Maintenance Expense Optimization Method for High Temperature Reactor Equipment Group

Shuping Che¹, Qiaojun Wu¹, Yanpeng Zhang¹ and Jie Geng²

¹ Suzhou Nuclear Power Research Institute Guangzhou, China
² School of Reliability and Systems Engineering, Beihang University Beijing, China
Email: bh0922@126.com

Abstract. The composition of the high-temperature reactor system is relatively complicated. The failure mechanism and degradation process of each component in the system are not the same, and the timing of failure is not the same, resulting it impossible to ensure all components being maintained by preventive planning maintenance. According to the fault correlation, time correlation, functional correlation and structural correlation between components in the multi-component system, the components that meet the maintenance conditions within a certain period of time can be integrated and repaired, which can not only share the fixed cost, but also reduce the downtime. It also increases the overall availability of the equipment.

1. Introduction
The new features of high-temperature reactor equipment, such as high power, multi-function, complex structure, automation, etc., leading to traditional maintenance can’t meet the requirements of current work and cause adverse effects [1]. The shortage of traditional maintenance methods is mainly due to the following two points: First, the maintenance strength is insufficient. In the restricted stage of the maintenance plan, the equipments have diseased operation conditions, which leads to further deterioration of the faults, directly increasing maintenance costs and even causing safety accidents; Secondly, excessive maintenance, unnecessary inspection and maintenance, resulting in waste of manpower, material resources and other resources, reducing the life cycle of equipment, and frequent maintenance is more likely to cause failure of some equipment.

In actual maintenance practice, for multi-component or complex systems, there are often multiple maintenance events occurring at the same time or appearing in a certain period of time. If there is no reasonable maintenance plan to arrange maintenance separately, it will not only result in maintenance labor waste, but also occupy a certain amount of maintenance resources. At the same time, may result in downtime damage costs, and will also reduce the effective use of equipment [2]. Due to the different impacts of these maintenance events on the operation of the equipment and the success of the mission, there are comprehensive decisions on maintenance activities based on the actual health status in the maintenance management to improve maintenance efficiency, reduce maintenance costs, and effectively reduce equipment maintenance downtime in the process.

Research on maintenance decision models for multi-component systems is more about opportunity maintenance, group maintenance and batch maintenance [3]. Classic static grouping strategies include maintenance strategies based on equipment age, based on number of failures, and that are comprehensively considered for age and number of failures. The batch maintenance strategy is different from the group maintenance strategy. It is based on the maintenance cycle set by the system,
take preventive maintenance or preventive replacement for each component in the equipment. Batch maintenance strategy can replace components that have failed during a defined service cycle.

For maintenance costs, maintenance will result in raw material consumption, equipment and human resources occupation. At the same time, maintenance may also cause equipment downtime, affecting normal production work, resulting in huge downtime losses, so it is not maintained in time, it may make more serious fault, causing greater losses. The expenses incurred in the maintenance process can be divided into three categories: the first is the direct maintenance cost incurred, including the repair material cost, the maintenance labor cost, etc.; the second is the fault loss cost, including the equipment loss and management expense; the third is the loss of downtime due to maintenance.

According to the actual operating state of the system, establish the maintenance decision model of the high temperature reactor equipment group to achieve dynamic decision making. Consider the impact of fault correlation, structural correlation, time correlation and functional relevance in the model, the decision-making process is made closer to reality, making decision making more scientific and practical [4].

2. Maintenance Expense Optimization Target
Select inner rod, outer rod, control rod assembly, thin-walled shell buffer, upper sealing barrel, shield sealing barrel, steering piece, rod position indicator, disc spring shock absorber, diaphragm coupling in high temperature reactor control rod system, eddy current limiter, limit device, final drive, stepper motor, chain for the object.

For systems with multiple events concurrent, different combinations of events will have different correlation effects on system maintenance expense, maintenance downtime and other aspects. When maintenance events are repaired separately, the impact is simple and cumulative; when the event has an associated impact relationship and combined maintenance, its impact will vary with the combination. Common maintenance expense includes time-related and structurally related expenses [5].

The time related can reduce the loss caused by the shutdown, set the unit time downtime loss to $C_{stop}(t)$, and the combined total maintenance time obtained by upper part, it can be seen that the reduced downtime loss is:

$$\Delta C^1_{ij}(t) = \Delta T^i_j(t) \times C_{stop}(t) \quad (1)$$

The structural related can not only share the fixed maintenance expense, but also directly reduce the labor expense caused by the maintenance, and also reduce the number of downtimes. Set the fixed maintenance expense reduced by allocation to $C_{fixed}^i_j(t)$, the labor expense per unit time to $C_p$, the reduced maintenance expense by structural related is:

$$\Delta C^2_{ij}(t) = C^i_j(t) + \Delta T^i_j(t) \times C_p \quad (2)$$

The combination of these two parts results in the common maintenance expense savings $\Delta C_{ij}(t)$:

$$\Delta C_{ij}(t) = \Delta C^1_{ij}(t) + \Delta C^2_{ij}(t) = \Delta T^i_j(t) \times C_{stop}(t) + C^i_j(t) + \Delta T^i_j(t) \times C_p \quad (3)$$

Similarly, half of the combined maintenance expense savings for all combinations is the total saved maintenance expense (calculated twice for each combination), shows:

$$\Delta C(t) = \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} \Delta C_{ij}(t) \quad (4)$$

Based on the analysis above, the decision making model targeting the minimum maintenance expense is as follows:
\[
\max \Delta C(t) = \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} \Delta C_{ij}(t) \\
\text{s.t. } P_{r_{i}} \leq P_{r_{j}} \leq P_{r_{l}}, \quad 1 \leq i \leq N
\]  

(5)

where \(\Delta C(t)\) is cumulative reduced maintenance expense. In order to achieve minimum maintenance expense, the cumulative reduction in maintenance expense should be maximized. \(\Delta C_{ij}(t)\) is the reduced maintenance expense of a combination, the expression is given above:

\[
\Delta C_{ij}(t) = \Delta C_{ij}^{1}(t) + \Delta C_{ij}^{2}(t) = \Delta T_{ij}^{1}(t) * C_{S_{ij}}^{1}(t) + C_{S_{ij}}^{2}(t) + \Delta T_{ij}^{1}(t) * C_{p}
\]  

(6)

\(P_{r}\) is the reliability of components, \(P_{r_{i}}\) is the minimum acceptable value for reliability, \(P_{r_{l}}\) is the maximum acceptable value for reliability.

Considering the association of the equipment, we take assumptions:

(1) Expression of reduced maintenance downtime of thin-walled shell buffer and limiter:

\[
\Delta C_{4,12}(t) = -1.2793*t_{1}^{2} + 2.6218*t_{1} - 1.8861 \quad \text{where } t_{1} = N * 10^{-5}
\]  

(7)

(2) Expression of reduced maintenance downtime of control rod assembly and disc spring shock absorber:

\[
\Delta C_{3,9}(t) = -8.2295*t_{2}^{2} + 10.8981*t_{2} - 9.5843 \quad \text{where } t_{2} = N * 10^{-6}
\]  

(8)

(3) Expression of reduced maintenance downtime of inner rod and shielded sealed bucket:

\[
\Delta C_{1,6}(t) = -6.7272*t_{3}^{2} + 5.2227*t_{3} - 5.6489 \quad \text{where } t_{3} = N * 10^{-8}
\]  

(9)

Know:

\[
\Delta C(t) = \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} \Delta C_{ij}(t)
\]

\[
= \frac{1}{2} \left[ \Delta C_{4,12}(t) + \Delta C_{12,4}(t) + \Delta C_{3,9}(t) + \Delta C_{3,9}(t) + \Delta C_{3,9}(t) + \Delta C_{6,1}(t) + \Delta C_{6,1}(t) \right]
\]

\[
= \Delta C_{4,12}(t) + \Delta C_{3,9}(t) + \Delta C_{6,1}(t)
\]

\[
= -1.2793*t_{1}^{2} - 8.2295*t_{2}^{2} - 6.7272*t_{3}^{2} + 2.6218*t_{1} + 10.8981*t_{2} + 5.2227*t_{3} - 17.1193
\]  

(10)

3. Optimization Algorithm Selection

For model solving, intelligent optimization algorithms such as genetic algorithm, simulated annealing algorithm and particle swarm optimization algorithm are generally used [6]. The intelligent optimization algorithm is to derive a new set of decision-making methods from life sciences and biological group activities, and iteratively optimizes by computer to approximate the optimal solution. This paper chooses the particle swarm algorithm and it has the following advantages: easy to describe; easy to implement; less parameters to be adjusted; use relatively small scale groups; less need to evaluate functions for convergence; and ability to search quickly through individual optimization and global optimization, the process of the algorithm is shown in figure 1.

The steps of the particle swarm algorithm are as follows:

(1) Initialize the particle swarm: Determine the number of particles in the initial population in the algorithm, and randomly generate the initial position and velocity of each particle within the decision interval of the particle;

(2) Calculating fitness: According to the relationship between each target, construct a suitable fitness function to judge the merits of each particle;
(3) Obtain Pbest and Gbest: Pbest is the optimal position of each particle found according to the fitness value, and Gbest is the optimal position of all particles in the group during the search process;

(4) Update speed and position: According to the calculated speed and position of all particles in the Pbest and Gbest update groups, the update method is as follows:

\[
V_i = \omega \cdot V_i + c_1 \cdot rand() \cdot (Pbest[i] - X_i) + c_2 \cdot rand() \cdot (Gbest[i] - X_i)
\]

\[
X_i = X_i + V_i
\]

(11)

where \( c_1 \) and \( c_2 \) are constants calling the learning factor; \( rand() \) is a random number on \([0, 1]\), \( \omega \) is inertia weight.

(5) Generating new ethnic groups: Particles are constantly updated, constantly generating new ethnic groups until the set termination condition or the set number of cycles.

\[
\begin{align*}
\Delta C(t) &= -1.2793 \cdot t_1^2 - 8.2295 \cdot t_2^2 - 6.7272 \cdot t_3^2 \\
&\quad + 2.6218 \cdot t_1 + 10.8981 \cdot t_2 + 5.2227 \cdot t_3 - 17.1193
\end{align*}
\]

s.t. \( P_{t_1} \leq 0.96557406 \)

s.t. \( P_{t_2} \leq 0.98002804 \)

s.t. \( P_{t_3} \leq 0.94853756 \)

s.t. \( P_{t_4} \leq 0.98491293 \)

s.t. \( P_{t_5} \leq 0.99594924 \)

s.t. \( P_{t_6} \leq 0.99157355 \)

(12)

The particle swarm optimization algorithm is used to solve the problem, when the time is \( t_1 = 1.02470101, t_2 = 0.66213621, t_3 = 0.38817784 \), the cumulative maintenance downtime reaches the maximum, and the maximum value is 11.1543.
5. Conclusion
This paper proposes a methodology on maintenance decision optimization with target of minimal time-related and structure-related expenses by taking combined maintenance based on the analysis result of associated relationship and the calculation result of mathematical model. The case of control rod system shows the validity and availability of the methodology. The particle swarm algorithm is also introduced to approximate the optimal solution. With the correlation of maintenance activities analysed in advance and fatigue life of components under given reliability level known, the maintenance of components of control rod system can be combined in pairs at specific time to obtain the minimal maintenance expense.

However, in actual scenario, mathematical expressions of combined maintenance downtime and expenses changes with reliability are not easy to establish, which also requires enough prior knowledge.

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