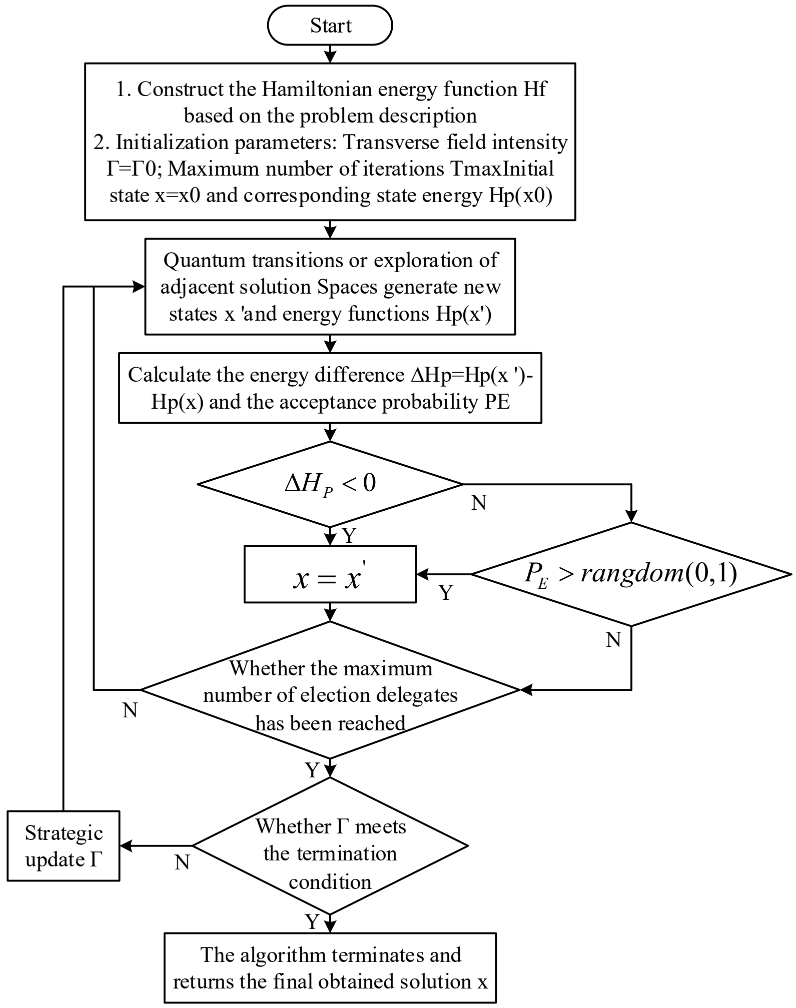

Figure 3: Flowchart of the quantum annealing algorithm

III. A. Simulation example analysis

The quantum annealing algorithm is integrated into the cross-border e-commerce physical network optimization model, and the following example simulation analysis is carried out.

III. A. 1) Distribution logistics

Assuming that a logistics company has 4 factories, 8 alternative distribution centers, and 14 users, i.e., I=4, m=8, and n=14 in the model, it is required to select 5 out of 8 alternative distribution centers, with the following specific data. Table 1 shows the supply capacity of the plant and its unit freight cost to each distribution center, and Table 2 shows the distribution center capacity and the unit freight cost to each user. In the data used, the total supply at the supply point is equal to the total demand at the demand point, and the sum of the inventory at the distribution center is more than the supply and demand, which reflects the idea of supply chain management.

Table 1: Factory supply quality and to the distribution center unit freight

Factory	Supply volume/ton	The unit freight from the factory to each distribution center /yuan							
		D1	D2	D3	D4	D5	D6	D7	D8
F1	30	5	10	6	14	9	18	10	14
F2	40	10	14	5	10	10	17	18	10
F3	50	15	19	11	10	8	11	7	9
F4	60	20	19	17	6	8	12	7	17
F5	80	15	17	15	18	7	15	12	16

Table 2: Distribution center capacity and to each user unit freight

User	User demand/ton	The unit freight from the distribution center to each user /yuan							
		D1	D2	D3	D4	D5	D6	D7	D8
Capacity limit of the distribution center/ton		40	25	70	50	35	15	35	60
U1	20	11	3	11	14	14	4	10	5
U2	5	10	5	13	13	6	7	8	12
U3	15	9	5	11	12	7	7	6	10
U4	8	9	4	2	14	2	13	14	9
U5	25	8	8	14	2	7	9	12	11
U6	18	5	11	9	7	13	10	3	13
U7	10	8	7	13	6	7	11	4	6
U8	25	11	2	7	9	6	8	11	12
U9	11	9	7	13	7	6	5	13	4
U10	30	5	10	5	12	6	5	7	4
U11	15	4	4	8	11	13	10	8	6
U12	20	12	8	13	6	5	7	11	7
U13	16	3	4	5	5	6	12	2	9
U14	8	4	6	7	5	11	13	8	16

From the above table, we can see that the factory-side transportation cost, calculating the total factory to distribution center freight cost (supply x unit freight cost) of each distribution center, in which the distribution center D5 freight cost is 2110 yuan and D7's 2750 yuan cost is lower, and D3 (3150 yuan), D4 (3120 yuan) and D8 (3570 yuan) is the next best.

User-side transportation cost, counting the total freight cost from each distribution center to the user, D5(1785 yuan), D7(1900 yuan), D8(1917 yuan), D4(1940 yuan) and D3(2092 yuan) perform better.

Capacity constraints: D3 (70 tons), D4 (50 tons), and D8 (60 tons) have higher capacity and can carry more cargo; D5 (35 tons) and D7 (35 tons) have smaller capacity but lower cost.

III. A. 2) Distribution center selection based on quantum annealing algorithm

Parameter selection strategy: quantum scale N=80, learning factor c1=1.6382, c2=1.47233, maximum number of iterations=1000, set the maximum range of variation of badness of fitness fval=0.6, set the initial temperature of simulated annealing T0=1e5, and the coefficient of cooling t=0.91.

The above problem was solved on a computer using Quantum Annealing Fusion Algorithm with programming tool MATLAB 8.4, operating system Windows X P, and 2 GB of RAM. The optimal solution of the problem was found to be 1392, and the following five distribution centers were selected by combining cost and capacity:

D3: The capacity is 70 tons, the factory freight is 3150 yuan, and the user freight is 2092 yuan. Large capacity, suitable for handling bulk cargo.

D4: The capacity is 50 tons, the factory freight is 3120 yuan, and the user freight is 1940 yuan. The shipping cost on the user side is low (e.g., U4 and U5 are the lowest).

D5: The capacity is 35 tons, the factory freight is 2110 yuan (the lowest), and the user freight is 1785 yuan. Key nodes, covering the lowest U12 shipping cost.

D7: The capacity is 35 tons, the factory freight is 2750 yuan, and the user freight is 1900 yuan. Cover the lowest shipping cost for users such as U3, U6, and U7.

D8: The capacity is 60 tons, the factory freight is 3570 yuan, and the user freight is 1917 yuan. Cover the lowest shipping cost for users such as U1, U2, U9, and U10.

The above fully proves that the quantum annealing algorithm in this paper has certain advantages in the location of distribution centers.

III. B. Simulation of Distribution Network Destruction Resistance

After analyzing and verifying the superiority of quantum annealing algorithm in distribution center siting through simulation examples, it is necessary to further explore the stability of the logistics network under external disturbances. Therefore, based on the same logistics network model, this section quantitatively analyzes the destructive characteristics of the network through simulation experiments of random attacks and deliberate attacks, revealing the impact of key nodes and paths on the overall connectivity.

III. B. 1) Random attacks

Random attack is to adopt a random strategy to randomly select and delete nodes or edges in the network, regardless of their size and traffic volume, treating them equally.

(1) Initialize the failed nodes and set the node per node deletion ratio;

(2) Randomly select the set of nodes in the conducted network and delete the set of nodes;

(3) Calculate the network connectivity rate after deletion using the network rate formula, and determine whether the connectivity rate is 0. If it is 0, jump to (4), if not, jump to (2), and repeat;

(4) Output the simulation result graph: take the deletion ratio as the horizontal coordinate and the network connectivity rate as the vertical coordinate.

The simulation process of randomly attacking edges is the same as above. The network connectivity of random attack nodes and edges is obtained as in Fig. 4.

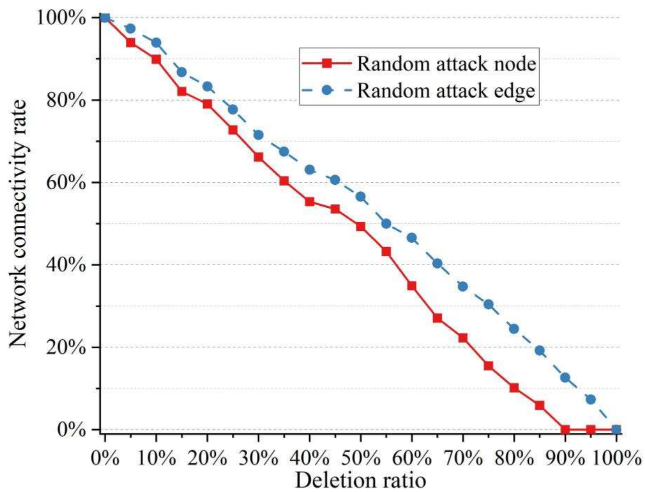

Figure 4: Randomly attack the network connectivity rate of nodes and edges

As can be seen in Fig. 4, the network connectivity rate shows a significant decreasing trend as the deletion ratio gradually increases from 0% to 100%. For example, when the deletion ratio is 10%, the connectivity rates of random attack nodes and edges are 89.88% and 93.91%, respectively; whereas when the deletion ratio reaches 50%, the connectivity rate of node attacks drops to 49.29%, and that of edge attacks drops to 56.55%. It is worth noting that the damage to network connectivity by edge attacks is always weaker than that by node attacks. For example, at a deletion ratio of 20%, the connectivity of node attacks is 79.04%, while edge attacks still maintain 83.31%. This discrepancy suggests that node failure cascades to the failure of its associated edges, resulting in a more severe chain reaction on the network structure. In addition, when the percentage of deletion reaches 90%, the network connectivity rate are reduced to 0%, which indicates that this logistics end-distribution network completely collapses under extreme random attacks, but it still shows some resistance to destruction under medium attack intensity.

III. B. 2) Deliberate attacks

Deliberate attack, the maximum median node or edge as the target of the attack, the node or edge receiving the attack fails then the network connectivity is affected, node median attack steps are as follows:

(1) Initialize the failed nodes and set the percentage of each deletion;

(2) Based on the normalized distance and traffic, calculate the number of meshes of each node node and edge in the network, and sort them in descending order;

(3) Delete the set of nodes sequentially and proportionally;

(4) Calculate the network connectivity using the network connectivity formula and determine whether the connectivity is 0. If it is 0, skip to (5), if not, skip to (3);

(5) Output the simulation result graph: take the deletion ratio as the horizontal coordinate and the network connectivity rate as the vertical coordinate.

Similarly output based on the node degree with the end of the improved node under the deliberate attack node, the network connectivity rate changes as shown in Figure 5 below.

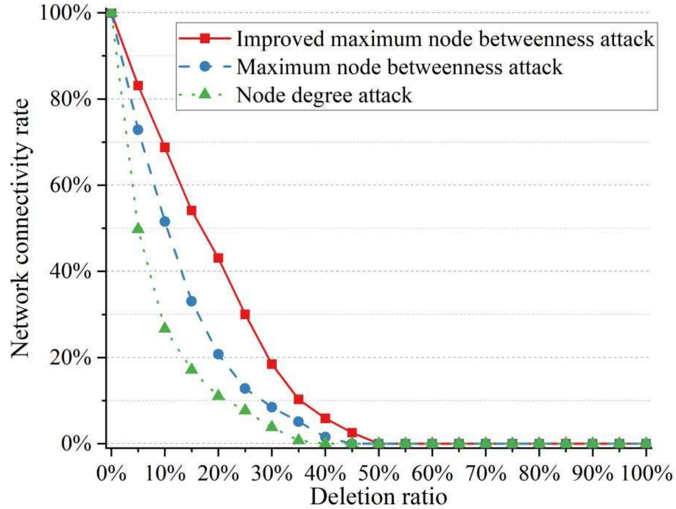

Figure 5: Deliberate node attacks on changes in network connectivity

As can be seen in Fig. 5, the improved maximum node median attack exhibits higher network connectivity, especially at low deletion ratios where the difference is significant. For example, at a deletion ratio of 5%, the connectivity of the improved median attack is 83.11%, while the traditional median and node-degree attacks drop to 72.86% and 49.77%, respectively. This indicates that the improved attack strategy integrates the node meshes, traffic flow and transportation distance, which is closer to the operational characteristics of the actual logistics network, and thus the identification of key nodes is more accurate and relatively less destructive. In contrast, the node degree attack is the most destructive to the network, e.g., when the deletion ratio is 10%, its connectivity is only 26.68%, which is much lower than the 68.76% of the improved median attack. In addition, all the attack strategies lead to complete network paralysis (0% connectivity) when the deletion percentage exceeds 50%, but the improved median attack still maintains 43.10% connectivity at medium attack intensity (e.g., 20% deletion percentage), which is significantly better than the other two strategies. This validates the effectiveness of the improved mediator model in improving network destructive analysis.

III. C. Performance Evaluation of Algorithm Comparison Experiments

Destruction resistance analysis verifies that the optimized network of quantum annealing algorithm has certain robustness, but the comprehensive performance of the algorithm needs to be further evaluated by side-by-side comparison. In this section, by introducing the GA-AI algorithm and the traditional heuristic algorithm, the comparison experiments are carried out in terms of CPU time, quality and quantity of solutions, etc., to comprehensively demonstrate the technical advantages and application value of the quantum annealing algorithm in the optimization of complex logistics networks.

In order to evaluate the performance of this paper's algorithm in solving the cross-border e-commerce logistics network optimization problem, this paper's algorithm is compared with the genetic algorithm GA-AI and traditional heuristic algorithms for multi-objective optimization of supply chain networks, and the test data sets used are shown in Table 3.

Table 3: Test dataset

Test set	Quantity of consignors	The quantity of third-party logistics	The number of original warehouses	The number of objective warehouses	The quantity of third-party logistics at the terminal	The number of customers
1	5	6	3	4	6	15
2	12	20	10	11	20	30
3	20	30	15	15	30	50
4	35	50	25	27	50	60
5	50	80	45	45	100	100

For each dataset, the algorithm runs were run 10 times respectively and the results were averaged. The results of the performance evaluation are shown below, Figure 6 shows the CPU running time of each algorithm and Figure 7 shows the average number of solutions and the ratio of optimal solutions produced by each algorithm.

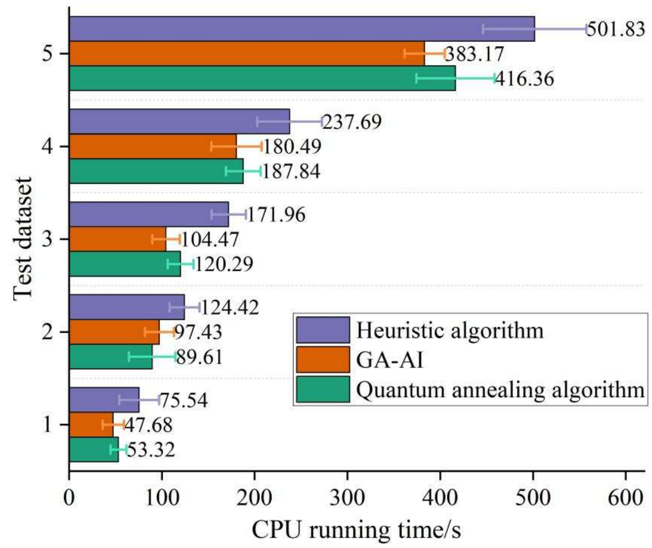

Figure 6: The CPU running time of each algorithm

In terms of CPU time, the computational elapsed time of all algorithms increases significantly as the test set size increases. The quantum annealing algorithm takes slightly more time than the GA-AI's 47.68s in the small and medium-sized problems, such as 53.32s in test set 1, but is better than the heuristic algorithm's 75.54s; and in the large-scale problems (test set 5), the quantum annealing algorithm takes 416.36s, which is slightly higher than the GA-AI's 383.17s, but is much lower than the heuristic algorithm's 501.83s, indicating that it has higher computational efficiency in large-scale optimization.

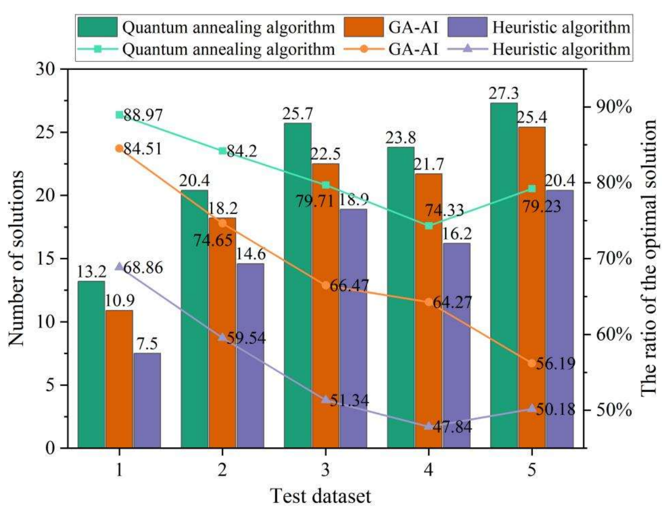

Figure 7: Number of solutions of each algorithm and the ratio of the optimal solution

The quantum annealing algorithm consistently performs optimally in terms of the average number of solutions. For example, it generates 13.2 solutions in test set 1, outperforming GA-AI and the heuristic algorithm by 20.7% and 76%, respectively. As the problem complexity increases, the quantum annealing algorithm generates 27.3 solutions on test set 5, which is still significantly ahead of the other algorithms, with 25.4 for GA-AI and 20.4 for the heuristic algorithms, verifying its extensiveness and stability in exploring the solution space.

In terms of the optimal solution ratio, the quantum annealing algorithm leads in all aspects, especially in the complex scenarios. Its optimal solution ratio is 88.97% in test set 1, much higher than the 84.51% of GA-AI and 68.86% of heuristic algorithm; in test set 5, quantum annealing still maintains 79.23%, while GA-AI and heuristic algorithm drop to 56.19% and 50.18%, respectively. This indicates that the quantum annealing algorithm effectively avoids the local optimal trap through the quantum tunneling effect, and is able to more accurately approximate the global optimal solution in the high-dimensional search.

In summary, the quantum annealing algorithm significantly outperforms the comparison algorithms in terms of the quality and quantity of solutions. Although its CPU time is slightly longer than that of GA-AI, this cost is exchanged for higher optimization accuracy, which is especially valuable for application in complex logistics networks. Heuristic algorithms, on the other hand, are gradually difficult to meet the large-scale optimization needs due to the double disadvantages of efficiency and solution quality.

IV. Conclusion

In this study, a multi-objective optimization model for cross-border e-commerce logistics network is constructed based on the quantum annealing algorithm, and the significant advantages of the algorithm in terms of optimal allocation of resources, network destruction resistance and global search capability are verified through simulation experiments and comparative analysis. The specific conclusions are as follows:

In the simulation example, the quantum annealing algorithm selects D3, D4, D5, D7 and D8 as the optimal combination from 8 alternative distribution centers, with a comprehensive cost of 1392 yuan. The scheme balances cost and capacity constraints and verifies the efficiency of the algorithm in multi-objective collaborative optimization.

Destruction resistance simulation shows that the optimized logistics network maintains 49.29% (node attack) and 56.55% (edge attack) connectivity under random attack (at 50% node deletion ratio). In the improved meso deliberate attack, the connectivity rate is 43.10% at 20% deletion ratio, which is significantly better than the traditional meso attack (20.79%) and node degree attack (11.04%). This indicates that the algorithm-optimized network can effectively resist external interference, and the redundant design of key nodes and resource synergy mechanism enhance the overall robustness.

Compared with the genetic algorithm GA-AI and the traditional heuristic algorithm, the quantum annealing algorithm achieves an optimal solution ratio of 79.23% in the large-scale test set, which exceeds GA-AI (56.19%) and the heuristic algorithm (50.18%) by 41.2% and 57.9%, respectively. The average number of solutions is 27.3, which is 7.5% and 33.8% higher than 25.4 for GA-AI and 20.4 for the heuristic algorithm. Although its CPU time (416.36 seconds) is slightly higher than that of GA-AI (383.17 seconds), its ability to break through the local optimum through quantum tunneling effect ensures the global nature and stability of the solutions in high-dimensional complex problems.

References

[1] Zhao, Y. (2020). Influencing factors of cross-border e-commerce trade between China and “Belt and Road” coastal and inland countries. Journal of Coastal Research, 103(SI), 70-73.

[2] Chen, B. (2017). Empirical study on cross border e-commerce enterprise logistics model under the background of economic globalization. Revista de la Facultad de Ingenieria, 32(12), 240-247.

[3] Xiao, L., & Zhang, Y. (2022). An analysis on the policy evolution of cross-border ecommerce industry in China from the perspective of sustainability. Electronic Commerce Research, 22(3), 875-899.

[4] Ma, Y. (2024). Exploring innovative business models in cross-border e-commerce under digital economy. Frontiers in Business, Economics and Management, 13(1), 205-209.

[5] Hu, B., & Luo, Q. (2018, July). Cross-border e-commerce mode based on Internet+. In IOP conference series: Materials science and engineering (Vol. 394, No. 5, p. 052014). IOP Publishing.

[6] Goldman, S. P., van Herk, H., Verhagen, T., & Weltevreden, J. W. (2021). Strategic orientations and digital marketing tactics in cross-border e-commerce: Comparing developed and emerging markets. International small business journal, 39(4), 350-371.

[7] Wang, D., Xu, P., An, B., & Song, Y. (2024). How does the development of the digital economy in RCEP member countries affect China’s cross-border e-commerce exports?. PloS one, 19(12), e0310975.

[8] Du, J. (2025). Innovation of cross border e-commerce supply chain management mechanism under digital background. International Journal of Networking and Virtual Organisations, 32(1-4), 291-312.

[9] Jin, Y. (2024). An Empirical Study on the Development Environment of Cross-border E-commerce Logistics in the Global Trade Context: Exploring the Digital Marketing Landscape. Comput Aided Des Appl, 21(S4), 290-305.

[10] Giuffrida, M., Jiang, H., & Mangiaracina, R. (2021). Investigating the relationships between uncertainty types and risk management strategies in cross-border e-commerce logistics. The International Journal of Logistics Management, 32(4), 1406-1433.

[11] Ho, Y. C., Chou, C. F., Yang, C. K., & Horng, D. J. (2021). CROSS-BORDER E-COMMERCE COMPANIES'EVALUATION MODEL FOR OVERSEAS WAREHOUSING AND LOGISTICS SERVICE PROVIDERS. Commerce & Management Quarterly, 22(3), 325-374.

[12] Cheah, L., & Huang, Q. (2022). Comparative carbon footprint assessment of cross-border e-commerce shipping options. Transportation Research Record, 2676(1), 584-595.

[13] Nie, X. (2022). Cross ‐ Border E ‐ Commerce Logistics Transportation Alternative Selection: A Multiattribute Decision ‐ Making Approach. Mathematical Problems in Engineering, 2022(1), 4990415.

[14] Qi, X., Qin, W., & Lin, B. (2024). Case study on synergistic development strategy of cross-border e-commerce and logistics: An empirically model estimation. Plos one, 19(6), e0304393.

[15] Van Asch, T., Dewulf, W., Kupfer, F., Cárdenas, I., & Van de Voorde, E. (2020). Cross-border e-commerce logistics–Strategic success factors for airports. Research in Transportation Economics, 79, 100761.
[16] Xue, C., Wen, W., & Li, S. (2022). Enterprise strategy analysis of synergy between cross-border e-commerce and logistics in a dynamic environment. Systems Science & Control Engineering, 10(1), 459-467.
[17] Do, Q. H., Kim, T. Y., & Wang, X. (2023). Effects of logistics service quality and price fairness on customer repurchase intention: The moderating role of cross-border e-commerce experiences. Journal of Retailing and Consumer Services, 70, 103165.
[18] Harrison, A., & Kortuem, S. (2018). Optimized analysis based on the characteristics of cross-border E-commerce logistics business. International journal of Smart Business and Technology, 6(2), 1-10.
[19] Li, X. Q., & Wan, B. (2022, June). Optimization of Cross-border E-commerce Logistics Distribution Network Based on Genetic Neural Network. In 2022 International Conference on Frontiers of Artificial Intelligence and Machine Learning (FAIML) (pp. 132-136). IEEE.
[20] Jiang, Y. H. (2020, September). Location and Path Planning of Cross-Border E-Commerce Logistics Distribution Center in Cloud Computing Environment. In International Conference on Advanced Hybrid Information Processing (pp. 30-40). Cham: Springer International Publishing.
[21] Xie, C. (2019). Research on logistics e-commerce distribution network optimization based on WebGIS. In Recent Developments in Mechatronics and Intelligent Robotics: Proceedings of International Conference on Mechatronics and Intelligent Robotics (ICMIR2018) (pp. 200-206). Springer International Publishing.
[22] Li, X. (2024). Evaluation of Optimization Strategies for Cross border E-commerce Logistics Network Based on ADASYN Algorithm. Procedia Computer Science, 247, 1036-1043.