Research on Quantitative Analysis Method of Combined Maintenance Task

Na Yu* and Tao Zhang
Su Zhou Nuclear Power Research Institute, Shenzhen 518000, China

*Corresponding author email: yuna0802@163.com

Abstract. In this paper, the delay time theory is used to establish the mathematical model of the combination of monitoring and periodic replacement tasks, and the impact of maintenance period of monitoring and periodic replacement is discussed. Through the optimization solution, the optimal cycle of combined maintenance tasks is obtained to minimize the maintenance cost while ensuring the reliability. Finally, an example is given to demonstrate the feasibility of this method.

Keywords: Quantitative analysis; Combination of Maintenance; Mathematical model.

1. Introduction
RCM is the most widely used maintenance program for nuclear power plants. Reliability centered maintenance [1] is a system engineering method commonly used internationally to determine equipment maintenance requirements and formulate and optimize maintenance strategies. It originated from the field of aviation in the United States and has been successively applied to military equipment, electric power (including nuclear power), railway (including subway), petroleum and petrochemical, processing and manufacturing, shipping and other industries. John moubray, the founder of Aladon company, which is engaged in the promotion and application of RCM in the United Kingdom, published a monograph RCM II [2]. Although RCM is widely used and can improve the reliability of equipment, it tends to qualitative analysis and lacks of quantitative analysis process.

From 2002 to 2014, although the U.S. nuclear power industry continued to achieve continuous improvement in safety and reliability, the average power generation cost (including nuclear fuel, capital and operation and maintenance) of the U.S. nuclear power industry increased by 28%. Therefore, since 2016, the American industry has launched the DNP industry plan - delivering the nuclear promise: promoting safety, reliability and economic performance, with the goal of reducing costs by 30% in 2020. The action was initiated by the American Nuclear Energy Association (NEI the agency responsible for communication on behalf of the general nuclear safety issues and Safety Bureau of nuclear power companies), coordinated by INPO, and EPRI (American Electric Power Research Institute) was responsible for the technical part. According to the DNP plan, the NEI industry working group issued a series of efficiency bulletins. In the DNP action plan, eb17-03a [3] is VBM (value based maintenance) - value oriented maintenance, which is mainly to solve the current problem of ensuring equipment reliability regardless of cost.

At present, the optimization technology of maintenance program mainly includes system fault modeling (using Monte Carlo simulation) and delay time maintenance model [4] [5]. System fault modeling mainly investigates equipment fault mode through fault distribution and resource availability to determine the optimal strategy, while delay time theory determines the optimal monitoring cycle of equipment by considering fault consequences.
Maintenance task combination refers to a maintenance method that implements two or more types of preventive maintenance. It has practical application value and is widely used in maintenance practice. For example, in order to reduce "temporary repair" and eliminate "machine failure", the maintenance of railway diesel locomotive gearbox often adopts the method of several minor repairs within an overhaul cycle: minor repairs mainly focus on condition monitoring, and measures are taken according to the performance status of the equipment; Overhaul is generally to renovate or replace to completely restore it to the new state.

Although, by definition, the combination of maintenance tasks can be the comprehensive implementation of any different tasks, However, in the process of maintenance work, two typical PM tasks, condition monitoring and periodic replacement, are usually combined. The advantage of condition monitoring is to find hidden trouble in time and avoid serious fault consequences through regular or irregular equipment condition evaluation or identification. The advantage of regular replacement is to update before reaching the fault wear period to restore the original fault resistance. It is not difficult to see that by combining these two typical PM tasks, the advantages of the two can be effectively integrated.

Aiming at the implementation of maintenance task combination, this paper adopts the delayed time maintenance model to explore the equipment maintenance process and characteristics under the maintenance strategy, and establishes the task cycle mathematical model according to different decision objectives, so as to provide a reference basis for analyzing and comparing the applicability and necessity of task combination strategy. On this basis, typical equipment is selected to verify the above decision-making model.

2. Research Questions

In the DNP action plan of American nuclear power plants, eb17-03a [1] is VBM (value based maintenance) - value oriented maintenance, which is mainly to solve the current problem of relatively blind ensuring equipment reliability regardless of cost. This problem is also severe in domestic nuclear power plants. In addition to reducing unnecessary maintenance of economic equipment, the maintenance cost of important equipment is often higher. So how to solve this problem is a research topic.

In the power plant, there are usually maintenance tasks of both regular maintenance or regular replacement and condition monitoring. The two maintenance tasks have their own advantages. After the implementation of maintenance task combination, whether the required maintenance cost has been reduced and whether the invested preventive maintenance cost has obtained greater benefits need to be scientifically and accurately calculated, and the maintenance process needs to be described and quantitatively calculated through mathematical model. From the perspective of economy, this paper establishes a mathematical model of unit time maintenance cost after combining condition monitoring and periodic replacement.

At present, the maintenance strategy for the dynamic and static rings of a typical steam pump in a nuclear power plant includes 1Month’s condition monitoring task and 36Month’s periodic replacement task.

3. Research Model

The main work of this paper is to demonstrate the impact of the two task combinations on the economy by establishing the economic model of condition monitoring and periodic replacement task combination, so as to find out the optimal combination of task cycle.

3.1. Model Basis

The specific implementation process of the combination of condition monitoring and periodic replacement task is as follows: condition monitoring is conducted after a certain time: if the product is found to be in a potential fault state during monitoring, preventive replacement is carried out; If there is no potential fault and the condition is good, no measures shall be taken to continue to use. In case of functional failure between two monitoring, it will immediately stop for repair. When the (k-1) condition monitoring is completed and the k-th condition monitoring is reached, a preventive replacement shall be carried out for the product regardless of its state (as shown in Figure 1).
Figure 1. Task combination of condition monitoring and periodic replacement.

- $T_n$ is the monitoring interval of the combined task and $T_r$ is the replacement interval;
- $U$: the service time in case of potential product failure, also known as initial time, whose density function and distribution function are $g(U)$ and $G(U)$ respectively;
- $H$: the service time from product potential fault to functional fault, also known as delay time, whose density function and distribution function are $f(H)$ and $F(H)$ respectively;
- $C_r$: cost of regular product replacement;
- $C_n$: cost of product condition monitoring;
- $CP$: cost of preventive maintenance for potential faults detected by product monitoring;
- $C_f$: the cost of repairing the product after functional failure;
- $T_{pr}$: the time required for regular product replacement.

According to the P-F interval of condition monitoring, the formation of equipment failure is divided into two stages, and it is assumed that the two stages are independent of each other: the first stage is the time process from putting the equipment into use to potential failure; The second stage is the time process from potential failure to functional failure (as shown in Figure 2 below).

3.2. Model Establishment

Assuming the initial defect time $u$ (i.e. potential fault point) and the fault delay time $h$ (immediately engraved $u+h$ product fault point), if it is monitored at time $u$, the defect can be found and updated; If the defect is not found, then after the delay time $h$, the defect will lead to failure, and the equipment will be updated. Figures 3 and 4 describe the process of product condition monitoring with $T$ as the interval, and $T_i$ represents the $i$-th monitoring point ($i = 1, 2, 3, ...$).

Assuming that a potential fault occurs at time $u$, its density function and distribution function are represented by $g(u)$ and $G(u)$ respectively, and the delay time $h$, its density function and distribution function are represented by $f(h)$ and $F(h)$ respectively, the probability of fault update before the monitoring time $t_i$ is $g(u) \cdot du \cdot F(t_i - u)$, and the probability of monitoring update during monitoring is $g(u) \cdot du \cdot [1 - F(t_i - u)]$.

By integrating $u$ on, $(t_{i-1}, t_i)$, we can get the probability of failure update (or failure risk) , It can be expressed as $P_f(t_{i-1}, t_i)$:

$$P_f(t_{i-1}, t_i) = \int_{t_{i-1}}^{t_i} g(u)F(t_i - u)du$$

The probability of monitoring update at any time is:
In order to obtain the best replacement cycle and minimize the average cost per unit time, the expected cost per unit time of the product can be expressed as

\[ C(T_n, T_r) = \frac{CP(T_n, T_r) + C_r}{T + T_{pr}} \quad (1) \]

Notice that \( CP(T_n, T_r) \) is the expected value of all costs except replacement costs at the end of the replacement cycle that combination of maintenance task is carried out when \( T_n \) is the detection period in the replacement period \( T_r \).

For the convenience of modeling and expression, the number of detection cycles included in each replacement cycle in the maintenance task combination is set as \( K - 1 \) (\( K = \left\lceil \frac{T_r}{T_n} \right\rceil \), \( \lceil \cdot \rceil \) represents the upper limit value after rounding). The solving process is as follows:

During each periodic replacement period \( T_r \), the condition monitoring strategy is adopted by the product and the maintenance cost \( CP(T_n, T_r) \) must consist of the following three incompatible situations:

**Case 1:** During the entire replacement cycle \( T_r \), the product has neither functional failure nor preventive replacement due to potential failure found during monitoring, that is, no update event occurs, and the maintenance cost is \( (k-1)C_n \). There are two possibilities for this event to occur:

A: No potential fault occurs before the replacement cycle \( T_r \), that is, \( U \geq T_r \);

B: Between the last monitoring and regular replacement \( ((k-1)T_n, T_r) \), there is no functional failure occurred before regular replacement. That is \( (K -1)T_n < U < K T_n \cap U+ H > K T_n \).

The probability of occurrence of case 1 is

\[ P_n(T_r) = 1 - \int_0^{T_r} g(u)du + \int_{(K-1)T_n}^{T_r} g(u)[1 - F(T_r - u)]du \quad (2) \]

**Case 2:** Update is carried out, and the first update is a preventive update when the potential fault is found during the first. In this case, the maintenance cost is: \( iC_n + Cp + CP(T_n, T_r - i \cdot T_n) \)

During the monitoring, the product defect appears at \( (u, u+du) \) \( ((i-1)T_n < u < iT_n) \), and the defect is found at the first monitoring including the following two conditions:

There was no defect before the \( (i-1)T_n \) and the defect was found in the \( i \)-th monitoring;

The product defect delay time must be greater than \( iT_n - u \)

The probability density of the event is \( g(u)du[1 - F(iT_n - u)] \), then we can get that:

\[ P_m(iT_n) = \int_{(i-1)T_n}^{iT_n} g(u)[1 - F(iT_n - u)]du \quad (3) \]

**Case 3:** Update and the update is due to the fault update of the product at moment \( X \) \( ((j-1)T_n < x < jT_n) \). At this time, the maintenance cost is: \( (J-1)C_n + C_f + CP(T_n, T_r - x) \)

The defect occurs in \( (u, u+du) \) and the fault occurs in \( (x, x+dx) \), when the delay time will satisfy \( x-u<h<x+dx-u \). \( (j-1)T_n < u < x \). The probability density of this event is:
\[
p_b(x) = \int_{(j-1)T_u}^{x} g(u) f(x-u) du
\]  
\hspace{1cm} (4)

Combining the above three situations, can be obtained
\[
CP\{T_n, T_r\} \cdot C = (K - 1)n + \sum_{j=1}^{K} [l \cdot C_p + CP\{T_n, T_r - l \cdot T_n\} \cdot P_m (l \cdot T_n)]
\]
\[+ \sum_{j=1}^{K} \int_{(j-1)T_u}^{T_u} [(j-1)C_n + C_f + CP\{T_n, T_r - x\}] \cdot p_b(x) dx
\]  
\hspace{1cm} (5)

The expected maintenance cost per unit time of maintenance task combination is obtained by Substitute Equation (5) into Equation (1). Then, by optimizing the monitoring cycle or replacement cycle, the maintenance cost and the optimal solution of the corresponding maintenance cycle are calculated.

4. Demonstrated the Implementation

We collect and summarize the relevant maintenance data of the dynamic and static ring of the mechanical seal of a steam driven feed pump (hereinafter referred to as the dynamic and static ring of the mechanical seal on the high pressure side). Firstly, the monitoring update, fault update and other data of the dynamic and static ring of the turbine seal are extracted from the maintenance data of the turbine driven feed pump, and the relevant information is filled into the standardized table, as shown in Table 1. From the table, it can be concluded that the dynamic and static ring of the turbine seal on the high pressure side has been monitored and updated for 9 times, 3 times for fault update.

The following specific information can be obtained from the table (time unit is month):

- Three fault updates were carried out at time \(T_j = (6, 15.5, 33)\) respectively, and the latest monitoring time before update was \((0, 13, 21)\) respectively;
- A total of 9 times monitoring updates were carried out at time \(TK = (41, 2.5, 2, 21.5, 2.5, 20, 16.5, 9.5, 25)\), and the latest monitoring time before the update was \((23, 0, 0, 11.5, 0, 9, 11.5, 8.5, 2)\);
- At the end of monitoring 3, the product is still working normally.

If it is temporarily difficult to determine the functional form of the initial time and delay time, the Weibull distribution is used for parameter estimation, and then the distribution form is judged by the shape parameters in the estimation results.

The maximum likelihood function of the above information can be obtained
\[
LogL = \sum_{j=1}^{3} Log[p_j(t_j)] + \sum_{k=1}^{9} Log[P(t_k)] + Log[P(3)]
\]

By maximizing it, the parameter values are \(\alpha_1 = 1, \beta_1 = 14, \alpha_2 = 1.5, \beta_2 = 6\). Here, the results show that the initial time of the dynamic and static ring defect of the mechanical seal follows the exponential distribution with an average of 14 months, and the delay time follows the Weibull distribution with a shape parameter of 1.5 and a scale parameter of 6 months.

Through data collection, the maintenance of the dynamic and static rings of the mechanical seal, as well as the time and cost information are obtained as follows:
- Under normal circumstances, the time required for condition monitoring is 0.5 days and the cost is 1000 yuan; the time required for regular replacement is 2 days and the corresponding maintenance cost is 10000 yuan.
- If defects are found through condition monitoring during operation, it can be recovered as new, with a time of 1 day and a cost of 8000 yuan; if an unexpected fault occurs, repairing is immediately conducted with a time of 5 days and a cost of 50000 yuan.
After processing and analyzing the relevant data and obtaining its reliability function, the previous model can be used for quantitative decision-making. The maintenance cost model under the task combination strategy has been established as

$$\begin{align*}
C(T_n, T_r) &= \frac{C_P(T_n, T_r) + C_r}{T_r + T_{pr}}
\end{align*}$$

Table 1. Data of the sealing ring on the high pressure side of a steam driven feed pump.

| Fault data | data type | potential faults times | Fault times | Start time | defect | fault | Time of occurrence | Duration / month | Monitoring time / month |
|------------|-----------|------------------------|-------------|------------|--------|-------|-------------------|-------------------|------------------------|
|            |           | 9                      | 3           |            |        |       |                   |                   |                        |
|            | Start time|                       |             | 2004.04.21 | √       |       | 2007.09.26        | 41                | 2.5;8.5;23              |
|            | 2007.10.01|                       |             | √          | 2008.03.26| 6      |                   |                   | 0                      |
|            | 2008.04.16|                       |             | √          | 2008.06.30| 2.5    |                   |                   | 0                      |
|            | 2008.07.04|                       |             | √          | 2008.09.06| 2      |                   |                   | 0                      |
|            | 2008.09.20|                       |             | √          | 2010.07.05| 21.5   |                   |                   | 6;8.5;9.5;11.5          |
|            | 2008.07.25|                       |             | √          | 2010.10.17| 2.5    |                   |                   | 0                      |
|            | 2010.11.09|                       |             | √          | 2012.06.22| 20     |                   |                   | 9                      |
|            | 2012.06.24|                       |             | √          | 2013.10.08| 16.5   |                   |                   | 11.5                   |
|            | 2013.10.12|                       |             | √          | 2015.01.21| 15.5   |                   |                   | 13                     |
|            | 2015.02.07|                       |             | √          | 2017.10.12| 33     |                   |                   | 9;21                   |
|            | 2017.10.16|                       |             | √          | 2018.08.01| 9.5    |                   |                   | 8.5                    |
|            | 2018.08.15|                       |             | √          | 2020.09.12| 25     |                   |                   | 2                      |
|            | 2020.09.20|                       |             | ending     | 2020.12.14| 3      |                   |                   | 2                      |

The established model was used to optimize the replacement cycle, and the calculation results were obtained as shown in Figure 3.

Figure 3. Maintenance cost optimization diagram.
It shows that when the condition monitoring period is 4 months and the replacement is performed every 28 months, the maintenance cost per unit time can be guaranteed to be the lowest, which is 1750.95 RMB/month.

5. Conclusion
This paper adopts the delay time maintenance model for the maintenance task combination to discuss the maintenance process and characteristics of the equipment under the maintenance strategy, and establishes the mathematical model of the task cycle according to different decision-making objectives, so as to provide a reference for analysing and comparing the applicability and necessity of the task combination strategy. On this basis, typical equipment is selected to verify the application of the decision model established above. The two task management problems of the same fault mode are solved and the maintenance cost of nuclear power plant is further reduced.

Reference
[1] Lu Hao, Hu Huaping, Liu Bo. Research on classification of malware. Application research of computers, 2006, 23 (9) : 4-7, 12.
[2] VARSHNEY U, VETTER R. Mobile commerce: framework, applications and networking support[J]. Mobile Networks and Applications, 2002, 7(3):185-198.
[3] Li Xiaodong, Zhang Qinghong, Ye Jinlin. Some theoretical problems in climatology research. Acta scientiarum naturalium universitatum pekinensis, 1999, 35 (1) : 101-106.
[4] Unwin G.[M]. Chen Shengzheng, trans. Beijing: China Books Publishing House, 1988.
[5] ROOD H J. Logic and structured design for computer programmers. 3rd ed.[S.l.]: Brooks/Cole-Thomson Learning, 2001