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To cite this article: Qiaoran Ran et al 2018 IOP Conf. Ser.: Earth Environ. Sci. 170 032021

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Maintenance man-hours calculation model based on the age replacement

Qiaoran Ran¹⁺*, Qiang Wang¹ and Zheng Sun¹
Army Engineering University, Shijiazhuang, China

*Corresponding author e-mail: 454738599@qq.com

Abstract. Scientifically formulating the number of maintenance personnel plays an important role in optimizing the configuration of maintenance personnel, using maintenance resources efficiently, and improving maintenance efficiency. According to the calculation process of maintenance personnel needs, the reliability centered maintenance theory and method are applied to establish the man-hour calculation model based on age replacement, and the practicability of the model is verified by a case study.

Keywords: Maintenance man-hours; Preventive maintenance; Age replacement.

1. Introduction
In the last few decades, personnel scheduling problems have been studied widely. The increase in research attention could be motivated by economic considerations [1].

With the Informationization, systematization and complexity of the current weaponry and equipment, the Army focuses on building an elite combat force of strong alliance, strengthens the field operations, modularization and information construction and strives to create a marine force system that is commensurate with the requirements of global operations. The corresponding integration of combat forces, the complexity of the equipment system, the maintenance of the difficulty of building power increases, the equipment maintenance and protection have higher requirements, maintenance personnel as the mainstay of equipment support, the key factor of maintenance and resource protection, having a significant impact on the maintenance effectiveness. A scientific maintenance personnel decision-making is needed to make the maintenance efficiency better, so as to achieve accurate guarantee and efficient maintenance.

In terms of personnel prediction. The literature on personnel scheduling exhibits a wide range of research methodologies that combine a certain type of analysis with some solution or evaluation technique. A large number of papers are classified into mathematical programming categories such as integer programming, linear programming [2][3][4], dynamic programming [5][6][7] and goal programming [8][9] [10] or as constructive [11] [12] [13] or improvement heuristics [14] [15] [16].

For ordinary personnel prediction and arrangement methods, there are two points in the analysis of the number of maintenance personnel: the type of work to determine the type of personnel; workload size to determine the number of personnel. To determine the number of personnel, first is the analysis of equipment maintenance work, then to determine all possible equipment failure modes and the need for the implementation of all maintenance tasks based on maintenance work analysis techniques;
According to the failure rate to predict the number of tasks required for each maintenance task, on this basis, calculating the number of personnel. Therefore, the man-hour calculation method is very important.

Nowadays, grassroots are using replacement maintenance methods. Under this condition, aiming at the problems and shortcomings of the traditional maintenance man-hour calculation, this paper takes the example of the repair strategy of age replacement, and studies the establishment of a preventive maintenance man-hour calculation model based on the change of working-age and explores the model solving algorithm to provide an effective method to accurately calculate maintenance man-hours and improve resource utilization.

2. Calculation model of maintenance man-hours for age replacement

2.1. Process analysis of maintenance man-hours
The age replacement [7] refers to the regular replacement of the time using time (working age) of the equipment unit. The modeling requirement is: how to use mathematical models to determine the replacement interval, so that the replacement work can achieve the specified goals, and the target (maintenance resources, economy and so on) is constrained to solve and optimize the interval. In the same way, the maintenance resources can be better optimized when the basic maintenance parameters of the equipment are known (working age and so on).

According to the concept of the age replacement, a unit in the equipment, even if no fault occurs during the operation, will be replaced by the required replacement age T. If a failure occurs when the T is not reached, then the fault is replaced. In this process, no matter how to prevent and replace or replace the failure, we need to record the working time of the unit again, which is equivalent to clearing the timer. The next period of prevention and replacement should be calculated from this update time [18].

According to the concept of the age replacement, the basic process of maintenance working hours can be obtained under the strategy of the age replacement. The maintenance work is mainly produced by replacement parts.

2.2. Assumptions and parameters
The specified parameters and assumptions are as follows:

- T: the age of replacement for each length of service to be replaced. If there is a fault during service, the fault is replaced and the time T is constant;
- S: Maintenance time calculation cycle, the unit is the same as time T;
- t: the usage time of the equipment component unit;
- EN(S, T): the number of working hours in the cycle S when the replacement age is T;
- Tp, Tf : respectively, the average prevent replacement time, the average fault replacement time.

Under normal circumstances, the age replacement T is far greater than the replacement time, and due to fault replacement need fault isolation and positioning, so Tf is often greater than Tp, so T > Tf > Tp;

- R(t), F(t), f(t), λ(t): are respectively the reliability function, the cumulative fault distribution function, the fault density function and the failure rate function, all of which are functions of t;

Assuming the unit is initially in a working condition, the failure rate is an increasing function, which shows a trend of degeneration with the time of use.

It is assumed that the preventive maintenance of unit is the age replacement, and it is a non-repairable unit. The repair method is replaced, restored to the new product after repair, and the situation of repair and reuse is not considered.

2.3. The establishment of the model
According to the actual conditions of equipment maintenance, according to the length of the cycle S, the production workload is analyzed as follows:
(1) When $0 \leq S \leq T_f$, when the unit fails, if the replacement is carried out, the replacement work has not been completed or has just been completed, which has reached the time limit of $S$. So, in this case, even if the unit has a failure, it does not need to be replaced, that is, the number of hours is equal to 0.

(2) When $T_f < S \leq T_0 + T_f$, when the unit reaches the preventive replacement cycle $T_0$, if it is prevented and replaced, it has reached the $S$ of service life before it has been replaced. Therefore, there is no need for preventive replacement in such a case. If the unit fails at a very close time to $S$, it will arrive at $S$ when it is not changed. The unit will fail to replace it only if it fails before $S - T_f$. Therefore, in this case, the work time calculation should only consider the replacement of the fault, and there is no prevention and replacement.

When $S > T_0 + T_f$, when the unit reaches the replacement age of $T_0$, it needs to be prevented and replaced, resulting in the prevention and replacement of work hours. When the unit fails at $S - T_f$ time, it will replace the fault and produce a fault replacement task time. Therefore, this situation has both failure and replacement, as well as prevention and replacement.

According to the above analysis, according to the length of the cycle $S$, the following three cases will be described below. The calculation model of non-repairable time under one-dimension preventive maintenance strategy is established respectively.

1. The first case ($0 \leq S \leq T_f$)

This case belongs to the first problem, through the above analysis, $0 \leq S \leq T_f$, the number of hours is 0, i.e.

$$EN(S, T_0) = 0$$ (1)

2. The second case ($T_f < S \leq T_0 + T_f$)

From the above second situations, we can see that there is no mathematical expectation that the number of working hours is equal to the time of failure to replace spare parts, that is, the number of failures in the time of unit $[0, S]$, which is the update process corresponding to the fault distribution function $F(T)$. Therefore, according to the update process, the expression of the calculation of the number of hours in this case is:

$$EN(S, T_0) = \int_0^{S-T_f} \left[ 1 + \frac{EN(S - t - T_f, T_0)}{T_f} \right] \cdot dF(t) \cdot T_f$$

$$EN(S, T_0) = \int_0^{S-T_f} \left[ 1 + \frac{EN(S - t - T_f, T_0)}{T_f} \right] \cdot f(t) dt \cdot T_f$$ (2)

3. The third case ($S > T_0 + T_f$)

From the third case, it can be seen that this kind of situation has not only the failure replacement but also the prevention and replacement. It is assumed that the time of the first failure of the unit is $t$, and it needs to be considered in two cases.

When $t < T_0$: At this time, there was no time to prevent change, the unit failed, so it should be replaced by failure, resulting in the task time to replace the failure, and the replacement time is $T_f$

$$EN(S, T_0) = T_f + EN(S - t - T_f, T_0)$$ (3)
When \( t > T_0 \): When the failure occurs at this time, after the prevention replacement of the cycle \( T_0 \), therefore, the prevention and replacement should be carried out first, resulting in a prevention replacement work time, and the replacement time is \( T_p \).

\[
EN(S, T_0) = T_p + EN(S - t_0 - T_p, T_0)
\]  

(4)

The probability of a fault in the known unit \([0, T_0]\) is equal to its unreliability at the time of \( T_0 \). In contrast, the probability of reliable work in the unit in \([0, T_0]\) is equal to its reliability at \( T_0 \) time. Therefore, the calculation formula for the number of hours in the case of \( S > T_0 + T_f \) is as follows:

\[
EN(S, T_0) = \int_0^{T_f} \left[ 1 + \frac{EN(S - t - T_f, T_0)}{T_f} \right] \cdot f(t) dt \cdot T_f + [T_p + EN(S - T_0 - T_p, T_0)] \cdot R(T_0)
\]  

(5)

The formula, the expression of the requirement for the spare parts of the whole period \( S \), that is,

\[
EN(S, T_0) = \begin{cases} 
0 & \text{if } 0 \leq t \leq T_f \\
\int_0^{T_f} \left[ 1 + \frac{EN(S - t - T_f, T_0)}{T_f} \right] \cdot f(t) dt \cdot T_f & \text{if } T_f < t \leq T_0 + T_f \\
\int_0^{T_f} \left[ 1 + \frac{EN(S - t - T_f, T_0)}{T_f} \right] \cdot f(t) dt \cdot T_f + [T_p + EN(S - T_0 - T_p, T_0)] \cdot R(T_0) & \text{if } t > T_0 + T_f
\end{cases}
\]  

(6)

2.4. Model solving steps

It is obvious that the expression (1) - (5) of the work time calculation has a recursive relation, and it is difficult to calculate and solve it by the general solution algorithm. With the idea of numerical solution, a model approximation algorithm based on discrete method is proposed, and the specific solving process is as follows:

Step 1: set the discrete step length of the time \( t \). To this end, the step size of the time \( t \) can be set up according to the requirement of the calculation precision. In order to facilitate the calculation, the discrete step size of \( T \) is set to 1. Then, the length of the cycle is calculated on the basis of the number of hours \( S \), and the \( T \) is taken from 1 to \( S \) according to the step length of 1.

Step two: make a judgment. Make the judgment for a given \( t \) one by one, if \( 0 \leq t \leq T_f \), go to the third calculation step; \( T_f < t \leq T_0 + T_f \), go to the fourth calculation step; if \( t > T_0 + T_f \), go to the fifth step to calculate.

Step three: Calculate the work hours in the case of \( 0 \leq t \leq T_f \). When \( t \) satisfies the condition \( 0 \leq t \leq T_f \), by the formula (6) shows that \( EN(t, T_0)=0 \), namely \( EN(1, T_0), EN(2, T_0), \ldots, EN(T_f, T_0) \), all the value of them is 0.

Step four: Calculate the work hours in the case of \( T_f < t \leq T_0 + T_f \). First, the number of hours at \( t = T_f + 1 \) time should be calculated.

\[
EN(T_f + 1, T_0) = EN(T_f, T_0) + \int_0^{T_f} \left[ 1 + \frac{EN(1-t, T_0)}{T_f} \right] \cdot f(t) dt \cdot T_f
\]
Thus recursion, when \( t = T_f + 2 \):

\[
EN(T_f + 2, T_0) = EN(T_f + 1, T_0) + \int_0^{T_f} \left[ 1 + \frac{EN(2-t, T_0)}{T_f} \right] f(t) dt \cdot T_f
\]

Thus, a recursive formula for computing any time within \( tx \) hours in the case of \( T_f < t \leq T_0 + T_f \) is:

\[
EN(t, T_0) = EN(t - 1, T_0) + \int_0^{T_f} \left[ 1 + \frac{EN(t - T_f, T_0)}{T_f} \right] f(t) dt \cdot T_f
\]

According to the above, it has been calculated to the \( t = T_0 + T_f \) moment. The working hours in \( T_0 + T_f \) time can be obtained:

\[
EN(T_0 + T_f, T_0) = EN(T_0 + T_f - 1, T_0) + \int_0^{T_f} \left[ 1 + \frac{EN(T_0 - t, T_0)}{T_f} \right] f(t) dt \cdot T_f
\]

Step five: calculate the working hours in the case of \( t > T_0 + T_f \). As in the case of step four, the number of hours at the time of \( t = T_0 + T_f + 1 \) should be calculated first.

\[
EN(T_0 + T_f + 1, T_0) = EN(T_0 + T_f - 1, T_0) + \int_0^{T_f} \left[ 1 + \frac{EN(T_0 + 1 - T_f, T_0)}{T_f} \right] f(t) dt \cdot T_f
\]

When \( t = T_0 + T_f + 2 \):

\[
EN(T_0 + T_f + 2, T_0) = EN(T_0 + T_f + 1, T_0) + \int_0^{T_f} \left[ 1 + \frac{EN(T_0 + 2 - T_f, T_0)}{T_f} \right] f(t) dt \cdot T_f
\]

In the same way, in the case of \( t > T_0 + T_0 \), the recursive formula for the time calculation within \( tx \) at any time is as follows:

\[
EN(t, T_0) = EN(t - 1, T_0) + \int_0^{T_f} \left[ 1 + \frac{EN(t - T_f, T_0)}{T_f} \right] f(t) dt \cdot T_f
\]

According to the previous calculation to \( t = S \), the expected value \( EN(S, T_0) \) of the working hours in the period \( S \) of the replacement time interval \( T_0 \) can be calculated.

### 3. Example analysis

In order to verify the model established in this paper and its solution algorithm, it is assumed that the replacement repair method is adopted in the maintenance of the equipment, 10 units are selected as replacement units from the composition structure of the equipment. The lifetime of each unit is subject to Weibull distribution. All of them are not repairable. They all adopt the strategy of age replacement. Their reliability distribution and maintenance time parameters are shown in Table 1. It is known that the service life of the equipment is 12 years, the first 4 years are expected to run 1000h every year, the average 6 years in the middle run 1600h, and the last 2 years run 800h annually. According to the reliability distribution of spare parts and maintenance time data in Table 1, the maintenance work time of the whole life cycle of a single equipment is calculated at the early stage of the equipment life.
### Table 1. The parameters for components reliability function and maintenance time

| Serial number | Weibull parameter | Price | $T_0$ (h) | $T_p$ (d) | $T_f$ (d) |
|---------------|-------------------|-------|-----------|-----------|-----------|
|               | $\alpha$ | $\beta$ (h) |           |           |           |
| S01           | 2.6     | 190   | 200       | 80        | 1         | 2         |
| S02           | 1.8     | 545   | 400       | 200       | 2         | 5         |
| S03           | 3.0     | 280   | 220       | 120       | 1         | 4         |
| S04           | 2.8     | 340   | 320       | 140       | 2         | 3         |
| S05           | 3.2     | 260   | 200       | 120       | 1         | 4         |
| S06           | 4.8     | 452   | 300       | 160       | 2         | 4         |
| S07           | 2.4     | 1108  | 550       | 350       | 2         | 5         |
| S08           | 1.8     | 665   | 350       | 280       | 2         | 5         |
| S09           | 4.1     | 220   | 200       | 80        | 1         | 3         |
| S10           | 3.5     | 175   | 150       | 80        | 1         | 2         |

In this paper, the model and the traditional model established in this paper are used to calculate the life cycle maintenance hours of the equipment, and the comparison and analysis are carried out.

3.1. Using this model to calculate

(1) Parameter transformation

Because the reliability distribution function and replacement interval of all units in the equipment are working hours, and the replacement time is calendar time, and the annual running time of the equipment is known. In order to simplify the calculation, the work time is first converted to calendar time. Suppose the usage rate of the equipment is $r$, the $u$ represents the working time (the unit is working hour), and the $t$ represents the calendar time (the unit is the day). Suppose that the working time $u$ and the calendar time $t$ are linear, that is, $t=u/r$. Assuming 365 days per year, there are: $t=365 \times u/1000$ (d) in 1~4, $t=365 \times u/1600$ (d) in 5~10, $t=365 \times u/800$ (d) in 11~12. Therefore, the working hours in Table 1 can be converted to a calendar time, as shown in Table 2.
Table.2. The results of parameters transformation

| Serial number | 1~4 years | 5~10 years | 11~12 years |
|---------------|-----------|------------|-------------|
|               | $\beta$ (d) | $T_0$ (d) | $\beta$ (d) | $T_0$ (d) | $\beta$ (d) | $T_0$ (d) |
| S01           | 69        | 29         | 43          | 18        | 87          | 37         |
| S02           | 199       | 73         | 124         | 46        | 249         | 91         |
| S03           | 102       | 44         | 64          | 27        | 128         | 55         |
| S04           | 124       | 51         | 78          | 32        | 155         | 64         |
| S05           | 95        | 44         | 59          | 27        | 119         | 55         |
| S06           | 165       | 58         | 103         | 37        | 206         | 73         |
| S07           | 404       | 128        | 253         | 80        | 506         | 160        |
| S08           | 243       | 102        | 152         | 64        | 303         | 128        |
| S09           | 80        | 29         | 50          | 18        | 100         | 37         |
| S10           | 64        | 29         | 40          | 18        | 80          | 37         |

(2) calculate in stages
According to the model established in this paper and its solving algorithm, the program is written in MATLAB. The above parameters are replaced in the program, and the number of hours can be calculated at each stage, as shown in Table 3.

Table.3. The results of calculating working hours based on the proposed model

| Serial number | 1~4 years’ | 5~10 years’ | 11~12 years’ | total |
|---------------|------------|-------------|--------------|-------|
| S01           | 61         | 199         | 22           | 282   |
| S02           | 50         | 125         | 19           | 194   |
| S03           | 42         | 113         | 16           | 171   |
| S04           | 59         | 152         | 23           | 234   |
| S05           | 43         | 118         | 16           | 177   |
| S06           | 48         | 114         | 18           | 180   |
| S07           | 24         | 59          | 9            | 92    |
| S08           | 38         | 94          | 14           | 146   |
| S09           | 51         | 132         | 20           | 203   |
| S10           | 57         | 175         | 21           | 253   |

3.2. Calculation by traditional model
If there is preventive maintenance work, the traditional man hour calculation method is to calculate the hours of repair and preventive maintenance separately, and then calculate it simply.

$$EN(S,T_0) = N_c + N_p$$

In the upper form: $N_c$ is the number of hours produced for repair maintenance. $N_p$ is the number of hours produced for preventive maintenance.

The life span of the spare parts is known to be Weibull distribution, as well as the prevention and replacement interval of the spare parts, so the following can be obtained:
\[ EN(S,T_o) = \sum_{t=0}^{\infty} \lambda(t) \cdot T_o \cdot M_o + \frac{S}{T_o} \cdot M_pe \]

In this formula: \( M_o \) and \( M_pe \) respectively indicate the working hour of the single repairmen and preventive maintenance of the components. The result of the maintenance of the equipment according to the formula is shown in Table 4.

**Table 4.** The results of calculating working hours based on the traditional model

| Serial number | 1~4 years’ | 5~10 years’ | 11~12 years’ | total |
|---------------|------------|-------------|--------------|-------|
| S01           | 80         | 265         | 29           | 374   |
| S02           | 63         | 168         | 24           | 255   |
| S03           | 55         | 151         | 22           | 228   |
| S04           | 78         | 206         | 30           | 314   |
| S05           | 56         | 160         | 22           | 238   |
| S06           | 62         | 150         | 24           | 236   |
| S07           | 32         | 78          | 12           | 122   |
| S08           | 51         | 120         | 18           | 189   |
| S09           | 68         | 172         | 26           | 266   |
| S10           | 76         | 236         | 28           | 340   |

### 3.3. Analysis of calculation results

Through the analysis of the above examples, we can further compare the calculation results of the working hours, as shown in the picture; It can be seen that the error of the traditional model calculated in this paper is 35.72% compared with the results considering the effect of preventive maintenance. It is fully demonstrated that the influence of preventive maintenance must be fully considered in the calculation of working hours. There is much error in the traditional model. The calculation model of man hour in preventive maintenance strategy proposed in this paper can significantly improve the accuracy of its calculation.

**Figure 1.** Comparative analysis
4. Conclusion
The calculation of working hours is the basic work of maintenance personnel forecast in maintenance support. Taking the maintenance strategy of age replacement as an example, this paper establishes a maintenance time calculation model considering preventive maintenance, and the algorithm of the model is discussed by discrete method. The modeling process and the solving method of the model are described in detail. Finally, using the model established in this paper, the model is applied and verified with a specific example, and the model is compared with the traditional model. The research results show that the proposed man hour calculation model proposed in this paper can significantly improve the accuracy of calculation and improve the utilization rate of maintenance resources compared with the traditional model and lay a solid foundation for the rationality of staffing. However, the model established in this paper only considers the age replacement strategy of maintenance and needs to consider more maintenance strategies and man hour modeling under maintenance work combination.

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