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Modeling and Assessing a New Warship Maintenance System

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Abstract: The authors developed a prototype of a warship maintenance system. The process started by defining the maintenance requirements of warship equipment. Next, a planning scheme was development for a maintenance network. An optimization target for the plan and indexes for assessment were established. Based on the above work, a simulation model was proposed with two layers: a base and a workshop. Dispatching rules were then formulated for the simulation. Experimental results proved the validity of the model and the dispatching algorithm. It was found that the model can solve the capacity evaluation problem for maintenance systems and provides a scientific basis for decision-maker to make decisions regarding equipment maintenance.
Keywords: capability assessment; planning optimization; heuristic regulation; warship maintenance system
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1 Introduction

Complexity of the maintenance system is illuminated as three points. Firstly, the system framework is complicated. Extraction of solid model is restricted by flexible resource, and it is difficult to confirm resource, working procedure relation and simplex resource capability. Secondly, the maintenance action is complicated. The choke point of algorithm selection includes scheduling correlation, resource restriction and breaking out simultaneously. Thirdly, the maintenance technology is complicated. Extraction of network planning scheme and quantization of working procedure are very difficult due to project implication and technical restriction. So, it is not easy to model and simulate the maintenance system.

RTI Company of America, the Boeing Company, and the Lockheed Martin Company have gained great achievements in research for simulating the maintenance system and the maintenance training system (Yao, 2005), but the research laid particular stress on the evaluation of product maintainability, simulating fault detection, simulating fault disassembly and repair, which are very different from evaluation of the maintenance system's capability and planning optimization. Scholars at home and abroad made many researches on maintenance system modeling, such as modeling methods (Peng *et al*., 2003) based on Petri net (Yang *et al*., 2004), MAS (Xie *et al*., 2005), IDEFO (Zhang, 2004) and UML (Mila *et al*., 2006). Besides, many research workers also concerned dispatching for production plan and complicated maintenance system (Zou *et al*., 2005). Although research workers laid different stress on it and used different methods, it can be classified into five kinds, that is, the methods based on operational research, heuristic regulation, artificial intelligence, computing intelligence and colony intelligence (Cao *et al*., 2006). However, practical achievements fitting for modeling and simulation of warship maintenance system are limited. In this paper, the simulation framework of warship maintenance system and heuristic algorithm are advanced to optimize the maintenance plan and evaluate combat readiness and support capability of the maintenance system.

2 Problem description

It is supposed that R is an aggregation, $R=\{R_1, R_2, \cdots, R_i\}$, R_i shows workshop resource of the maintenance system. Every workshop can take on tasks of polytype equipments and repairs at the same time. Conception of project resource was introduced for describing framework and capability of workshop resource.

Definition 1. According to the requirements of certain type of equipment and repair, workshop dispatchers' tasks are divided according to specialties. Some skilled workers are transferred to form a specialty technology detachment as r_{ij} so that the detachment has ability of maintaining the type of equipment and facility. r_{ij} shows the *j*th project resource of the *i*th workshop, which is corresponding to maintenance of the *j*th equipment and facility.

Definition 2. The *i*th workshop can carry on maintenance tasks of n kinds of equipment and facilities. Value of r_{ij} shows the amount of the *j*th type of equipment and facilities carried on by the *i*th workshop, so $(r_{i1}, r_{i2}, \cdots, r_{ij}, \cdots, r_{in})$

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shows capability of the ith workshop. Capability of r_{ij} is unaided because of the overlaping tasks of skilled workers and dynamic reconstruction.

Prototype model of warship maintenance system was designed based on definition 1 and definition 2.

$$R = \begin{vmatrix} r_{11} & r_{12} & \cdots & r_{1j} \\ r_{21} & r_{22} & \cdots & r_{2j} \\ \vdots & \vdots & \vdots & \vdots \\ r_{i1} & r_{i2} & \cdots & r_{ij} \end{vmatrix}$$

$$r_{ij} = f(r_1, r_2, \cdots, r_k)$$

where r_k shows technology type of work, k shows its amount.

Definition 3. Warship maintenance engineering is an aggregation of i maintenance projects and $P=(x_1, x_2, \cdots, x_i)$, where, there are m working procedures in project x_i, and x_{ij} shows the jth working procedure in project x_i.

Definition 4. Warship maintenance engineering is an aggregation of i maintenance projects, and every project x_i which has m working procedures is parallel and non-correlative. So, the working procedures aggregation of i maintenance projects can be called as network planning scheme, which is noted as P_{NG}.

$$P_{NG} = \begin{vmatrix} x_{11} & x_{12} & \cdots & x_{1j} \\ x_{21} & x_{22} & \cdots & x_{2j} \\ \vdots & \vdots & \vdots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} \end{vmatrix}$$

It shows there is no working procedure when x_{ij} is 0, and it also shows there is working procedure when x_{ij} is 1. i shows project amount, which is corresponding to resource. j shows working procedure amount, and $j \le m$. $x_{1\text{end}1} < x_{1\text{end}2} < j$, which lays on the first line of matrix. $x_{1\text{end}1}$ shows the finishing working procedure of the first engineering in shipyard, and $x_{1\text{end}2}$ shows the finishing working procedure of the second engineering in shipyard.

Definition 5. If warship maintenance system is required to fulfill maintenance missions of q warships during the time of T and maintenance level, the maintenance projects and the time of commencement of every warship are different from each other, the overall arrangement plans of q warships can be called plan of warship furnishment's support, noted as 'P_p'.

$$P_p = (P_1, P_2, \cdots, P_q)$$

$$P_q = (x_1, x_2, \cdots, x_i)$$

$$t_\text{b} + \Delta t_1 \le t(P_q) \le t_\text{b} + \Delta t_1 + \Delta t$$

t_b shows scheming time of commencement, Δt_1 shows time of commencement difference of actual delay, and Δt shows maintenance period.

So, the problem of evaluation and maintenance plan optimization of warship maintenance system can be transformed to the problem of overall dispatchment of working procedure plan figure of multiple resources restriction and multiple projects conducted at the same time.

3 Optimization purpose and evaluation index

Generally, the requirements of furnishment support are shown as follows. The first is that warships undertaking missions must be ensured firstly so that tactical plan can be carried out successfully. The second is that the amount of support missions finished during short period is required to be many as much as possible to maintain battle effectiveness. The third is that all warships must be repaired before combat readiness transform. Requirements of furnishment support departments are shown as follows. The first is that maintenance resources are plentiful so that the repair missions can be finished successfully. The second is that the utilization rate of maintenance resources is required to be balanced as much as possible to reduce risk caused by non-uniform labor intensity. The third is that the furnishment support rate is required to be high as much as possible. The fourth is that the furnishment support missions must be finished on schedule according to the direction of decision department. So, the high undamaged rate and plenty support resources are not only requirements of furnishment support department, but also the goal of maintenance missions allocation and maintenance plan optimization. Similarly, warship furnishment support rate and ample resources' amount can be used to evaluate capability of warship maintenance system, that is, more maintenance missions are finished in the same time limit, better maintenance capability can be gained. When the same maintenance mission requires to be finished, resources utilization is more balanced, labor intensity of every specialty is more average. When the effect of choke point is small and that of ample resources' amount is large, better capability of warship maintenance system carrying on new missions of rushing to repair can be gained, which conforms to the fact of coexistence plan of rushing to repair on the eve of a war and rushing to repair. Thereby, system of evaluation indices of warship maintenance system is shown as follows.

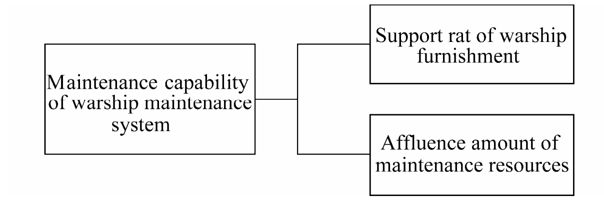

Fig.1 Item of maintenance capability

Its mathematical model is shown as follows:

$$\max\left(K_{\text{Sup-R}}\right)=\frac{N_{\text{Sup}}}{N_{\text{Infactr}}}$$

$$\min\left(\bar{K}_{\text{Afflu}}\right)=\frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\frac{r_{ij}}{R_{ij}}}{n}$$

$$\text{s.t.}\sum_{m=1}^{M}\delta_m r_{ij}\left(m\right)\le R_{ij}$$

s.t. $T \le$ time limit of combat readiness transform, r_{ij} shows actual utilization amount of the *j*th kind of resource, R_{ij} shows overall amount of the *j*th kind of resource, and δ_m shows working procedure.

In simulation, for scanning optimization results visually, we calculated the overall period of completing maintenance plan and compared the optimization results of different regulations to judge optimization effect, evaluate warship support capability of the maintenance system during the course of combat readiness and evaluate furnishment support rate in the gross.

4 Algorithm design based on heuristic regulation

Aiming at special operational mechanism of the maintenance system and considering practicability of project research, we selected heuristic algorithm which is better for warship maintenance action as the support for experimental verification.

4.1 Simulation model of two layers

In the light of actual maintenance actions, the authors built the model of maintenance plan for simulation and optimization of two layers of base and workshop. That is, after the maintenance system of base has received furnishment support plan sent down by higher authority 'plan', the system running goal and regulation are confirmed according to present situation of maintenance resource and capability of the base, and the support plan is optimized initially and the maintenance missions are sent down to workshop. After workshop has received missions, the maintenance plan of ground floor is optimized according to reasonable allocation of working procedure of resource conditions, and the optimized results are fed back to the base. Base adjusts furnishment support plan according to feedback information. The organization structure and operational mechanism of simulation are shown as Fig.2.

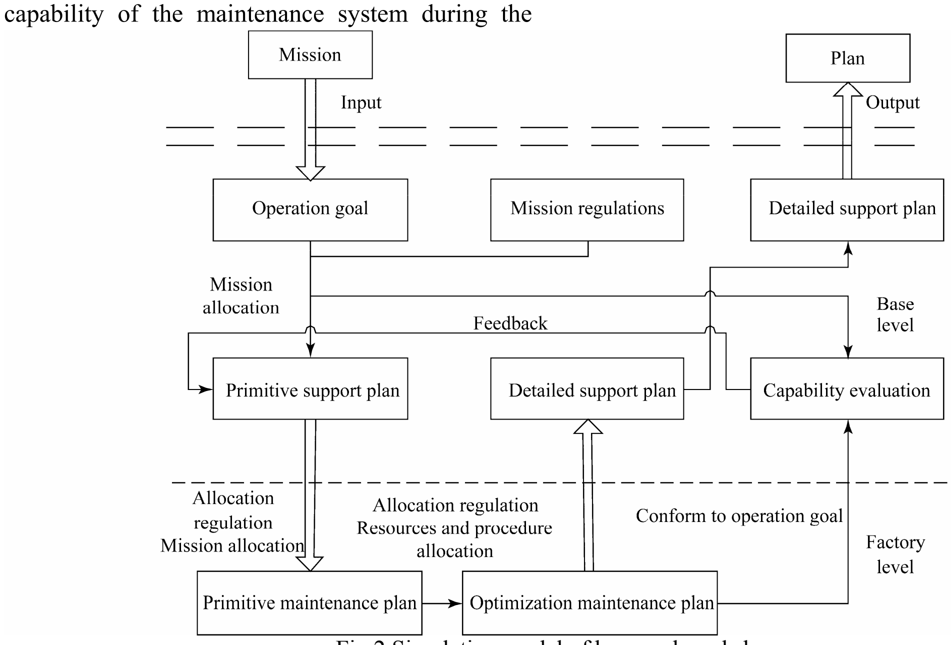

Fig.2 Simulation model of base and workshop

4.2 Support plan allocation and missions allocation regulation

According to regulation of readiness for urgent need, balanced use of resources and high utilization rate, six kinds of regulation of maintenance missions allocation are confirmed, namely, heuristic regulation. The first is priority regulation. That is, according to priority order of missions arrangement and results of man-machine interference, missions arranged ahead are repaired first and missions arranged later are repaired later. The second is match regulation of maximum resources. That is, on analysis of match level between resource vacancy and maintenance projects, warships of high match level of resources have the priority to be allocated for repair. The third is minimum conflict regulation. That is, on analysis of the conflict level between saturation state of resource mission and maintenance projects' requirement, warships of lower conflict level are arranged to be repaired. The fourth is the earliest terminal time. That is, to shorten the time of warships being repaired, avoid taking too many maintenance resources of the base and slowing down of the pace which affects the maintenance effect of earlier stage. It can be taken for increasing furnishment support rate furthest, so as to arrange maintenance resources firstly for warship being repaired whose terminal time is the earliest. The fifth is self-adapting regulation. Results of resources analysis showed that if key resources are not vacant but there're plenty of correlative resources, warships can be arranged for repair. Other specialties can start to work in advance in terms of network planning figure except the engineering project in shipyard. Docking can be postponed properly, and it must be ensured by time at latest of going into operation so that repair of all projects in shipyard will be finished before terminal time at latest. All projects in shipyard can not be postponed and should be conducted respectively. Time can not be postponed later than warship undocking. The sixth is limitless resources regulation. That is, partial local resources can be mobilized to solve the choke point problem of maintenance resources.

Property 1. From definition 1, project resources denoted as r_{ij} are unaided resources, and there is no problem of nonlinear correlation among them. Project denoted as x_k is supposed to be unaided project, technical restriction among projects is solved in project detailed list. For the convenience of description, suppose that $r_{ij} = r_k$, k shows total amount of project resources, so, relationship between r_k and x_k is one to one.

Based on property 1, match coefficient between missions and resources can be used to restrict utilization of heuristic regulation. N_C shows correlative coefficient of match between missions and resources at t moment.

$$N_C(r,x,t) = \frac{\left(\sum_{k=1}^{K} r_k x_k\right)^2}{\left(\sum_{k=1}^{K} r_k\right)^2 \left(\sum_{k=1}^{K} x_k\right)^2} \quad \text{or} \quad \frac{k}{n}$$

where, k shows the number of conflict projects, namely, $x_i \neq 0$ and $r_i = 0$. n shows the number of projects required to be repaired.

In terms of different heuristic regulations of different missions allocation, threshold values are selected reasonably. After calculating, it is judged whether $N_C(r,x,t)$ is bigger than threshold value. It is analysed and judged whether there is conflict between r_{key} and x_k, and whether t(terminal time at latest of engineering in shipyard)- t(the earliest time started at latest of engineering in shipyard)- ΔT (in shipyard) is bigger than t(terminal time at latest of engineering in shipyard)-t(present time). At last, it is confirmed whether other warships can be arranged to be repaired to realize allocation of furnishment support plan.

4.3 Maintenance plan optimization and maintenance resources allocation

On the basis of agent technology, warships agent, and missions agent, the same resources agent are created. Through cooperation among these agents, maintenance resources allocation, progression regulating and control, ground layer optimization of maintenance plan and capability evaluation are realized (Zhao *et al*., 2007). Resources allocation regulations are shown as follows. The first is correspondence regulation. That is, relationship between common project resources and maintenance projects is one to one, but key resources are allowed to be one to multiple. The second is regulation of add or subtract. That is, if resources are taken, the number of resource vacancy is subtracted by 1. And if resources are abandoned, the number of resource vacancy is added by 1. Allocation algorithms are shown as follows. The first is ordinal allocation algorithm. That is, the maintenance resources are allocated strictly according to warship maintenance order confirmed by the missions allocation algorithm, so as to change conditions of resources occupancy. When resources are scarce, it can be used to increase correlative resources by limitless resources allocation algorithm or to adjust maintenance procedure. The second is allocation algorithm of jumping the queue. A condition can appear in resources allocation when maintenance procedure was postponed in former simulation period because of resources conflict, which led to working procedure time of partial projects exceeding time limit and the total maintenance period postponing a time step. So, after regulation and control programs of maintenance procedure were transferred, the mission sequence of the warship should be brought forward a place to avoid time limit for a project, so the warship could postpone again and again. This algorithm can be conducted through changing mission sequence of warships being repaired, and it can only benefit from the next simulation period.

5 Experimental verification of algorithm and conclusion

In practical simulation, we selected twelve warships whose mode, maintenance level, engineering scope and time limit of going into operation were different from each other.

Maintenance network planning figures were made automatically through project detailed lists and project resources prepared by hand, and simulation calculations were conducted in terms of the order of calculating primitive period, first-in first-out and earliest terminal time having priority. It is illuminated in Fig.3 that the total period of primary plan, total period under allocation of FIFO regulation and total period under allocation of regulation of the earliest terminal time have priority.

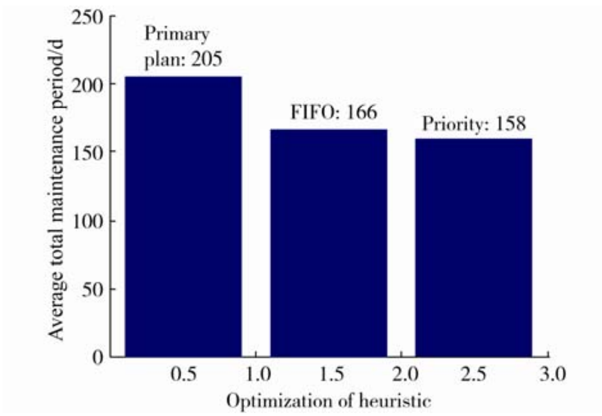

Fig.3 Comparison of total periods of maintenance plans optimization of twelve warships

Fig.4 illuminates the whole utilization condition of scores of maintenance projects in simulation period. Results showed that the utilization rate of every kind of resource was different. Utilization rate of some resources was high and their utilization intensity was hard; while the utilization rate of some resources was low and their utilization intensity was not hard. However, every kind of resource has some affluent amount in mission period. It is illuminated that one, resources utilization has some affluent amount in the mission period and some occasional missions rushing to repair can be taken. Another one, the utilization intensity of different resources is different, and decision-maker can adjust support plans to lighten utilization intensity of heavy duty resources or mobilize some local resources as a preparation for use in emergency.

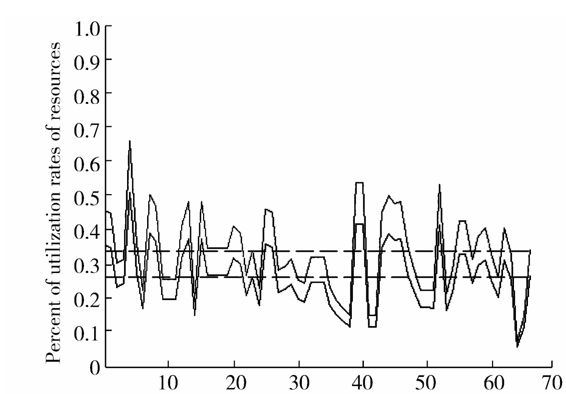

Fig.4 Utilization rates of resources

Fig.5 illuminates the resources balanced rate of total maintenance period calculated by formula of average amount of ample resources. Transverse axis shows time, and vertical axis shows average utilization rate of resources. From curves in Fig.4, along with the increase of maintenance plan and optimization of heuristic algorithm, resources balanced rate was improved and the loading intensity of all resources tends to be balanced, which is the goal of the algorithm, and the algorithm is proved to be effective.

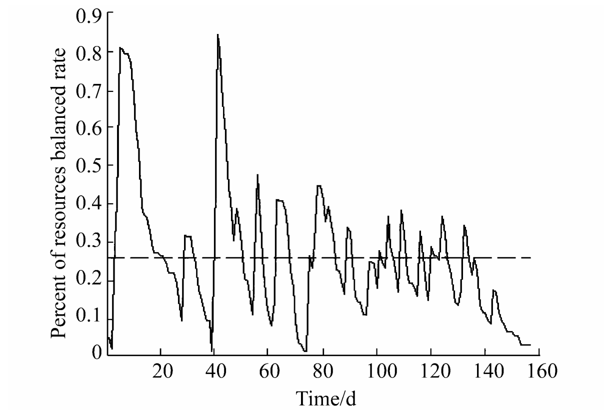

Fig.5 Resources balanced rate after optimization

It is illuminated by experimental results that first, the maintenance system model based on agent is feasible, which can realize simulation calculation of the maintenance plan and be used to evaluate maintenance system capability. Second, the optimization result according to FIFO regulation is clearly shorter than the total period of primary plan, and the optimization result according to regulation of the earliest terminal time having priority is shorter than the result according to FIFO regulation. So, these two heuristic regulations are effective in maintenance plan optimization. Third, decision-maker of furnishment support can maintain system capability of finishing missions and temporary missions of rushing to repair in terms of the comparison results of total maintenance period, resources utilization rate and balanced rate to regulate and control the support plan for controlling risks of mission accomplishing.

6 Conclusions

This paper has defined the maintenance support plan of warship equipment, built the prototype model of maintenance system, extracted the network plan of maintenance, established the optimization target of plan and the indexes of capability assessment, built two-layer modeling of base and workshop and established the algorithm based on agent. In the experiment, twelve warships and the corresponding resources has been selected as the object to modeling and assess.The results of experiment include the comparison of total periods and resources utilization rates and balanced rate. The experiment has proved the validity of modeling and algorithm. It provides a scientific approach for decision-maker to make decisions of equipment support, and moreover, lays the foundation for the establishment of the decision support system.

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