Research on Optimization of Heterogeneous Air Cargo Network Based on Hybrid Particle Swarm Algorithm

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Abstract. In order to solve the problem of poor timeliness and high operating cost caused by the failure to consider the types of cargo aircrafts and the lack of scientific and reasonable optimization model in the process of transportation scheduling optimization of China's air cargo network, a transport network optimization model of heterogeneous cargo aircraft formation is established, which takes the total flight cost and the number of all-cargo aircrafts as two optimization objectives. The model takes into account the demand time window of air nodes, the maximum payload constraint of cargo aircrafts, the dynamic loading and unloading time of cargo aircrafts, the take-off and landing time and the handover time of cargo aircrafts. In this paper, a hybrid particle swarm algorithm is proposed. The crossover operator of genetic algorithm is used to keep the directivity of particles, and the acceptance criterion of simulated annealing is used to enhance the ability of the algorithm to jump out of local optimum. The effectiveness of the algorithm and the model is verified by the simulation optimization and comparative analysis of a numerical example.

1. Introduction
The competition of logistics industry and express industry in China is increasingly fierce now after the initial extensive development period. Logistics enterprises are now developing towards the road of intensification, that is committed to reducing logistics costs, and to improving the level and efficiency of transport management by using the advanced information technology and optimization model. Aviation logistics has the highest timeliness in logistics express transportation mode. In the global international trade, aviation logistics accounts for only 1% ~ 2%, but the value of goods is as high as 33%, which plays a very important role in logistics transportation. Therefore, the major logistics and express enterprises in China are also accelerating the development of their own aviation logistics network. At present, the number of all-cargo aircrafts in China's mainland airlines has reached 164 \textsuperscript{[1]}, SF, YTO and China Post have set up their own all-cargo airline aircrafts. With the rapid development of China's economy and the improvement of information technology level, the aviation logistics value chain has a great space for optimization after disintermediation \textsuperscript{[2]}. The rapid development of cargo airlines inevitably brings a series of management and optimization problems, among which the optimization of express air transport network is very important, because it directly affects the cost and timeliness of air transport. Due to the late start of air cargo in China, there are few researches on the optimization scheduling of express air transport network. Existing studies mainly focus on three aspects as follows: The first is about effective models and tools of air transport path optimization. At present, many scholars study how to establish reliable models to improve the efficiency of air transport network.
Peng Y. (2019) [3] established a data-driven air cargo redistribution model based on multiple programming (MP) method. The model can transport high-priority cargo effectively and balance the utilization rate of cargo flights. Chu Y. L. (2017) [4] established a multi-objective double-layer optimization model of cargo aircraft flight allocation and cargo transportation path selection, aiming at maximizing network accessibility and utilization, designed the NSGAII algorithm to solve the model, and concluded that cargo aircraft flight was inversely proportional to network utilization.

The second is that flight cost is not the same with different types of cargo aircrafts and different payloads. At present, there has not been any research on optimization of heterogeneous cargo aircraft transportation network, but some references can be provided by optimization of road transportation path of heterogeneous fleet [5]. Susilawati et al. (2018) [6] established a path optimization model for heterogeneous fleets taking cost and total travel time as optimization objectives, and solved it. The results showed that heterogeneous fleets with different load masses could greatly save fuel cost and travel time compared with homogeneous fleets with the same load masses. Ge X. L. et al. (2018) [7] took the total cost of vehicle running as the goal, the carbon emissions, vehicle speed and vehicles with different load weights as the constraint conditions to establish the vehicle transport path optimization model of heterogeneous fleets. Through calculation and example, it was proved that heterogeneous fleets could effectively reduce vehicle carbon emissions, cost and travel time.

Finally, the algorithm of air transport network optimization is studied. It is necessary to study the algorithm of specific encoding, decoding and parameter setting for air transport network. At present, there are few researches on the optimization algorithm of air transport network, but intelligent optimization algorithm can be used for modeling and solving by referring to the algorithm of highway vehicle path optimization modeling and solving [8].

From the above literatures review, it can be seen that there has not been any research on the optimization of heterogeneous cargo aircraft express air network, but the above researches provide a reference to establish an optimization model of heterogeneous air cargo network based on hybrid particle swarm optimization algorithm. The optimization model of heterogeneous cargo aircraft aviation network presented in this paper includes constraints of cargo gathering time and customer demand window, constraints of maximum payload, constraints of loading and unloading time, selection of different types of all-cargo aircrafts, route sequence to different aviation nodes, and targeted optimization algorithm, etc. To reach two targets, minimizing the total cost and the number of cargo aircrafts, a method of selecting air cargo nodes is proposed, and an optimization model of heterogeneous cargo aircraft aviation network is established. Finally, the hybrid particle swarm optimization algorithm is used to verify the numerical example.

2. Problem Description

2.1 Heterogeneous Cargo Aircraft Formation Flight Mode

Generally, the larger the payload of cargo aircrafts, the lower the unit transport cost. By adopting heterogeneous cargo aircraft formation, logistics companies can optimize the scheduling scheme reasonably according to the limit of cargo aircraft payload and the unit transport cost of different cargo aircrafts, thus it can save the total flight transport cost greatly. It is mainly reflected in: ① The use of smaller air freighters on routes with small traffic volume can improve the load factor of air freighters, so as to save transportation costs. ② The cost of cargo aircraft flight is inversely proportional to the duration of flight. Under the same load factor, a cargo aircraft with a large payload capacity can visit more aviation nodes than a cargo aircraft with a small payload capacity, thus making the flight time longer and the total cost lower. ③ In the process of loop flight, if the transportation demand to B and C from A are both 14 tons, two air freighters are needed if the smaller one (B737) is used, and only one air freighter is needed if the larger one (B757) is used, so the total flight cost can be reduced. This is shown in Figure 1. Therefore, it can reduce the total transportation cost greatly by using a reasonable optimization of heterogeneous cargo aircraft formation scheduling scheme.
The flight path of heterogeneous cargo aircraft formation between nodes is the mode of "milkman route", that is, an all-cargo aircraft loading of goods to be shipped to other nodes like B, C, D, E, etc. starts from some node A, the payload of which does not exceed the maximum payload (different types of cargo aircrafts with different payloads). And then it traverses each node according to the planned route, and finally returns to the original departure node A for maintenance and preparation for the next flight. It should be noted that the cargo aircraft needs to unload the goods transported from node A and B after it arrives at a certain node, such as C, and meanwhile it needs to load the goods to be transported from C to the other nodes D, E, ..., A. This is shown in Figure 2. When the cargo aircraft reaches a certain node, the remaining part is transported by other aircrafts if the cargo that needs to be loaded exceeds the maximum payload, until all the node transport requirements are met.

Figure 2 Flight route and payload constraints

2.2 Symbol Description

\( G = (V, E) \) is a complete graph, representing the air transport network. \( V = \{1, \ldots, N\} \) is the set of aviation nodes; \( E \) represents arc set, \( E = \{(i, j) | (i, j) \in V \text{ and } i \neq j\} \). \( d_{ij} \) is the path distance between nodes \( i \) and \( j \); \( v \) represents the average cruising speed of cargo aircrafts; \( m_{ij} \) represents the quantity of goods to be transported from node \( i \) to node \( j \); \( K \) represents a collection of cargo aircrafts, \( k \) is for a cargo aircraft, and \( \forall k \in K : q_k \) denotes the actual loading capacity of cargo aircraft \( k \); \( Q_k \) denotes the payload (maximum payload) of cargo aircraft \( k \); \( t_k \) represents the flight time of cargo aircraft \( k \); \( g_j^k \) represents the total amount of loading and unloading of cargo aircraft \( k \) at aviation node \( j \); \( s_j^k \) represents the service time of aviation node \( j \); \( s_{j1}^k \) represents the time of take-off, landing and handover; \( s_{j2}^k \) represents the time of loading and unloading. \( [\bar{e}_j, \bar{e}_j] \) represents the earliest start and lasted end time windows of a node receiving services; \( h_j^k \) and \( \bar{h}_j^k \) represent the arrival and departure time of node \( j \) for cargo aircraft \( k \); \( X_{ij}^k \) is the decision variable with the value of 0 or 1, \( X_{ij}^k = 0 \) represents cargo aircraft \( k \) passes through the path between nodes \( i \) and \( j \), and \( X_{ij}^k = 0 \) represents it does not pass through.

2.3 Assumptions

(1) Each cargo aircraft takes off from different aviation nodes and returns to the origin (the departure aviation node) after single-loop transportation;
The cargo aircraft collects goods during the day and carries goods at night. That is, the transportation starts from 6 pm every day till 6 am the next day;

(3) After the cargo aircraft arrives at the aviation node, it needs to go through the service time, including the time of take-off, landing and handover, as well as the time of loading and unloading;

(4) There is a sufficient number of various types of cargo aircrafts for the logistics company;

(5) For each aviation node, there are goods to be transported to and from multiple other nodes;

(6) The cargo aircraft has the maximum payload constraint. After unloading the goods transported from other nodes, the cargo aircraft should load goods transported to other nodes but no more than its maximum payload.

3. Modelling

3.1 Calculations of Cost, Time, and Distance of the Flight

(1) Cost. The model takes the total flight cost of one-day transportation of all cargo aircrafts, and the total number of various types of cargo aircrafts as dual optimization objectives. The unit cost of cargo aircraft flight decreases with the increase of flight time \([9]\). In this paper, the piecewise function is adopted to obtain the unit cost of cargo aircraft flight at different flight time according to the empirical cost function of cargo aircraft flight. When the flight time \(t_k\) of cargo aircraft \(k\) is less than 1 hour, the flight cost is \(a\) ten thousand yuan per hour; when the flight time \(t_k\) of cargo aircraft \(k\) is greater than or equal to 5 hours, the flight cost is \(b\) ten thousand yuan per hour; When the flight time of cargo aircraft \(k\) is greater than or equal to 1 hour and less than 5 hours, the flight cost is a linear function of \(a\) and \(b\). The flight cost of cargo aircrafts in different time periods can be expressed as

\[
f(t_k) = \begin{cases} a, & t_k < 1 \\ (t_k + 5a - b)/4, & 1 \leq t_k < 5 \\ b, & 5 \leq t_k \end{cases}
\]

(2) Time. The completion of a single-loop transport by the cargo aircraft \(k\) includes not only the flight time \(t_k\), but also the service time \(s^k_i\) of node \(i\), that is, between the time when the cargo aircraft arrives at node \(i\) \(h^k_i\) and the time when it leaves node \(i\) \(h^k_i\). Service time can be expressed as

\[
s^k_i = h^k_i - h^k_i = s^k_{i1} + s^k_{i2}.
\]

where, \(s^k_{i1}\) is a constant, representing the time of formalities handover; \(s^k_{i2}\) is the loading and unloading time of the cargo aircraft at node \(i\), that is a function of \(g^k_i\) which is the total weight of cargo loaded and unloaded by the aircraft at node \(i\).

(3) Distance. In this paper, according to the longitude and latitude of nodes, the distance between two nodes is calculated by using the great circle distance, and the calculation formula can be expressed as

\[
d_{ij} = R \cdot \arccos[\cos(n_{j1}) \cdot \cos(n_{j2}) \cdot \cos(n_{i1} - n_{i2}) + \sin(n_{j1}) \cdot \sin(n_{j2})].
\]

where, \(R\) is the earth radius which is 6371.0km, \((n_{i1}, n_{i2})\) and \((n_{j1}, n_{j2})\) represent the longitude and latitude of the two nodes \(i\) and \(j\) respectively.

3.2 Model Establishment

The objective functions of optimization model of heterogeneous cargo aircraft aviation network are

\[
\min \sum_{i=1}^{K} \sum_{j=1}^{N} \sum_{k=1}^{N} d^k_{ij} f(t_k) - X^k_{ij},
\]

\[
\min \{K\}.
\]

Equation (4) represents the minimum sum of the total flight cost of cargo aircrafts, and equation (5)
represents the minimum sum of the number of various types of cargo aircrafts used on all routes. The objective function constraints (S.T.) are:

\[
\sum_{i=1}^{N} \sum_{j=1}^{K} X^i_j \geq 1, j \in \{1, 2, \cdots, N\}, k \in K; \tag{6}
\]

\[
\sum_{i=1}^{N} m_j \cdot X^i_j \leq Q_k, j \in \{1, 2, \cdots, N\}, k \in K; \tag{7}
\]

\[
h^i_k > e_\cap h^k_i < e_\cap, i \in \{1, 2, \cdots, N\}, k \in K; \tag{8}
\]

\[
\sum_{i=1}^{N} X^i_j = \sum_{j=1}^{N} X^i_j = 1, (i, j) \in \{1, 2, \cdots, N\}, k \in K; \tag{9}
\]

\[
X^i_j = [0, 1], (i, j) \in \{1, 2, \cdots, N\}, k \in K. \tag{10}
\]

Equation (6) indicates that all aviation nodes are accessed at least once. Equation (7) represents the maximum payload constraint of different types of cargo aircrafts. Equation (8) represents the time window constraint of cargo aircrafts operating at aviation nodes. Equation (9) indicates that the cargo aircraft starts from the origin and returns to the starting point after a loop transportation. Equation (10) represents the decision variable of the cargo aircraft's flight path.

4. Algorithm Design

Heterogeneous air transport network model belongs to the VRP (Vehicle Routing Problem, VRP) problem, and it is also a NP (Non-deterministic Polynomial Hard) complete problem. It is difficult to solve this kind of problem by mathematical analysis method, and most of them are solved by using intelligent optimization algorithms to obtain satisfactory solutions quickly. Particle Swarm Optimization (PSO) is a distributed intelligent optimization algorithm, which adjusts the search direction by two extreme values of particle individual optimal \(p_{best}\) and global optimal \(g_{best}\). It has the characteristics of fast convergence and memory. However, PSO is easy to fall into local optimum, and it is difficult to achieve real number coding for VRP. In this paper, the crossover operator of genetic algorithm (GA) is used to update the two extremums of PSO, and the Metropolis acceptance criterion of simulated annealing algorithm is used to increase the ability of the algorithm to jump out of local optimum. The process of hybrid particle swarm optimization is shown in Figure 3.

![Flow chart of hybrid particle swarm algorithm](image-url)
where, the Metropolis acceptance criterion formula is

$$\psi = \exp\left(-\frac{f[p_{\text{best}}(t)] - f[g_{\text{best}}(t)]}{T}\right)$$

(11)

representing if \(f[p_{\text{best}}(t)] \geq f[g_{\text{best}}(t)]\), or \(\psi\) is greater than the random number in the interval \([0,1)\), then \(g_{\text{best}}(t) = p_{\text{best}}(t)\) is accepted. At the beginning of algorithm iteration, the annealing temperature \(T\) is higher, and the acceptance probability \(\psi\) is also larger, which is conducive to the algorithm to jump out of local optimal.

4.1 Fitness Function

In the construction of fitness function, it should consider the minimum cost, the minimum number of cargo aircrafts, the order of magnitude relationship and weight of the two objectives. In this paper, an adaptive method is adopted to adjust the order of magnitude of the two objectives, and the calculation method is as follows:

$$f(t) = \lambda_1 \frac{\max(C(t)) - C(t)}{\max(C)} + \lambda_2 \frac{\max(K(t)) - K(t)}{\max(K)}$$

(12)

where, \(\max(C)\) and \(\max(K)\) represent the maximum of the total flight cost of all particles and the number of cargo aircrafts used in an iteration respectively; \(C(t)\) and \(K(t)\) represent the total flight cost of the current particle and the number of cargo aircrafts used respectively; \(\lambda_1\) and \(\lambda_2\) represent the weight coefficients of the cost and the number of cargo aircrafts.

4.2 Algorithm Coding

The model is encoded in real numbers, and each particle contains information about the origin, the flight path, and the type of cargo aircraft used. "|" is used as a separate tag of every cargo aircraft circuits in a particle, and the last real digit in the cargo code indicates the type of cargo aircraft and the preceding digit indicates the flight path. Such as the segments of particles shown in Figure 4, the flight path is the 1-3-12-1 and the cargo type is 1 for the first cargo aircraft |11 31 121 11|, the flight path is the 2-7-10-2 and the cargo type is 3 for the second cargo aircraft |23 73 103 23|.

4.3 Updating Method of Particles

The model adopts the crossover operator in genetic algorithm to update the particles, which is beneficial to copy the excellent gene of the global optimal particle \(g_{\text{best}}\) and retain the characteristics of the particle itself.
The method of crossovers is shown in Figure 5, where two crossing points R1 and R2 (R1 < R2) are randomly generated at the separate tag of the cargo *gbest*, and the fragments between the two crossing points are copied directly to the corresponding position of the particle, and then the other parts of the particle are reorganized to adjust the conflict (for example, two cargo aircrafts may re-transport the goods at the same node and need to remove one).

5. Simulation Examples

5.1 Example Data
This paper takes the data of a domestic logistics enterprise as an example. The Table 1 shows that the aviation node city, latitude and longitude are established by the enterprise.

| City       | Beijing | Chongqing | Wuhan | Chengdu | Wuxi | Weifang |
|------------|---------|-----------|-------|---------|------|---------|
| Latitude N | 39.55   | 29.35     | 30.35 | 30.40   | 31.34| 36.43   |
| Longitude E| 116.24  | 106.33    | 114.17| 104.04  | 120.18| 119.06  |
| Hangzhou   | 30.16   | 26.05     | 28.12 | 27.42   | 25.03| -       |
| Longitude E| 120.10  | 119.18    | 112.59| 106.55  | 121.30| -       |

Table 1 Longitude and latitude table of air node city

The air traffic volume between each node is counted according to the operation data of logistics enterprises in recent one year. Firstly, the distribution function of node transport data is identified, and then the parameter estimation and fitting degree test are carried out. Finally, the random example value of the transport volume of each node is simulated according to the distribution function, as shown in Table 2.

| City       | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1          | 0   | 2510| 3664| 4826| 11555| 12120| 12039| 5336| 2448| 2188| 1718|
| 2          | 1015| 0   | 812 | 0   | 837  | 0   | 1002 | 0   | 0   | 0   | 0   |
| 3          | 2901| 967 | 0   | 1222| 1511 | 1267 | 2234 | 1232| 0   | 692 | 0   |
| 4          | 3501| 0   | 1148| 0   | 1448 | 1269 | 1570 | 902 | 925 | 0   | 615 |
| 5          | 13794| 2070| 3616| 4807| 0    | 8694 | 0    | 1918| 8780| 2804|    |
| 6          | 9549| 840 | 1219| 1926| 5445 | 0    | 6104 | 2186| 1112| 3165| 1182|
| 7          | 13995| 4650| 4476| 9060| 0    | 13951| 0    | 3183| 13327| 5366|    |
| 8          | 7825| 836 | 1514| 2264| 0    | 3074 | 0    | 1364| 5866| 3601|    |
| 9          | 1603| 0   | 781 | 1174| 953  | 1372 | 853  | 0   | 888 | 584 |    |
| 10         | 2670| 0   | 550 | 517 | 6661 | 2429 | 9982 | 3153| 0   | 3302|    |
| 11         | 1501| 0   | 0   | 2227| 782  | 2806 | 2866 | 0   | 4651| 0   |    |

The types of cargo aircrafts used by logistics enterprises, the calculation coefficients of flight cost and the maximum payload are shown in Table 3.

| Types of Aircrafts | Coding | \(a\) | \(b\) | Maximum payload (ton) |
|--------------------|--------|-------|-------|-----------------------|
| B737               | 1      | 4.5   | 5.5   | 14                    |
| B757               | 2      | 6.5   | 7.5   | 28                    |
| A300               | 3      | 7.5   | 8.5   | 40                    |

5.2 Simulation Result
In this paper, Matlab2019 is used as a tool to optimize and simulate the air cargo network model of heterogeneous cargo aircraft by using hybrid particle swarm optimization algorithm. The Pareto solutions of the dual objective function in the model are related to the weighting coefficients of the optimized objective. In the fitness function, the values of weighting coefficients \(\lambda_1\) and \(\lambda_2\) are 0.7 and 0.3 respectively, average cargo aircraft cruising speed \(v=800\text{km/h}\), the average time of take-off,
landing and handover procedure $s_{j1}^k$ is 0.7 hours after cargo aircraft $k$ arrives at the node $j$, and the average time of loading and unloading $s_{j2}^k$ is 0.05 hours/ton. Uniform design test method [10] is used to determine the parameter values of the model. The initial particle swarm size is 500, the initial annealing temperature $\Gamma$ is 2000, and the cross rate is 0.25. The termination condition of the algorithm is: the cycle iteration is 200 times, and the fitness value of the algorithm does not change any more, then the algorithm terminates, and the optimal result of the simulation is output.

The air cargo network model of heterogeneous cargo aircraft is simulated for 30 times, and the average value is obtained. The simulation optimization result is that the average flight cost is 4.1475 million yuan, and the average number of cargo aircrafts used is 15.12. Taking one of the simulations for analysis, the optimal particles are [83 23 43 103 33 83 | 52 22 42 12 52 | 102 52 92 112 102 | 111 51 111 | 71 61 31 21 71 | 12 32 112 72 12 | 111 51 111 | 91 51 91]. The minimum total flight cost is 4.1374 million yuan, and 15 cargo aircrafts are needed, including 6 B737 aircrafts, 7 B757 aircrafts and 2 A300 aircrafts. The flight paths of various types of cargo aircrafts are shown in Figure 6.

![Figure 6 Optimized flight path](image)

The effectiveness of the proposed model can be verified by comparing the optimization results of heterogeneous cargo aircraft and homogeneous cargo aircraft. A homogeneous fleet is formed by using cargo types of B737, B757 and A300. Simulation calculation is conducted according to the example in 4.1, and the results are shown in Table 4.

| Types of aircrafts | Total cost (ten thousand Yuan) | Quantity of aircrafts required |
|--------------------|--------------------------------|--------------------------------|
| B737               | 410.21                         | 21.42                          |
| B757               | 442.77                         | 17.71                          |
| A300               | 532.11                         | 14.56                          |
| Heterogeneous fleet| 414.75                         | 15.12                          |

As can be seen from Table 4, if only B737 cargo aircraft is used, the transport cost is 1.09% lower than that of heterogeneous fleets, but the number of aircrafts needed increases by 41.67%. As the number of cargo aircrafts used by enterprises increases, the required costs of depreciation, maintenance and labor will increase greatly. When only A300 cargo aircraft is used, although the number of cargo aircrafts is slightly lower, the total cost of daily flight transport increases by 28.3%. When only B757 cargo aircraft is used, the number of aircrafts increases by 17.13% and the flight transport cost increases by 6.76% compared with the heterogeneous fleet. From the above data and analysis, it can be seen that the transportation cost and the number of cargo aircrafts can be saved.
greatly with a reasonable arrangement of heterogeneous fleet transport scheduling, under the premise of ensuring the timeliness of transportation.

6. Conclusions
In response to the problem of high timeliness demanding and high flight cost in air transport network, an optimization model is established. Under the constraints of the time window to meet the demand of each aviation node, heterogeneous all-cargo aircraft formation transportation is used in this optimization model with different types and maximum payload of cargo aircrafts. It is taking the lowest flight cost and the least number of cargo aircrafts used as dual objectives, considering both the dynamic loading and unloading situation in the process of transportation and handover procedure time constraints. A particle swarm optimization algorithm combining GA, Metropolis acceptance criteria and PSO is proposed. A numerical example is used to simulate and optimize the calculation. By comparing with homogeneous cargo aircrafts, the feasibility and effectiveness of the heterogeneous cargo aircraft air transport model are demonstrated.

This paper assumes that the flight conditions are well and there is no delay in flight execution. In follow-up studies, it can consider the impact of unexpected events such as weather and mechanical failure on heterogeneous air cargo network. Furthermore, only the flight cost of cargo aircrafts is considered in the model of this paper, and other costs of cargo aircrafts, such as costs of manpower, depreciation and maintenance, should also be considered into the optimization category in the subsequent research.

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