A multi-agent based intelligent configuration method for aircraft fleet maintenance personnel

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Configuration;
Fleet;
Maintenance-planning;
Multi-agent system;
Personnel

Abstract  A multi-agent based fleet maintenance personnel configuration method is proposed to solve the mission oriented aircraft fleet maintenance personnel configuration problem. The maintenance process of an aircraft fleet is analyzed first. In the process each aircraft contains multiple parts, and different parts are repaired by personnel with different majors and levels. The factors and their relationship involved in the process of maintenance are analyzed and discussed. Then the whole maintenance process is described as a 3-layer multi-agent system (MAS) model. A communication and reasoning strategy among the agents is put forward. A fleet maintenance personnel configuration algorithm is proposed based on contract net protocol (CNP). Finally, a fleet of 10 aircraft is studied for verification purposes. A mission type with 3 waves of continuous dispatch is imaged. Compared with the traditional methods that can just provide configuration results, the proposed method can provide optimal maintenance strategies as well.

1. Introduction

As one of the key maintenance recourses, maintenance manpower is the subject of equipment maintenance. With the rapid development of technology, for instance, high velocity maintenance is becoming a trend, and three level maintenance is being transferred to two level maintenance; maintenance systems need improving and optimization. A maintenance system involves multiple factors, and all maintenance actions are performed by personnel. Therefore, the number of maintenance personnel is affected by multiple relevant factors, and is difficult to determine. Meanwhile, aviation unit maintenance (AVUM) is directly related to combat effectiveness, while resources are limited. Therefore, the configuration of maintenance personnel of AVUM is very important.

At present, AVUM oriented fleet maintenance personnel configuration methods can be classified into 3 categories. The first is historical methodology. For instance, the empirical formula: the total maintenance time equivalent is first acquired, and then the maintenance time of each task is predicted, finally, the number of maintenance personnel is determined by judging the available maintenance time of a single person. The second is mathematical programming. For instance, the mixed integer linear programming: an enumerative algorithm with bounding is proposed, in which each node of the enumeration tree represents a mixed integer linear problem (MILP), then the MILP is reformulated such that it becomes...
tractable for commercial MILP solvers. Ant colony algorithm: a multi-objective mathematic optimization model for time and personnel is established by using the multi-objective constraint theory, then the model is studied based on the theory of modified ant colony algorithm. And genetic algorithm (GA): business objective and process models are established, while the problem of deciding service staff is pointed out. A three-phase approach to decide service staff is put forward, applying an improved GA and a specific evaluation pattern.

The third is simulation: a discrete event simulation model is presented for aircraft maintenance operation, which involves various characteristics and behaviors of an aircraft maintenance system. Optimization modules of the simulation software generate an optimum maintenance plan, and the optimum number of maintenance personnel to match the increased workload in the future.

Of all these approaches, the empirical formula is the most widely used in practice, but the result is far from reality due to its excessive simplification, and it needs to be adjusted according to the maintenance personnel of similar equipment. Mathematical programming is more accurate due to more consideration of various factors, but it is still far from precise and is difficult to solve. Simulation can account for even more factors and avoid complex theoretical derivation. Therefore, simulation is a more promising method.

However, current research is still far from being able to solve an actual maintenance personnel configuration problem. For example, new equipment that lacks historical data is not suited to historical methodology. Meanwhile, more attention is paid to the overall view of fleet maintenance problem, while individual pieces of equipment and person are largely ignored, which does not match the reality very well, nor is appropriate or accurate. Besides, in literature, maintenance tasks are usually regarded as time equivalent, while the effect of human error is not fully considered. Finally, current configuration methods usually follow certain rules to solve the optimal number of personnel and/or estimate the strategies, but the optimal maintenance strategy is not so easily obtained.

As an advanced modeling technique, multi-agent modeling has been successfully applied to maintenance modeling and optimization. Agents can imitate the interaction and collaboration in the process of fleet maintenance, and can improve the accuracy of fleet maintenance model. The application of multi agent modeling can be divided into two aspects.

The first is maintenance optimization. For instance, Bouzidi-Hassini and Benbouzid-Sitayeb proposed a joint production and maintenance scheduling that takes into account human resources availability and skills to propose realistic schedules, where multi-agent systems are used for modeling the floor shop.

The second is maintenance influence factor analysis and evaluation. For instance, Feng et al. established a carrier aircraft operation and maintenance support model, and analyzed the influence of RMS level on the dispatch capacity of the carrier aircraft fleet.

Although multi-agent has not been applied to maintenance personnel configuration, it has laid a good foundation for the fleet maintenance personnel configuration problem, and can provide reference for its model framework and corresponding modeling elements. Compared with maintenance personnel configuration, the gap lies in: (A) the description of maintenance personnel is not detailed enough; (B) the analysis capacity of the model is not sufficient because generation of strategy is not very well achieved.

Based on multi-agent modeling, an intelligent aircraft fleet maintenance personnel configuration method for field maintenance is proposed in this paper. The multi-agent model can imitate the detailed behavior of the maintenance personnel, including their major, capability level, personnel cooperation, human error, and the result is more accurate; moreover, the number of personnel and personnel dispatching strategy can be solved at the same time, which can provide more support for maintenance system optimization.

2. Problem descriptions

2.1. Analysis of the maintenance process

An aircraft contains multiple parts which may fail. When a combat mission instruction is delivered to an aircraft, the aircrew conducts a pre-flight inspection, and once an aircraft returns from a mission, the aircrew conducts a post-flight inspection. If failures don’t occur, the aircraft conducts the mission, or the aircraft is sent to the maintenance process. During the maintenance, human errors may occur, so a test is required before the maintenance task is completed. Once the maintenance is done, the aircraft waits for mission instructions again. The detailed process is shown in Fig. 1.
2.2. Analysis of factors

Fleet maintenance, on the other hand, is quite different from single aircraft maintenance. In fleet maintenance, the aircrew should consider many more factors, dispatch maintenance resources as a whole, and form an integrated maintenance scheme.

As is analyzed, fleet maintenance involves 3 factors: maintenance workload (MW), maintenance resource (MR) and maintenance strategy (MS), shown in Table 1. Maintenance is considered successful when the number of aircraft available is no less than the number of aircraft required.

Based on an analysis of the factors above, maintenance personnel number and scheduling strategy can be obtained at the same time. The strategy means a certain person of a certain major and a certain level will fix a certain part at a certain opportunity with a certain method, and so on. The relationship among them is shown in Fig. 2, the PREF₁ is pre-flight inspection and the POST₁₁ is post-flight inspection.

2.3. Problem description

Consider a fleet consisting of \( m \) aircraft, and a mission requiring \( n \) aircraft (\( n \) is not fixed and \( n \leq m \)). Each aircraft contains \( p \) parts, and all \( p \) parts may fail during the mission, while failures can be forecasted before a mission starts. The whole fleet is supported by a limited maintenance staff, and the total number of spare parts is limited.

To define the maintenance personnel configuration problem, some basic assumptions are listed below.

**Assumption 1.** Maintenance method (MM): for each part, there are two maintenance methods, namely replace and repair. Replacing a part requires less time but more spare parts, while repairing a part requires no spare part but more time.

**Assumption 2.** Personnel major \( P_M \): different parts require different personnel majors. The same part with the same maintenance method costs the same maintenance time, and other situations cost different maintenance times.

**Assumption 3.** Personnel level \( P_L \): maintenance staff are divided into different levels. Assume the maintenance personnel of the \( i \)th major are divided into \( n \) levels (Level 1 up to Level \( n \)), and the difference lies in MT, including \( T_{L} \), \( T_{D} \), \( T_{RN} \), \( T_{RP} \), \( T_{A} \), and \( T_{T} \).

**Assumption 4.** Human errors \( H_E \) may occur during the process of maintenance. The probability of human error when maintaining the \( i \)th part with the \( j \)th level is expressed as \( p_{ij} \), and the consequence of human error is a waste of time and/or spare parts.

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**Table 1**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Influencing element</th>
<th>Sub-element</th>
<th>Source of influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance workload</td>
<td>Failed parts (FP)</td>
<td>None</td>
<td>Reliability level &amp; the number of aircraft in fleet ( F_N )</td>
</tr>
<tr>
<td></td>
<td>Aircraft required (AR)</td>
<td>None</td>
<td>Mission &amp; the number of aircraft in fleet ( F_N )</td>
</tr>
<tr>
<td>Maintenance resource</td>
<td>Maintenance time (MT)</td>
<td>Logistic delay time ( T_{LD} )</td>
<td>Supportability level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time to locate a failure ( T_{L} )</td>
<td>Maintenance personnel &amp; testability level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time to disassemble ( T_{D} )</td>
<td>Maintenance personnel &amp; maintainability level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time to renew ( T_{RN} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time to repair ( T_{RP} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time to assemble ( T_{A} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maintenance personnel (MP)</td>
<td>Personnel number ( P_N )</td>
<td>All elements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Personnel major ( P_M )</td>
<td>Training &amp; investment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Personnel level ( P_L )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Human error ( H_E )</td>
<td></td>
</tr>
<tr>
<td>Spare parts (SP)</td>
<td>Spare part number ( SP_N )</td>
<td>Investment</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spare part type ( SP_T )</td>
<td></td>
</tr>
<tr>
<td>Maintenance strategy</td>
<td>Maintenance method (MM)</td>
<td>Renew ( R_N )</td>
<td>Maintainability level &amp; spare part number</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Repair ( R_P )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maintenance level (ML)</td>
<td>AVUM</td>
<td>Supportability level</td>
</tr>
<tr>
<td></td>
<td>Maintenance opportunity (MO)</td>
<td>Pre-flight inspection</td>
<td>Failure detecting and handling strategies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post-flight inspection</td>
<td></td>
</tr>
</tbody>
</table>

---

**Fig. 2** Relationship among all factors.
**Assumption 5.** Concurrent maintenance (CM): parts in different sections can be maintained concurrently, while parts in the same section can only be maintained following certain sequences.

**Assumption 6.** Personnel cooperation (PC): a part can be maintained by one or more staff. When the part is maintained by personnel of the same level, assume $T_i(j)$ stands for the time required when the $i$th part is maintained by $j$ men, and the cooperation effect can be classified into 4 categories: (A) non-cooperational, or $j = 1$; (B) cooperation effect neutral, or $T_i(j) = T_i(1)/j, (j > 1)$; (C) cooperation effect positive, or $T_i(j) < T_i(1)/j, (j > 1)$; (D) cooperation effect negative, or $T_i(j) > T_i(1)/j, (j > 1)$. When the part is maintained by personnel of different levels, according to current personnel configuration, the proportion of personnel in different levels is fixed. Assume a combination of maintenance personnel (CMP) includes the basic number of personnel in different levels and $T_i(CMP)$ stands for the time required when the $i$th part is maintained by combination CMP. However, cooperation involving too many staff is meaningless, so the maximum number of maintenance personnel is limited, and the limit decreases as the level increases.

The main purpose of this paper is to acquire the optimal configuration of maintenance personnel, as well as the maintenance personnel dispatching scheme. Through the analysis of the problem, the factors in Table 1 are handled below.

The objective of the problem is to minimize the total number of personnel. To stress the key point, the proportion of personnel in different levels is fixed. And the objective is:

$$
\text{min} : \sum P_N \text{ based on fixed proportion CMP}
$$

The main constraints of the problem are in Table 2. To optimize the number of maintenance personnel, as well as the optimal maintenance personnel dispatching scheme, the variables are in Table 3. Based on the problem, the parameters, or the factors following the current system, are in Table 4.

### 3. Process modeling

#### 3.1. Model framework

The fleet maintenance process involves aircraft, maintenance resources, and the overall management. Based on the multi-agent technique, the whole process can be described as three classes of agents, namely aircraft agent, maintenance agent and management agent.

Among them, the aircraft agent and maintenance agent stem from the actual system. The aircraft agent provides the description of aircraft, represents the reliability of an aircraft, and generates maintenance demands. The maintenance agent provides the description of maintenance resources, represents the maintenance capacity, and performs maintenance actions.

To increase simulation efficiency, one major of maintenance resources is modeled into one maintenance agent. The number of personnel can be regarded as a property of the maintenance agent, while other properties include major, maintenance time, human error probability and spare parts.

Management agent stems from the process of management, and is in charge of the overall maintenance process.

In reality, maintenance actions are performed under management. Therefore, the management agent has priority over aircraft agent and maintenance agent. Apart from communication, the internal reasoning mechanism may also affect the model output. Therefore, the overall model structure can be divided into 3 layers. The first two layers are communication layers, and the 3rd layer is the reasoning layer.

The 1st layer is the global communication layer. The management agent communicates with aircraft agents and maintenance agents, respectively, to coordinate the whole process. The 2nd layer is the local communication layer. Aircraft agents and maintenance agents communicate with each other, to obtain maintenance strategies and the number of personnel. The 3rd layer is the reasoning layer. The original data is put into the system, processed through a reasoning mechanism, and transferred into results. The whole process includes generating the original scheme, participating in cooperation, as well as

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Main constraints for maintenance personnel optimization problem.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constraint</td>
<td>Description</td>
</tr>
<tr>
<td>AR</td>
<td>Given the MR, the number of aircraft available (including maintained) $\geq$ AR. For theoretical analysis, a mission success rate can be set. When the rate is 1, maintenance must be successful; when the rate is lower than 1, the result is optimistic, and the result is reliable to some extent</td>
</tr>
<tr>
<td>Maintenance time required (MTR)</td>
<td>A successful maintenance must be completed before the TR (the next task)</td>
</tr>
<tr>
<td>SP_N</td>
<td>Spare parts are replaced according to types, and the SP_N is limited</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Variables for maintenance personnel optimization problem.</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>Constraint</td>
</tr>
<tr>
<td>1</td>
<td>$P_N$</td>
</tr>
<tr>
<td>2</td>
<td>MM</td>
</tr>
<tr>
<td>3</td>
<td>CM</td>
</tr>
<tr>
<td>4</td>
<td>PC</td>
</tr>
</tbody>
</table>
assessing and adjusting results. The detailed process is shown in Fig. 3.

Although the model is divided into three layers, in the actual process, the three layers are mixed, rather than separated.

### 3.2. Communication and reasoning among agents

Based on the contract net protocol (CNP)\(^{19}\) and internal reasoning mechanisms, the optimal configuration of fleet maintenance personnel can be achieved through communication and reasoning among agents. The logical decision process of agents’ communication and decision making through fleet maintenance is shown in Fig. 4.

#### 3.2.1. Configuration of maintenance strategies

In the process of maintenance strategy configuration, the management agent communicates with aircraft agents, to acquire the number of available aircraft, and determine whether mission can succeed. If not, the management agent then communicates with maintenance agents, to acquire the number of spare parts, and arrange the maintenance sequence according to the number of total faulted parts. Parts are preferred to be replaced, and the number of personnel is allowed to increase. However, if mission can succeed, parts are preferred to be repaired, and the number of personnel is not allowed to increase. Then the management agent dispatches the maintenance strategy to corresponding aircraft agents and maintenance agents.

#### 3.2.2. Configuration of maintenance resources

In the process of maintenance resource configuration, aircraft agents mainly communicate with maintenance agents. Then, they must communicate with the management agent for response. The whole process is listed below.

An aircraft agent checks the faulted parts, and gets its maintenance sequence determined by the management agent. If more than one part can be repaired concurrently, then multiple repair bids are sent at one time, or repair bids may be sent separately. When the maintenance agents get bids, an initial maintenance plan is generated by dispatching a single person of the lowest level. Then maintenance agents counterbid to aircraft agents, start maintenance activities following the order of logistic delay, locate a failure, disassemble, renew (repair), assemble and test. Assume \( TTR = T_L + T_D + T_{RN}(T_{RP}) + T_A + T_T \), and the total maintenance time \( TM = T_{LD} + TTR \). Before the maintenance actions are over, a test is required to determine whether a human error has occurred. If so, an extra test is needed to judge whether the part is declared worthless. If so, an extra spare part and some extra time are required, or just some extra time is required. Then repeat the process till a maintenance task is done.

When all the maintenance tasks are done, the maintenance agents should judge if the maintenance time is within the mis-

### Table 4 Parameters for maintenance personnel optimization problem.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML</td>
<td>MO</td>
</tr>
<tr>
<td></td>
<td>In this paper, maintenance level is limited to AVUM</td>
</tr>
<tr>
<td>MO</td>
<td>According to current maintenance system, two maintenance opportunities are selected, the PRE and the POST</td>
</tr>
<tr>
<td>FP</td>
<td>Estimated according to ( F_N ) and the reliability level, and affects the MW</td>
</tr>
<tr>
<td>( P_M )</td>
<td>According to current maintenance system, maintenance personnel is divided into different majors, and is set according to reality</td>
</tr>
<tr>
<td>( P_L )</td>
<td>According to current maintenance system, maintenance personnel is divided into different levels, and is set according to reality, affects the MT</td>
</tr>
<tr>
<td>( H_E )</td>
<td>Select the probability of human error ( p_i ) to estimate ( H_E ), affects the MT and SP</td>
</tr>
<tr>
<td>( T_{LD} )</td>
<td>Estimated according to historical data or experience, affects the MT</td>
</tr>
<tr>
<td>( T_L )</td>
<td>Estimated according to historical data or experience, is related to testability level, ( P_N ), ( P_M ) and ( P_L ), and affects the MT</td>
</tr>
<tr>
<td>( T_D )</td>
<td>Estimated according to historical data or experience, is related to maintainability level, ( P_N ), ( P_M ) and ( P_L ), and affects the MT</td>
</tr>
<tr>
<td>( T_{RN} )</td>
<td>Estimated according to historical data or experience, is related to MM, ( P_N ), ( P_M ) and ( P_L ), exclusive to ( T_{RP} ), also related to ( SP_N ), and affects the MT</td>
</tr>
<tr>
<td>( T_{RP} )</td>
<td>Estimated according to historical data or experience, is related to MM, ( P_N ), ( P_M ) and ( P_L ), exclusive to ( T_{RN} ), unrelated to ( SP_N ), and affects the MT</td>
</tr>
<tr>
<td>( T_A )</td>
<td>Estimated according to historical data or experience, is related to maintainability level, ( P_N ), ( P_M ) and ( P_L ), and affects the MT</td>
</tr>
<tr>
<td>( T_T )</td>
<td>Estimated according to historical data or experience, is related to inherent characteristics, ( P_N ), ( P_M ) and ( P_L ), and affects the MT</td>
</tr>
</tbody>
</table>

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*Fig. 3 Fleet maintenance model based on multi-agent.*
sion demands. If it is, then end maintenance and report to the management agent. If not, the maintenance agent checks if cooperation is applied for. If so, the maintenance agent reports to the management agent to add personnel; if not, the maintenance agent tries to dispatch personnel of a higher level and cooperate sequentially, starts the maintenance action and counts the time. If maintenance cannot be performed within the demanded time, the maintenance agent reports to the management agent to add personnel.

The management agent checks reports from the maintenance agent, determines if adding a worker is needed. If adding personnel is not needed, then add no one; if adding personnel is needed, then consider mission success rate. If the mission success rate is not met, then add personnel and restart simulation; or add no personnel this time. When adding maintenance personnel, the management agent adds a minimum number of personnel of all levels according to the combination CMP, reallocates maintenance strategies, and repeats the whole process, till mission requirements are met. Then the number of maintenance personnel is acquired.

4. Design of algorithms

The configuration of fleet maintenance personnel includes two parts, the configuration of maintenance strategies and the configuration of maintenance personnel. With the help of AUML, the negotiation algorithms are established based on CNP.
4.1. Maintenance strategy configuration algorithm

The maintenance strategy configuration algorithm is shown in Fig. 5.

**Step 1.** The management agent calls for bids.

When a mission is required, the management agent calls all aircraft agents for bids IB(T, AR), where T represents the time before a mission starts.

**Step 2.** Aircraft agents counter bid.

Aircraft agents check the health state $S_i$ of each part $i$, $i = 1, 2, ..., p$. Assume the reliability of part $i$ is $R_i$, and a random failure occurs following the probability $1 - R_i$. The failure state is represented as $S_i = 0$, and the healthy state is represented as $S_i = 1$. For each part $i$, if $S_i = 1$ is true, then the aircraft agent counter bids to the management agent to participate in the mission; else, report to the management agent the number of faulted parts $F_i$.

**Step 3.** The management agent assesses all counter-bids.

The management agent analyses all counter bids and decides the maintenance method according to the function Schedul-e_MM(). Assume the number of healthy aircraft is $m_1$. If $m_1 < AR$, then all healthy aircraft are put on mission, while the management agent communicates with maintenance agents to evaluate the number of spare parts $S_{PN}$ according to the function Evaluate_SP(). If $S_{PN} > 0$, then the maintenance sequence is arranged according to the total number of faulted parts. Different parts $a_i$ are renewed till the number of healthy aircraft $m_1 \geq AR$, and the number of personnel can be added. If $S_{PN} = 0$, then the maintenance sequence is arranged according to the total number of faulted parts, different parts $a_i$ are repaired till the number of healthy aircraft $m_1 \geq AR$, and the number of personnel can be added. If $m_1 \geq AR$, then $m_1$ random healthy aircraft are put on mission, the faulted aircraft are repaired following the first come first served (FCFS) rule, and the number of personnel cannot be added.

Then the management agent dispatches the mission and maintenance sequence to aircraft agents, and the maintenance method to maintenance agents.

4.2. Maintenance personnel configuration algorithm

The maintenance personnel configuration algorithm is shown in Fig. 6.

**Step 1.** Aircraft agents call for bids.

Aircraft agents follow their maintenance sequences, judge whether their faulted parts can be maintained concurrently according to the function Evaluate_CM(). If so, multiple bids $i: IB(a_i, t_{ai})$ are called to corresponding maintenance agents at the same time. If not, bids are called separately. In the above equation $a_i$ represents the name of faulted parts, and $t_{ai}$ represents the maintenance time required.

**Step 2.** Maintenance agents generate the initial maintenance scheme.

Maintenance agents analyze all bids. Assume there are $k$ similar bids. For each bid $j$, select the first available person (if more than one is available, select the person with the lowest level). Then the maintenance agents counter bids to aircraft agents: $IB(a_i, L_j, T_{LDj}, TTR_j)$, where $a_i$ represents the number of maintenance personnel for bid $j$ (starts from 1). $L_j$ represents the level, $T_{LDj}$ represents the logistic delay time, or the earliest start time, and $TTR_j$ represents the maintenance time, $TTR_j = T_{LDj}$.

**Step 3.** Maintenance action.

The aircraft agent responds to the maintenance agent, and maintenance agents start maintaining part $i$ after time $T_{LDj}$ dispatch personnel $a_i$ and lasts time $TTR_j$. When maintaining the $j$th part with the $i$th level, human error may occur at the probability $p_i$, so a test is required to determine whether the maintenance is successful. If it is successful, then the health state $S_i = 1$, while the maintenance personnel $a_i$ turns available. If it is unsuccessful, the part may be declared worthless at the probability $p_i$, which may cost $a_i$ extra maintenance time and/or $b_i$ extra spare parts. Repeat maintenance till it is successful.

**Step 4.** Maintenance agents access and adjust maintenance schemes.

When all maintenance tasks are completed, the maintenance agent counts the actual maintenance time $T_{aj}$. If $T_{aj} \leq t_{ai}$, then the current maintenance scheme can meet the mission demand and doesn’t need adjusting, and the maintenance agent reports to the management agent that maintenance action is over. If $T_{aj} > t_{ai}$, then check if cooperation is applied before. If cooperation is applied, then the maintenance agent reports to the management agent that maintenance failed, and adds personnel; if cooperation is not applied for, then check if there is personnel of a higher level available. If
there is, then select a single person of the higher level, repeat Steps 2 and 3 to generate maintenance schemes, maintenance actions, count the maintenance time and report to the management agent; if there is no higher level available, then cooperate with personnel of the same or lower level, repeat Steps 2 and 3 to generate maintenance schemes, maintenance actions, count the maintenance time and report to the management agent.

The management checks if adding personnel is allowed according to the function Evaluate_AM(). If it is not allowed or mission success rate is not met, then stop and count the number of personnel. If allowed, then add the minimum number of personnel of all levels according to the combination $C$, repeat Steps 2-4 to generate maintenance schemes, maintenance actions and add personnel, till the mission demand is met. Then count the number of personnel.

The pseudo-code indicating the process of maintenance personnel configuration is listed below:

```
Aircraft check parts
Aircraft bids
  Maintenance generates scheme
  Execute logistic delay
  Delay time $T_{LD}$
  Execute locate a failure, disassemble, renew (repair)
Assemble and test
  Maintenance time TTR
  Judge human error
  Count time $T_{\text{aj}}$
  If $T_{\text{aj}} \leq t_{\text{ai}}$
    Report “end mission”
  Else
    When $T_{\text{aj}} > t_{\text{ai}}$
      If cooperation = = true
        Report “add $P_N$”
      Else if higher level ! = null
        Select higher level
        Jump to “maintenance generates scheme”
      Else if higher level = = null
        Cooperation = true
        Jump to “maintenance generates scheme”
    End
  If Evaluate_AM() = = false or mission success rate is not met
    Add no $P_N$
  Else
    Add $P_N$ (based on combination C)
    Jump to “maintenance generates scheme”
End
```

5. Case study

5.1. Introduction

Imagine a fleet consisting of 10 aircraft. A mission lasts 3 waves. Each wave requires 8 aircraft, lasts 180 min and has 120 min of preparation time.

Each aircraft contains 4 different parts A, B, C and D. These parts are repaired by the majors below: special equipment, machinery, ordnance and avionics. The reliability of each part is 0.7, and the number of spare parts is 10 for each part. Part A and Part B are located in the same area, and A must be maintained first, while other parts can be maintained concurrently.

In each major, the maintenance personnel are divided into 2 levels. There are 3 situations: (A) for Level 1 (or the lowest level), the probability of human error is 0.05; (B) for Level 2 (or the highest level), the probability of human error is 0.01; (C) for combination, assume the proportion of personnel with 2 levels is 1:1, and the probability of human error is 0.02. The consequence of human error is: 50% of human error may lead to double maintenance time and one extra spare part, while the other 50% may lead to a half of extra maintenance time but no extra spare parts.

For illustration purposes, the total maintenance time, TTR, for each part, is given in Tables 5-8. In engineering application, the time to each activity should be divided.

Consider the 3 situations: (A) all Level 1; (B) all Level 2; (C) combination 1:1. After 10000 times of simulation, the results of the number of personnel are illustrated in Fig. 7, where the horizontal axis indicates personnel majors and levels, and the vertical axis indicates the corresponding personnel numbers (>1 people).

5.2. Comparison

In practice, the most widely applied solution to fleet maintenance personnel configuration is the empirical formula. For
maintenance personnel configuration for a short term combat mission the following model is applied:

\[ M = \sum N \beta_i d_i/n_i \]  

where \( N \) stands for the total number of aircraft, \( x \) for the mission participation ratio, \( \beta_i \) for the damage ratio of the \( i \)th damage mode, \( d_i \) for the maintenance man-hours (MMH) of the \( i \)th damage mode, \( n_i \) for the working hours of a single person.

Since the number of personnel cannot be a fraction, the final result is rounded up to an integer. Based on the 3 situations, the first 2 can be compared. As for the 3rd situation, since the empirical formula doesn’t involve personnel level, the comparison is based on the average MMH. The results are listed in Table 9.

Compared with the empirical formula, in all different situations, our agent based model can reduce personnel.

In the 1st situation, the reduction of major special equipment and major avionics is due to the adjustment of maintenance time, and the reduction of major machinery is due to the adjustment of maintenance time.

In the 2nd situation, the reduction of major machinery is due to the adjustment of maintenance time, and the reduction of major ordnance is due to the adjustment of maintenance time and the application of cooperation.

In the 3rd situation, the reduction of major machinery and ordnance are due to the adjustment of maintenance time and the application of cooperation.

5.3. Analysis

As space is limited, only the first situation is analyzed. During simulation, the variables associated with maintenance strategy are listed below:

(1) Maintenance method

As Table 10 shows, during simulation, failures occur 350662 times. In 273502 cases, parts are renewed, in all cases \( m_1 \leq AR \); in 77160 cases, parts are repaired, while in 10857 cases \( m_1 \leq AR \), and in 66303 cases \( m_1 > AR \).

Therefore, the optimal value of variable MM is: when \( m_1 \leq AR \), renew is preferred, unless \( S_{PN} \) is not sufficient; and when \( m_1 > AR \), repair is preferred.

(2) Personnel cooperation

As Tables 11–14 shows, during simulation, 90522 failures occurred to Part A, and all are repaired by 1 person. 87299 failures occurred to Part B, among which in 66015 cases Part

<table>
<thead>
<tr>
<th>Table 9</th>
<th>Comparison results of person numbers according to personnel level.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Situation</td>
<td>Model</td>
</tr>
<tr>
<td>All Level 1</td>
<td>Agent based</td>
</tr>
<tr>
<td></td>
<td>Empirical formula</td>
</tr>
<tr>
<td>All Level 2</td>
<td>Agent based</td>
</tr>
<tr>
<td></td>
<td>Empirical formula</td>
</tr>
<tr>
<td>Combination 1:1</td>
<td>Agent based</td>
</tr>
<tr>
<td></td>
<td>Empirical formula</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 10</th>
<th>Maintenance method simulation results.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy</td>
<td>Failures 350662</td>
</tr>
<tr>
<td></td>
<td>Repair</td>
</tr>
<tr>
<td>Number</td>
<td>66303</td>
</tr>
<tr>
<td>Situation</td>
<td>( m_1 \leq AR )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 11</th>
<th>PC simulation results for Part A.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part A</td>
<td>Total cases 90522</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Case</td>
<td>90522</td>
</tr>
</tbody>
</table>
B is repaired by 1 person, in 21284 cases by 2. 88413 failures occurred to Part C, among which, in all cases, Part C is repaired by 2 persons. 84428 failures occurred to Part D, among which, in 73649 cases, Part D is repaired by 1 person, in 10779 cases by 2.

Therefore, the optimal value of variable PC is: for a single part, if cooperation effect is positive, then cooperation is preferred, and as many persons are arranged as possible. However, if cooperation effect is not positive, then solo action is preferred, and as few persons are arranged as possible.

(3) Concurrent maintenance

As Table 15 shows, during simulation, in 27169 cases, Parts A and B cannot be repaired concurrently, and concurrent maintenance is not considered. When parts can be concurrently maintained, in 56647 cases, parts are repaired concurrently. In 18403 cases, parts fail to be repaired concurrently.

Therefore, the optimal value of variable CM is: if multiple parts require maintenance in a single aircraft, concurrent maintenance is preferred.

### Table 12 PC simulation results for Part B.

<table>
<thead>
<tr>
<th>Part B</th>
<th>Total cases 87299</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>66015 21284</td>
</tr>
</tbody>
</table>

### Table 13 PC simulation results for Part C.

<table>
<thead>
<tr>
<th>Part C</th>
<th>Total cases 88413</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>88413</td>
</tr>
</tbody>
</table>

### Table 14 PC simulation results for Part D.

<table>
<thead>
<tr>
<th>Part D</th>
<th>Total cases 84428</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>73649 10779</td>
</tr>
</tbody>
</table>

### Table 15 Concurrent maintenance simulation results.

<table>
<thead>
<tr>
<th>Situation</th>
<th>Parts A and B</th>
<th>Non concurrent</th>
<th>Concurrent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>27169</td>
<td>18403</td>
<td>56647</td>
</tr>
<tr>
<td>Strategy</td>
<td>Separately</td>
<td>Separately</td>
<td>Concurrent</td>
</tr>
</tbody>
</table>

6. Conclusions

To tackle the fleet maintenance personnel configuration problem, an agent-based fleet maintenance personnel configuration method is put forward. The factors affecting the process of fleet maintenance are discussed, and their relationship is analyzed. The optimal configuration of maintenance personnel can be obtained through communication and reasoning among agents. A 3-wave mission is cited to illustrate and verify this model. The main advantages of this method are:

1. The defect of traditional methods, which depend heavily on historical data, is overcome.
2. In the process of fleet maintenance personnel configuration, the interaction between human and machine, human error, personnel cooperation and concurrent maintenance, are systematically considered, which can describe the fleet maintenance process more precisely.
3. The multi-agent based method can not only yield the optimal number of personnel, but also the optimal maintenance strategy which can be inferred from the communication among agents. This is superior to traditional maintenance personnel configuration methods that can only yield the number of personnel.

In this paper, 3 categories (20 small classes) of factors are analyzed, which is close to engineering reality. A reasonable model and algorithm are proposed, in which parameters like personnel major, time to disassemble, etc., are given. Their values can be obtained from experience or statistical data, so the model has the potential to be applied to engineering.

The risk of this method comes from: (A) model accuracy; (B) data source availability; (C) data source reliability. For the risk of model accuracy, the model should be validated through existing data. For the risk of data source availability, the data source for parameters should be investigated and confirmed. If certain data is not available, then transfer or adjust the parameters. For the risk of data source reliability, highly reliable data (for instance, military field data) should be selected. If possible, select more than one data source and compare.

The multi-agent based model can provide theoretical support for maintenance personnel configuration. Based on strict tests and pilot experiments, the model can then be applied to improve existing maintenance systems and regulations. Meanwhile, responsibility should be implemented, and supervision should be strengthened.

This model is the supplement of multi-agent modeling applied to maintenance modeling and optimization. With appropriate modification, this model can be used to evaluate the maintenance system itself or optimize other factors in the maintenance system.
References


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