

Article

Capacity Evaluation Method of Ship Terminal Area Based on Network Maximum Flow

Gang Zhong , Yuhang Fei, Jia Yi, Dikun Feng and Ouge Feng

College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

* Correspondence: zg1991@nuaa.edu.cn; Tel.: +86-15952083939

Abstract: With the development of modern military ship equipment, the airspace operation environment of shipboard aircraft is becoming increasingly complex. The objective and accurate evaluation of ship-terminal capacity is the basis of air traffic flow management for shipboard aircraft, and it is also the premise of improving the efficiency of airspace resources. First of all, this paper divides the airspace and ship terminal areas and realizes the route network planning for the arrival and departure of shipboard aircraft. Following this, according to the airspace characteristics of the ship terminal area and the operation process of the shipboard aircraft, an arrival-and-departure network flow model for shipboard aircraft is established by using capacity-limitation and flow-conservation conditions. Finally, simulated annealing (SA) is used to solve the maximum flow in the arrival-and-departure network flow model, and the capacity evaluation results of the ship terminal area are obtained. The results show that when the number of gates is $n_g \geq 7$, the bottleneck in the ship terminal area's operation capacity is the deck runway. When $3 \leq n_g < 7$, imbalanced take-off and landing tasks lead to a waste of runway resources, and when $n_g < 3$, the number of gates becomes the bottleneck which limits the capacity. With the number of gates being reduced from seven to three, the capacity is reduced from twenty sorties per hour to six sorties per hour. The model and core idea proposed in this paper can not only quickly evaluate the capacity of the terminal area of ships but also provide a solid foundation for the development of future fleet groups and the full use of maritime airspace.

Keywords: carrier aircraft; terminal area capacity; network maximum flow; simulated annealing (SA)



Citation: Zhong, G.; Fei, Y.; Yi, J.; Feng, D.; Feng, O. Capacity Evaluation Method of Ship Terminal Area Based on Network Maximum Flow. *Sustainability* **2022**, *14*, 10470. <https://doi.org/10.3390/su141710470>

Academic Editor: Laura Eboli

Received: 19 July 2022

Accepted: 18 August 2022

Published: 23 August 2022

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1. Introduction

An aircraft carrier is a large naval vessel used for naval operations and is the sea base for the take-off and landing of its main combat weapon—shipboard aircraft. The emergence of aircraft carriers has effectively applied aircraft to maritime operations, greatly enhancing the combat capability of the navy [1]. With the development of modern military ship equipment, the number of ships in a formation is gradually increasing, and the airspace operation environment of arrival and departure is becoming increasingly complex. Objective and accurate evaluation of the ship terminal area's capacity is the basis of air traffic flow management for shipboard aircraft, and it is also the premise for improving the efficiency of airspace resources. The reasonable evaluation of terminal capacity can alleviate the imbalance between capacity supply and flow [2], delays in shipboard aircraft tasks, and airspace congestion. In addition, it can also lay the foundation for finding operation bottlenecks in the ship terminal area, which is conducive to making full use of limited resources to improve operational efficiency and provides an effective basis for relevant departments to reasonably arrange tasks related to shipboard aircraft. In the field of civil aviation, the airport terminal capacity-evaluation method has been rendered nearly perfect. Capacity evaluation is implemented in four main ways, being mainly based on mathematical modeling, historical data mining, control-load analysis, and computer simulation.

1.1. Capacity Evaluation Methods Based on Mathematical Modeling

In the field of capacity evaluation, the development of the capacity-evaluation method based on mathematical modeling is the earliest. This method originated from the use of Poisson distribution to simulate the arrival flow [3]; assuming that the service time of the runway for each arrival flight is a certain value, it is believed that there is always a deviation in the actual arrival time of the aircraft, and this model is used to estimate the average delay time of the landing aircraft. Following this, according to the concept of ultimate capacity, the influence on airport capacity of the runway occupancy time, the aircraft arrival interval, and the final approach route length is analyzed [4]. At present, the most commonly used mathematical capacity-evaluation models include the FAA (Federal Aviation Administration) airport-capacity model released by the Federal Aviation Administration of the United States, LMI (Institute of Logistics Management) [5] runway capacity model established by the United States Institute of Logistics Management and the MACAD (MANTEA Airfield Capacity And Delays) model [6] based on FAA model and LMI model. Overall, the mathematical analysis model can obtain relatively accurate macro evaluation results, but it cannot reflect the operation of airport and airspace capacity at the micro level.

1.2. Capacity-Evaluation Methods Based on Historical Data

The method of airport-operation capacity evaluation based on historical data mining can also be called historical airport peak-service evaluation [7]. This method abstracts the convex capacity curve by analyzing the flight history data of the airport operation. On this basis, it analyzes the interaction between the take-off flow and the arrival flow. By establishing the airport capacity and delay model, it is applied to the actual capacity evaluation of multiple airports, and remarkable results are achieved. The application of this method has high requirements for data quality. Data collection, cleaning, feature selection, and other work will directly affect the accuracy of the evaluation results [8]. The method of evaluating airport operation capacity through airport historical operation data mining is applicable to busy airports. Aircraft take-off and landing sorties during peak hours are considered to reflect the actual service capacity of the airport, which approaches the airport capacity.

1.3. Capacity Evaluation Methods Based on Control Load

The control workload can be defined as the flight of aircraft in an airspace, forming objective task requirements for controllers. In order to meet these requirements, the controller needs to bear physical and mental pressure, which can be converted into time consumption. Through time consumption, the controller can relieve the pressure and meet the requirements of objective tasks. The length of time consumption is the size of the controller's workload [9]. The capacity-evaluation method based on control load can be distinguished subjectively and objectively; the DORATASK method and MBB method, among others, are commonly used [10]. In recent years, some scholars have begun to integrate network flow theory into the airspace-capacity evaluation method based on control workload. They regard the route sector as the "sub-network" in the entire terminal network and calculate the sector capacity of several sectors in the terminal by analyzing the communication load of controllers. The obtained sector capacity is regarded as the arc capacity (Arc capacity) of the terminal network, and then the "maximum flow-minimum cut" (ultimate capacity) theorem is used to solve the capacity of the terminal [11].

1.4. The Capacity Evaluation Method Based on Computer Simulation

The airspace capacity evaluation method based on computer simulation is to realize the modeling of the airport airspace and operation structure through computer technology, with the inclusion of factors such as aircraft operation rules, scene infrastructure, and controller behaviors. This method can solve the complex problem of the airport capacity evaluation and make up for the deficiency of the mathematical model method that relies on assumptions and simplification [12]. At present, the relatively mature airspace capacity

evaluation and analysis software include SIMMOD, TAAM, RAMS, AIRTOP, etc. [13]. They are all micro, dynamic, and comprehensive airport simulation software, which can simulate the operation of aircraft in airspace and various parts of the airport. The application of computer simulation in capacity evaluation provides great help for the construction of airports. By comparing the operation of different design schemes in advance, the best scheme is selected to avoid the construction of physical systems, which is both practical and economical.

However, the total length of the ship's flight deck is about 300 m. Compared with the land airport runway, the landing runway of the shipboard aircraft is shorter. At the same time, the multi-degree-of-freedom movement of the ship itself and the complexity of the marine environment make it very difficult for the shipboard aircraft to land, which seriously affects the safety of the landing [14]. After decades of experience in the United States and other countries, there is a complete set of procedures for approaching and landing shipboard aircraft. Research on automatic landing technology for shipboard aircraft has become increasingly mature [15]. Among them, more research focuses on the flight dynamics of the shipboard aircraft, analyzes the influence of aerodynamic flow field on the arrival and departure performance of an aircraft carrier [16], and records the landing data of shipboard aircraft through the development of a simulation system [17]. However, the research on queuing network in the arrival and departure process of shipboard aircraft is still at the micro level of deck gas stations and catapults, and little attention is paid to the flow and capacity of the whole arrival and departure route network.

Combined with the characteristics of shipboard aircraft arrival and departure, the applicability of civil aviation capacity evaluation methods in the capacity evaluation of ship terminal area is analyzed. The capacity evaluation mathematical model can quickly and directly calculate the theoretical capacity of a facility, such as the runway, apron, etc., but the capacity evaluation of their coupling operation is not accurate enough. The arrival and departure of shipboard aircraft are more stringent than those of civil aviation. Therefore, the single capacity evaluation method based on a mathematical model is difficult to meet the requirements.

Additionally, due to the lack of a large-scale operation of shipboard aircraft in history, and the lack of continuous and stable take-off and landing scenarios, it is difficult to obtain data on peak service. Therefore, the capacity evaluation method based on historical data is still not available. Due to the open airspace around the ship, the runway structure on the deck is simple, and all are single runway operations. Furthermore, the air traffic management load of shipboard aircraft is low, which cannot reach the upper limit of the controller's work. Therefore, the capacity evaluation method based on the control load is not applicable.

More importantly, since computer simulation requires researchers to build a large simulation platform and simulate the operation of the large-flow shipboard aircraft to obtain simulation data, certain economic benefits are needed. It is difficult to quickly and conveniently realize the capacity evaluation, so the capacity evaluation method based on computer simulation is less applied in the ship terminal area.

In view of the above problems, according to the airspace characteristics of the ship terminal area and the operation process of the shipboard aircraft, the capacity evaluation method of civil aviation airport is used for reference in this paper. The rest of the paper is organized as follows. Section 2 designs the airspace structure of the ship terminal area and builds the arrival and departure network flow model of shipboard aircraft. Section 3 presents the capacity evaluation method of the ship terminal area based on the network maximum flow theory. Section 4 introduces the algorithm used to solve the capacity of the ship terminal area. Section 5 conducts the numerical experiment and analyzes the results. Section 6 concludes the study and forwards recommendation for future study.

2. Network Flow Model of Ship Terminal Area

2.1. Problem Description

This paper mainly studies the capacity evaluation of a single ship as a maritime terminal area, as shown in Figure 1. The ship is regarded as the carrier of shipboard aircraft arrival and departure at sea while accepting shipboard aircraft arrival and departure applications. The capacity of the ship terminal area mainly measures its ability to ensure the normal and orderly execution of take-off and landing tasks.

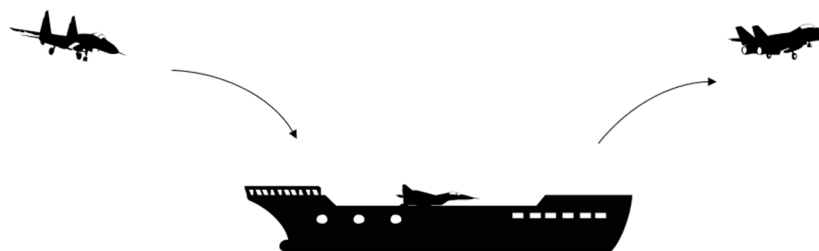


Figure 1. Chart of arrival and departure of shipboard aircraft.

Therefore, on the basis of reference to the capacity of a civil aviation airport, the capacity of the ship terminal area can be defined as the maximum number of arrival and departure aircraft the ship can handle in unit time.

The movement characteristics of the shipboard aircraft in the ship terminal area are in line with the network flow theory model. In this paper, the maximum flow theory is used to solve the capacity of the ship terminal area.

2.2. Airspace Structure Design of the Terminal Area

In order to provide a safe and efficient air traffic control environment for shipboard aircraft, so as to improve the landing efficiency of shipboard aircraft, it is necessary divide the near airspace of the ship reasonably.

With reference to the public classification standards for the return landing area of the US shipboard aircraft and the flight profile parameters of the shipboard aircraft at different stages of arrival and approaching, the landing process is divided into a homing guidance area beyond 50 n miles and a ship terminal area within 50 n miles according to the distance from the ship. The terminal area includes the holding area (20–50 n miles), the arrival and approaching area (3–20 n miles), as well as the landing area (3 n miles). Each area is a concentric circle, which corresponds to different stages of the approaching and landing process.

As shown in Figure 2, in the vertical direction, when the altitude is still higher than 1800 m, the carrier aircraft is in the homing guidance stage. The upper bound of the holding area is 1800 m, and the lower bound is 1500 m, which is mainly used as the waiting program to occupy the airspace. The upper bound of the arrival and approaching area is 1500 m, and the lower bound is 300 m, which is mainly used for arrival and approaching routes to occupy airspace. The upper bound of the landing area is 300 m, and the lower bound is the height of the aircraft carrier deck, which is mainly the airspace occupied by the final approach to the landing route and the missed approach point route. The homing guidance area does not belong to the range of the aircraft carrier terminal area, and its lower bound is 1800 m. It is mainly used as the airspace of the shipboard manned/UAV early homing guidance and the self-destruction area, and the refueling area.

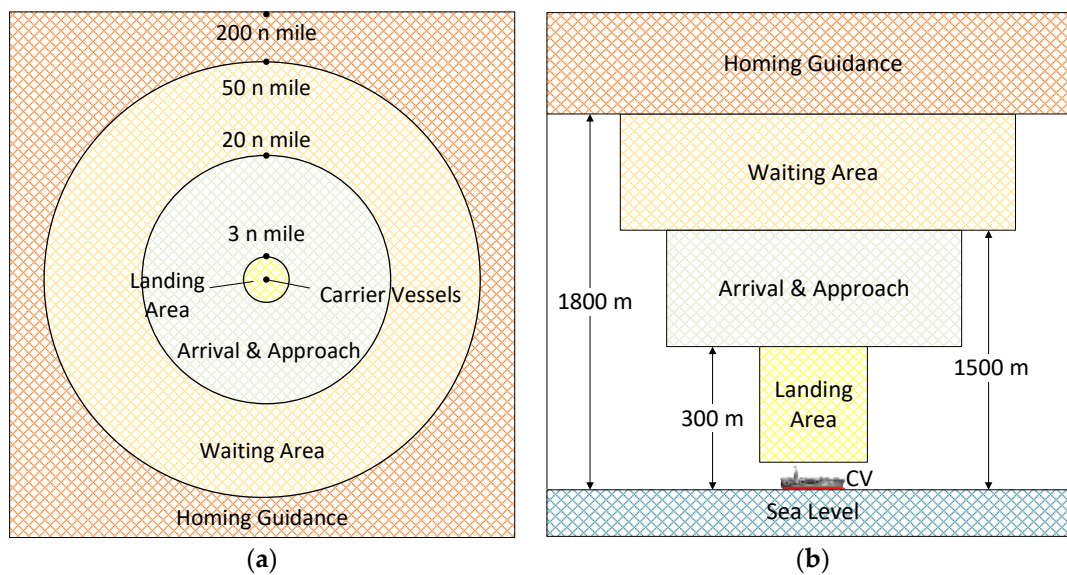


Figure 2. Ship terminal airspace. (a) Horizontal dimension. (b) Vertical dimension.

With the increasing number of shipboard aircraft, it is necessary to divide the busy terminal area into three sectors. Taking 120 degrees as a unit, the airspace of the aircraft carrier terminal area is divided into three grades, and three control sectors are obtained so as to reduce the command and deployment pressure of the aircraft carrier air traffic control center controller. The horizontal range of the ship terminal area should include all airspace elements, including arrival procedure, approach procedure, missed approach point procedure, holding route, etc. The flight procedure and arrival and departure route design of shipboard aircraft should follow the following principles:

1. For route design, the overall flight time should be as short as possible, and the airspace occupied should be as small as possible.
2. In view of the flight characteristics of shipboard aircraft at different stages, the risk of a collision with ships and obstacles is considered to ensure that the shipboard aircraft has sufficient safety during landing.
3. Shipboard aircraft routes should not cross multiple aircraft carrier control sectors in a short distance so as to avoid a large load on the aircraft carrier air traffic control center.
4. The climb or descent phase of shipboard aircraft routes shall be avoided as far as possible near the boundary of the control sector, thereby avoiding the transfer of control during the climb or descent phase.

According to the sector division method of the ship terminal area and the route design principle, the shipboard aircraft arrival and departure route network, shown in Figure 3, is drawn. In Figure 3, the red arrows represent the approach route of the carrier aircraft, the blue arrows represent the go-around route, and the green arrows represent the departure route. The stars represent the key nodes in the approach process of the carrier aircraft.

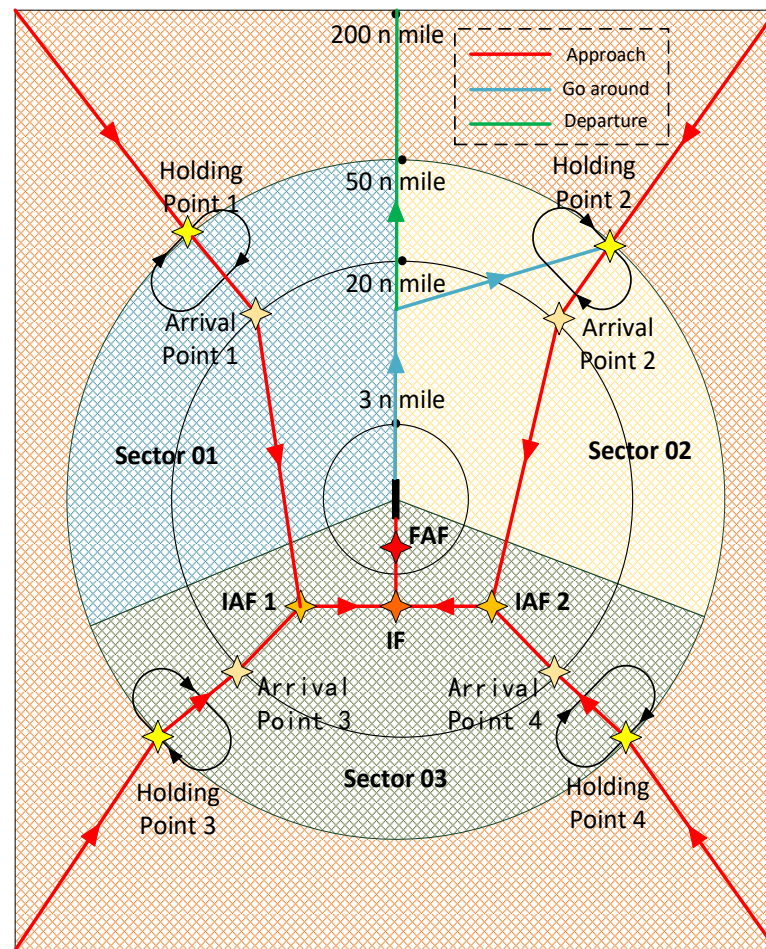


Figure 3. Route Network of Ship Terminal Area.

2.3. Shipboard Aircraft Arrival and Departure Network Flow

Network flow theory is a branch of graph theory that is usually used to solve the optimization problems in networks [18]. A network $N = (V, S, T, A, C)$ is a connected acyclic directed graph, as shown in Figure 4:

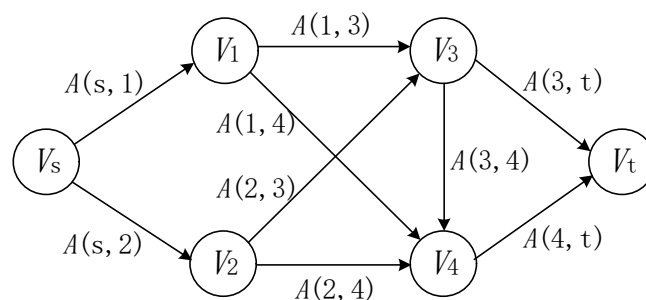


Figure 4. Network Flow Model.

In Figure 4, S is the source point set of the network, T is the sink point set of the network, V and A are the vertex set and the arc set, respectively. The vertex in the network, except the source and sink, is called the transit point. The source points and sink points correspond to the entrance and departure of the network in the actual network. C is the capacity function of the network. It is a non-negative function defined on arc set A , which corresponds to the capacity of the corresponding route. The flow in the network refers to the flow body passed per unit time at a certain point, and the flow on each arc in the actual network should not exceed the corresponding capacity.

The maximum flow problem is a combinatorial optimization problem in network flow research, which maximizes the flow of the whole network by reasonably allocating the flow on each arc. Therefore, the maximum flow is also called network capacity. In the process of solving the maximum flow, the three most obvious characteristics of the network flow model should be followed: capacity limitation, flow conservation, and anti-symmetry.

Therefore, by establishing the network flow model of shipboard aircraft arrival and departure and solving the maximum flow in the network, the maximum number of shipboard aircraft arrival and departure per unit time can be obtained, that is, the capacity of the ship terminal area.

The key points are abstracted from the route network of Figure 3 as network nodes, and the route point set D is constructed. Each element can be found in Table 1.

Table 1. Name and Meaning of Route Points.

Name	Meaning
s	Starting point
h_i	Holding point i
a_i	Arrival point i
o_i	Initial approach fix i
c	Intermediate approach point
f	Final approach point
m	Missed approach point
d	Ship landing area
r	Ship runway
g	Gates
t	Departure point

According to the behavior of shipboard aircraft holding, arriving, approaching, re-flying, landing, taking off, climbing, and so on, the arc connecting each node is established, and the network flow of the ship terminal area is obtained, such as Figure 5.

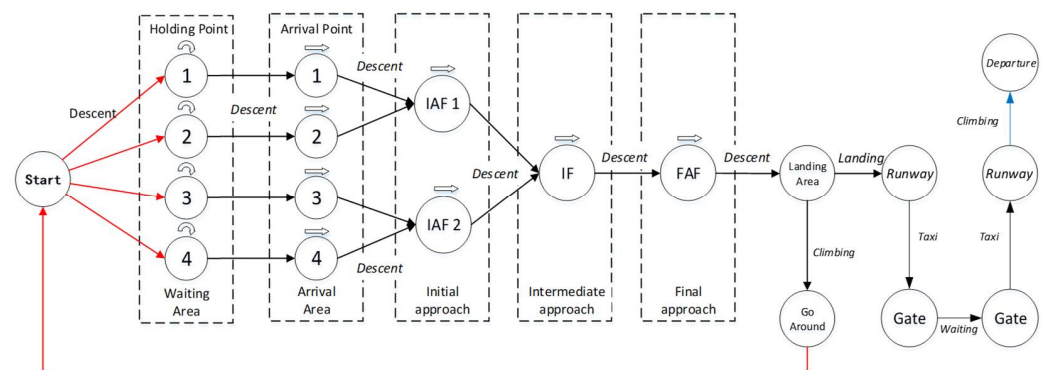


Figure 5. Network flow in ship terminal area.

In Figure 5, the red arrows indicate the initial flow, including the missed approach flow. The blue arrow indicates the end flow.

In order to reflect the basic characteristics of the shipboard aircraft in carrying out the mission, after landing, the shipboard aircraft needs to slide into the apron through the runway for a certain period of time for maintenance and preparation, and then the next phase of the take-off mission can be carried out. In the network flow model above, each stop is divided into two nodes: the slide-in node and the slide-out node. The state transition from the slide-in node to the slide-out node is the maintenance process. In the whole network flow, the shipboard aircraft does not stay on any node, each node only playing the role of connecting the segment arc.

3. Capacity Evaluation Method Based on Network Flow Model

3.1. Assumption Conditions

The route structure of the ship terminal area is abstracted as the network $G = (D, A, C)$. The network flow model can be established according to the arrival and departure behavior of the shipboard aircraft, and the network node set D and the directed arc set A connecting each node are obtained. The capacity of each arc in the network is calculated, respectively, and the route capacity set C is obtained. After the network containing arc capacity is established, the capacity of the ship terminal area can be obtained by calculating the maximum flow in the network so as to evaluate its arrival and departure serviceability.

On this basis, in order to better build the model, assuming:

1. The same deck runway is used during the arrival and departure of the shipboard aircraft;
2. The length and position of each segment in the arrival and departure route of the shipboard aircraft are known;
3. The shipboard aircraft shall fly at a constant speed in each segment;
4. A certain safety separation should be maintained between the shipboard aircraft;
5. The shipboard aircraft executes a fixed length of holding route.

3.2. Model Establishment

3.2.1. Objective Function

According to the definition of the capacity of the ship terminal area in Section 2.1, the objective function is set as the maximum sum of the arrival flow and the departure flow of the shipboard aircraft.

$$\max F = F_{app} + F_{dep} \quad (1)$$

where, F is the total flow, which includes the arrival flow and the departure flow of the shipboard aircraft, and F_{app} is the sum of shipboard aircraft arrival flow, and F_{dep} departure flow.

The landing flow of shipboard aircraft can be expressed as:

$$F_{app} = \sum_{i=1}^n q_{sh_i} - q_{ms} \quad (2)$$

The departure flow of shipboard aircraft can be expressed as:

$$F_{dep} = q_{rt} \quad (3)$$

where, $q_{sh_i}, q_{ms}, q_{rt} \in N$, N is a non-negative integer set, where q_{sh_i} is the flow from the starting point to each holding point, q_{ms} is the flow from the missed approach point to the starting point, q_{rt} is the flow from the ship runway to the departure point, and n is the number of holding points.

3.2.2. Constraint Conditions

As shown in Figure 5, in the shipboard aircraft flight network, each node is unidirectionally connected, and the asymmetry of network flow can be ignored. Therefore, for the network flow model in the ship terminal area, only capacity limitation and flow conservation conditions need to be considered.

The capacity limitation is that the actual flow on each segment should not be greater than the capacity of the segment. The flow conservation condition is that the flow of each node is balanced, and there is no flow convergence or dissipation at a certain point. Among all the traffic constraints, q_{ij} represents the traffic between the nodes i, j , with $q_{ij} \in N$.

In order to calculate the dynamic capacity of the terminal area, it is necessary to calculate the maximum number of shipboard aircraft that can serve each segment in unit time, namely the capacity of the segment. The specific formula is:

$$C_{ij} = \frac{1}{\sum_{n \in H} \sum_{m \in H} (T_m^{ij} - T_n^{ij}) P_m P_n} \quad (4)$$

$$T_n^{ij} = \frac{L_{ij}}{v_{n(c)}^{ij}} \quad (5)$$

$$T_m^{ij} = \frac{L_{ij} + d}{v_{m(c)}^{ij}} \quad (6)$$

$$v_c = v_g - v_0 \cos \beta \quad (7)$$

$$v_g = v_t + v_w \cos \alpha \quad (8)$$

$$v_t = k_{ij} \cdot v_I \quad (9)$$

where, m and n are the types of adjacent shipboard aircraft on the segment, and H is the collection of shipboard aircraft types; P_m and P_n are the proportions of corresponding shipboard aircraft in the fleet. T_m^{ij} and T_n^{ij} refer to the flight time required by the corresponding shipboard aircraft type on segment A_{ij} ; L_{ij} is the length of segment A_{ij} ; d is the minimum safety separation to be maintained during the arrival and departure procedures of shipboard aircraft; v_c is the speed of the shipboard aircraft relative to the ship; v_g is the ground speed of the shipboard aircraft; v_0 is the ship speed; β is the included angle between the ship speed and the ground speed of the shipboard aircraft; v_t is true airspeed. v_w is wind speed; α is the included angle between the wind speed and the true airspeed of the shipboard aircraft; v_I is the indicated airspeed of the shipboard aircraft; k_{ij} is the speed conversion factor corresponding to the altitude of segment A_{ij} , which can be obtained by querying the conversion factor table. If the corresponding altitude is not listed, its value can be obtained by interpolation.

In the arrival flow of shipboard aircraft, the shipboard aircraft flows from the starting point to the holding point and continues to decline to the arrival point. If the waiting task is performed, it flows from the holding point and then flows again. Therefore, for the holding point:

$$q_{sh_i} \leq C_{sh_i}, \forall i \quad (10)$$

$$q_{h_i a} \leq C_{h_i a}, \forall i \quad (11)$$

$$q_{h_i h_i} \leq C_{h_i}, \forall i \quad (12)$$

$$q_{sh_i} + q_{h_i h_i} = q_{h_i a} + q_{h_i h_i}, \forall i \quad (13)$$

where, Formulas (10) and (11) denote the capacity limitation of the arrival flow and the departure flow segments, and Formula (12) denotes the capacity limitation of the holding segment, where C_{h_i} is the i th standard capacity of the shipboard aircraft at the holding point before arrival; Formula (13) is the flow conservation condition.

The shipboard aircraft passes through the holding point, flows into the arrival point, and flows to the initial approach point. According to the approach flow network diagram, the arrival flow from the holding point to the approach point of the shipboard aircraft is a one-by-one correspondence, while the departure flow from the arrival point to the initial approach point is a convergence relationship:

$$q_{a_i o_1} \leq C_{a_i o_1}, i = 1, 2 \quad (14)$$

$$q_{a_i o_2} \leq C_{a_i o_2}, i = 3, 4 \quad (15)$$

$$q_{h_i a_i} = q_{a_i o_j}, \forall i \quad (16)$$

Formulas (14) and (15) are the capacity limitation, where arrival point 1 and 2 flow to starting point 1 and arrival point 3 and 4 flow to starting point 2; Formula (16) is the condition of flow conservation.

The shipboard aircraft descended from the arrival point to the initial approach point and then began their approach, flying towards the middle approach point. Therefore, for the initial approach point, the arrival flow was received and further converged to the intermediate approach point:

$$q_{o_i c} \leq C_{o_i c}, \forall i \quad (17)$$

$$\sum_j q_{a_j o_i} = q_{o_i c}, j = 1, 2, i = 1 \quad (18)$$

$$\sum_j q_{a_j o_i} = q_{o_i c}, j = 3, 4, i = 2 \quad (19)$$

Formula (17) is the capacity limitation, and Formulas (18) and (19) are the flow conservation condition.

The shipboard aircraft drops from the initial approaching point to the intermediate approaching point. After the convergence of the intermediate approaching point, there is only one flow direction, namely the final approaching point. Therefore, for the intermediate approach point:

$$q_{cf} \leq C_{cf} \quad (20)$$

$$\sum_i q_{o_i c} = q_{cf}, i = 1, 2 \quad (21)$$

Formula (20) is the capacity limitation, and Formula (21) is the flow conservation condition.

The shipboard aircraft drops from the intermediate approach point to the final approach point and then continues to decline to the ship landing zone. Therefore, for the final approach point:

$$q_{fd} \leq C_{fd} \quad (22)$$

$$q_{cf} = q_{fd} \quad (23)$$

Formula (22) is the capacity limitation, and Formula (23) is the flow conservation condition.

The shipboard aircraft drops from the last approach point to the landing area of the ship. The ship controller should comprehensively judge whether it has the landing conditions according to the meteorological conditions, navigation speed, shipboard aircraft performance, and other factors. If the landing conditions are met, then it continues to fall to the ship runway; if there is no landing condition, it begins to climb to the missed approach point and executes the missed approach route. Therefore, for the ship landing area:

$$q_{dr} \leq C_{dr} \quad (24)$$

$$q_{dm} \leq C_{dm} \quad (25)$$

$$q_{fd} = q_{dr} + q_{dm} \quad (26)$$

Formulas (24) and (25) are the capacity limitation, and Formula (26) is the flow conservation condition.

If the shipboard aircraft does not have the conditions for landing in the take-off and landing area of the ship, it will climb to the missed approach route again, return to the starting point again, and wait for the subsequent approach. Therefore, for missed approach routes:

$$q_{ms} \leq C_{ms} \quad (27)$$

$$q_{dm} = q_{ms} \quad (28)$$

Formula (27) is the capacity limitation, and Formula (28) is the flow conservation condition.

If the shipboard aircraft has landing conditions in the take-off and landing area of the ship, it will land on the ship runway and slide into the gates. In the departure flow, the shipboard aircraft slides out of the gates and enters the ship runway, then takes off and climbs to the departure point. Since the ship runway is used for the landing and take-off of shipboard aircraft, the flow characteristics on the ship runway should also consider the flow of arrival and departure:

$$q_{rg} + q_{gr} \leq C_r \quad (29)$$

$$q_{dr} = q_{rg} \quad (30)$$

$$q_{gr} = q_{rt} \quad (31)$$

Formula (29) is the capacity limitation, where the q_{rg} is the slide-in flow and q_{gr} is the slide-out flow, which have different meanings, not the net flow on the arc. C is the runway capacity. Formulas (30) and (31) are the flow conservation conditions.

The runway used for shipboard aircraft is similar to that of a civil aviation airport. At the same time, only one aircraft can be accommodated for landing or taking off. Therefore, the runway capacity can be calculated by using the runway occupation time of shipboard aircraft as the arc capacity connecting the landing point and the ship stand:

$$C_r = \frac{1}{\overline{T_r}} \quad (32)$$

where, $\overline{T_r}$ is the average time that the shipboard aircraft occupies the runway, and 1 is the unit time.

After landing, the shipboard aircraft slides into the gates and can perform refueling tasks or wait at the stand. Therefore, it can be considered that the shipboard aircraft staying at the gates are on the self-holding arc. For the stand:

$$q_{rg} - q_{gr} = \Delta q_{gg} \quad (33)$$

$$q_{gg} = q_0 + \Delta q_{gg} \quad (34)$$

$$q_{gg} \leq C_g \quad (35)$$

$$C_g = n_g \cdot \frac{1}{\overline{T_g}} \quad (36)$$

Formula (33) shows that the change of gate occupancy is the difference between the slide-in and slide-out of shipboard aircraft. Formula (34) denotes that the occupancy of the gates is the sum of the initial gates volume and the variation, where q_0 is the initial occupancy of the gates and q_{gg} is the actual occupancy. Formula (35) is the limitation of the number of gates, where C_g is the capacity of gates. Formula (36) calculates the capacity of the gates, $\overline{T_g}$ is the average maintenance time of shipboard aircraft, that is, the occupancy time of the gates, and n_g is the number of gates.

4. Algorithm Solution

In this paper, simulated annealing (SA) is used to solve the capacity of the ship terminal area combined with the above shipboard aircraft operation data and arc capacity calculation results.

SA was first proposed by N. Metropolis et al. It is a stochastic optimization algorithm based on the Monte Carlo iterative strategy. It finds out the relationship between the cooling process of the object in physics and the problem solved by combination. First, the object is heated to a specific high temperature and then cooled slowly [19]. With the continuous decline in temperature, the global optimal solution of the objective function is randomly found in the solution space combined with the probability jump characteristics; that is, the local optimal solution can jump out probabilistically and eventually tend toward the global optimal. The steps of SA are as follows:

Step 1: Randomly generate the positive integer as the initial flow on all of the segments and determine whether it meets the network flow model constraints. If the conditions are not satisfying, set the penalty function $D(X)$, the objective function is $f(X) = F(X) - D(X)$, where $F(X)$ is the total flow, X is the decision vector, namely the flow on each segment.

Step 2: According to the flow disturbance generated by the current temperature in the capacity range, a new solution is obtained, and the objective function value of the new solution is calculated, and it will be compared with the function value of the initial solution.

Step 3: Make the corresponding judgment according to the solution of the objective function. If the total flow of the new solution is greater than that of the current solution, determine whether to update the current solution according to the Metropolis acceptance criteria.

The Metropolis criterion can be expressed as:

$$P = \begin{cases} 1 & \text{if } E_{\text{new}} \geq E_{\text{now}} \\ e^{\frac{f_{\text{new}} - f_{\text{old}}}{kT}} & \text{if } E_{\text{new}} \leq E_{\text{now}} \end{cases} \quad (37)$$

where E is the internal energy at temperature T , ΔE is the change number, and k is the Boltzmann constant.

Step 4: Repeat steps 2 and 3 until the cooling is completed or the specified number of iterations is reached.

According to the above steps, the specific implementation method can be represented by Algorithm 1:

Algorithm 1: Ship terminal capacity calculation method based on simulated annealing

Input: Ship terminal network flow capacity matrix C , including each segment capacity C_{ij} , deck runway capacity C_r and capacity of gates C_g ; flow constraint matrix $A_{m \times n}$.

Output: Ship terminal capacity based on SA Capacity.

Initialization: Set initial annealing temperature, termination annealing temperature $T_{\text{final}} = 1$, cooling parameter $\alpha = 0.98$, inner loop length $\text{meanMarkov} = 100$, step size in search $\text{scale} = 0.5$, randomly generate decision vector Q_0 in the capacity matrix range, including each segment flow q_{ij} and relaxation variable q_k .

$Q_{\text{now}} \leftarrow Q_0$, according to the Formulas (1)–(3), the current network total flow F_{now} is calculated, and the penalty function $D_{\text{now}} = \max(0, (A_{m \times n} Q_{\text{now}})^2)$ and the current objective function $f_{\text{now}} = F_{\text{now}} + D_{\text{now}}$ that the current flow configuration does not meet the constraints are calculated.

$T_{\text{now}} \leftarrow T_{\text{initial}}$

while $T_{\text{now}} \geq T_{\text{final}}$

for $k = 0, 1, 2, \dots, \text{meanMarkov}$

 The random disturbance in decision vector Q_{now} is generated to obtain Q_{new} and calculate the objective function f_{new} .

if $f_{\text{new}} > f_{\text{now}}$

$Q_{\text{now}} \leftarrow Q_{\text{new}}, f_{\text{now}} \leftarrow f_{\text{new}}$

else

$P = e^{\frac{f_{\text{new}} - f_{\text{now}}}{kT_{\text{now}}}}$, Randomly generated real number of intervals $[0, 1]$ *random*

if $P > \text{random}$

$Q_{\text{now}} \leftarrow Q_{\text{new}}, f_{\text{now}} \leftarrow f_{\text{new}}$

end

end

end

$T_{\text{now}} \leftarrow \alpha \cdot T_{\text{now}}$

end

After annealing, find the best flow configuration $Q_{\text{best}} \leftarrow Q_{\text{now}}$, corresponding ship terminal area capacity $\text{Capacity} \leftarrow F_{\text{now}}$

5. Example Analysis

5.1. Parameter Settings

5.1.1. Ship Parameters

The researcher searched the ship-related data and extracted the important parameters affecting the arrival and departure capacity: the length of the ship's deck runway, the blocking device, and the ejection device jointly determined the time of the shipboard aircraft occupying the runway, namely the average landing time and the average take-off time. The number of gates determines its carrying and storage capacity to the shipboard aircraft, and the gates are regarded as the static capacity of the ship. The shipboard aircraft needs to be overhauled and maintained after landing. According to the personnel configuration, the average overhaul time for all types of shipboard aircraft is determined. A ship is a movable take-off and landing platform, and its moving speed directly affects the landing and take-off speed of shipboard aircraft.

According to the typical data in the literature [14], the experimental parameters are set in Table 2.

Table 2. Ship-related parameters.

Parameter	Number	Unit
Length of deck runway	260	m
Number of gates	13	/
Average maintenance time	20	min
Maximum speed	30	kn
Average landing time	5	min
Average take-off time	3	min

5.1.2. Shipboard Aircraft Parameters

According to the relevant information about the shipboard aircraft, the approach process of the shipboard aircraft is summarized as follows:

The shipboard aircraft enters the standby stage at a distance of 50 n miles from the aircraft carrier. The flight altitude is no less than 6000 ft, the flight speed is 250 kn, and the vertical separation of the aircraft is 1000 ft. This stage is guided by TACAN or air surveillance radar.

The shipboard aircraft began to prepare for approaching at 21 n miles from the aircraft carrier and entered the approaching stage at 20 n miles from the aircraft carrier. The instrument landing system was used to guide the approaching. The initial approaching altitude was 5000 ft, and it began to decline from the initial approaching point. It dropped from 12.5 n miles from the aircraft carrier to 1200 ft to maintain level flight. At the same time, the aircraft configuration was changed, and the speed was reduced to 140 kn. At 4 to 8 n miles from the aircraft carrier, the automatic landing system was used to guide the aircraft.

The shipboard aircraft entered the landing phase at 3 n miles from the aircraft carrier and dropped from 1200 ft according to the specified gradient. At 0.75 n miles from the aircraft carrier, the Fresnel landing system was used to guide the landing.

The important parameters affecting the arrival and departure capacity are extracted: the average airspeed at different approaching stages and the longitudinal safety separation that the shipboard aircraft needs to maintain during approach all have an impact on the capacity of each segment.

According to the relevant information, combined with civil aircraft approach data, the experimental parameters are set in Table 3.

Table 3. Parameters of shipboard aircraft.

Parameter	Number	Unit
Take-off airspeed	130	kn
Final approach average airspeed	140	kn
Intermediate approach average airspeed	140	kn
Average initial approaching airspeed	250	kn
Average arrival airspeed	250	kn
Longitudinal safety separation	5	n mile

5.1.3. Segment Parameters

Combined with the approach segment in the field of civil aviation, the important parameters affecting the arrival and departure capacity are extracted: the altitude of different segments determines the different air pressure, which affects the conversion factor between the airspeed and the ground speed of the shipboard aircraft. The length of each segment and the safe separation of shipboard aircraft jointly determine the static capacity of the segment. Shipboard aircraft can accelerate, they climb rapidly after departure, and perform different tasks, which is to say that they are not limited by the capacity of the segment and the safe separation between the front and rear aircraft. In particular, after taking off, the carrier aircraft accelerates and climbs to the departure point and then continues to perform different tasks. When the rear aircraft leaves the deck, the front aircraft has reached a certain height, and the speed of the front aircraft is far greater than the speed of the rear aircraft. As a result, the departure of the shipboard aircraft is not limited by the segment capacity and safety interval. Therefore, the departure segment capacity can be regarded as infinite.

Therefore, according to the characteristics of the aircraft carrier [17] and common airport terminal area data [2], the experimental parameters are set in Table 4.

Table 4. Related parameters of segment.

Parameter	Number	Unit
Length of descending segment	150	n mile
Average altitude of descending segment	10,000	ft
Length of holding segment	8	n mile
Average altitude of holding segment	6000	ft
Length of arrival segment	30	n mile
Average altitude of arrival segment	6000	ft
Length of initial approach segment	7.5	n mile
Average altitude of starting segment	3100	ft
Length of intermediate approach segment	9.5	n mile
Average altitude of intermediate segment	1200	ft
Length of last approach	3	n mile
Average altitude of final segment	600	ft
Length of departure segment	∞	n mile

5.2. Result Analysis

5.2.1. Arc Capacity Analysis

According to the above ship parameters, the shipboard aircraft parameters, the segment parameters, and the missed approach parameters, combined with the calculation formulas of arc capacity in the network flow model, the unit time is 1 h, and the arc capacity of each segment can be solved, as shown in Table 5.

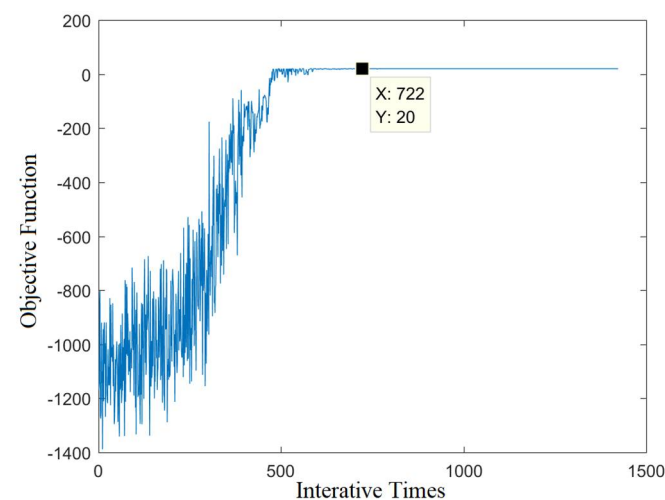
Table 5. Calculation results of arc capacity.

Segment	Arc Capacity (Number)
Descending segment	89
Arrival segment	53
Initial approach segment	48
Intermediate approach segment	31
Final approach section	27
Missed approach segment	45
The deck runway (landing)	12
Gates	39
Deck runway (takeoff)	20
Departure segment	∞

From Table 5, it can be seen that with the decreasing altitude of the shipboard aircraft, the length and speed of the approach section decrease, as does the arc capacity of each section. Due to the different average arrival and departure time, the corresponding deck runway arrival and departure arc capacity is also different. Since the departure segment is considered to be infinite, its arc capacity is also ∞ .

5.2.2. Analysis of Arrival and Departure Capacity

According to the arc capacity settlement results based on MATLAB R2018a software (Nanjing, China), SA is used to solve the arrival and departure capacity results. The annealing process is shown in Figure 6:

**Figure 6.** Simulated annealing process.

As shown in the figure, since the penalty function is set, the objective function remains negative at the beginning of annealing, indicating that it does not meet the flow constraint of the arrival and departure network flow of shipboard aircraft at this time. With the dropping temperature, the number of iterations increases gradually, and the objective function value fluctuates, which reflects that the SA accepts the new solution based on probability, and the flow on each route grows closer to the flow constraint requirements.

Through 722 iterations, the maximum flow rate converges to 20 aircraft/h, and the arrival flow $F_{app} = 0$ and departure flow $F_{dep} = 20$ meet the constraints in the network flow model.

Comparing the final ship terminal capacity results with the arc capacity of each segment, it can be demonstrated that the number of shipboard aircraft served by the ship deck per unit time becomes the flow bottleneck of the whole system, and the terminal capacity is equal to the departure capacity of the deck runway. Of course, this state is the limit of all shipboard aircraft departure flow and cannot reach a stable state. Consequently,

the flow balance limit is added to analyze the ship terminal capacity when the arrival and departure flow of the shipboard aircraft are as balanced as possible, as shown in Figure 7.

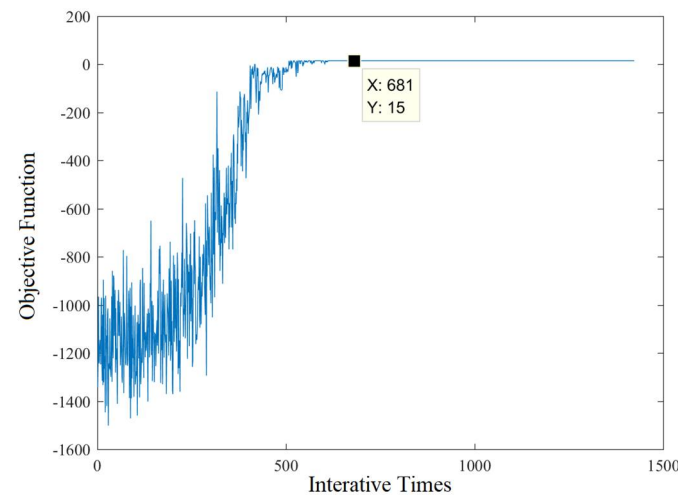


Figure 7. SA process in equilibrium condition.

As shown in Figure 7, the total flow of the system finally converges to 15, which is between the arrival capacity and the departure capacity of the deck runway. At this time, the arrival flow $F_{app} = 7$ and the departure flow $F_{dep} = 8$. The reason is that the arrival and departure of the shipboard aircraft share the same runway, and there are arrival and departure shipboard aircraft tasks at the same time in unit time. The arrival behavior of the runway that takes a longer time will take up the available time of the departure task so that the operating flow cannot reach the departure capacity of the deck runway theoretically.

5.2.3. Sensitivity Analysis

(1) Number of gates

Since different types of ships have a different number of gates, it is necessary to carry out the sensitivity analysis on the gates of ships and summarize their influence on the arrival and departure capacity. According to the above basic data, the shipboard aircraft flow envelope curve was drawn, as shown in Figure 8.

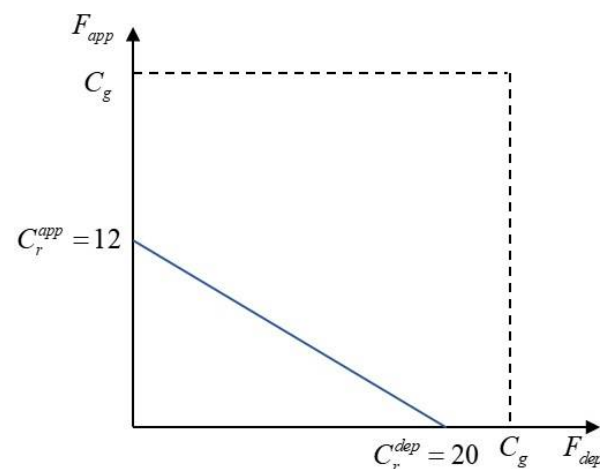


Figure 8. Arrival and departure flow envelope, $n_g \geq 7$.

As shown in Figure 8, all of the integer points below the blue real line are realizable flows, and there is a certain probability in the actual operation of the shipboard aircraft. Because the capacity of gates is $C_g \geq 20$; that is, when the average maintenance time

is 20 min, and the number of gates is $n_g \geq 7$, the bottleneck of the network flow of the shipboard aircraft is the ship's deck runway.

Considering the extreme situation, even if the type of tasks performed by the shipboard aircraft per unit time is take-off or landing, the ship with a sufficient number of gates can still ensure that the deck runway is fully utilized. Of course, such an extreme situation requires that the gates are empty during the full landing mission and full during the full take-off mission, and the flow state is difficult to maintain.

When the capacity of gates is $12 \leq C_g < 20$, that is, when the average maintenance time is 20 min, and the number of gates is $4 \leq n_g < 7$, the shipboard aircraft arrival and departure flow envelope is shown in Figure 9.

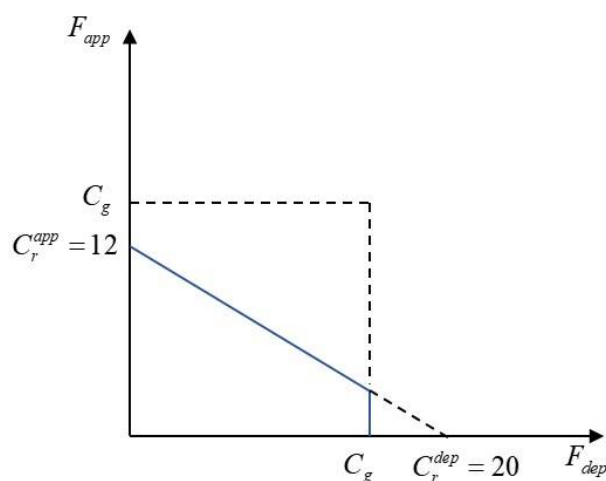


Figure 9. Arrival and departure flow envelope, $4 \leq n_g < 7$.

As shown in Figure 9, all of the integer points below the solid blue line are achievable flows. Compared with Figure 8, the decrease in the number of stops leads to the fact that the ship no longer meets all of the imbalanced tasks. When the limit of the full take-off task occurs, the runway will not be fully utilized, and idle time will be left.

When the capacity of gates is $8 \leq C_g < 12$; that is, the average maintenance time is 20 min, and the number of gates $n_g = 3$, the flow envelope of the shipboard aircraft is shown in Figure 10.

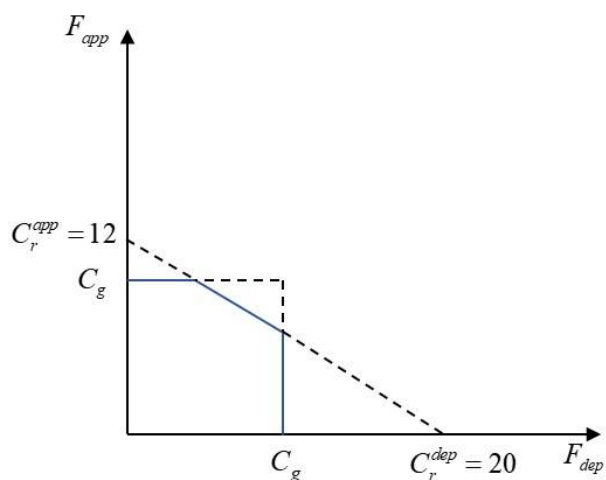


Figure 10. Arrival and departure flow envelope, $n_g = 3$.

As shown in Figure 10, all of the integer points below the solid blue line are achievable flows. Compared with Figure 9, the number of gates further decreases. In the face of imbalanced tasks, the number of gates is insufficient, resulting in the failure to make

full use of deck runways in the case of full take-off and full landing and the waste of resources. Of course, in general, when the arrival and departure tasks of shipboard aircraft are relatively balanced, the runway can still reach saturation.

When the capacity of gates is $C_g < 8$, that is, the average maintenance time is 20 min, and the number of gates $n_g \leq 2$, the flow envelope of the shipboard aircraft is shown in Figure 11.

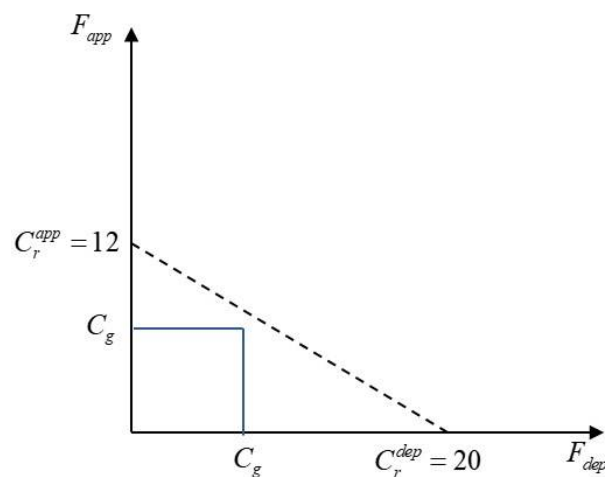


Figure 11. Arrival and departure flow envelope, $n_g \leq 2$.

As shown in Figure 11, all of the integer points below the solid blue line are achievable flows. Compared with Figure 10, the number of gates further decreases. At this time, the bottleneck of the shipboard aircraft arrival and departure network flow system is owing to the number of gates, and the runway capacity no longer limits the overall flow. No matter the task, the deck runway is not saturated, and there must be idle conditions.

Based on the influence of the number of gates on the runway utilization and the arrival and departure flow of shipboard aircraft, the quantitative relationship between the number of gates and the operational capacity of the ship terminal area is summarized, as shown in Figure 12:

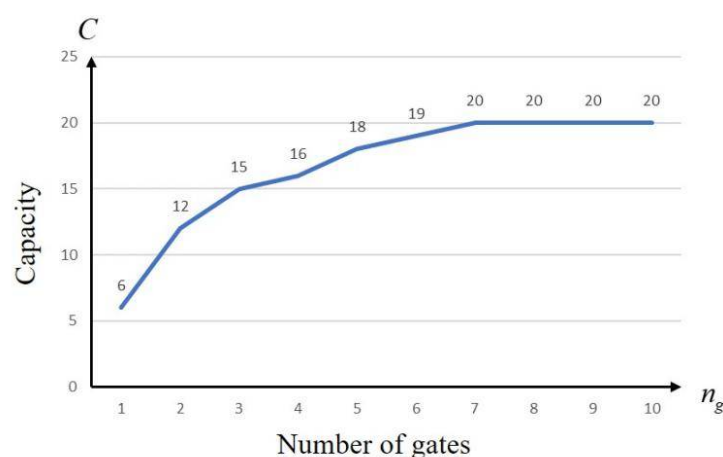


Figure 12. Influence of number of gates.

As shown in Figure 12, when the number of gates is $n_g < 7$, the operational capacity of the ship terminal area is positively correlated with it, and when $n_g \leq 3$, the capacity growth rate is larger; when $n_g \geq 7$, the ship terminal area operational capacity is no longer increased, the bottleneck of the network flow is the deck runway.

It should be pointed out that the maximum flow of the terminal area under the above conditions is in a stable state, that is, the sustainable capacity. A larger flight flow could be

achieved in a short time period when the gates are all available at the initial stage, even if the number of gates is insufficient. However, the flight flow is obviously not sustainable and will cause network congestion.

(2) Ship Moving Speed

Since the arc capacity is calculated according to the relative speed of the shipboard aircraft to the ship and the vacuum speed is fixed on the corresponding segment, whether the ship moves or not and the speed of movement will affect the calculation of arc capacity, which may further change the operation capacity of the ship. Regarding the landing direction of the shipboard aircraft as the positive direction, the corresponding ship operation capacity is calculated according to different ship moving speeds, as shown in Figure 13:

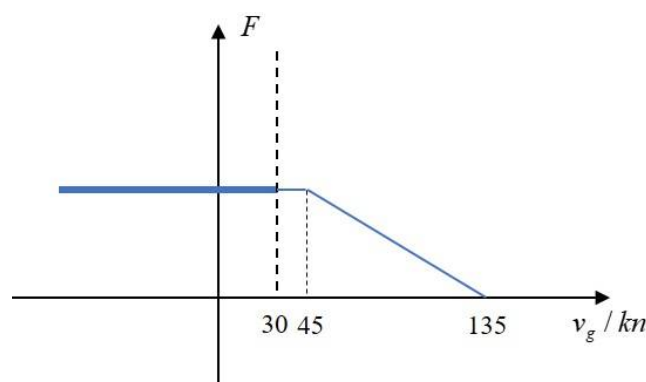


Figure 13. Influence of ship moving speed.

As shown in Figure 13, when the ship moves at speed $v_g > 45$ kn, the operation capacity of the ship will decrease, and the final approach section becomes the bottleneck of the network flow of the shipboard aircraft. When $v_g = 135$ kn, the relative velocity between the shipboard aircraft and the ship is too low. Under the conditions for ensuring a safe separation, there is almost no shipboard aircraft that can land in unit time.

However, the common ship speed is 30 kn, so in the actual operation, the ship's own motion does not affect the terminal area capacity.

In summary, under general conditions, the bottleneck of the network traffic in the ship terminal area is the deck runway, and the serviceability of the runway depends on the average time of the shipboard aircraft landing and taking off, which further determines the capacity of the ship terminal area. The number of gates is crucial to the capacity of the ship terminal area. It not only ensures that the runway can be fully utilized but also provides sufficient imbalanced flow protection under extreme tasks. The more gates that there are, the more sufficient the degree left for maintenance time for shipboard aircraft. The ship's movement is relatively small relative to the shipboard aircraft's flight speed. The impact on the terminal area capacity is still purely theoretical, which can be ignored in the actual situation.

6. Conclusions

In this paper, a method for airspace division and sector division of the ship terminal area is proposed. On this basis, the route network division of shipboard aircraft arrival and departure is realized. According to the airspace characteristics of the ship terminal area and the operation process of the shipboard aircraft, the key nodes of the route are abstracted, and the network flow model of the arrival and departure of the shipboard aircraft is established by using the capacity limitation and flow conservation conditions. A ship terminal capacity evaluation model based on integer programming is proposed by using the maximum flow theory.

According to the capacity evaluation results of the ship terminal area obtained from SA, when the number of gates $n_g \geq 7$, the bottleneck of the ship terminal area operation

capacity is the deck runway. When $3 \leq n_g < 7$, imbalanced take-off and landing tasks lead to waste of runway resources. Furthermore, when $n_g < 3$, the number of gates becomes the bottleneck, which limits the capacity. With the number of gates reduces from seven to three, the capacity reduces from twenty sorties per hour to six sorties per hour. Moreover, the ship's own operation speed has little impact on the actual operation.

To sum up, the reasonable evaluation of the capacity of the ship terminal area can alleviate the imbalance of capacity supply and flow, airspace congestion, and other issues so as to make full use of limited resources to improve the operational efficiency of the ship-board aircraft. This paper provides a rapid evaluation method for the capacity of the ship terminal area, which makes up for the limitations of a single mathematical model analysis in the actual operation. In the future, we will further consider the influence of the bad weather to promote the development of fleet groups and the full use of maritime airspace.

Author Contributions: Conceptualization, G.Z.; methodology, G.Z. and Y.F.; software, Y.F. and J.Y.; validation, G.Z., Y.F. and J.Y.; formal analysis, J.Y. and D.F.; investigation, D.F.; resources, G.Z. and Y.F.; writing—original draft preparation, G.Z. and Y.F.; writing—review and editing, G.Z., Y.F. and O.F.; visualization, Y.F. and O.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China (71971114).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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