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Carrier-based aircraft support operation scheduling based on improved tabu search algorithm

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Abstract: [**Objectives**] The sortie generation capacity is an important index of the operational capability of an aircraft carrier and largely determined by the support operation scheduling of the carrier-based aircraft. Therefore a good scheduling of carrier-based aircrafts on the deck can effectively improve the operational capability of aircraft carrier. [**Methods**] This paper establishes the operation scheduling module by converting the carrier-based aircraft support operation scheduling into job-shop scheduling problem. And through improvement of initial solution, search strategy and tabu list length, an improved tabu search algorithm is proposed to solve the model, with the purpose of minimizing the makespan. [**Results**] The simulation test results show that the improved tabu search algorithm can solve the carrier-based aircraft support operation scheduling problem effectively, and it is better than the traditional tabu search algorithm in terms of speed calculation and result optimization. [**Conclusions**] The proposed algorithm provides an effective way to solve the carrier-based aircraft support operation scheduling problem.

Key words: carrier-based aircraft; support operation; job-shop scheduling problem; tabu search
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0 Introduction

As the core combat equipment of aircraft carrier, carrier-based aircraft has a great influence on its operational capability [1], and the sortie generation capacity of carrier-based aircraft is a key indicator for judging the operational capability of the aircraft carrier [2]. Therefore, the overall design of the aircraft carrier has always been around how to effectively improve the sortie generation capacity of carrier-based aircraft [3]. The carrier-based aircraft must go through support on deck strictly in accordance with the pre-determined deck operation procedure before taking off by the catapult to perform a task [4], so the sortie generation capacity of carrier-based aircraft is closely related to the support operation scheduling strategy on the aircraft carrier deck. The limited support resources, the variable operating environment and the complicated operation process on the deck of the aircraft carrier determine that the support operation scheduling of carrier-based aircraft is the key factor that restricts the sortie generation capacity of carrier-based aircraft [5].

The support operation scheduling of carrier-based aircraft provides a reasonable support station and support sequence under limited deck space and support resources. It aims to shorten the hauling distance of the carrier-based aircraft and reduce the total support operation time, so as to ensure the completion of the support task before takeoff. This is a resource-constrained optimal scheduling problem [5].

At present, scholars all over the world have carried out extensive research on the support operation scheduling of aircraft carrier decks. For example, the Computer Science and Artificial Intelligence Laboratory of Massachusetts Institute of Technology developed a human-machine interactive Deck Course of Action Planner (DCAP) that can be used to make intelligent decision on the support operation scheduling of carrier-based aircraft [6]. Dastidar et al. [7] pro-

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posed a distributed strategy based on queuing network, which can be used to solve the scheduling problem of aircraft carrier deck. Han et al. [8] adopted genetic algorithm to solve the support operation problem of carrier-based aircraft, and intuitively presented a support procedure for carrier-based aircraft. Si et al. [9] established the basic model of carrier-based aircraft scheduling, and solved the scheduling problem using the improved particle swarm algorithm after the fusion of multi-population and chaotic local search. Han et al. [10] established a multi-target integrated maintenance support model and proposed an adaptive hybrid differential evolution algorithm, which can improve the maintenance support efficiency of multi-target carrier-based aircraft.

At present, computational simulation methods and intelligent optimization algorithms are mainly used in China and abroad to solve the support operation scheduling of carrier-based aircraft. Among them, the computational simulation method generally constructs the model through logical relationship and parameter selection, but different system models lead to different conclusions. Intelligent optimization algorithm is faster in calculation, can be combined with other algorithms, and has more advantages than simulation method. At the same time, the existing research work mainly focuses on the allocation of support stations for carrier-based aircraft, and there is little research on the support sequence scheduling during resource conflicts. Moreover, the impact of the takeoff time of each carrier-based aircraft on support plan is not considered. This paper will comprehensively consider the carrier-based aircraft support operation, takeoff time and transit time to optimize the support sequence so as to solve the feasible scheduling scheme in a short time. In view of the similarity between the support operation scheduling of carrier-based aircraft and the job-shop scheduling, it is proposed to convert the support operation scheduling problem of carrier-based aircraft into a Job-shop Scheduling Problem (JSP) and solve it by intelligent optimization algorithm. As a result, an improved algorithm based on Tabu Search (TS) with higher efficiency is proposed.

1 Model description and conversion

1.1 Support operation scheduling problem of carrier-based aircraft

This paper will take the traditional multi-station support of the Nimitz-class aircraft carrier as a reference and appropriately simplify it. That is to say, the interference factors during the support operation and the influence among multiple waves are not considered and it is assumed that the station and sequence of each carrier-based aircraft to complete support operation have been worked out in advance by the scheduling staff.

It is assumed that there are two carrier-based aircrafts in a wave (set to F1 and F2) that need to take off to perform the mission, the takeoff time of this wave is 8:00, and the takeoff time interval is 10 minutes (the takeoff time of F1 should not be later than 8:00, and F2 should not be later than 8:10). In addition, it is necessary to complete support tasks such as replenishing fuel/lubricating oil/special liquids and gases, charging, and mounting ammunition before takeoff [11]. The execution of support task is divided into serial execution and parallel execution. In serial execution, multiple support tasks can only be completed in sequence, and the total completion time is equal to the sum of the completion time of the individual support tasks. In parallel execution, multiple support tasks can be performed simultaneously, and the total completion time is equal to the maximum completion time of a single support task. Since the real support operation completion time will dynamically change within a certain range and has certain randomness, this paper only considers the case where the time fluctuation interval is small, and takes the approximate value as the support completion time. It is assumed that the support tasks of two carrier-based aircrafts are completed at five stations (A1, A2, A3, A4, A5), and each station can provide several support services, but can only serve one carrier-based aircraft at the same time. It is assumed that the scheduling process is as follows: F1 goes to A1, A2, A4 stations to complete the support service; F2 goes to A3, A2, A5 stations to complete the support service. The sequence, station, task and time of each carrier-based aircraft to complete the support operation are shown in Table 1. When the carrier-based aircraft completes the support operation at one station, it is towed to the next support station, so the hauling transit time is proportional to the hauling distance. This paper ignores the catapult-assisted takeoff time of the carrier-based aircraft, so its support operation completion time is the takeoff time.

Since each station can only provide support for one carrier-based aircraft at the same time, when two carrier-based aircrafts need to complete their re-

Table 1 Support operation of carrier-based aircraft

Carrier-based aircraft	Suport station	Support task	Support time /min
F1	A1	Replenishing fuel, lubricating oil, etc.	20
	A2	Charging	15
	A4	Mounting ammunition	15
F2	A3	Replenishing fuel, lubricating oil, etc.	18
	A2	Charging	15
	A5	Mounting ammunition	17

spective support operations at five stations, there may be two carrier-based aircrafts at the same station simultaneously if scheduling is not performed, as shown by the shaded A2 station in Fig. 1. In order to solve the station conflict, the total time of the support operation must be as short as possible, and the following conditions must be met:

1) Each carrier-based aircraft needs to complete the support operation at each station in accordance with the preset support operation sequence.

2) A single station can only serve one carrier-based aircraft at the same time, and a single carrier-based aircraft can only be supported at one station at the same time.

3) Each carrier-based aircraft must complete all support operations prior to takeoff.

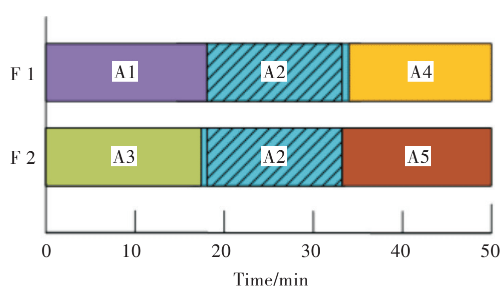

Fig.1 Infeasible schedule

1.2 JSP

JSP is a classic production scheduling problem and a typical NP-hard problem, where NP refers to non-deterministic polynomial. This problem originated in the processing and manufacturing industry and is now widely used in transportation, network communication and other fields. The JSP can be described as follows: A number of workpieces and several machines are given, and each workpiece goes sequentially to each machine for completing processing tasks according to a preset processing route. Since there are several workpieces to be processed on each machine, the scheduling scheme needs to determine the processing sequence of workpieces on each machine so as to minimize the makespan.

The objective function of JSP is

$$\min t_n \tag{1}$$

The constraints of JSP are

$$t_i \geqslant 0;\quad i \in O \tag{2}$$

$$t_j - t_i \geqslant d_i;\quad (i,j) \in A \tag{3}$$

$$t_j - t_i \geqslant d_i \vee t_i - t_j \geqslant d_j;\quad (i,j) \in E_k, k \in M \tag{4}$$

Where t_n is the makespan; t_i and t_j are the start time of the process i and the process j, respectively; $O=\{0,1,\cdots,n\}$ is the set of the process i and the process j, where 0 and n are virtual processes, with process 0 as the starting point and process n as the end point; $D=\{d_1, d_2, \cdots, d_n\}$ is the processing time set of each process, where $(d_i, d_j) \in D$; A is the constraint set of processing sequence determined by the workpiece's own process route. E_k is the constraint set processed on machine k; $M=\{1,2,\cdots,m\}$ is the set of machines.

Eq. (1) indicates that the scheduling target is to minimize the makespan, Eq. (2) indicates that the start time of a process must be greater than 0, Eq. (3) indicates that a workpiece must be processed sequentially according to the process route, and Eq. (4) indicates that a machine can only process one workpiece at the same time.

1.3 Differences and conversion between two models

It can be seen from the above that the support operation scheduling problem of carrier-based aircraft is very similar to JSP, but there are two differences between the two models:

1) In JSP, each workpiece starts from a fixed point and is processed on different machines according to the processing sequence and reaches the end point. Therefore, in different scheduling schemes, each workpiece reaches the end point at different time. In the case of the support operation scheduling of carrier-based aircraft, the takeoff time of each is different, and each carrier-based aircraft must complete all support operations before takeoff. In simple terms, JSP can be viewed as a sort from a fixed starting point to a non-fixed end point, while the support operation scheduling of carrier-based aircraft considers the takeoff time to be a fixed end point. If it is simply converted into a JSP, an effective solution may not be obtained.

2) In the JSP model, the transit time from the previous machine to the next machine when a process of one workpiece is completed is not considered. In the

support operation scheduling problem of carrier-based aircraft, the effect of transit time on the final scheduling scheme cannot be ignored. Therefore, the transit time should be considered during the scheduling process.

Based on this, the paper reversely transforms the support sequence constraint of the carrier-based aircraft into the processing sequence constraint of the workpiece in the job-shop scheduling, and each support operation corresponds to the processing sequence in reverse order. The carrier-based aircraft set is converted into the workpiece set in job-shop scheduling. A virtual process is inserted before the first process of each workpiece, namely, the latest takeoff time of all carrier-based aircrafts is taken to subtract the takeoff time of the carrier-based aircraft represented by the workpiece, and the difference is used as the processing time of the virtual process (if the difference is 0, the virtual process is not inserted). Moreover, a virtual process is inserted between the remaining adjacent processes, and the transit time of carrier-based aircraft is used as the processing time of the process.

According to the above processing steps, Fig. 1 can be converted to Fig. 2. In Fig. 2, JOB1 corresponds to F1; JOB2 corresponds to F2; M1, M2, M3, M4, M5 correspond to A1, A2, A3, A4, A5, respectively. The processing time of the non-gray process is the same as the time of carrier-based aircraft support operation. The gray node is the inserted virtual process, and the processing machine is M0, which is a special machine that can process infinite workpieces at the same time. The processing time of the first gray process in JOB1 is the difference between the takeoff time of F2 and F1, and the processing time of the other gray processes is the transit time between adjacent stations.

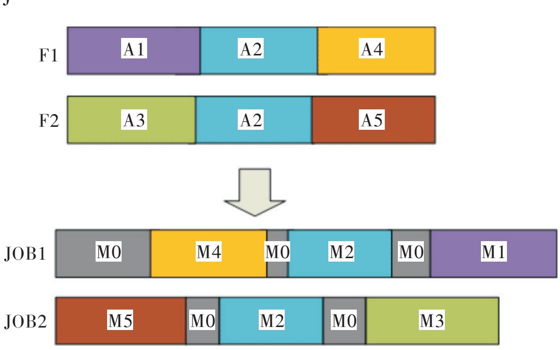

Fig.2 Model transformation

2 Solving algorithm

The JSP solution method can be mainly divided into two types: optimization algorithm and heuristic algorithm. The optimization algorithm (for example, the branch and bound method) is very computationally intensive and difficult to apply to the aircraft carrier deck. In the heuristic algorithm, the convergence rate of the simulated annealing algorithm is too slow, the search space is too large, and the temperature is difficult to be controlled. Genetic algorithm has the problem of prematurity and low efficiency. TS algorithm has an acceptable computational efficiency after solving problems such as initial solution, search strategy and tabu list length. Therefore, based on the TS algorithm, this paper proposes an improved heuristic algorithm for solving the support operation scheduling of carrier-based aircraft.

The TS algorithm adopts the idea of local search, and conducts progressive optimization globally. The search process is shown in Fig. 3. The main idea of TS is to search the neighborhood of the initial solution and find the candidate solution as the current solution. Furthermore, it adopts tabu list to store the searched area information, so as to avoid returning to the previously searched area in the subsequent iterative search. The TS algorithm has six basic elements: initial solution and objective function, neighborhood structure, candidate solution, tabu list and length, aspiration criterion, and termination rule [12]. The Improved Tabu Search (ITS) algorithm proposed in this paper will focus on the length of the tab list, generation of initial solution, and incorporation of the scat-

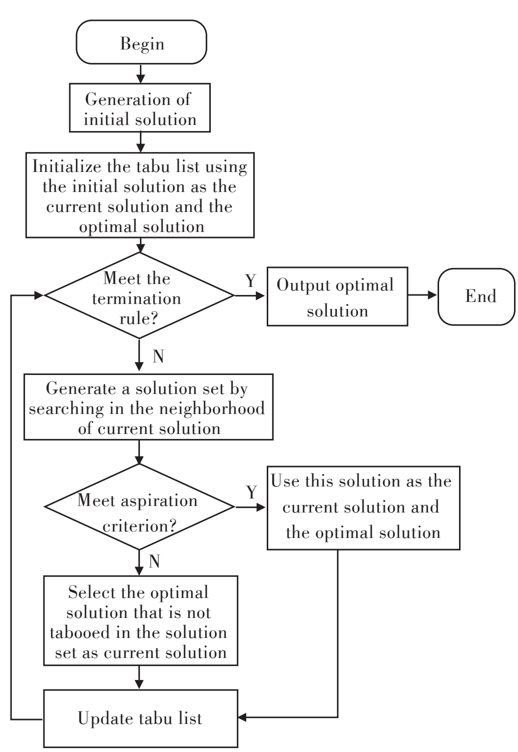

Fig.3 Tabu search process

ter search strategy and the centralized search strategy.

1) Tabu list. The tabu list is used to store objects that are tabooed to prevent repeated search for previously searched regions. If the length of the tabu list is too long, the search will be suppressed; if the length is too short, it will cause repeated search and enter the loop [13]. The ITS algorithm will employ the dynamic tabu list length L, whose value will dynamically change between the two limits L_{min} and L_{max}, specifically:

(1) If a solution superior to the current solution is found, $L-1$ is taken as the length of the tabu list, and $L \geqslant L_{min}$ is maintained.

(2) If a solution superior to the current solution is not found, L+1 is taken as the length of the tabu list and $L \leqslant L_{max}$ is maintained.

(3) It is assumed that the initial value of tabu list length L is L_{min}, where $L_{min} = 2w/3$, $L_{max} = 2w$, and w is the number of workpieces in the job shop.

2) Generation of an initial solution. An initial solution must be given before the TS, and a good initial solution can significantly improve the performance of the TS algorithm [12]. Considering that the shifting bottleneck algorithm can not only solve the job-shop problem quickly, but also generate a solution better than that of the priority allocation criteria such as SPT and FCFS, this paper will use the shifting bottleneck algorithm to provide the initial solution for TS. The shifting bottleneck algorithm is a heuristic algorithm, and it finds the bottleneck machine with the largest delay in all machines and then performs single-machine scheduling. After the scheduling is completed, the above steps are repeated for the remaining machines.

3) Scatter search strategy. Scatter search strategy can perform extensive search on the region of the solution set to avoid falling into local search. If a solution that is better than the current optimal solution has not been found in a certain area, the search will be started again in a new area. If a scheme shorter than the makespan of the current scheduling scheme in a search is not found, the number of iterations should be recorded. When the number reaches the preset upper limit, a new solution will be found to serve as the initial solution of the next iteration, and then the tabu list is emptied.

4) Centralized search strategy. When the optimal solution is updated, if the current region is further searched, it is possible to find more optimal solutions. If a solution better than the current optimal solution is found in the local region, the optimal solution should be updated and the tabu list should be emptied to make the follow-up search of the current region freer.

In the process of converting the support operation scheduling problem of carrier-based aircraft into JSP, this paper introduces a virtual machine M0. Since M0 has an infinite capacity and allows to process infinite workpieces at the same time, the workpiece processing sequence of M0 will not affect the total processing time. Therefore, in the ITS algorithm, the workpiece processing order on M0 will not be swapped to save computation time.

3 Experimental simulation results

In order to verify the improving effect of the proposed algorithm, two examples are designed with reference to the USS Nimitz and Carrier airwing nine surge demonstration in 1997 and related references [14-15]. The station and time of the carrier-based aircraft support operation in case 1 are shown in Table 2. The transit time of the carrier-based aircraft to the next station is proportional to the distance between the stations. It is assumed that six carrier-based aircrafts (F1-F6) need to be dispatched at a certain wave, each carrier-based aircraft must complete the four support tasks of refueling, flight preparation, charging, and mounting ammunition before takeoff, and each support operation has two support stations (Y1/Y2, P1/P2, S1/S2, G1/G2) to pro-

Table 2 Deck operation (case 1)

Carrier-based aircraft	Support station				Support time/min			
	Refueling	Flight preparation	Charging	Mounting ammunition	Refueling	Flight preparation	Charging	Mounting ammunition
F1	Y1	P1	S1	G1	15	15	10	15
F2	Y2	P1	S2	G1	16	15	12	15
F3	Y1	P2	S1	G2	15	10	10	10
F4	Y2	P2	S2	G1	16	10	12	15
F5	Y2	P1	S2	G2	16	15	12	10
F6	Y2	P2	S1	G2	16	10	10	10

vide services. The takeoff time of this wave starts at 10:35 and the takeoff interval is 5 minutes.

The experimental platform is developed in Java language. The running machine environment is Core i5-6200U, the CPU basic frequency is 2.3 GHz, the memory capacity is 8 GB, and the operating system is Windows 10. Due to the high dependence of the TS algorithm on the initial solution, in order to verify the improving effect of the shifting bottleneck algorithm on TS efficiency, the random solution (ITS-R), the solution generated by the FCFS rule (ITS-FCFS) and the solution generated by the shifting bottleneck algorithm (ITS-M) are adopted as initial solutions to perform comparison on the basis of the ITS algorithm. The termination rule of the TS algorithm is as follows: the current optimal solution is updated for no more than 60 times. Table 3 shows the comparison results of 10 times of repeated independent calculations. In the table, the average value of optimal solution corresponding to ITS-R is 110, and the average value of calculating time is 0.964 s. The average value of optimal solution corresponding to ITS-FCFS is 110, and the average calculating time is 0.825 s. The average value of the optimal solution corresponding to ITS-M is 110, and the average calculating time is 0.682 s.

It can be seen from Table 3 that although the optimal solutions corresponding to the three initial solutions are the same, the efficiency of calculating the initial solution by the shifting bottleneck algorithm is the highest. Therefore, the initial solution generated by the shifting bottleneck algorithm can effectively improve the TS algorithm, and its Gantt chart is shown in Fig. 4. The gray portion of the figure indicates the transfer process of the carrier-based aircraft from the previous station to the next station.

Table 3 Comparison of calculation results of different initial solutions

Calculation times	Initial solution ITS-R		Initial solution ITS-FCFS		Initial solution ITS-M	
	Optimal solution	Calculating time/s	Optimal solution	Calculating time/s	Optimal solution	Calculating time/s
1	110	1.035	110	0.843	110	0.745
2	110	0.809	110	0.807	110	0.766
3	110	0.83	110	0.845	110	0.59
4	110	0.903	110	0.792	110	0.747
5	110	1.171	110	0.93	110	0.639
6	110	0.947	110	0.799	110	0.602
7	110	0.91	110	0.84	110	0.671
8	110	1.195	110	0.747	110	0.758
9	110	0.964	110	0.833	110	0.711
10	110	0.879	110	0.815	110	0.59

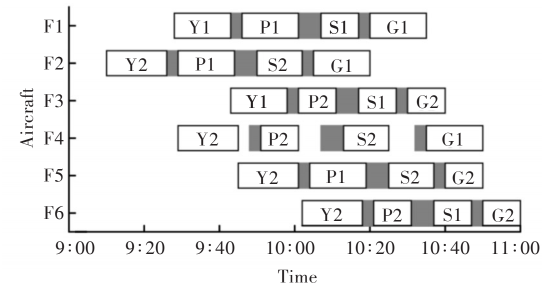

Fig.4 Gantt chart of case 1

The total time of the support operation scheme solved by the improved algorithm is 110 minutes, and the entire support operation flow runs from 9:10 (F2 refueling) to 11:00 (F6 takeoff).

In order to compare the computational efficiency of the ITS algorithm and the traditional TS algorithm, the two algorithms are used to perform 10 repeated independent calculations for case 1. The comparison results are shown in Table 4. It can be seen from Table 4 that the average value of the optimal solution corresponding to the ITS algorithm is 110, and the average value of the calculating time is 0.682 s. The average value of the optimal solution corresponding to the TS algorithm is 110.1, and the average value of the calculating time is 1.029 s. Therefore, the calculation speed of the ITS algorithm is faster than that of the TS algorithm, and the TS algorithm occasionally cannot find the optimal solution 110.

Table 4 Comparison between ITS algorithm and TS algorithm (case 1)

Calculation times	ITS algorithm		TS algorithm	
	Optimal solution	Calculating time/s	Optimal solution	Calculating time/s
1	110	0.745	110	1.153
2	110	0.766	110	1.025
3	110	0.590	110	1.012
4	110	0.747	110	0.925
5	110	0.639	110	1.127
6	110	0.602	110	1.051
7	110	0.671	111	0.859
8	110	0.758	110	0.998
9	110	0.711	110	1.094
10	110	0.590	110	1.050

In order to further verify the computational performance when different numbers of carrier-based aircrafts are dispatched, case 2 is also designed. It is assumed that 10 carrier-based aircrafts are dispatched with a takeoff time of 10:42 and a takeoff interval of 2 minutes. The support operation is arranged as shown in Table 5.

For case 2, the comparison of computational performance between ITS algorithm and traditional TS

Table 5 Deck operation (case 2)

Carrier-based aircraft	Support station				Support time/min			
	Refueling	Flight preparation	Charging	Mounting ammunition	Refueling	Flight preparation	Charging	Mounting ammunition
F1	Y2	P1	S2	G1	16	15	12	15
F2	Y1	P1	S1	G1	15	15	10	15
F3	Y1	P2	S1	G2	15	10	10	10
F4	Y2	P1	S2	G2	16	15	12	10
F5	Y2	P2	S2	G2	16	10	12	10
F6	Y2	P2	S1	G1	16	10	10	15
F7	Y1	P2	S2	G1	15	10	12	15
F8	Y2	P1	S1	G2	16	15	10	10
F9	Y2	P2	S1	G1	16	10	10	15
F10	Y1	P1	S2	G2	15	15	12	10

Table 6 Comparison between ITS algorithm and TS algorithm (case 2)

Calculation times	ITS algorithm		TS algorithm	
	Optimal solution	Calculating time/s	Optimal solution	Calculating time/s
1	145	3.555	147	4.254
2	145	3.904	145	4.241
3	145	4.057	150	4.256
4	145	3.421	147	4.427
5	145	3.515	147	4.776
6	145	3.756	145	4.861
7	145	3.715	145	4.291
8	145	4.121	145	5.249
9	145	3.714	150	4.313
10	145	3.621	145	5.461

algorithm is shown in Table 6. The average value of the optimal solution corresponding to the ITS algorithm is 145, and the average value of the calculating time is 3.73 s. The average value of the optimal solution corresponding to the TS algorithm is 146.6, and the average value of the calculating time is 4.613 s. Therefore, the computational efficiency and optimization effect of the ITS algorithm are better than those of TS algorithm.

4 Conclusions

In this paper, the support operation scheduling problem of carrier-based aircraft is converted into JSP. The support operation scheduling model is established, and an ITS algorithm is proposed to solve the model. Compared with the traditional TS algorithm, the improved algorithm derives the initial solution using the shifting bottleneck algorithm, incorporates the scatter search strategy and the centralized search strategy, and makes the length of the tabu list dynamically change with the search. The calculation results of different scales of example verification show that the ITS algorithm can effectively optimize the support operation process of carrier-based aircraft, and its optimization results and calculation speed are better than those of the traditional TS algorithm.

References

[1] LIU X C. A technology system for the carrier/air vehicle integration[J]. Chinese Journal of Ship Research, 2016, 11(3): 1-4, 10 (in Chinese).

[2] ZHOU X G, ZHAO R H, WANG S Y, et al. Research on influence of flight deck operation exerts upon sortie generation of carrier-based aircraft [C]. //Proceedings of 2014 China simulation conference. Xi'an: China System Simulation Society, 2014 (in Chinese).

[3] ZHU Y F, XIONG Z G, HU Y L. On the development trends of aircraft carriers[J]. Chinese Journal of Ship Research, 2016, 11(1): 1-7 (in Chinese).

[4] YANG B H, BI Y Q, ZHANG B, et al. Deck workflow of carrier multi-aircraft sortie[J]. Ship Electronic Engineering, 2016, 36(8): 150-152 (in Chinese).

[5] LIU A, LIU K. Advances in carrier-based aircraft deck operation scheduling [J]. Systems Engineering-Theory & Practice, 2017, 37(1): 49-60 (in Chinese).

[6] RYAN J, CUMMINGS M, ROY N, et al. Designing an interactive local and global decision support system for aircraft carrier deck scheduling[C]//Infotech@Aerospace 2011. St. Louis, Missouri: AIAA, 2011.

[7] DASTIDAR R G, FRAZZOLI E. A queueing network based approach to distributed aircraft carrier deck scheduling[C]// Infotech@Aerospace. St. Louis, Missouri: AIAA, 2011.

[8] HAN Q T, CAO W J, SU T. Research on maintenance support schedule for carrier aircraft based on genetic algorithm [J]. Science Technology and Engineering, 2012, 12(35): 9784-9787 (in Chinese).

[9] SI W C, HAN W, SONG Y, et al. Takeoff scheduling of carrier plane based on multi-colonies cooperation and CLS intelligence algorithm [J]. Application Re-

search of Computers, 2013, 30(2): 454-457 (in Chinese).

[10] HAN W, SU X C, CHEN J F. Integrated maintenance support scheduling method of multi-carrier aircrafts [J]. Systems Engineering and Electronics, 2015, 37(4): 809-816 (in Chinese).

[11] WEI C Q, CHEN C L, WANG B R. Research on the aircraft support scheduling model of carrier-based aircraft based on launch mode [J]. Journal of Naval Aeronautical and Astronautical University, 2012, 27 (1): 111-114 (in Chinese).

[12] WANG Q X. Mixed scheduling algorithm for job-shop scheduling problem [D]. Nanjing: Southeast University, 2009 (in Chinese).

[13] PEZZELLA F, MERELLI E. A tabu search method guided by shifting bottleneck for the job shop scheduling problem[J]. European Journal of Operational Research, 2000, 120(2): 297-310.

[14] JEWELL A, WIGGE M A, GAGNON C M, et al. USS Nimitz and carrier airwing nine surge demonstration [R]. Alexandria, Virginia : Center for Naval Analyses, 1998.

[15] WEI C Q, CHEN C L, WANG B R. Study of aircraft support scheduling of aircraft on carrier based on space restriction[J]. Control Engineering of China, 2013, 20(4): 669-702, 706 (in Chinese).

基于改进禁忌搜索算法的舰载机保障作业调度

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摘　要：[**目的**] 舰载机出动能力是航母综合作战能力的重要指标，而舰载机保障作业调度将直接影响舰载机的出动能力，因此对舰载机保障作业进行合理调度能有效提高航母的作战能力。[**方法**] 通过将舰载机保障作业调度问题转换成车间作业调度问题，建立保障作业调度模型。对传统禁忌搜索算法的初始解、搜索策略和禁忌列表长度进行改进，以减少最大完工时间为目标，提出一种改进的禁忌搜索算法来求解该模型。[**结果**] 通过实验仿真验证了改进的禁忌搜索算法对于舰载机保障作业调度问题的适用性，且该改进算法在计算速度和优化结果方面均优于传统禁忌搜索算法。[**结论**] 改进禁忌搜索算法可以有效地对舰载机保障作业调度问题进行求解。
关键词：舰载机；保障作业；车间作业调度问题；禁忌搜索

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通过式消磁站线圈系统仿真设计

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摘　要：[**目的**] 为了实现船舶方便和快速的退磁，提出一种通过式消磁站的线圈系统设计方案。[**方法**] 构建相应的仿真模型，包括垂向补偿线圈、横向补偿线圈和垂向工作线圈，并采用MagShip软件进行仿真分析。[**结果**] 垂向补偿线圈可产生80 A/m的垂向补偿磁场，均匀度约95%；横向补偿线圈可产生40 A/m的横向补偿磁场，均匀度约95%；二者组合可抵消被退磁船舶所受到的地磁场作用。垂向工作线圈可产生超过2 000 A/m的交变工作磁场，为船舶退磁提供工作能量。[**结论**] 数值仿真结果表明，所提出的消磁线圈设计方案不但能较好地补偿地磁场，而且能产生足够幅值的交变磁场。所得结果对通过式消磁站线圈系统工程设计具有一定的理论指导意义。
关键词：退磁；通过式消磁站；线圈系统