Optimization Method of Equipment Maintenance Resource Scheduling Based on Hidden Semi-Markov Model

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***Abstract*—Aiming at the problems of uneven distribution of maintenance resources and poor planning in the process of complex equipment maintenance, a complex equipment maintenance resource scheduling optimization method based on the hidden semi-Markov model is proposed. Establish a hidden semi-Markov model based on the monitoring data of each maintenance point to evaluate the health status of the equipment, and calculate the importance and priority of each maintenance point based on the health status. Establish the transportation time matrix between the support points and the maintenance points, and propose the maintenance resource scheduling plan between the maintenance points and the support points. The experimental results show that using the monitoring data of four self-propelled artillery to be repaired, the accuracy of the calculated priority is 1.2% higher than the importance. Therefore, the priority of the maintenance point is selected to optimize the resource scheduling plan under the condition of meeting the task requirements and the given maintenance support resources, and shorten the average waiting time of the self-propelled artillery.**

Keywords-Hidden Semi-Markov Model; Maintenance Resources; Resource Conflict; Resource Scheduling; Scheduling Optimization Model

I. INTRODUCTION

In order to solve the problems of uneven distribution of maintenance resources, poor planning, and inaccurate forecasts in the process of coordinated maintenance of complex equipment, a complex equipment maintenance resource scheduling optimization method based on hidden semi-Markov model is proposed. Establish the transportation time matrix between the support

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points and the maintenance points, and propose the maintenance resource scheduling plan between the maintenance points and the support points. Make full use of existing resources, shorten the average waiting time for equipment to be repaired, restore the combat effectiveness of the equipment in a relatively short time, and maintain and restore the integrity of the equipment to the maximum.

At present, most of the research on resource scheduling problems is aimed at the management of emergency systems. Literature [1] proposes a multi-objective solution model based on fuzzy sets and decision satisfaction, and introduces weight coefficients in satisfaction and methods, so that program decision makers can configure different weights for multi-object satisfaction membership functions to make decisions [1]. However, research in this area focuses more on processing deterministic information, which has great limitations in practical applications. Literature [2] analyzed the relationship between the various elements of resource scheduling and the causes of resource conflicts based on the wartime equipment maintenance support resource scheduling system, and established a multi-maintenance point resource optimization scheduling model. A resource optimization scheduling method based on the priority of maintenance points is proposed [2], but the real-time health status of complex equipment cannot be accurately predicted, which makes resource scheduling uncertain. Literature [3] established a multi-demand-multi-supplier maintenance resource scheduling optimization model with soft time windows used by the scheduling optimization module in the system, and applied genetic algorithm to analyze the solution of the model [3]. However, the genetic algorithm parameters are more complicated and time-consuming, and are too dependent on the initial population selection. Literature [4] established a multi-objective optimization model, and transformed it into a single-objective model through objective priority decision-making. The adaptive genetic algorithm based on niche and the genetic algorithm based on spanning tree are used to solve the problem [4], but the research is mainly for the situation of a single maintenance demand point. Literature [5] established a highway network model and a mathematical model for optimal scheduling, and used dynamic programming and LINGO software to solve and calculate, and scientifically schedule maintenance resources [5]. However, the scheduling priority between maintenance points is not determined, resulting in poor scheduling efficiency.

Due to the complexity of the combat environment and resource allocation, the existing research methods have a narrow scope of application, strong limitations, strong specificity, and poor versatility. There is a lack of research on the optimal scheduling of maintenance support resources in the overall environment [6]. On this basis, this paper proposes an optimization method for complex equipment maintenance resource scheduling based on hidden semi-Markov model. Establish a hidden semi-Markov model based on the monitoring data of each maintenance point to evaluate the health status of the equipment, and calculate the importance and priority of each maintenance point based on the health status. Establish the transportation time matrix between the support points and the maintenance points, and propose the maintenance resource scheduling plan between the maintenance points and the support points [7].

II. HIDDEN SEMI-MARKOV MODEL

Hidden Semi-Markov Model is an ideal mathematical model that uses observable sensor signals to predict unobservable health status. The Hidden Semi-Markov Model is constructed by adding the state duration to the defined Hidden

Markov Model. Different from the state in the standard hidden Markov model, the generation of the state in the hidden semi-Markov model is an observable segment instead of a single observation set in the hidden Markov model. The parameters of the hidden semi-Markov model are: initial state distribution, transition matrix, state duration distribution, observation model. Only when the object of observation transfers from one state to another different state can the conditional independence between the past state and the future state be ensured [8]. The hidden semi-Markov model models the observation information between the state transition intervals, so it not only has the flexibility of the hidden Markov model to approximate the complex probability distribution, but also the flexibility of the semi-Markov model to express the state duration.

Before reaching the state to be repaired, complex equipment usually goes through several different operating states. Suppose the operating state is divided into n discrete states: $1,2,3,...,n-1$ and F .The trained Hidden Semi-Markov Diagnostic Model can test the health status at each sampling time point, so it can be regarded as a random process: $H=\{H_t : t \geq 0\}$.If $H_t = i$, it means that the equipment is in state H_i at time t.Assuming that when the equipment is in state H_i, the transition probability P_{ij} from the state of health to the next point in time j is fixed [9], for the hidden Markov chain, the conditional distribution of the future state H_{t+1} and the past state $H_1,...,H_t$ is:

$$P(H_{t+1}=j \mid H_t=i, H_{t-1}=i_{t-1},...,H_2=i_2,H_1=i_1)=P(H_{t+1}=j \mid H_t=i)=P_{ij} \quad (1)$$

The state of the segmented hidden semi-Markov model is called the macro state, and each macro state is composed of several individual micro states [10]. Suppose a macroscopic state sequence has n segment, let q_i be the time index of the end point $(1 \leq i < n-1)$ of the i-th segment, and q_F be the time index of the end point F ,the parameter mapping of the hidden semi-Markov model is shown in Figure 1.

	A macro state	micro state			
Time unit	$1,...,q_1$	$q_1+1,...,q_2$	...	$q_{n-2}+1,...,q_{n-1}$	q_F
Observation	$o_1,...,o_{q_1}$	$o_{q_1+1},...,o_{q_2}$	...	$o_{n-2}+1,...,o_{n-1}$	o_F
status	$s_1,...,s_{q_1}$	$s_{q_1+1},...,s_{q_2}$	...	$s_{n-2}+1,...,s_{n-1}$	s_F
duration	$d_1=q_1$	$d_2=q_2-q_1$	...	$d_{n-1}=q_{n-1}-q_{n-2}$	$d_F=\infty$
Part	1	2	...	$n-1$	F

Figure 1. Parameter mapping for hidden Semi-markov moder

$$q_{ij}(k)=P(H_{t+1}=j, X_j=k \mid H_t=i) \quad (2)$$

$q_{ij}(k)$ is the initial state distribution from state i to state j ,the result depends on when the equipment is in state H_i at the previous moment t and $t+1$ is in state H_j at the latter moment, and X_j is the duration of a certain state j expressed as a non-negative integer k.

III. Optimization Method of Maintenance Resource Scheduling

A. Importance of maintenance points

The importance of maintenance points refers to the degree to which battle-damaged equipment can be restored to combat effectiveness as soon as possible under certain conditions at various maintenance locations at a certain time. It is determined by the weighted sum of four indicators: the urgency of combat tasks (β_1), the maintainability of damaged equipment (β_2), the completion rate of maintenance tasks within the specified time (β_3), and the timeliness of equipment maintenance (β_4) [11], namely:

$$\lambda_j = \sum_{k=1}^{4} \alpha \beta_k \omega_k \tag{3}$$

In the formula: λ_j—the importance of the j -th maintenance point;

β_k is the k -th index value, where β_1 refers to the urgency of the combat mission undertaken by the equipment to be repaired; β_2 refers to the ease of maintenance of the equipment to be repaired; β_3 refers to the probability of completing the maintenance task within the specified time for the equipment to be repaired; β_4 refers to the effective period of completing the maintenance task. ω_k is the weight of the k -th indicator.

1) Confirmation of β_k

$\beta_k(k=1,...,4)$ can be determined by experts in scoring through specific analysis of the combat environment and equipment to be repaired[12], and stipulate $0 \le \beta_k \le 1$ .In order to facilitate the calculation, fuzzy processing is adopted for β_4 .Which is:

$$\beta_4 = \begin{cases} 1, & f \le m \\ \dfrac{M-f}{M-m}, & m < f < M \\ 0, & f \ge M \end{cases} \tag{4}$$

Among them, f is the index value that requires the repairing time of damaged equipment to be as small as possible; M is the maximum allowable time for repairing damaged equipment; m is the minimum allowable time for repairing damaged equipment.

2) Confirmation of ω_k

The index weight can be determined according to the importance of the damaged equipment to restore combat effectiveness as soon as possible [13], and $\sum_{k=1}^{4} \omega_k = 1$.

B. Priority of maintenance points

Under the condition of limited resources, when there are multiple maintenance points requesting maintenance resources at the same time, the resource scheduling for each point must be carried out in a certain order [14]. Therefore, the concept of priority is introduced, and the protection priority of the j -th point is ξ , then

$$\xi = (1-\gamma_j)\lambda_j \qquad j = 1,2,...,n \tag{5}$$

When the importance λ_j of the j -th maintenance point is larger, the resource guarantee degree γ_j is smaller, the ξ is larger, and the guarantee problem of this point is given priority, otherwise the guarantee order of this point will be lower. Sorting by the size of ξ can get the guarantee order of maintenance points, which provides a basis for decision-making for resource scheduling [15].

IV. MAINTENANCE RESOURCE SCHEDULING OPTIMIZATION PROCESS

Figure 2 shows the flow chart of maintenance resource scheduling optimization based on hidden semi-Markov model.

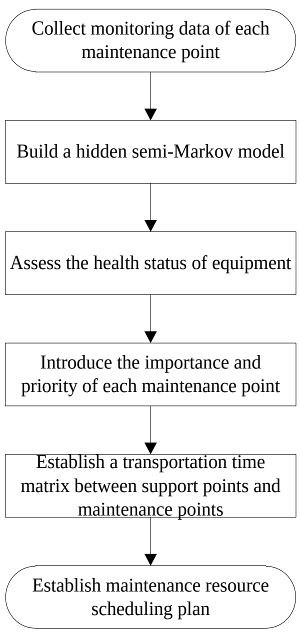

Figure 2. Maintenance resource scheduling optimization process based on hidden semi-Markov model

a. Collect the monitoring data of each maintenance point, and monitor the trend of the data as the time point increases.

b. Establish a hidden semi-Markov model to evaluate the real-time health status of the equipment.

c. Introduce the importance and priority of each maintenance point, determine the judgment matrix of the weight of each index, and sort the maintenance points according to the calculation results of the importance and priority.

d. Establish the transportation time matrix between the support point and the maintenance point.

e. Establish a maintenance resource scheduling plan.

V. EXPERIMENTAL RESULTS AND ANALYSIS

In order to evaluate the optimization performance of the proposed complex equipment maintenance resource scheduling optimization method based on the hidden semi-Markov model in the complex equipment maintenance resource scheduling, the electrical subsystem of a certain type of self-propelled gun is used to test it [16]. The electrical subsystem of a certain type of self-propelled artillery is mainly composed of three subsystems: fire control system, follow-up system, and electrical system. The factory allowable values of the state characteristic parameters of each subsystem component are set, and the limit values are known. And use the sensors on the subsystem to obtain the monitoring values of the state parameters to evaluate the health of the all-gun electrical system of the self-propelled artillery.

In this experimental study, it is assumed that the maintenance unit needs to maintain 4 maintenance points, namely artillery A, artillery B, artillery C, and artillery D. Use the monitoring data of the sensors on the artillery to evaluate the repair status of the self-propelled artillery. The monitoring data of 4 artillery is selected to show the change trend of the sensor monitoring data in the case of increasing time points, and data preparation is carried out for evaluating the health status of the artillery [17]. Table 1 shows the monitoring data of the maintenance point sensors.

TABLE I. MONITORING DATA OF MAINTENANCE POINTS

repair point/time point	1	7	14	21
artillery A	2.7349	5.2847	0.0617	0.7418
artillery B	2.1748	5.1935	0.0589	0.7049
artillery C	2.5172	5.1493	0.0626	0.5816
artillery D	2.4375	4.7218	0.0836	0.8217

The training curve of the Hidden Semi-Markov Model is shown in Figure 3.

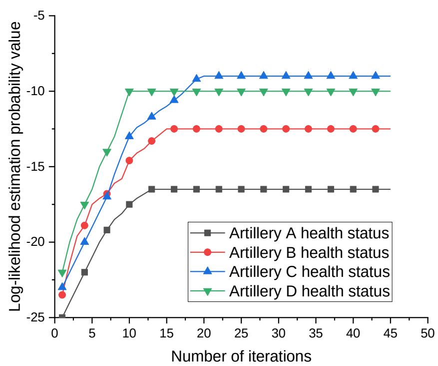

Figure 3. Hidden semi-Markov model training curve

According to Figure 3, during the model training process, as the number of iterations increases, the health of the artillery gradually deteriorates. But when the importance and priority are introduced, the increase of the log-likelihood estimation probability value curve is gradually slow, and the convergence error is limited to a fixed value. The log-likelihood estimation probability values of the four artillery can reach the set error within less than 50 iterations, indicating that the method has strong real-time signal processing capabilities. Among them, artillery A maintains a fixed value after the 12th iteration, artillery B maintains a fixed value after 15 iterations, artillery C maintains a fixed value after 20 iterations, and artillery D maintains a fixed value after the 10th iteration.

A. Calculate the weight of each index of the importance of maintenance points

According to formula (4), the weight of each index of the importance of the maintenance point is calculated, which can be determined by the experts through the specific analysis of the combat environment and the equipment to be repaired.

TABLE II. JUDGMENT MATRIX OF EACH INDEX

	β_1	β_2	β_3	β_4	ω_k
β_1	1	3	2	3	0.455
β_2	1/3	1	1/2	1	0.141
β_3	1/2	2	1	2	0.263
β_4	1/3	1	1/2	1	0.141

After calculation, the maximum eigenvalue of the judgment matrix is $\lambda = 4.01$; the consistency test index $CI = 0.03$; the average consistency index $RI = 0.9$; the relative consistency index $CR = CI / RI = 0.004 < 0.1$ meets the requirements, and the index weights are determined reasonably.

B. Calculate the importance of maintenance points

According to formula (3), the importance is comprehensively evaluated, It is determined by the weighted sum of four indicators: the urgency of combat tasks (β_1), the maintainability of damaged equipment (β_2), the completion rate of maintenance tasks within the specified time (β_3), and the timeliness of equipment maintenance (β_4).

TABLE III. IMPORTANCE OF MAINTENANCE POINTS

	β_1	β_2	β_3	β_4	α	λ_j
ω_k	0.455	0.141	0.263	0.141		
artillery A	0.5	0.9	1	0.4	1	0.674
artillery B	0.8	0.8	0.5	0.8	1	0.721
artillery C	0.2	0.5	0.7	0.9	1	0.473
artillery D	0.6	0.6	0.3	0	1	0.436

According to the calculation results, the maintenance points are sorted into Artillery B, Artillery A, Artillery C, and Artillery D according to their importance.

C. Calculating the priority of maintenance points

According to formula (5), the resource guarantee degree and the priority of maintenance points are calculated.

TABLE IV. PRIORITY OF MAINTENANCE POINTS

	Artillery A	***Artillery B***	***Artillery C***	***Artillery D***
y_j	24	12	30	45
z_j	8	4	18	26
γ_j	0.33	0.33	0.60	0.58
λ_j	0.67	0.72	0.47	0.44
ξ	0.45	0.48	0.19	0.18

In order to facilitate the calculation, reorder the maintenance points according to the size of ξ to get the sequence artillery B, artillery A, artillery C, and artillery D. The accuracy of the priority of the maintenance point is 1.2% higher than the importance of the maintenance point. Therefore, the calculation result of the priority of the maintenance point is selected to establish the transportation time matrix and the scheduling plan between the support point and the maintenance point.

D. Establish a transportation time matrix and scheduling plan for supporting points to maintenance points

TABLE V. THE TRANSPORTATION TIME MATRIX BETWEEN THE SUPPORT POINTS AND THE MAINTENANCE POINTS

	y_j	z_j	***Support point A***	***Support point B***	***Support point C***
x_i			5	10	8
artillery B	12	4	3	5	8
artillery A	20	9	8	2	3
artillery C	30	18	6	8	10
artillery D	45	26	2	4	8

The calculation process and plan of the scheduling plan are shown in Table 6.

TABLE VI. OPERATION PROCESS AND PLAN TABLE OF SCHEDULING PLAN

j	sort x_1, x_2, x_3	k	φ_j	$T(\varphi_j)$	$N(\varphi_j)$
artillery B scheduling plan	$x_2x_1x_3$	1	（support point B，8）	2	1
artillery A scheduling plan	$x_1x_3x_2$	3	（support point A，5），（support point C，8）	3	3
artillery C scheduling plan	x_2x_1	2	（support point B，2）	4	2
artillery D scheduling plan	$x_3x_2x_1$	3	（support point C，6）	（10）	（4）

It can be seen from Table 6 that the resource scheduling scheme enables maintenance points to optimally schedule resources in order of priority. For the insufficient part such as $j = \text{artillery D scheduling plan}$, it is necessary to make a new decision to further increase the resource inventory at each point to ensure that the training and wartime maintenance points are urgently needed.

VI. CONCLUSIONS

This paper proposes an optimization method for complex equipment maintenance resource scheduling based on hidden semi-Markov model. Establish a hidden semi-Markov model based on the monitoring data of each maintenance point to evaluate the health status of the equipment, and calculate the importance and priority of each maintenance point based on the health status. Establish the transportation time matrix between the support points and the maintenance points, and propose the maintenance resource scheduling plan between the maintenance points and the support points. The advantages of this method are:

1) Taking into account the maintenance support situation of the entire combat environment, a hidden semi-Markov model is introduced to evaluate the health status of complex equipment, and the real-time health status of complex equipment is taken as one of the priority considerations for resource scheduling.

2) Introduce the importance and priority of each maintenance point. The accuracy of the priority of the maintenance point is 1.2% higher than the importance of the maintenance point. Therefore, the calculation result of the priority of the maintenance point is selected to establish the transportation time matrix and the scheduling plan between the support point and the maintenance point. It can ensure the priority supply of key troops, key directions, and key equipment maintenance support resources.

3) Establish a transportation time matrix between the support point and the maintenance point, which improves the efficiency of resource protection in terms of time and reduces the maintenance cost.

4) In view of the complexity of the combat environment and resource allocation, a multi-maintenance point-multiple support point scheduling optimization plan was considered. This makes the method applicable to a wide range, reduces the limitation on the basis of the previous method, and improves the versatility.

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