On-line Schedule Model for Reusable Equipment Maintenance and Support Resource in Wartime

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***Abstract*—Based on the discussion of reusable equipment maintenance and support resource in wartime, an on-line schedule model is proposed. Firstly, this paper analyzes the difference of the scheduling process between reusable resource and consumption resource in wartime. Secondly, the model takes the following issues into account: the priority of fault node, the acceptable waiting time of fault node, the different Mean Time Between Failures (MTBF) of fault node, the centralized control and distributed control. Furthermore, with the temporal and priority constraints, the on-line scheduling process returns the best solution in real time by using the Genetic Algorithm. An on-line simulation system based on System Effectiveness Analysis Simulation (SEAS) is designed to confirm that, comparing with the FIFO model and minimum distance model, the on-line schedule model can reduce the mean-latency-time of the fault node effectively in war time.**

Keywords—on-line schedule; maintenance and support resources; genetic algorithm (GA) ; SEAS

I. INTRODUCTION

For the information age war with the characteristics of high-tech, high-speed and high-consumption, many factors produce lots of maintenance and support tasks, such as environment, random failures, damage by enemy, etc. Therefore, maintenance and support tasks are stochastic, dynamic and regional distribution [1]. Equipment maintenance and support process involves a lot of resources, including spare parts required, personnel and maintenance facilities. Rational deployment and scheduling of maintenance and support resource can reduce the average waiting time; thereby improve the combat capability in a short period of time.

Maintenance and support resources can be divided into two groups by consumption characteristic. First group is the one-time consumption resource, such as spare parts, which can't be used by others after the maintenance activities. Second group is the reusable resource, such as maintenance facilities, maintenance tools, personnel, which can be used by others after the completion of maintenance tasks [2].

To date, most research focus on maintenance and support of the continuous consumption system in wartime, there are only a few researches which are about reusable maintenance and support resource scheduling issues. Papers [2-6] proposed the concept of continuous consumption emergency resource, studied on equipment maintenance and support resource scheduling issues under the conditions of scarcity of resources, dynamic scheduling based on timely battlefield information updated response to the demand points. Papers [7-8] studied the ambulance beforehand positioning and afterwards dispatched problem. Paper [9] established the mathematical model to solve the problem after the accident occurred, the joint scheduling using a helicopter and ambulances to speed up the wounded transported to the nearest hospital. Paper [10] provided emergency medical services, dynamic allocation problems in the real-time management of the ambulances; the dynamic model and ambulance configuration management system were portrayed. Papers [11-12] proposed the ambulance dispatch and the re-configuration decision support tools by ambulance dynamic adjustment model to improve the ability of rescuing the wounded, and to reduce the waiting time of the wounded.

However, the models and methods mentioned above can't apply to the schedule of reusable equipment maintenance and support resource directly. By contrast with continuous consumption resource, the reusable equipment maintenance and support resource can be assigned to different demand points in different time. Comparing with ambulance, the reusable equipment maintenance and support resource don't necessarily return back to the appointed sites after completing the task every time. The research presented here will reference the models and methods above, first introduce the scheduling process of maintenance and support resource, then an on-line scheduling model based on extending multi-travelling sales men problem (MTSP) is given. Finally, experimental results and conclusion are given based on SEAS. The results prove that the on-line schedule model is better than the FIFO model and minimum distance model.

II. SCHEDULING PROCESS OF MAINTENANCE AND SUPPORT RESOURCES IN WARTIME

The configuration strategy and scheduling of reusable maintenance and support resource are closely related. The former indicates the affiliation of resource and scheduling object through the analysis, while the latter focuses on the analysis of how to better meet mission requirement under the given conditions and constraint.

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A. Description of the problem

Figure 1 shows the scheduling process of reusable equipment maintenance and support resource in wartime. Up to the present time, field repair vehicle is a typical application as reusable equipment maintenance and support resource, which is a combination of various repair techniques, such as fault detection and diagnostic equipment, with high maneuverability, lifting and protective capability. This research focuses on the stages B to D, using the on-line scheduling reduces the response time.

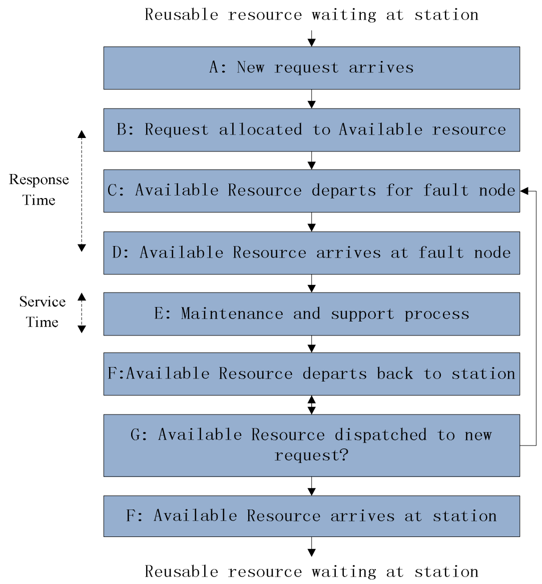

Figure 1. Scheduling process of reusable equipment maintenance and support resource

Taking example for field repair vehicle, the scheduling problem of reusable equipment maintenance support resources in wartime can be described as:

(1) The number of weapon equipment type is N, the number of type i is N_i, $i \in [1, N]$. The weapon equipments are deployed on different locations in the battle space, service request of fault node dynamically was generated in accordance with some fault probability distribution over time (MTBF).

(2) The number of reusable maintenance and support resource type is M, the number of type j is M_j, $j \in [1, M]$.

(3) The configuration strategy of maintenance and support resource can be divided into centralized and distributed in the battle space.

- Centralized maintenance and support: generally the reusable resource are deployed in the centre of the battle space, when the service request arrives, the command and control centre assigns the task to the reusable resources.
- Distributed maintenance and support: according to the degree of concentration of the weapon equipment, the battlefield space can be partitioned to several sections; a certain number of reusable resources are assigned for each section, and only response to the service request in its own section.

On the assumption that each service request only need one reusable resource, considering battlefield injury, random failure and human error and other factors, the service requests are stochastic, dynamic and regional distribution. Let the combat duration be T, then at the moment t, $t \in [0, T]$:

Definition 1: the state of maintenance and support system

$$State(t) = (LOW_{FN}(t), LOA_{FN}(t), LOS_{FN}(t), LOI_{SV}(t), LOA_{SV}(t), LOS_{SV}(t)) \quad (1)$$

$LOW_{FN}(t) : ListOfWait_{FaultNode}(t)$, define the service requests in system at time t, which have not been assigned any reusable resources.

$LOA_{FN}(t) : ListOfAssigned_{FaultNode}(t)$, define the service requests in system at time t, which have been assigned reusable resources but the reusable resources have not arrived at the corresponding fault nodes.

$LOS_{FN}(t) : ListOfServicing_{FaultNode}(t)$, define the service requests in system at time t, which have been assigned reusable resources and are undergoing maintenance and support service.

$LOI_{SV}(t) : ListOfIdle_{ServiceVehicle}(t)$, define the idle field repair vehicle list in system at time t, which have not been assigned to any service requests.

$LOA_{SV}(t) : ListOfAssigned_{ServiceVehicle}(t)$, define the busy service vehicle list in system at time t, which have been assigned to service requests but have not arrived at the corresponding fault node.

$LOS_{SV}(t) : ListOfServicing_{ServiceVehicle}(t)$, define the busy field repair vehicle list in system at time t, which have been assigned to service requests, and are servicing the assigned fault node.

Definition 2: The waiting time of fault node i

$$\Delta t_i = t_s - st_i \quad (2)$$

t_s : indicate the time of field repair vehicle arriving at fault node i.

st_i : indicate the time of fault node i sending a service request.

That the combat mission can't be executed due to equipment malfunction and battlefield damage is fatal, therefore the scheduling of maintenance and support resources is urgent. The command and control centre should complete the scheduling scheme as soon as possible, and the scheme should make the field repair vehicle arrive at the fault node in the shortest time. The objective of on-line scheduling is minimizing the response time, reducing the fault node's waiting time.

B. Model of the problem

The research presented in this paper is about the reusable maintenance and support resources, the field repair vehicle can go to the next fault node from current location after finishing one servicing task. Therefore the distance between the field repair vehicle and fault node is dynamic, the rescheduling is needed when a new service request arrives, which makes sure the total of fault node's wait time is minimal.

At time t, waiting list of the fault node in system is $LOW_{FN}(t)+LOA_{FN}(t)$, the list of available service resource is $LOI_{SV}(t)+LOA_{SV}(t)$, for service request from fault node i, the arrive time is st_i, the priority is C_i, the acceptable wait time is LT_i. For each feasible scheduling scheme:

$$\varphi(t)=(\varphi_1(t),\varphi_2(t),\cdots,\varphi_{LOI_{SV}(t)+LOA_{SV}(t)}(t)) \quad (3)$$

$$\varphi_k(t)=\left[x_{ijk}\right], \text{the scheduling scheme of field repair vehicle k} \quad (4)$$

$$x_{ijk}=\begin{cases}1, & \text{field repair vehicle k travels from fault node i to fault node j}\\ 0, & \text{otherwise}\end{cases} \quad (5)$$

$$y_{ki}=\begin{cases}1, & \text{field repair vehicle k head for fault node } i\\ 0, & \text{otherwise}\end{cases} \quad (6)$$

$$i,j\in[0,LOW_{FN}(t),LOA_{FN}(t)] \quad (7)$$

$$k\in[0,LOI_{SV}(t)+LOA_{SV}(t)] \quad (8)$$

Given the scheme $\varphi(t)$, $\varphi_k(t)$ describes the maintenance and support task and the order of the fault nodes assigned of field repair vehicle k. Therefore, the object function at time t can be defined as:

$$Min \sum_{i=0}^{LOW_{FN}(t)+LOA_{FN}(t)} (C_i\Delta t_i+C_i Max(\Delta t_i-LT_i,0)) \quad (9)$$

$$\Delta t_i=g(\varphi(t),[D_{ij}]) \quad (10)$$

LT_i: indicate the acceptable waiting time of fault node i.

C_i: indicate the priority of fault node i.

D_{ij} is defined as the cost from the fault node i to fault node j, such as the time, distance, etc.

For the combat duration T, the equation (9) can be transformed to:

$$Min\int_0^T f(\varphi(t))dt=\int_0^T(\sum_{i=0}^{LOW_{FN}(t)+LOA_{FN}(t)}(C_i(t-st_i)+C_i Max(t-st_i-LT_i,0)))dt \quad (11)$$

st.

$$\sum_{k=1}^{LOI_{SV}(t)+LOA_{SV}(t)} y_{ki}=\begin{cases}LOI_{SV}(t)+LOA_{SV}(t), i=0\\ 1, i=1,2,\cdots,LOW_{FN}(t),LOA_{FN}(t)\end{cases} \quad (12)$$

$$\sum_{i=0}^{LOW_{FN}(t),LOA_{FN}(t)} x_{ijk}=y_{kj};\ \begin{matrix}j=[0,LOW_{FN}(t)+LOA_{FN}(t)]\\ k=[0,LOI_{SV}(t)+LOA_{SV}(t)]\end{matrix} \quad (13)$$

$$\sum_{j=0}^{LOW_{FN}(t),LOA_{FN}(t)} x_{ijk}=y_{ki};\ \begin{matrix}i=[0,LOW_{FN}(t),LOA_{FN}(t)]\\ k=[0,LOI_{SV}(t)+LOA_{SV}(t)]\end{matrix} \quad (14)$$

III. MODEL SOLUTION PROCESS

A. Algorithm thought

Through the modeling and analysis of reusable equipment maintenance and support resource in wartime, we realize that the model is the extension of multi-travelling salesman problem, mainly reflected in the following aspects:

1) The number and location of the fault node changes over time, namely, the cities needed to traverse in space change dynamically.
2) The available field repair vehicle are determined at time t, which means the number of salesman is determined, but not means each service vehicle will be assigned some fault nodes.
3) The priority and cost constraint should be considered.
4) In considering the shortest path does not emphasize service vehicle eventually return to the current location, but back to the original starting point, except the first scheduling, other scheduling make field repair vehicle in the path not a ring, this is different from multi-travelling salesman problem.

The scheduling algorithm at time t can be described as:

Step 1:
Check the state of system, if a new service request arrives(the state has changed), then jump to step 2; else jump to step 4;
Step 2:
Refresh the $LOW_{FN}(t)+LOA_{FN}(t)$ and $LOI_{SV}(t)+LOA_{SV}(t)$;
Step 3:
Run the function of calculating the optimal scheme and re-allocate the maintenance and support tasks for each scheduling maintenance and support resources;
Step 4:
Simulation time advance.

B. Scheduling algorithm solving function

The key to the genetic algorithm applied to the on-line schedule of reusable maintenance and support resource in wartime is the efficient encoding and appropriate decoding methods. The scheduling algorithm optimization process based on GA includes the following steps:

Step 1: Encoding mode

On the assumption that each field repair vehicle' current location is encoding as 0, the fault node's current locations can be encoding as 1to the length of $LOW_{FN}(t)+LOA_{FN}(t)$, therefore, the code of fault node can be described as a random permutation from 1 to the length of $LOW_{FN}(t)+LOA_{FN}(t)$.

Meanwhile, we define the breakpoint for how to divide the code of fault node into sections, each section represents the fault node that one field repair vehicle should service orderly. The breakpoint is defined as selecting the number from 0 to the length of $LOW_{FN}(t)+LOA_{FN}(t)$ repeatedly and randomly, the length of breakpoint code is equal to the length of $LOI_{SV}(t)+LOA_{SV}(t)$-1, this is different from the multi- travelling salesman problem, the reason is that the each field repair vehicle is not assigned some fault nodes every scheduling necessarily.

Such as 8 fault nodes and 3 field repair vehicles, the code of chromosome and breakpoint can be defined as:

TABLE I. THE CODE OF CHROMOSOME AND BREAKPOINT

	The code of chromosome and breakpoint							
Chromosome	2	4	5	3	7	1	8	6
Breakpoint	3	6						

Step 2: Population size

Appropriate population size on the convergence of the genetic algorithm is important. Groups are too small to be difficult obtaining satisfactory results, and groups are too large to be computational complexity. According to the experience, the population size is generally taken 10 to 160.

Step 3: The fitness function

Genetic algorithm during the selection operation will produce problem: usually produce some extraordinary individuals in the early stages of genetic evolution, if selecting individuals in accordance with the proportion of these abnormal individuals, these extraordinary individuals will control of the selection process by their prominent competition, affect the overall optimize performance; reduce genetic evolution of in the late stage that the algorithm is close to convergence, due to the smaller of the differences of individual fitness value in the populations, to continue optimizing may be a local optimal solution. Fitness function poorly designed may be the cause of such problems.

Optimization objective is minimized cost value, so that the objective function can be done the exponential transform, the fitness function:

$$f = \alpha \ \exp(-\beta * \sum_{i=1}^{LOW_{FN}(t)+LOA_{FN}(t)} \Delta t_i) \tag{14}$$

α, β are real number.

Step 4: Selection

Reference with the MTSP, the selection can be defined as the stochastic tournament selection, which divide the population group into several subgroups, select the best population chromosome from each subgroup as the next generation chromosome, crossover and mutation will be based on this selection results.

For keeping the population size of group, the population size of subgroup is 8; select the best population chromosome and the corresponding breakpoint from each subgroup as one of the next generation chromosome and breakpoint, and Crossover and Mutation will produce other 7 chromosomes and breakpoints for next generation.

Step 5: Crossover and Mutation

Crossover and mutation play an important role in the genetic manipulation, for avoiding the unfeasible chromosome, and keeping the Variation and Convergence of GA, we will define the next seven manipulations to produce the next generation. Randomly selecting two intersection points in the chromosome, i and j:

1) Flip: exchange the values at i and j, keep the corresponding breakpoint same.
2) Swap: fill in the values from i to j with j to i, keep the corresponding breakpoint same.
3) Slide: fill in the values from i to j with i+1 to j and i, keep the corresponding breakpoint same.
4) Update the breakpoint randomly, keep the chromosome same.
5) Update the breakpoint randomly and doing flip manipulation.
6) Update the breakpoint randomly and doing Swap manipulation.
7) Update the breakpoint randomly and doing Slide manipulation.

Step 6: Decoding

The codes described above (TABLE I) can be decoded as TABLE II:

TABLE II. THE DECODE OF CHROMOSOME AND BREAKPOINT

0	2	4	5	the original starting point
0	3	7	1	the original starting point
0	8	6		the original starting point

The decoding chromosome and breakpoint can be explained as follows:

The field repair vehicle 1 will service fault nodes 2-4-5 orderly;

The field repair vehicle 2 will service fault nodes 3-7-1 orderly;

The field repair vehicle 3 will service fault nodes 8-6 orderly.

IV. CASE STUDY

Given the battlefield space Ω and the file of its transportation network (Figure 2), the optimal distance matrix D_{ij} between node i and node j can be calculated through the transport network file.

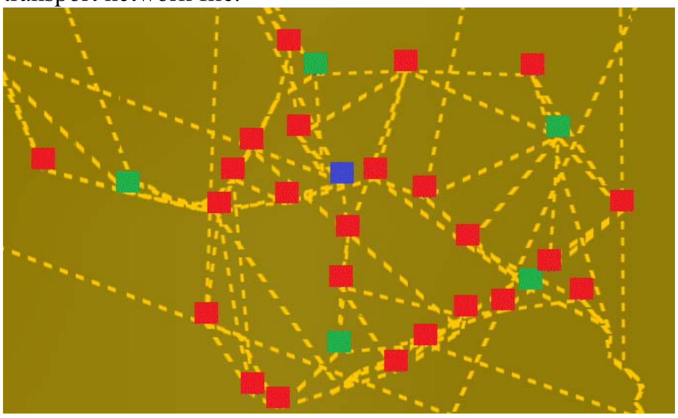

Figure 2. Simulation of On-line Scheduling based on SEAS

In figure 2, the yellow lines represent the transportation network; the red icons are the potential fault node sites; the blue icon in the centre of the battlefield space is the centralized maintenance and support station, the field repair vehicles are deployed at this station when the command and control mode is centralized maintenance and support; the green icons describe the distributed maintenance and support station, each takes charge of one section, there are 5 potential fault nodes in each section, and each distributed maintenance and support station is assigned one field repair vehicle.

Other parameters are given as TABLE III:

TABLE III. PARAMETERS OF SCENARIO

Equipment Type	1
Equipment Number	25
Field repair vehicle Type	1
Field repair vehicle Number	5
Field repair vehicle Speed	60 km/h
Combat duration T	800 min

We develop this case on SEAS; use Tactical Programming Language modeling the behavior of each agent, such as fault node, field repair vehicle, command and control center, etc.

A. Experimental design

For analyzing efficiency of the on-line scheduling model of reusable equipment maintenance and support resource in wartime, we consider the factors which may influence the response time (given in TABLE IV), and will compare the on-line scheduling model with FIFO and Minimal Distance First. FIFO means that the service request from fault node which arrives first will be assigned a field repair vehicle first, and Minimal Distance First means that the field repair vehicle will service the fault node which is closest.

TABLE IV. PARAMETERS OF EXPERIMENTAL DESIGN

MTBF	200 min	400 min	600 min
Schedule strategy	FIFO(1)	Minimal Distance First(2)	On-line Schedule Model(3)
Command and control	Centralized maintenance and support(CMS)	Distributed maintenance and support(DMS)	
Acceptable waiting time	20 min	30min	
Population size	80		
Iteration time	200		

To validate on-line scheduling model, we generate 36 scenarios based on the MTBF, schedule strategy, command and control mode and acceptable waiting time. To avoid the random number influencing the simulation results, each scenario will be run 100 times, and we use the average of the 100 times as the result of each scenario.

B. Analysis of experimental results

On the basis of the experimental design, we get the simulation results. Figure 3 shows the comparison of response time when the acceptable waiting time is 20 min, Figure 4 shows the comparison of response time when the acceptable waiting time is 30 min, and Figure 5 shows the comparison of response time when the acceptable waiting time is different.

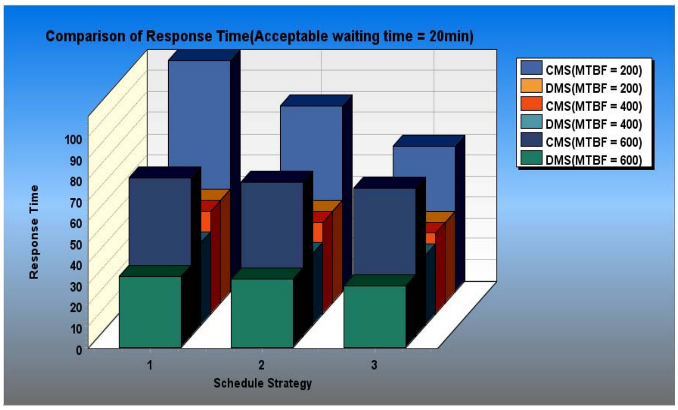

Figure 3. Comparison of Response Time(Acceptable waiting time = 20min)

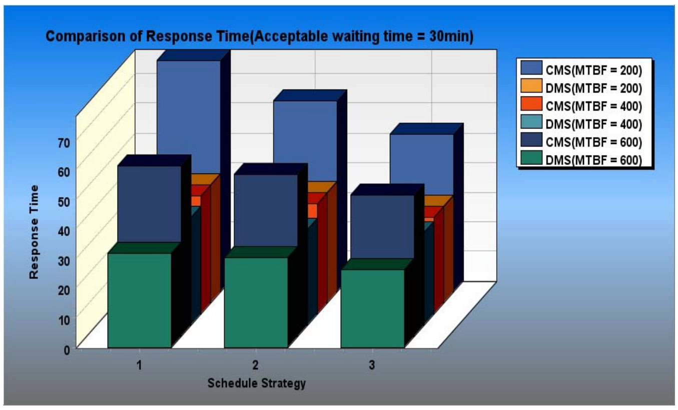

Figure 4. Comparison of Response Time(Acceptable waiting time = 30min)

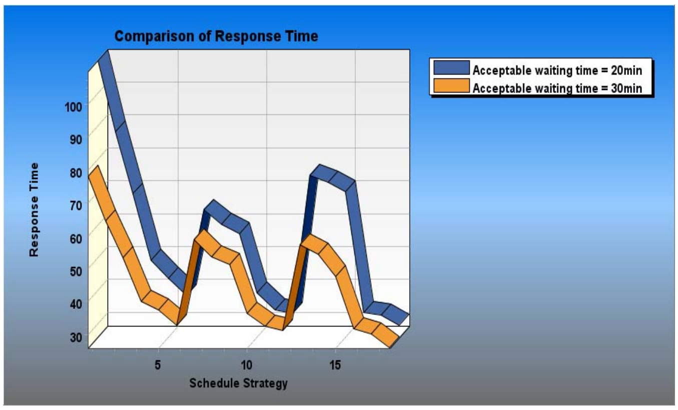

Figure 5. Integrated Comparison of Response Time

By figure 3 and figure 4 we can note that:

1) First, without regard to MTBF and command and control, figure 3 and figure 4 show that the response time of on-line schedule model is better than others, especially when the MTBF is small.
2) Second, when the MTBF is increasing, the predominance of the on-line schedule model is decreasing, this is because that when the MTBF is increasing, meanwhile the interval of the service request from the fault node is increasing, the field repair vehicles will return back to the original starting

point(service station) mostly when they finish the service process. Therefore when the new service request arrives, the state of the service system is same usually, this results in the similar response time.

3) Third, the response time of distributed maintenance and support (DMS) is better than centralized maintenance and support (CMS), the reason is that for distributed maintenance and support mode, the field repair vehicles are deployed in different sections, which are close to the fault nodes, and more quick to arrive at the fault nodes.
4) Last, when the MTBF is 600 min, the response time is bigger than the MTBF is 400 min, the reason is similar to the cause mentioned in second. When the service request arrives, the field repair vehicle departs from the original starting point usually, therefore the distance between the fault node and the field repair vehicle is longer than others.

By figure 5 we can note that, when the acceptable waiting time is increasing, the response time is decreasing. This is because that the acceptable waiting time is bigger, the field repair vehicles are easier to arrive at the fault node without the punishment, the $C_i Max(t - st_i - LT_i, 0)$ in object function is smaller.

V. CONCLUSIONS

This paper analyzes the differences of the scheduling process between reusable resource and consumption resource in wartime. Bringing the on-line scheduling model to the reusable equipment maintenance and support resource, we get a quite acceptable result in optimizing the scheduling process and decreasing the responding time of the service request. Based on the model established and solution process, we use the genetic algorithm to solve the optimizing problem. Finally we testify our model and algorithm based on SEAS, the result proves that the on-line scheduling is effective for the reusable equipment maintenance and support resource. Based on the research presented here, we will study the deployment of field repair vehicle later.

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