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Improved firefly algorithm for the stochastic duration optimization of the ship maintenance

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Abstract: [**Objective**] Ship maintenance projects have such characteristics as complex implicated tasks, space interference and uncertain task durations. A mathematical model and optimization algorithm are proposed to solve the stochastic duration optimization problem of ship maintenance. [**Methods**] According to the scenario concept, this paper designs the expected duration as an objective function and constructs a mathematical model, then proposes an improved firefly algorithm to solve the problem. Finally, a group of benchmark projects and one dock maintenance engineering project are carried out to test the validity of the proposed method. [**Results**] The results show that the proposed method has the best performance in solving the problem. The optimized dock maintenance engineering project has 89.6 d of the expected duration and a 95.6% confidence level. Compared with the original method, the expected duration is reduced by 13.4 d and 13.1%. [**Conclusion**] This method can provide a basis for planning the schedules of ship maintenance projects.

Key words: maintenance schedule; project scheduling; stochastic scheduling; scenario; firefly algorithm

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0 Introduction

The ship maintenance project has the property of complex multi-system integration. Its maintenance process is characterized by complex implicated task and space interference, as well as task rework. Especially in the actual maintenance construction, there is uncertainty in the maintenance program. If the traditional deterministic maintenance schedule development method is used, the maintenance program is too rigid to cope with the uncertainty of the maintenance process, which will inevitably cause duration delay and other situations. With the continuous promotion of project scheduling in practice and the increasingly refined management of maintenance schedule, the traditional project scheduling method can not meet the needs of the actual maintenance project. Therefore, it is of great theoretical and practical significance to fully analyze the characteristics of ship maintenance projects, reconstruct the duration optimization model of ship maintenance project, and develop efficient project scheduling algorithms to optimize the duration of ship maintenance projects.

For the duration optimization of uncertain ship maintenance project, it is often realized by approximate conversion, i. e., converting the uncertainty problem into a deterministic problem. Taking the stochastic task working hours as an example, the median or expected value of the task working hours is often used to replace the task working hours, ignoring the uncertainty brought by

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the fluctuation of the task working hours. This method is more suitable for some scenarios where the fluctuation of the task working hours is small [1]. In addition to the commonly used approximate conversion methods, uncertainty handling methods have also become a hot spot of current scholars' research[2]. Herroelen et al. [3] categorized the scheduling methods for projects with uncertain task working hours into four categories, i. e., reactive, stochastic, fuzzy and proactive scheduling methods. Rahman et al. [4] used reactive scheduling method for real time scheduling of constrained resources. Bonnal et al. [5] proposed a conversion method corresponding to exact durations and fuzzy numbers based on summarizing the results of previous research. Wang et al. [6] studied project scheduling trade-off optimization in stochastic environments. During the project scheduling with stochastic task working hours, the execution of the project is determined by a scheduling strategy instead of a deterministic baseline scheduling plan[7-8]. It is a multi-stage decision-making process. However, considering the unpredictability of the ship maintenance process, the factors such as the degree of corrosion of the ship's maintenance parts can lead to a large fluctuation in the task working hours of a maintenance project. Based on the bullwhip effect, the cumulative fluctuation of task working hours will inevitably lead to a large deviation of the whole maintenance plan, making the original maintenance plan become a white elephant. Consequently, to optimize the duration of ship maintenance project, a more reasonable uncertainty handling mechanism needs to be adopted.

The duration optimization of uncertain ship maintenance project belongs to the NP-hard problem. Its solution algorithms are mainly divided into the following three categories: exact algorithms, heuristic algorithms, and meta-heuristic algorithms [9-10]. The exact algorithms include linear programming method and branch-and-bound method, whose biggest advantage is to pursue the lower bound of the problem. Currently, this method is only suitable for solving the maintenance duration optimization problems of small and medium-sized ships. For medium and large maintenance projects with more than 60 maintenance tasks, its computation time is too long and the solution effect is poor [11]. Sallam et al. [12] used an augmented learning algorithm to solve the scheduling problem of uncertain resource-constrained projects. Heuristic algorithms are refined based on the experience of managers and workers. The algorithms are widely used in practice for quickly obtaining feasible solutions under certain guiding rules with fast computation speed. However, the method can not guarantee the quality of the solution. Especially for medium and large-scale maintenance works, sub-optimal solutions or satisfactory solutions are obtained, resulting in an average quality of the solution.

With the emergence of artificial intelligence technology, scholars at home and abroad have studied meta-heuristic algorithms more and more widely. Currently commonly used meta-heuristic algorithms include genetic algorithm (GA), artificial bee colony algorithm (ABC), particle swarm optimization (PSO), seagull optimization algorithm (SOA) and firefly algorithm (FA), etc. These algorithms have been successfully applied in resource-constrained project scheduling. In pursuit of faster and better quality solutions, efficient meta-heuristic algorithms are still the difficulty and focus of research. FA is a meta-heuristic algorithm proposed by Yang[13] based on the flickering behavior of fireflies, which has the advantages of simplicity, few parameters and easy implementation. It has achieved better applications in many fields. In this paper, the advantages of scenario concept design and firefly algorithm are integrated to achieve uncertainty handling and solution for ship maintenance duration optimization.

1 Problem description

Duration optimization of ship maintenance project can be outlined as the optimal allocation of manpower, equipment and other resources, and the reasonable execution of a series of maintenance tasks with priority relationship and requiring a specific amount of resources. The goal is to achieve the minimum duration of ship maintenance project. In the actual ship maintenance process, the maintenance task working hours has high volatility. Hence, the problem can be summarized as resource-constrained project scheduling under stochastic task working hours [14-15].

It is specifically described as: a ship maintenance project contains J maintenance tasks $j = \{1, 2, \dots, J\}$, k renewable resources $k = 1, 2, \dots, K$, and the total supply of each class of renewable resources is R_k. The expected value of working hours for maintenance task j is d_j, its degree of fluctuation is denoted as $\pm\sigma$, and the number of category k resources required is r_{jk}. It is assumed that a maintenance task is uninterruptible once started and must be started only after all immediate predecessor maintenance tasks are completed. To ensure that there are unique maintenance tasks at the earliest start moment and the last finish moment, maintenance task 1 and maintenance task J are dummy maintenance tasks that do not take up time and resources, and only indicate priority relationships. Maintenance task 1 is the starting point of all maintenance tasks, and maintenance task J is the end point of all maintenance tasks. A feasible scheduling scheme should satisfy both the immediate predecessor relationship constraints and the resource constraints [16-18].

The problem has the minimum desired duration as the optimization objective. Monte Carlo simulation is used to generate N scenarios. The desired duration is equal to the average of N scenarios, and $C_{TJ,i}$ is the duration of maintenance task J under scenario i. The objective function O_{BJ} of the problem is

$$O_{BJ}=\min\frac{1}{N}\sum_{i=1}^{N}C_{TJ,i} \tag{1}$$

The maintenance tasks in each scenario are required to satisfy two conditions: priority relationship constraints and resource constraints. The priority relationship constraint for maintenance tasks means that all maintenance tasks must be completed before all their immediate predecessor maintenance tasks can start, as shown in Equation (2).

$$C_{Th}\leqslant C_{Tj}-d_j,\ \ h\in P_j,\ \ \forall j \tag{2}$$

where C_{Tj} is the completion time of maintenance task j; d_j is the desired working hours of the maintenance task; P_j is the set of immediate predecessor maintenance tasks of maintenance task h.

The resource constraint is that the total demand for resources at each moment cannot exceed the total supply, as shown in Equation (3).

$$\sum_{j=1}^{J}x_{jt}r_{jk}\leqslant R_k,\ \forall t,k \tag{3}$$

where t is the time series $t=\{0, 1, \ldots, T\}$; T is a preset value, which must be greater than the completion time of maintenance task J; x_{jt} is a variable from 0 to 1, and 1 means that maintenance task j is implemented at time t, otherwise it is equal to 0.

2 Improved FA solution framework

Combined with the characteristics of ship maintenance engineering, Monte Carlo simulation is used to generate N scenarios of random task working hours. The improved FA is applied to generate the maintenance schedule plan under N scenarios to evaluate and optimize the duration of the maintenance project under random task working hours. Generally speaking, the larger the value of scenario N is, the more realistic the expected duration is, and the higher the computational complexity is; the smaller the value of scenario N is, the larger the error in the expected duration is, and the larger deviation is easy to occur in the actual execution process. In order to balance the computational complexity and deviation, the value of scenario N is suggested to be equal to the size of the improved firefly population. Combined with the size of the problem, the size of the improved firefly population is generally 100 to 500.

2.1 Steps of improved FA

The improved FA distributes the feasible solutions throughout the three-dimensional space, and each feasible solution in the space is viewed as a firefly. Individuals with optimal fitness values of feasible solutions are given to fireflies with strong luminescence, and fireflies with strong luminescence will attract fireflies with weak luminescence. Fireflies with weak luminescence will move towards fireflies with strong luminescence, and the cycle is iterated continuously to obtain the optimal position.

Monte Carlo simulation is used to generate N scenarios, and each scenario corresponds to one firefly, i. e. N fireflies. The fitness function is the duration of each scenario, and the average fitness value of the firefly population is the desired duration of the maintenance project, which is performed as follows:

1) Initializing the parameters. N scenarios are generated based on Monte Carlo simulation with a firefly population of N, a maximum attraction β_0, a light intensity absorption coefficient γ, a step factor α, a maximum number of iterations Max, and a random initialization of the firefly's position.

2) No-delay scheduling is used to generate the fluorescence brightness I of the fireflies, which is the inverse of the duration of the current

maintenance project, i. e., the smaller the duration, the higher the fluorescence brightness.

3) Calculating the firefly attractiveness β in the population.

$$\beta(r) = \beta_0 \mathrm{e}^{-\gamma r_{ij}^2} \tag{4}$$

where γ is the light absorption coefficient, which is a constant; r_{ij} is the distance between fireflies i and j. The Euclidean distance is used to determine the positions of fireflies i and j.

4) Updating the spatial location of fireflies. If the fluorescence brightness I_j of firefly j is higher than the fluorescence brightness I_i of firefly i, the position of firefly i is updated according to Equation (5).

$$x_i(t+1) = x_i(t) + \beta\left(x_j(t) - x_i(t)\right) + \alpha\left(rand - \frac{1}{2}\right) \tag{5}$$

where x_i and x_j are the spatial positions of fireflies i and j, and $rand$ is a random factor obeying a uniform distribution on [0, 1].

5) When the number of search iterations reaches the maximum number of iterations, go to step 6); otherwise, go to step 2).

6) Outputting the final population and the desired duration.

2.2 Scenario generation

As can be seen from the previous section, the task working hours obey a uniform distribution with mean d and fluctuation degree $\pm\sigma$. In order to evaluate the duration in a statistical sense, the Monte Carlo concept is used, which assumes that the task working hours obey a uniform distribution, and generates N scenarios randomly for each task, i.e., generates N random numbers in the upper and lower bounds of the duration of each task, with upper and lower bounds of $d+\sqrt{\sigma}$ and $d-\sqrt{\sigma}$ respectively, and each scenario is accurate to one decimal place.

2.3 Encoding and decoding

The gene positions of each firefly are encoded using real numbers whose length is the total number of maintenance tasks, and each gene position corresponds to a sequence of maintenance tasks $j = \{1, 2, \dots, J\}$, and each gene value represents the weight value of the corresponding maintenance task.

The decoding process is to transform the individuals in the coding space into a maintenance schedule program, to obtain the duration. Adopt the parallel scheduling mode to generate the scheduling plan, read the gene positions with high priority in turn, and generate the current feasible maintenance any subset according to the priority relationship until all gene positions have been read. The decoding process is shown in Fig. 1, where j is the activity number, k is the number of iterations, K is the maximum number of iterations, and S_j is the start time of activity j, which is taken to be the maximum of the earliest available time of the resource and the maximum front-end sequence of the completion time. F_j is the end time of activity j, which is equal to the sum of the start time and the activity time.

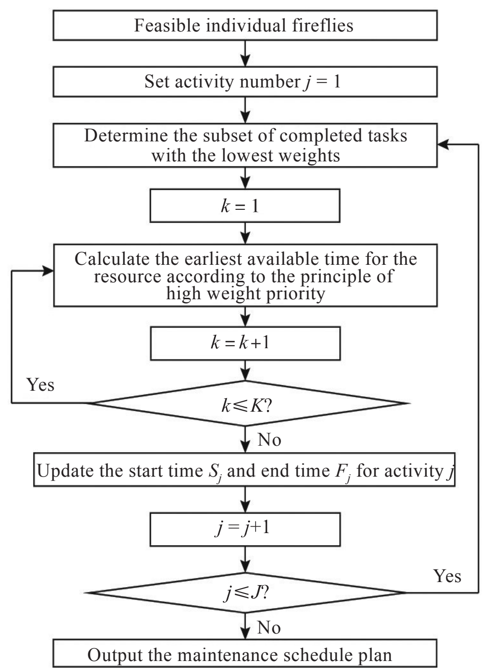

Fig. 1 The flowchart of encoding

2.4 Fitness function

The fitness value is an important indicator to guide the evolution of individual fireflies towards the optimal duration. The desired duration target is transformed into the fitness value to evaluate, i. e., the larger the fitness value, the shorter the desired duration. The fitness function of individual i under scenario s is shown in Equation (6).

$$F(i) = \frac{1}{\dfrac{1}{N}\sum_{s=1}^{N} C_{TJ,s}(i)} \tag{6}$$

where denominator $\frac{1}{N}\sum_{s=1}^{N} C_{TJ,s}(i)$ is the desired duration of individual i; $F(i)$ is the fitness value of individual i; $C_{TJ,s}(i)$ is the duration of individual i under scenario s.

3 Experimental results and analysis

In order to verify the performance of the improved FA, four algorithms, namely GA, ABC, PSO, SOA, are selected for comparative analysis. All algorithms were programmed using MATLB 2019a, and the program was run on AMD Ryzen 75800H with Radeon Graphics 3.20 GHz and 16 GB of RAM.

3.1 Algorithm performance analysis

The cases tested were derived from the benchmarked case set. Three types of cases, J30, J60 and J120, were selected from the benchmark case set depending on the number of activities included, and 10 cases of each type were randomly selected as test cases. In order to be fair, the population size and the number of iterations of the five algorithms are 100, and the experimental results are shown in Table 1.

From Table 1, it can be seen that the improved FA always obtains the shortest desired duration, which indicates that the FA has an excellent optimization search capability. Further, 150 sets of cases of 30, 60 and 120 are selected to verify the statistical performance of the improved FA, which is illustrated by using relative percentage deviation ($R_{\rm PD}$), which is calculated as

$$R_{\rm PD}=\frac{O_{BJr}-O_{BJ\min}}{O_{BJ\max}-O_{BJ\min}} \tag{7}$$

where O_{BJi} is the objective function value of algorithm r; $O_{BJ\max}$ and $O_{BJ\min}$ are the maximum and minimum objective function values of the five algorithms, respectively. The calculation results of $R_{\rm PD}$ are shown in Fig. 2.

As can be known from Fig. 2, the improved FA algorithm has the best performance in 150 sets of engineering cases, and its performance gets better as the number of activities increases. The GA algorithm also has better performance. The ABC algorithm has the worst performance and its performance decreases sharply as the number of activities increases.

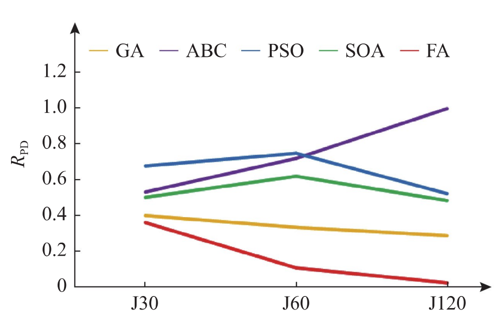

Fig. 2 $R_{\rm PD}$ value for different algorithms

Table 1 Comparison results of algorithm

No.	GA	ABC	PSO	SOA	FA
J30_1	45.57	48.76	50.96	51.03	45.83
J30_2	48.66	48.33	47.71	48.21	49.79
J30_3	48.48	48.04	48.65	48.82	47.99
J30_4	62.42	63.62	64.01	63.99	63.46
J30_5	41.88	43.35	43.44	40.05	40.98
J30_6	47.91	48.32	52.02	49.21	48.30
J30_7	60.10	59.54	61.18	61.66	60.47
J30_8	56.06	55.71	57.49	55.87	55.34
J30_9	53.29	52.14	55.76	53.34	51.41
J30_10	46.48	47.35	51.33	47.87	47.53
J60_1	83.19	87.66	89.42	90.11	78.41
J60_2	80.10	83.12	79.95	80.03	74.05
J60_3	76.23	76.09	88.02	78.46	72.23
J60_4	91.40	94.77	97.65	95.2	92.01
J60_5	79.31	83.45	85.21	86.52	76.49
J60_6	66.76	71.71	71.33	70.27	66.37
J60_7	79.81	87.97	87.99	86.24	79.29
J60_8	88.76	98.42	93.67	91.56	81.84
J60_9	93.34	101.12	98.29	98.94	89.5
J60_10	83.34	89.07	89.66	84.82	81.28
J120_1	149.75	186.50	154.55	155.18	144.24
J120_2	155.47	192.88	155.69	162.83	149.00
J120_3	161.64	176.92	164.85	165.94	151.26
J120_4	136.75	166.60	152.29	131.76	133.04
J120_5	144.93	190.90	170.22	153.00	144.46
J120_6	114.88	143.79	125.51	127.43	112.17
J120_7	154.89	204.65	177.12	172.18	135.89
J120_8	140.21	171.43	151.39	149.58	147.66
J120_9	159.11	185.86	153.54	161.10	152.17
J120_10	147.62	176.66	152.52	164.14	138.65
Running time/s	5 496	10 339	5 525	5 561	98 314

3.2 Algorithm convergence analysis

120 maintenance tasks are relatively large, so the J120_9 project case is selected as an example. The optimal expected duration obtained by the improved FA is 85.9 d, and its convergence diagram is shown in Fig. 3.

Fig. 3 shows that the FA has fast convergence performance. At an iteration number of 28, the algorithm converges gradually and at an iteration number of 45, the algorithm basically converges to the optimal solution.

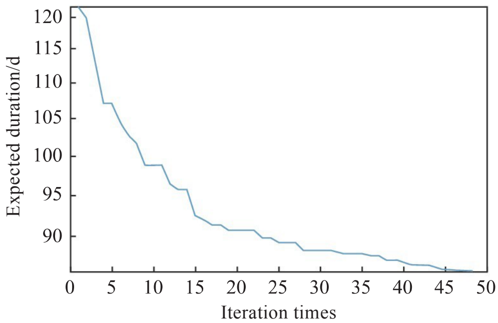

Fig. 3 Convergence graph for the improved firefly algorithm

4 Application of engineering example

Taking the dock project of a ship maintenance project as an example, after many discussions, it is determined that there are 248 maintenance tasks in this maintenance section, and there are logical relationship constraints between tasks such as process and space. It is assumed that the duration of each maintenance task obeys a uniform distribution, and the upper and lower bounds of the duration of each maintenance task are $d \pm \sqrt{d}$. Based on this distribution, some data are shown in Table 2.

Table 2 Part of the project case data

No.	Name	Pre-conditions	Duration/d	Workers
1	Docking	None	[8.5, 15.5]	32
2	Fouling removal of left and right propeller blades	1	[8.5, 15.5]	10
3	Mechanical seals of left and right stern shaft	2	[12.0, 20.0]	16
4	Ejector pumps of left and right stern bilge	3	[0.6, 3.4]	2
5	Left and right stern bilge	4	[1.3, 4.7]	2
6	Right rudder shaft bearing of steering engine	1	6.0	8
7	Rudder blade	1	[8.5, 15.5]	14
8	1, 2, 3, 4# Hydraulic pressure	None	[12.0, 20.0]	10
9	Monitoring box of steering engine	None	[5.2, 10.8]	2
10	No. 1 cylinder bleeder valve	None	[0.1, 2.0]	1
11	Emergency rudder inlet valve	None	[0.1, 2.0]	1
12	Isolation bypass valve set of steering engine	1	[2.0, 6.0]	2
13	Spare oil tank of steering engine	1	[0.6, 3.4]	2
14	Cooling water pressure gauge of steering engine	1	[0.1, 2.0]	1

The current actual maintenance plan is based on the experience of the maintenance management personnel, giving each maintenance task a certain duration margin, and adopting the critical path method for the development of the duration, which is 102 d. After adopting this method, it is necessary to determine the expected value and the degree of fluctuation of each maintenance task according to the experience of the maintenance management personnel. The optimized duration is 89.6 d, which is 13.4 d less than the original method's duration, shortening the duration by 13.1%.

The confidence level, i. e., the percentage of N scenarios in which the actual maintenance duration is less than or equal to 89.6 d, is further used to verify the reliability of the optimized duration to cope with the fluctuation of the maintenance tasks, so as to avoid the loss caused by duration delay. The idea of Monte Carlo simulation is used to generate 1 000 scenarios with the expected value of the maintenance task as the mean and the degree of fluctuation as the standard deviation, and substitute the 1 000 scenarios into the optimized maintenance schedule plan and the original maintenance schedule plan, respectively. It is found that the duration of 956 sets of scenarios in the optimized maintenance plan is less than 89.6 d, and that the duration of 992 sets of scenarios in the original maintenance plan is less than 102 d. In other words, the confidence level of the optimized maintenance plan is 956/1 000 = 95.6%, and that of the original maintenance plan is 992/1 000 = 99.2%, which means that the non-delay probability of the optimized maintenance plan is lower than that of the original maintenance plan by (99.2%−95.6%) = 3.6%. After discussing with the maintenance management personnel, it is considered that 95.6% of the non-delay probability is acceptable in the actual maintenance process, and the duration can basically be achieved without delay through management means. Therefore, it can be inferred that this method can effectively shorten the duration optimization of maintenance works under random working hours, and provide a basis for the formulation of actual maintenance plan.

5 Conclusion

In this paper, based on the actual ship maintenance project, and taking random task working hours as the starting point, the scientific problem of the duration optimization of ship maintenance project under random task working hours is condensed. By generating N scenarios through Monte Carlo simulation, a scenario-based duration optimization model of ship maintenance project under random working hours is established, and an improved FA is proposed to achieve duration optimization. The experimental results show that the improved FA can effectively optimize the duration of ship maintenance project. Finally, taking the dockyard works of the ship maintenance project as an example, the actual data are fully investigated. The method is compared with the actual maintenance schedule development method to verify the effectiveness of the method.

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基于萤火虫算法的随机工时下船舶维修工期优化

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摘　要：［**目的**］针对船舶维修牵连工程复杂、空间干涉多、任务工时不确定等特性，提出一种解决随机工时下船舶维修工期优化的模型和算法。［**方法**］基于情景理念设计维修工程的期望工期指标，构建该问题的数学模型；基于并行调度模式解码，提出一种改进萤火虫算法求解该模型；采用工程案例测试集和某船舶坞内维修工程实例，验证所提模型和算法的性能。［**结果**］某船舶坞内维修工程实例优化结果表明，其工期估值为 89.6 d，置信度 95.6%，与原方法工期相比减少 13.4 d，可缩短 13.1% 的工期。［**结论**］改进的萤火虫算法可有效优化船舶维修工程的工期，为不确定条件下的船舶维修进度计划制定提供依据。

关键词：维修进度计划；项目调度；随机调度；情景；萤火虫算法