Research Article

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Extended warranty decision model of failure dependence wind turbine system based on cost-effectiveness analysis

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Abstract: The wind turbine system is the core equipment of wind power generation. Scientific formulation of an extended warranty (EW) scheme to optimize the cost-effectiveness ratio per unit time for a wind turbine system is one of the key concerns both for users and manufacturers. Based on the failure dependence analysis of the multi-component system, the EW cost model and availability model of the multi-component system are established. Based on the EW cost model and availability model, the cost-effectiveness ratio model per unit time is constructed. Through the case study, the optimal EW scheme of the wind turbine system is obtained *via* genetic algorithm, so as to minimize the cost-effectiveness ratio per unit time. The results of fitting prediction analysis and flexible decision analysis show that the model can excellently predict the minimum warranty cost and maximum availability of failure dependence wind turbine systems and can supply different EW schemes for users and manufacturers to choose from under a specific cost–effectiveness ratio. Through sensitivity analysis, reasonable suggestions for optimizing the EW scheme of the wind turbine system are proposed.

Keywords: failure dependence, wind turbine system, preventive maintenance, extended warranty, cost-efficiency ratio

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1 Introduction

At present, a large number of modern technological equipment are used in various fields of industrial production. This equipment has a complex structure and high integration, and is a typical mechanical electrical and hydraulic integration system [1]. The failure dependence between components is more obvious, which increases the difficulty of equipment maintenance and daily management. A wind turbine system is typical modern technological equipment. With the continuous progress of productivity, people's demand for electric energy is gradually increasing. Compared with traditional hydropower and thermal power generation, wind power generation has more advantages, which are clean, pollution-free, renewable, short capital construction cycle, and good environmental benefits. The wind turbine system is the core equipment of wind power generation.

The wind turbine system is composed of more than ten complex subsystems such as transmission system, pitch system, wind wheel system, braking system, and yaw system. Each subsystem is composed of many components, so its structure is very complex. In fact, the failure among the components of the wind turbine system is related. For example, the wear of the main shaft will aggravate the vibration of the gearbox and increase the failure rate of the gearbox. Therefore, the warranty decision model based on failure dependence is more in line with the engineering practice to a certain extent. During the basic warranty period, it is difficult for users to form independent support capability for this equipment, so it is very necessary to rely on manufacturers to carry out equipment extended warranty (EW). In the research of EW, it is one of the hotspots of current research to scientifically formulate EW schemes, reduce EW costs, and maintain availability.

EW means that after the basic warranty, the user and the manufacturer sign a warranty service contract, and the manufacturer carries out the follow-up service for a certain period of time. Generally, the user needs to pay a certain fee separately. For manufacturers, EW is an effective means to enhance product competitiveness and has become a new source of profit for manufacturers. For users, EW ensures that the product can be repaired in time in case of failure. In addition, EW is also a sign of product quality. Generally speaking, it is more common for manufacturers to provide EW services for products with good quality and high reliability.

In the existing research on EW decision-making, most of its decision-making objectives are the lowest cost of EW [2]. The reduction of EW costs can make manufacturers obtain more profits, which is beneficial to them [3]. Wang [4] established a warranty cost model based on customer utilization and product failure history to calculate the manufacturer's expected warranty cost and expected profit, so as to determine the optimal warranty price. Tong *et al.* [5] studied the best maintenance degree during the EW period based on the dynamic utilization rate of consumers to reduce the EW cost; Su and Wang [6] introduced the preventive maintenance (PM) strategy on the basis of Tong *et al.* [5] and optimized the maintenance strategy with the goal of minimizing the cost of product EW.

Other studies consider the availability of warranty objects. For users, the improvement of the availability of warranty objects means the reduction of unexpected failure, which is the ideal state expected by users. Song *et al.* [7] formulated the equipment maintenance plan with the minimum maintenance cost per unit time in the replacement cycle as the goal and the availability as the constraint and verified the effectiveness of the model through an example analysis. On the premise of ensuring that the equipment availability meets the military requirements, Yang *et al.* [8] took the lowest equipment warranty cost as the goal to obtain the optimal PM scheme of equipment under partial outsourcing and complete outsourcing modes, respectively; Huang *et al.* [9] classified different users according to their usage during the initial warranty period, provided differentiated EW schemes for different types of users and improved consumer satisfaction and marketing competitiveness by maximizing the availability of products; ref. [10] takes the maximum availability of two-dimensional warranty products as the optimization objective and uses a numerical algorithm and particle swarm optimization algorithm to obtain the optimal PM interval, which provides a scientific basis for manufacturers to formulate two-dimensional warranty strategy. Authors of ref. [11] studied the system with competitive failure mode, comprehensively considered the availability and average long-term cost rate, and obtained the optimal periodic inspection and imperfect maintenance strategy of the system. The ratio of input cost to output benefit is known as the cost-effectiveness ratio. As a result, users and producers alike strive for a lower cost-effectiveness ratio. Reference may be found in the research of warranty decisions based on cost-effectiveness analysis [12–15].

Through literature review, it can be seen that although the current academic circles have carried out some research on EW cost optimization, availability optimization, and cost-effectiveness ratio optimization, most of the research objects are single-component systems, ignoring the failure dependence between multiple components. To some extent, it affects and restricts the formulation of EW strategy.

Failure dependence mainly refers to that in a multi-component system, the occurrence of a component failure will lead to a change in the overall environment of the system and then affect the state of other components, resulting in the increase of failure [16,17]. Sun *et al.* [18] introduced the concept of interactive failure, established a model for quantitative analysis of failure interaction between components, and gave an experimental derivation method of the failure correlation coefficient between components, which belongs to the earlier research on failure dependence. Zhang *et al.* [19] studied the periodic inspection strategy for a class of k-out-of-n systems with Class I failure dependence. The highly degraded or failed components are replaced. The short-term and long-term maintenance costs of the system are derived based on the Markov renewal process. Han [20] calculated the inherent reliability and comprehensive reliability of the subsystem respectively based on the failure dependence analysis and full probability formula of the wind turbine, further calculated the failure rate of the subsystem, and studied the optimal maintenance scheme of the wind turbine based on the failure rate of the subsystem. Qian and Jiang [21] studied the PM strategy of the multi-component system with one-way failure correlation based on the Class II failure dependence between multiple components and established the PM task grouping optimization model with the PM interval as the decision variable and the minimum maintenance cost within the specified operation time as the goal; Wang *et al.* [22] used the failure chain to describe the failure dependence between components, implemented the grouping maintenance strategy of the indefinite cycle for components with the goal of minimum maintenance time and cost, and optimized the maintenance plan by using genetic algorithm.

Based on the above analysis, this article mainly carries out EW research for failure dependence multi-component systems. Considering the failure dependence between components, aiming at minimizing the cost-effectiveness ratio per unit time, this article solves the optimal EW period and PM interval, which is acceptable to both manufacturers and users. It provides a quantitative basis for the formulation of the EW scheme of failure dependence multi-component system. The case study takes the wind turbine system as the research object and obtains the optimal EW decision-making scheme for the wind turbine system through the method established in this study.

The organizational structure of the rest of this article is as follows: Section 2 puts forward the model description and assumptions. In Section 3, the cost model and the availability model are constructed. The case analysis is carried out in Section 4, and Section 5 draws the conclusion of the article.

2 Model description and assumptions

2.1 Failure dependence analysis

Failure dependence can be divided into unidirectional failure dependence and bidirectional failure dependence. According to the failure chain model [23], if a component actively affects other components, the component is the failure starting point. If a component not only passively receives the effect of other components but also actively affects other components, it is called the failure midpoint. If a component only passively receives the effect of other components, it is called the failure ending point. This article mainly considers the case related to unidirectional failure dependence. The unidirectional failure dependence model is shown in Figure 1.

In Figure 1, A is the failure starting point, B and C are the failure midpoint, and D is the failure ending point. The actual failure rate of each component during operation is influenced by two factors in a multi-component system with failure dependence: intrinsic failure rate and related failure rate. The intrinsic failure rate of the component is defined by design and manufacture; the failure rate induced by the failure of other components in the system is referred to as the related failure rate [24]. The real failure rate of each component of a multi-component system with numerous components may be stated in the following matrix form [20] under the condition of failure dependence:

$$h_a(t) = h_{a0}(t) + \sum_{ab}[\omega_{ab}(t)][h_{ab}(t)], \tag{1}$$

where $h_a(t)$ represents the actual failure rate of a single component, $1 \le a \le q$ and $a \in N^+$; $h_{a0}(t)$ represents the intrinsic failure rate of each component; $[h_{ab}(t)]$ is a $p \times 1$-dimensional matrix, $1 \le p \le q$, $b \in \{b|b = 1, 2, 3, \ldots, q \text{ and } b \ne a\}$, and $[h_{ab}(t)]$ represents the related failure rate caused by component b to component a; $[\omega_{ab}(t)]$ is the $1 \times p$-dimensional non-negative real matrix, $[\omega_{ab}(t)]$ represents the failure influence coefficient of component b on component a, $0 \le \omega_{ab}(t) \le 1$. When $\omega_{ab}(t)$ value is 0, it indicates that there is no interaction between components, and when $\omega_{ab}(t)$ value is 1, it indicates that component b failure leads to component a failure.

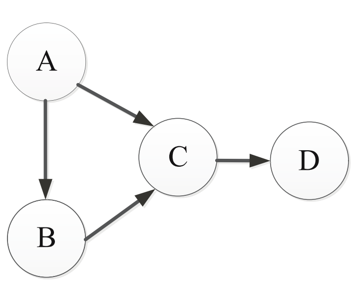

Figure 1: Unidirectional failure dependence model.

2.2 Model description

This article mainly studies the failure dependence of a two-component system, which can be regarded as a failure dependence multi-component system composed of the key component and the subsystem. The warranty strategy is that we implement the minimum maintenance after failure for the multi-component system in the basic warranty period, the imperfect PM for the system in the EW period, and the minimum maintenance for unexpected failure. The failure rate of the key component and the subsystem are expressed by $h_\psi(t)$ and $h_s(t)$, respectively. The failure of the key component will increase the failure rate of the subsystem to a certain extent. Taking PM interval and EW period as decision variables, the cost model, availability model, and cost-effectiveness model of per unit time for equipment multi-component system in EW period are established respectively, and case analysis and optimization solution are carried out.

2.3 Model assumptions

For the convenience of research, the establishment of the model is mainly based on the assumption that

1) The system only carries out the minimum maintenance after a failure during the basic warranty period. Imperfect

PM shall be adopted during the EW period, and the minimum maintenance after failure shall be adopted within the interval of PM during the EW period.
2) The system failure rate increases with time.
3) The PM cost does not change with the change of PM time and times.
4) The minimum maintenance cost is fixed.
5) Minimum maintenance does not change the failure rate of components.

3 Model construction

3.1 Imperfect PM strategy

The effect of imperfect PM is between “good as new” and “bad as old” [25]. This article uses the virtual age method to describe the effect of imperfect PM; that is, each imperfect PM will reduce the actual age of the equipment for a period of time [26–28]. Let δ indicates the improvement factor of imperfect PM. Assuming that the kth imperfect PM is performed at time t, the failure rate of the equipment in the k-the PM interval can be expressed as:

$$h(t) = h(t - \delta(k-1)T_0). \tag{2}$$

T_0 is the interval of imperfect PM. Using the virtual age method, the change in equipment failure rate after each imperfect PM is shown in Figure 2.

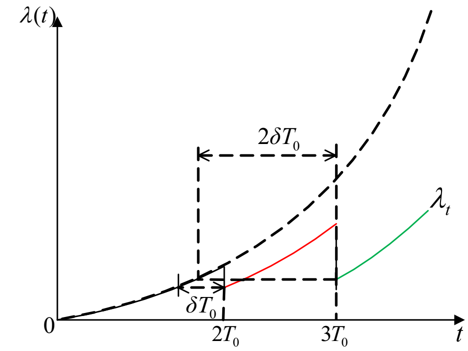

Figure 2: Schematic diagram of virtual age method.

3.2 Minimum maintenance strategy

The minimum maintenance strategy is adopted for the failure of components within the basic warranty period and PM interval. The characteristic of the minimum maintenance is that the arrival of failure follows the Non-Homogeneous Poisson Process [29,30]. The expected number of failures of the system in a period of time is as follows:

$$E[N(t)] = \int_0^t h(s)\mathrm{d}s, \tag{3}$$

where $N(t)$ is the number of system failures in time $[0, t]$, and $h(s)$ is the system failure rate.

3.3 Warranty cost model

The number of imperfect PM of the multi-component system during the EW period is as follows:

$$m = \operatorname{int}[(W_E - W)/(T + T_p)], \tag{4}$$

where “int” represents the downward rounding function, and T_p represents the time required for an imperfect PM. W_E represents the EW ending period, and W represents the basic warranty ending period.

Then the warranty cost $\mathrm{EC}(T, W, W_e)$ of the multi-component system during the EW period can be expressed as:

$$\begin{aligned}\mathrm{EC}(T, W, W_E) = mC_p + \sum_{k=1}^{m} EC_{fk}(T) \\ + \mathrm{EC}_f(W + m(T+T_p), W_E),\end{aligned} \tag{5}$$

where $\mathrm{EC}_f(W + m(T + T_p), W_E)$ represents the expected minimum maintenance cost in time $[W + m(T + T_p), W_E]$, that is, the expected minimum maintenance cost in the last PM interval; $\mathrm{EC}_{fk}(T)$ is the expected minimum maintenance cost in the kth PM interval.

The failure rate function of the key component in the kth PM interval can be expressed as:

$$h_{k\psi}(t) = \begin{cases} h_\psi(t) & k = 1 \\ h_\psi[t - \delta(W+(k-1)T] & k = 2, 3, 4, \ldots, m. \end{cases} \tag{6}$$

The failure of the key component will increase the failure rate of subsystem to a certain extent. According to the failure dependence analysis in 1.1, it can be obtained that the failure rate function of subsystem in the kth PM interval is [31]:

$$h_{ks}(t) = \begin{cases} h_s(t) + \dfrac{\omega}{2} l_{k\psi} h_{k\psi}(t) & k = 1 \\ h_s[t - \delta(W+(k-1)T)] + \\ \omega\left\{ \displaystyle\sum_{i=1}^{k} [l_{i\psi} h_\psi(t - \delta(W+(i-1)T))] \right. \\ \qquad \left. - \dfrac{1}{2} l_{k\psi} h_{k\psi}(t) \right\} & k = 2, 3, 4, \ldots, m, \end{cases} \tag{7}$$

where $l_{k\psi}$ represents the number of failures of the key component in the kth PM interval.

Therefore, it can be concluded that in the kth PM interval, the total expected cost of failure minimum maintenance of the multi-component system is as follows:

$$EC_{fk}(T)=\int_{W+(k-1)(T+T_p)}^{W+kT+(k-1)T_p} h_{k\psi}(t)\mathrm{d}tC_{f1}+\int_{W+(k-1)(T+T_p)}^{W+kT+(k-1)T_p} h_{ks}(t)\mathrm{d}tC_{f2}, \quad (8)$$

where C_{f1} represents the minimum maintenance cost of the key component and C_{f2} represents the minimum maintenance cost of the subsystem.

Similarly, the minimum maintenance cost of the expected failure of the multi-component system in $[W+m(T+T_p), W_E]$ is:

$$\begin{aligned}\mathrm{EC}_f(W+m(T+T_p), W_E) = &\int_{W+m(T+T_p)}^{W_E} h_{(m+1)\psi}(t)\mathrm{d}tC_{f1}\\ &+\int_{W+m(T+T_p)}^{W_E} h_{(m+1)s}(t)\mathrm{d}t,\ C_{f2}.\end{aligned} \quad (9)$$

To sum up, the total expected warranty cost of the multi-component system within the EW period is:

$$\begin{aligned}\mathrm{EC}(T, W, W_E) \quad &= mC_p + C_{f1}\left[\sum_{k=1}^{m}\int_{W+(k-1)(T+T_p)}^{W+kT+(k-1)T_p} h_{k\psi}(t)\mathrm{d}t\right.\\ &\left.+\int_{W+m(T+T_p)}^{W_e} h_{(m+1)\psi}(t)\mathrm{d}t]\right]\\ &+C_{f2}\left[\sum_{k=1}^{m}\int_{W+(k-1)(T+T_p)}^{W+kT+(k-1)T_p} h_{ks}(t)\mathrm{d}t\right.\\ &\left.+\int_{W+m(T+T_p)}^{W_E} h_{(m+1)s}(t)\mathrm{d}t\right].\end{aligned} \quad (10)$$

3.4 Multi-component system availability model

If the expected total downtime $\mathrm{ED}(T, W, W_E)$ during (W, W_E) can be obtained, the availability of the multi-component system during the EW period can be calculated by the following formula [32]:

$$\mathrm{EA}(T, W, W_E) = \frac{(W_E - W) - ED(T, W, W_E)}{W_E - W}, \quad (11)$$

$\mathrm{ED}(T, W, W_E)$ can be expressed in a similar way to $\mathrm{EC}(T, W, W_E)$, as long as C_p, C_{f1}, and C_{f2} in formula (10) are replaced with T_p, T_{f1}, and T_{f2}, respectively.

$$\begin{aligned}&\mathrm{ED}(T, W, W_E)\\ &= mT_p + T_{f1}\left[\sum_{k=1}^{m}\int_{W+(k-1)(T+T_p)}^{W+kT+(k-1)T_p} h_{k\psi}(t)\mathrm{d}t\right.\\ &\left.+\int_{W+m(T+T_p)}^{W_E} h_{(m+1)\psi}(t)\mathrm{d}t\right]\\ &+T_{f2}\left[\sum_{k=1}^{m}\int_{W+(k-1)(T+T_p)}^{W+kT+(k-1)T_p} h_{ks}(t)\mathrm{d}t\right.\\ &\left.+\int_{W+m(T+T_p)}^{W_E} h_{(m+1)s}(t)\mathrm{d}t\right].\end{aligned} \quad (12)$$

According to the above model, the maximum availability of the system in the EW period can be obtained by solving the PM interval under different EW periods.

3.5 Cost-effectiveness ratio model of per unit time

The EW cost and availability of the multi-component systems are a pair of mutually restrictive contradictions. For manufacturers, the lower the EW cost of the multi-component system, the better. However, the availability of the multi-component system cannot be guaranteed to be the highest; for users, the higher the availability of the multi-component system, the better. At this time, the warranty cost of the multi-component system cannot be guaranteed to be the lowest. From this point, it is one-sided to only emphasize the warranty cost or system availability. It is a more scientific and acceptable way for manufacturers and users to ensure the availability on the basis of controlling the warranty cost. The cost-effectiveness ratio function V per unit time is adopted to comprehensively weigh the warranty cost and availability.

Cost-effectiveness ratio per unit time refers to the ratio of warranty cost per unit time to availability within the EW period. The cost-effectiveness ratio per unit time considers both warranty cost and system availability quantitatively, which can be used as an important basis for warranty decision-making. The cost-effectiveness ratio function of per unit time can be expressed as [32]:

$$V = \frac{EC(T, W, W_E)}{W_E - W} \frac{1}{EA(T, W, W_E)}. \quad (13)$$

4 Case analysis

4.1 Problem description

There is unidirectional failure dependence between the main shaft and gearbox of the wind turbine system. The main shaft can be regarded as the key component, and the gearbox can be regarded as the subsystem. When the wear of the main shaft exceeds the failure threshold, it will aggravate the vibration of the gearbox and increase the failure rate of the gearbox. Through the investigation, during the basic warranty period, the user cannot fully form the independent maintenance ability for the main shaft and gearbox. It is necessary to introduce the maintenance force of the manufacturer to carry out technical services during the EW period. Since the failure rate of the main shaft and gearbox during the basic warranty period is low, only the minimum maintenance after failure is considered. During the EW period, the main shaft and gearbox have been in service for a period of time, and the failure rate has increased significantly. Besides the minimum maintenance after failure, it is very necessary to carry out imperfect PM. It is assumed that the main shaft failure follows the following two-parameter Weibull distribution:

$$\lambda_{\psi}(t) = \frac{\alpha}{\beta}\left(\frac{t}{\beta}\right)^{\alpha-1}, \quad (14)$$

where the shape parameter $\alpha = 3$ and the scale parameter $W = 2$ years. It is known that the basic warranty period of the equipment W is 2 years, the failure rate of the gearbox λ_s is 6×10^{-4}/day, the minimum maintenance time of the main shaft T_{f1} is 4 days, and the cost is 900 CNY. The minimum maintenance time of gearbox $T_{f2} = 6$ days, the cost is 1,300 CNY. The PM time $T_p = 3$ days, the cost is 600 CNY, and the improvement factor of imperfect PM within the EW period $\delta = 0.8$. According to the maintenance experience and data analysis, the failure of the main shaft will increase the failure rate of the gearbox, and the failure influence coefficient $\omega = 0.5$. By minimizing the cost-effectiveness ratio per unit time for the wind turbine system, the optimal EW period and PM interval of the wind turbine system are obtained, and then, an EW scheme of the wind turbine system acceptable to both manufacturers and users is formed.

4.2 Numerical algorithm

According to the investigation, the EW period of the wind turbine system generally does not exceed 10 years. Therefore, the value range of the EW period W_E is set as [3 years, 10 years], and the value range of the PM interval is [0.1 years, 3 years]. The value steps of PM interval and EW period are 0.1 years. The numerical algorithm is used to calculate the EW cost, availability, and cost-effectiveness ratio per unit time for the multi-component system corresponding to any combination of W_E and T. The algorithm flowchart is shown in Figure 3.

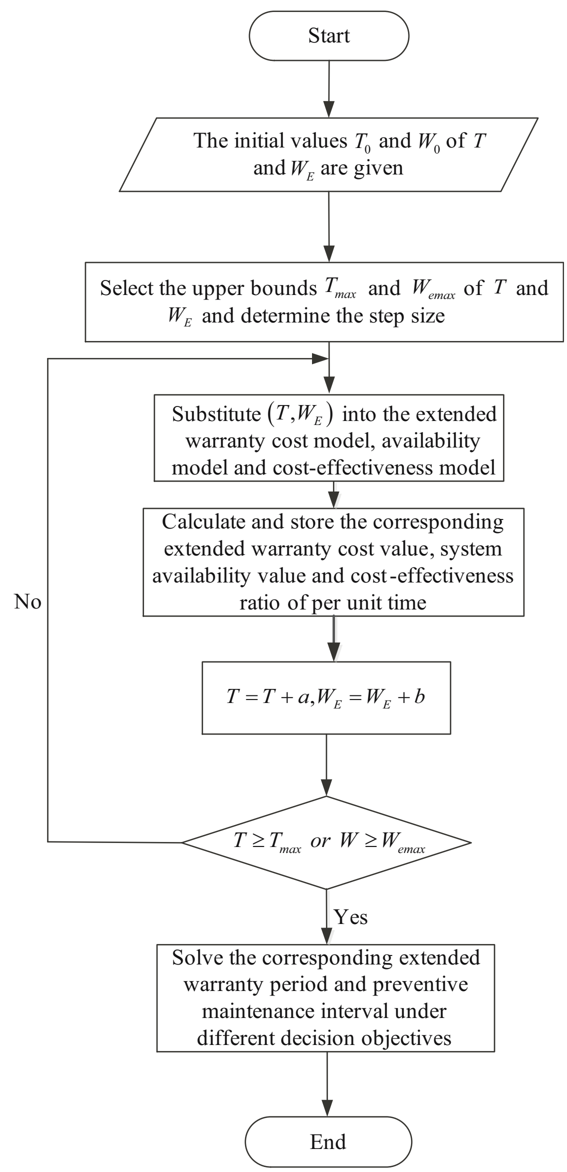

Figure 3: Flowchart of numerical algorithm.

Using the stored combination of W_E and T and the EW cost, availability, and cost-effectiveness ratio per unit time for the multi-component system corresponding to the combination of W_E and T, the change trend diagram of EW cost, availability, and cost-effectiveness ratio per unit time for the multi-component system can be drawn.

In order to study the variation law of EW cost, availability, and cost-effectiveness ratio per unit time for the wind turbine system with EW period W_E and PM interval T, and to analyze the three-dimensional graphics intuitively, we make dimension-reduced analysis of the three-dimensional graphics here.

Figure 4a–c respectively shows the corresponding changes in EW cost, availability, and cost-effectiveness ratio per unit time with the EW period under the determined imperfect PM interval; Figure 4d–f respectively represent the corresponding changes of EW cost, availability, and cost-effectiveness ratio per unit time with the imperfect PM interval when the warranty period is a certain value. It can be seen intuitively from Figure 5 that when the imperfect PM is a certain value, with the extension of the EW period, the corresponding EW cost will increase, the availability will decrease, and the cost-effectiveness ratio per unit time will increase. When the EW period is a certain value and the imperfect PM interval changes, there are optimal values for the EW cost, availability, and cost-effectiveness ratio per unit time.

4.3 Genetic algorithm

Genetic algorithm is an adaptive global optimization probability search algorithm formed by simulating the genetic and evolution process of organisms in the natural environment. Its principle is that organisms maintain excellent genes and promote population evolution through selection, heredity, and mutation. Genetic algorithm has the outstanding advantages of population parallel search function and not easy to fall into local convergence. The algorithm flow is as follows:

Step 1 Coding, designing the objective function, and determining the fitness function. Designing the convergence condition or iteration times, setting the GA parameters, and establishing the initial population.

Step 2 Calculating the fitness function to judge whether the convergence conditions or the number of iterations are met. If yes, the optimal individual is output as the result, otherwise enter step 3.

Step 3 Completing the replication of new species.

Step 4 Completing the mating of new species.

Step 5 New species, gene mutation within the group, return to step 2.

In this example, the specific parameter settings of the genetic algorithm are shown in Table 1.

Table 1: Parameter setting

Parameters	Value
Population size	50
Elite count	3
Crossover fraction	0.8
Stopping criteria	200

Table 2: Optimal EW scheme under different EW periods

Scheme	W_E/Days	T^*/Days	EC (CNY)	EA	V
1	1,080	180	1094.2	0.9879	3.0767
2	1,152	216	1260.9	0.9884	2.9531
3	1,224	252	1446.6	0.9886	2.9034
4	1,296	288	1653.2	0.9886	2.9033
5	1,368	324	1882.8	0.9884	2.9395
6	1,440	360	2137.4	0.9882	3.0041
7	1,512	396	2419.3	0.9878	3.0924
8	1,584	432	2730.9	0.9874	3.2013
9	1,656	468	3074.8	0.9869	3.3287
10	1,728	504	3453.2	0.9863	3.4735
11	1,800	360	3807.4	0.9858	3.5761
12	1,872	396	4258.1	0.9851	3.7520
13	1,944	432	4763.8	0.9843	3.9540
14	2,016	432	5059.2	0.9843	3.9661
15	2,088	468	5653.5	0.9833	4.2028
16	2,160	360	6048.2	0.9830	4.2727
17	2,232	504	6688.8	0.9821	4.5044
18	2,304	396	7150.7	0.9817	4.5984
19	2,376	432	8068.6	0.9802	4.9705
20	2,448	432	8449.6	0.9801	4.9889
21	2,520	360	9087.4	0.9795	5.1543
22	2,592	468	9969.4	0.9783	5.4434
23	2,664	324	10597.6	0.9778	5.5751
24	2,736	288	11480.3	0.9768	5.8297
25	2,808	360	12746.9	0.9751	6.2608
26	2,880	360	13183.3	0.9751	6.2592
27	2,952	324	14406.9	0.9737	6.6294
28	3,024	288	15181.1	0.9731	6.7711
29	3,096	396	16374.7	0.9718	7.0916
30	3,168	360	18093.2	0.9697	7.6216
31	3,240	360	18625.2	0.9697	7.6215
32	3,312	288	19785.5	0.9688	7.8794
33	3,384	252	22520.5	0.9659	8.7567
34	3,456	252	23019.3	0.9655	8.7137
35	3,528	216	24306.8	0.9646	8.9742
36	3,600	288	25458.6	0.9637	9.1723

*Optimal preventive maintenance interval under different extended warranty periods.

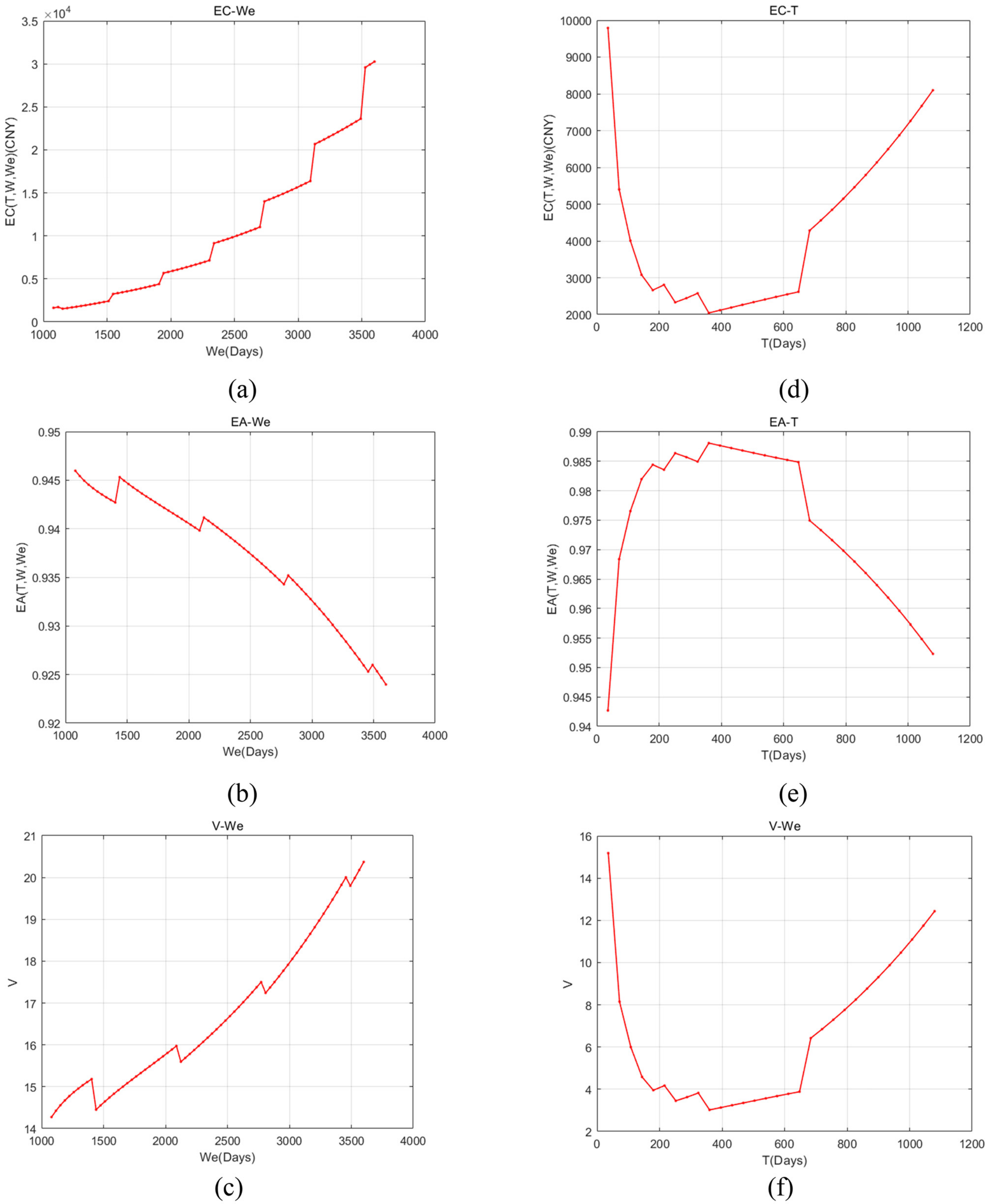

Figure 4: Dimension reduction analysis. (a) Schematic diagram of EC changing with W_e; (b) Schematic diagram of EA changing with W_e; (c) Schematic diagram of V changing with W_e; (d) Schematic diagram of EC changing with T; (e) Schematic diagram of EA changing with T; (f) Schematic diagram of V changing with T.

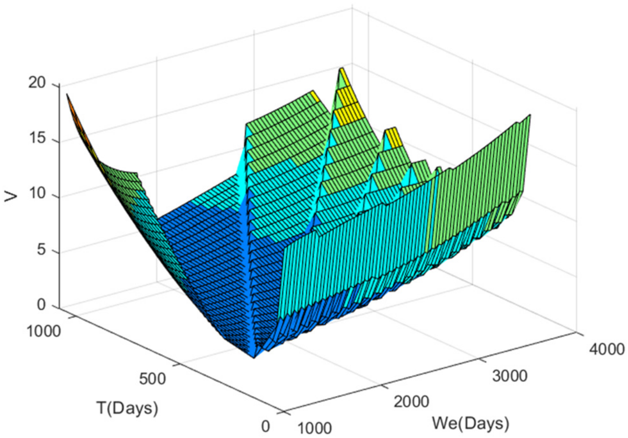

Figure 5: Change trend of cost-effectiveness ratio per unit time.

Figure 6 shows the iterative process of genetic algorithm. When taking the lowest EW cost as the decision goal, that is, Eq. (10) as the fitness function, the optimal EW period is 1,081 days and the optimal PM interval is 180 days. The EW cost is 1097.6 CNY, and the availability is 0.9869; When taking the highest availability as the decision goal, that is, when Eq. (11) is the fitness function, the optimal EW period is 1,241 days and the optimal PM interval is 259 days. At this time, the EW cost is 1653.2 CNY and the availability is 0.988; When the EW cost and availability are comprehensively considered and the cost-effectiveness ratio per unit time is the minimum, the optimal EW period is 1,224 days, and the optimal PM interval is 250 days. At this time, the EW cost is 1446.6 CNY, and the availability is 0.987.

Because this article takes the lowest cost-effectiveness ratio per unit time as the goal, the optimal EW scheme is 1,224 days of EW period and 250 days of PM interval.

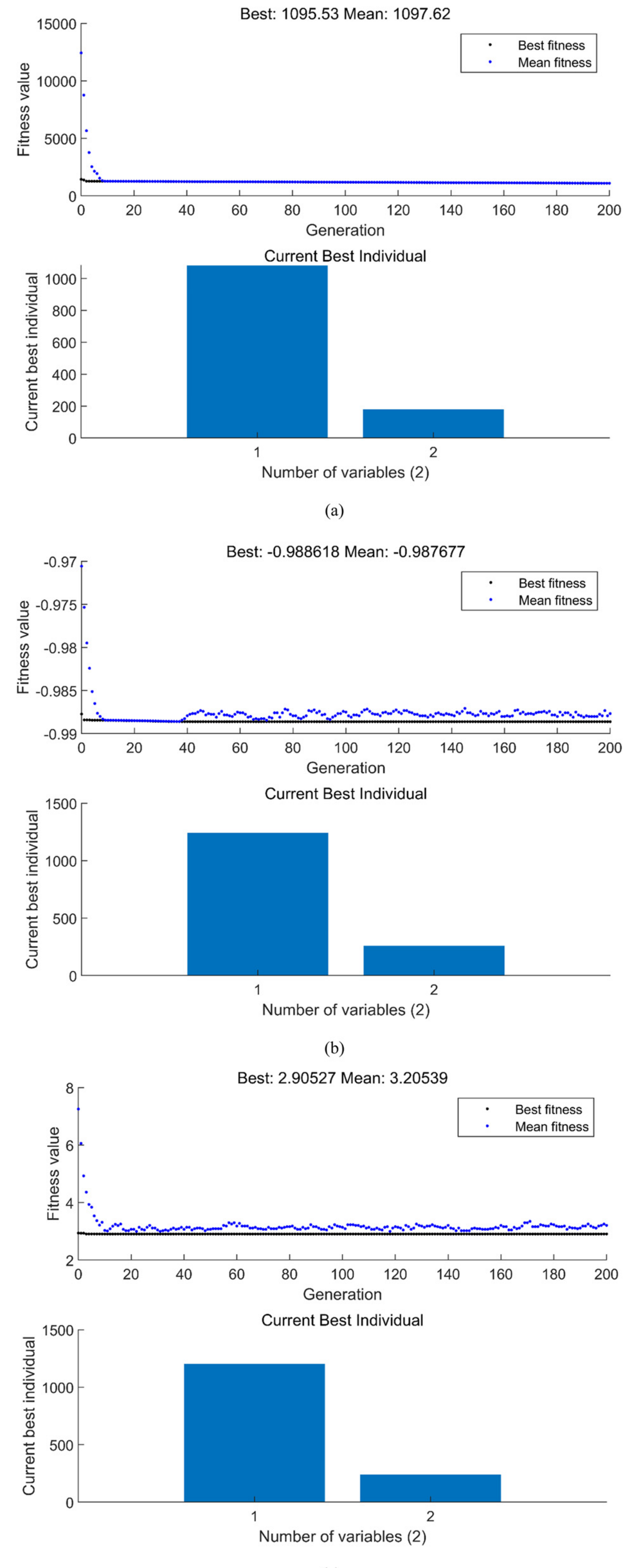

Figure 6: Schematic diagram of genetic algorithm iteration. (a) Aim at the lowest warranty cost; (b) Aim at the highest availability; (c) Aiming at the lowest cost-effectiveness ratio.

4.4 Result analysis

4.4.1 Scheme comparison and analysis

Based on the above analysis, the EW period is considered to be 1,224 days. When the wind turbine system does not carry out imperfect PM during the EW period, that is, set the PM interval to the same 1,224 days, the corresponding EW cost, availability and cost-effectiveness ratio per unit time can be obtained as follows:

$$W_E = T = 1{,}224 \text{ days}, \quad \text{EC} = 2176.4 \text{ CNY}, \quad \text{EA} = 0.94, \quad V = 4.6.$$

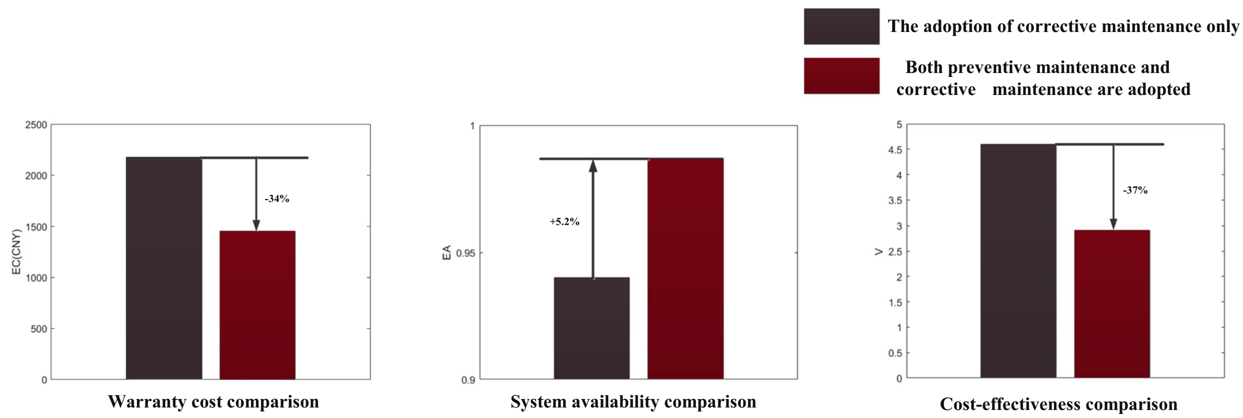

Figure 7: Comparison between with and without PM.

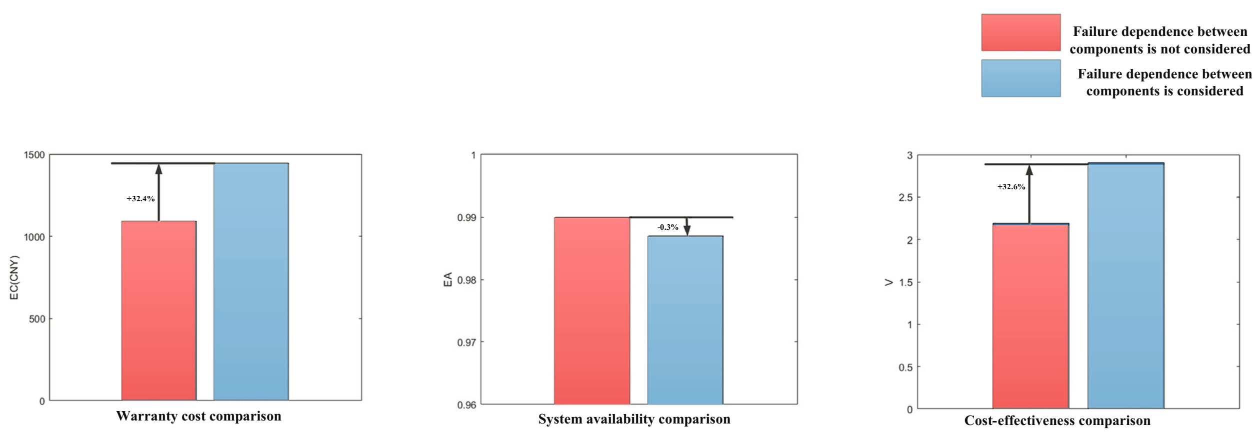

Figure 8: Comparison between considering and not considering failure dependence.

When the imperfect PM strategy is considered to be adopted in the EW period, the warranty cost, system availability, and cost-effectiveness ratio per unit time within the EW period are as follows:

$$W_E = 1{,}224 \text{ days}, \ T = 252 \text{ days}, \text{EC} = 1446.6 \text{ CNY}, \ \text{EA} = 0.987, \ V = 2.9034.$$

As shown in Figure 7, after adopting the imperfect PM strategy, the EW cost is reduced by 34%, the availability is increased by 5.2%, and the cost-effectiveness ratio per unit time is reduced by 37%. It can be seen that the imperfect PM strategy is a win–win strategy for the manufacturer and users.

(2) This article considers the failure dependence between the main shaft and gearbox. If the failure dependence between components is ignored, assuming that the failure between components is independent, the optimal PM interval can be obtained on the basis of 1,224 days of EW period, and the corresponding data of EW cost, system availability, and cost-effectiveness ratio per unit time can be obtained as follows:

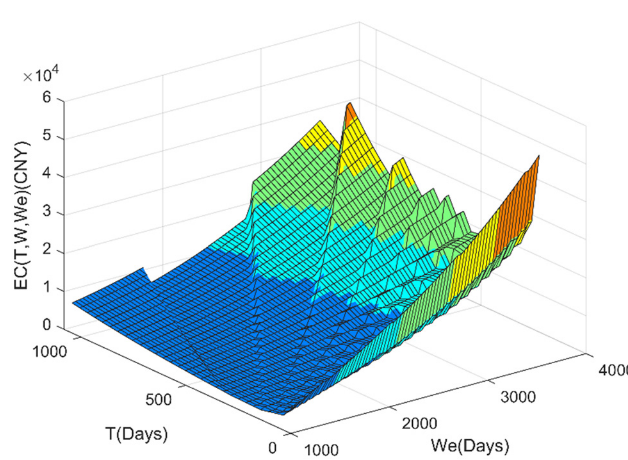

Figure 9: Change trend of system EW cost.

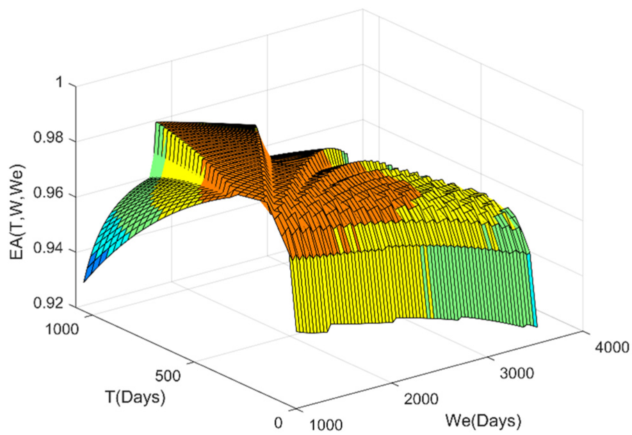

Figure 10: Change trend of system availability.

$$W_E = 1{,}224 \text{ days}, \ T = 324 \text{ days}, \quad EC = 1092.4 \text{ CNY}, \ EA = 0.99, \ V = 2.19.$$

As shown in Figure 8, by comparing the data considering the failure dependence between components, it is found that assuming that the failure between components is independent, the calculated EW cost is lower, the system availability is higher and the cost-effectiveness ratio is smaller. Although the data seems better than when considering the failure dependence between components, the assumption of independent failure is unrealistic, so the calculated results are inconsistent with the actual situation. This also proves that ignoring failure dependence will lead to unacceptable analysis errors, which will reduce the manufacturer's cost expectation and improve the user's expectation of system availability. In the actual warranty practice, the EW scheme and transaction contract based on the failure independence assumption will increase the manufacturer's cost risk, and the system will have more failures in the use stage, reducing the user's favor for the equipment and then reducing the user's loyalty to the equipment.

4.4.2 Regression fitting analysis

Based on the above calculation results, combined with Figures 5, 9, and 10, the maximum availability of the wind turbine system and corresponding optimal PM interval under different EW periods can be solved, as well as the cost-effectiveness ratio per unit time under this scheme, as shown in Table 2.

In Table 2, T^* stands for the optimal PM interval, EC stands for the EW cost of the wind turbine system, EA represents the availability of the wind turbine system, and V represents the cost-effectiveness ratio per unit time under the EW scheme. Table 2 shows that with the growing of W_E, the EW cost increases and the availability decreases. There is an obvious positive correlation between W_E and EC, while there is an obvious negative correlation between W_E and EA. Based on the data in Table 2, the relationship between W_E, EC, and EA is analyzed by regression analysis. MATLAB data fitting toolbox is used to fit the EW period and EW cost data. The fitting method is polynomial, and the maximum power is 2. The regression function can be expressed as follows:

$$EC = 0.003758 W_E^2 - 8.118 W_E + 5{,}987.$$

As shown in Figure 11, the correlation coefficient between W_E and EC is 0.9976, and the fitting effect of the model is good. The same method is used to fit the EW period and system availability data. At this time, the regression function can be expressed as follows:

$$EA = -3.295 \exp(-9) W_E^2 + 5.147 \exp(-6) W_E + 0.987.$$

As shown in Figure 12, the correlation coefficient between W_E and EA is 0.9942, and the fitting effect of

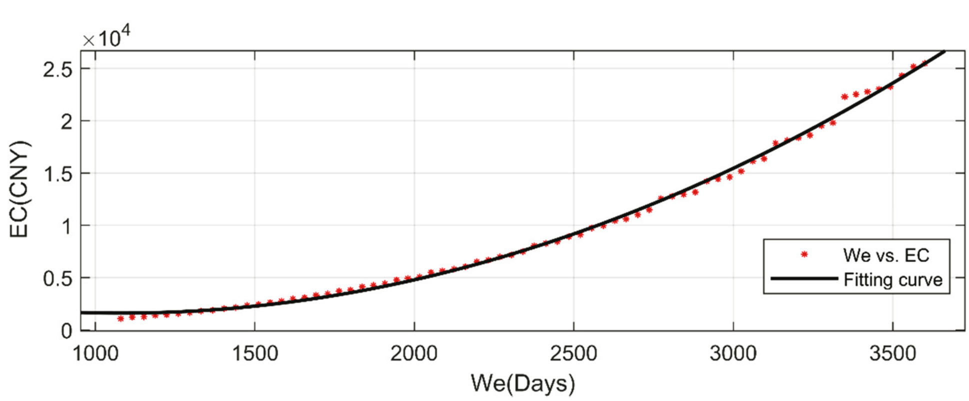

Figure 11: Fitting curve of W_E and EC.

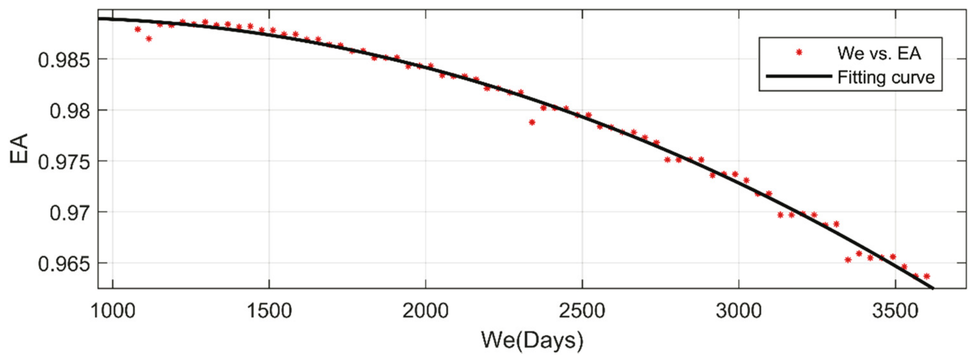

Figure 12: Fitting curve of W_E and EA.

the model is good. In practical application, the optimal warranty cost and system availability under different warranty periods can be estimated, which provides a scientific basis for formulating the warranty strategy of the wind turbine system.

4.4.3 Flexible decision analysis

It can be found from Figure 10 that the cost-effectiveness ratio per unit time may be the same under different combinations of EW period and PM interval. Based on this, the equal cost-effectiveness ratio per unit time curve under different combinations of EW period and PM interval is drawn, as shown in Figure 13.

According to the equal cost-effectiveness ratio per unit time curve, a more flexible warranty period and PM interval scheme can be provided for both manufacturers and users to choose from on the premise that the cost-effectiveness ratio of per unit time of the system does not increase. For example, when $V = 5.8417$, different combinations of W_E and T can be obtained from the corresponding equal cost-effectiveness ratio per unit time curve. Under these combinations, the cost-effectiveness ratio per unit time is 5.8417. The user and the manufacturer can choose any scheme according to the actual situation to meet the needs of both parties.

4.5 Sensitivity analysis

In the model established in this article, failure dependence coefficient ω and imperfect PM improvement factor δ will have a certain impact on the cost-effectiveness ratio per unit time. In order to test the impact of failure dependence coefficient ω and imperfect PM improvement factor δ on cost-effectiveness ratio per unit time, sensitivity analysis is carried out for ω and δ respectively, and the change trend of cost-effectiveness ratio per unit time for the wind turbine system is observed when the two parameters change.

4.5.1 Sensitivity analysis of failure dependence coefficient ω

The failure dependence coefficient ω indicates the failure dependence degree between two components. The larger the ω is, the stronger the failure dependence between the two components is. On the contrary, the failure

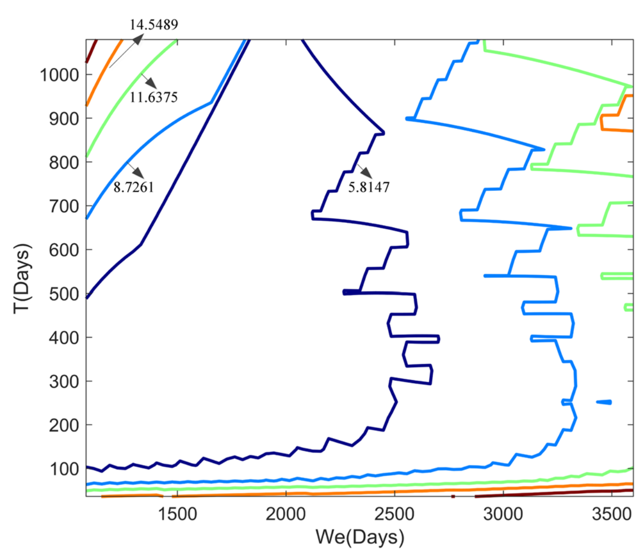

Figure 13: The equal cost-effectiveness ratio per unit time curve.

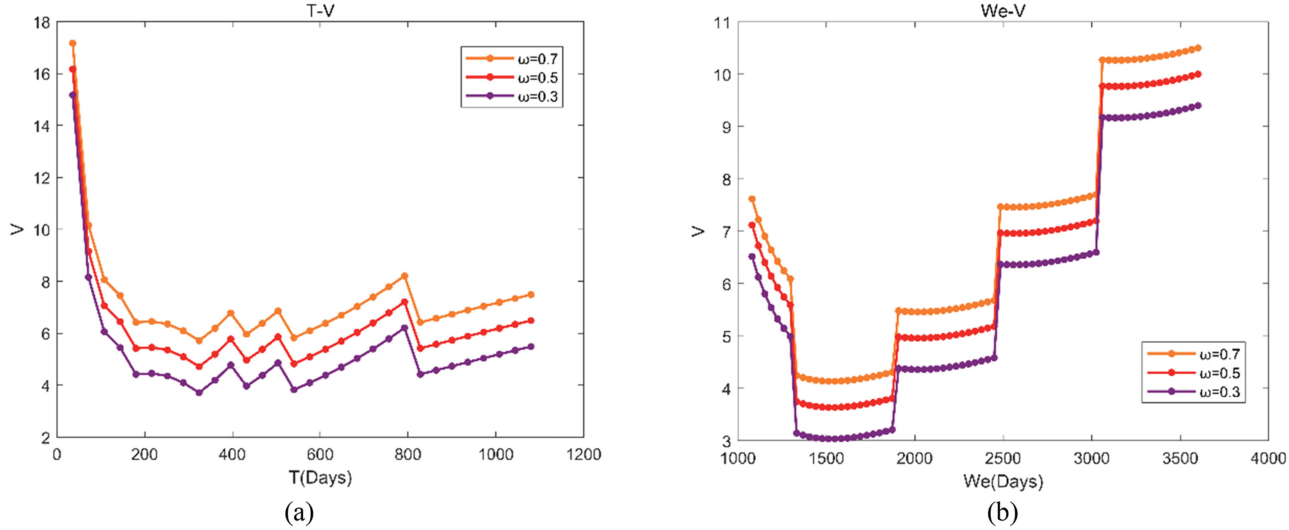

Figure 14: Sensitivity analysis of ω. (a) Sensitivity analysis of ω when W_e is fixed; (b) Sensitivity analysis of ω when T is fixed.

dependence between the two components is weaker. In order to further verify the impact of failure dependence coefficient on the cost-effectiveness ratio per unit time of the system, based on the fixed PM interval T and EW period W_E, the cost-effectiveness ratio per unit time corresponding to different values of ω is calculated, and the T–V curve and the W_E–V curve are drawn, respectively.

Figure 14(a) and (b) shows the variation trend of system cost-effectiveness ratio per unit time with failure dependence coefficient when W_E is 2,340 days and T is 576 days, respectively. It can be seen from the image that the cost-effectiveness ratio per unit time for the system increases with the increase in the failure dependence coefficient. The failure dependence coefficient is generally determined in the design stage of the system. Therefore, in the design stage, manufacturers should focus on the failure dependence between components and strive to reduce the failure dependence coefficient. Only in this way can the cost-effectiveness ratio per unit time for the system be reduced during the warranty period.

4.5.2 Sensitivity analysis of improvement factor δ

Imperfect PM improvement factor δ indicates the degree of imperfect PM. The larger the δ is, the better the effect of

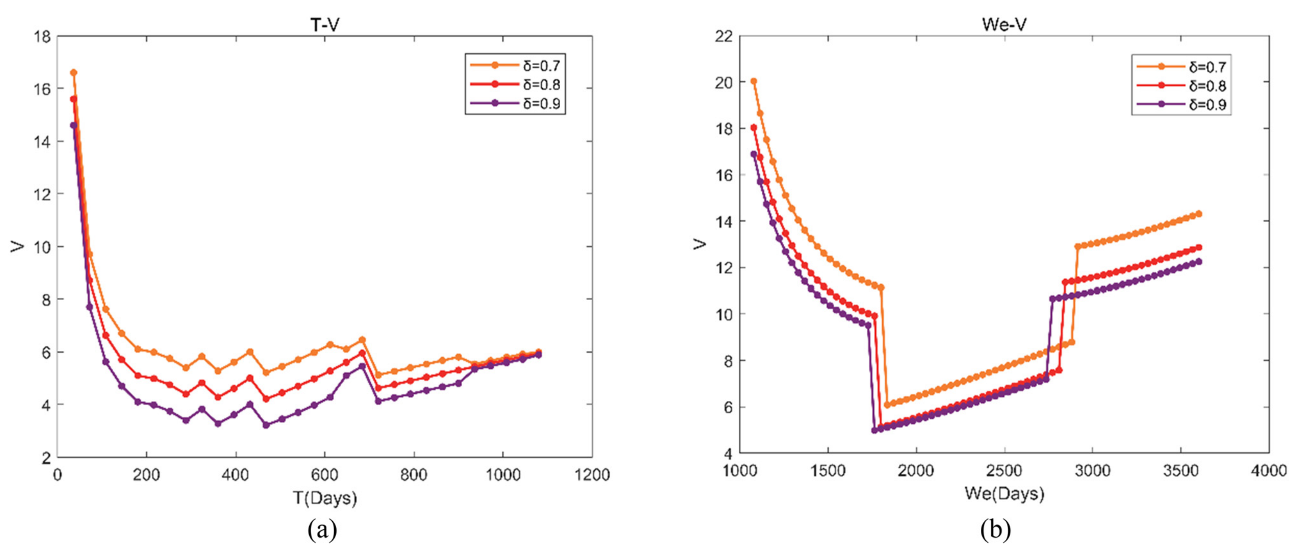

Figure 15: Sensitivity analysis of δ. (a) Sensitivity analysis of δ when W_e is fixed; (b) Sensitivity analysis of δ when T is fixed.

imperfect PM on reducing the system failure rate is. On the contrary, the effect of imperfect PM on reducing the system failure rate is worse. In order to further verify the impact of imperfect PM improvement factors on the cost-effectiveness ratio per unit time for the system, on the basis of fixed PM interval T and EW period W_E, the cost-effectiveness ratio per unit time corresponding to different values of δ is calculated, and the T–V curve and the W_E–V curve are drawn, respectively

Figure 15(a) and (b) shows the variation trend of the system cost-effectiveness ratio per unit time with the imperfect PM improvement factor δ when W_E is 1,260 days and T is 576 days, respectively. It can be seen from the image that the cost-effectiveness ratio per unit time of the system decreases with the increase in the imperfect PM improvement factor δ. The imperfect PM improvement factor δ generally reflects the maintenance level of the manufacturer. The manufacturer could pursue a higher imperfect PM improvement factor δ by improving the quality of maintenance workers, improving maintenance technology, and strengthening technological innovation, so as to reduce the cost-effectiveness ratio per unit time for the system.

5 Conclusion

Considering the failure dependence between components, the imperfect PM and minimum maintenance strategy are used to obtain the optimal EW scheme of the wind turbine system in this article. Through the result analysis, the following conclusions can be drawn:

1) The optimal EW scheme of the system can be obtained accurately and effectively by using the genetic algorithm.
2) The PM is necessary. The EW cost is reduced by 34%, the availability is increased by 5.2%, and the cost-effectiveness ratio per unit time is reduced by 37% with PM.
3) Ignoring failure dependence will lead to unacceptable analysis errors.
4) The model established in this article can provide a quantitative analysis method for EW decision-making of failure dependence wind turbine system.

   In the future, there are many interesting research directions on this topic:

5) More complex failure dependence relationships among system components can be considered, such as common cause failure, interactive failure, and reserve redundancy, and the corresponding EW decision model can be established.
6) It can also study the formulation of EW scheme for failure dependence multi-component system under two-dimensional warranty strategy.
7) Through the field data of the wind turbine system, the failure distribution of the system is determined by regression fitting, and the failure rate function and parameters of the system are obtained, and then, the warranty period model and PM interval model of the system are determined.

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Appendix

The derivation process of formula (1)

Assuming that the multi-component system contains Z components, $h_{a0}(t)$ represents the independent failure rate of component a, $h_a(t)$ represents the actual failure rate of components, and $\mathbf{h_{ab}(t)_B}$ represents the relevant failure rate of all components that affect component a. Therefore, the actual failure rate function of each component is as follows:

$$\begin{cases} h_1(t) = \kappa_1[h_{10}(t), \mathbf{h_{1b}(t)_B}, t] \\ h_2(t) = \kappa_2[h_{20}(t), \mathbf{h_{2b}(t)_B}, t] \\ \vdots \\ h_a(t) = \kappa_a[h_{a0}(t), \mathbf{h_{ab}(t)_B}, t] \\ \vdots \\ h_Z(t) = \kappa_Z[h_{Z0}(t), \mathbf{h_{Zb}(t)_B}, t]. \end{cases}$$

By expanding the function of the above formula through the Taylor series expansion theorem, the analytical formula of the actual failure rate function of component a can be obtained.

$$\begin{aligned} h_a(t) &= \kappa_a[h_{a0}(t), \mathbf{h_{ab}(t)_B}, t] \\ &= \kappa_a|_{\overrightarrow{h_{ab}(t)_B}=0} + \textstyle\sum_{ab} \frac{\partial\kappa_a}{\partial h_{ab}}\Big|_{\overrightarrow{h_{ab}(t)_B}=0} h_{ab}(t)_B \\ &+ \textstyle\sum_{ab,ac} \frac{\partial^2\kappa_a}{2\partial h_{ab} h_{ac}}\Big|_{\overrightarrow{h_{ab}(t)_B}=0} h_{ab}(t)_B h_{ac}(t)_B \\ &+ \textstyle\sum_{ab} \frac{\partial^2\kappa_a}{\partial {h_{ab}}^2}\Big|_{\overrightarrow{h_{ab}(t)_B}=0} {h_{ab}}^2(t)_B + \ldots. \end{aligned}$$

Merging $h_{ab}(t)_B$ with similar items to obtain:

$$\begin{aligned} h_a(t) &= \kappa_a|_{\overrightarrow{h_{ab}(t)_B}=0} \\ &+ \sum_{ab}\left\{\left[\frac{\partial\kappa_a}{\partial h_{ab}}\Big|_{\overrightarrow{h_{ab}(t)_B}=0} + \sum_{ac}\frac{\partial^2\kappa_a}{2\partial h_{ab}h_{ac}}\Big|_{\overrightarrow{h_{ab}(t)_B}=0} h_{ac}(t)_B \right.\right. \\ &+ \left.\left.\frac{\partial^2\kappa_a}{\partial {h_{ab}}^2}\Big|_{\overrightarrow{h_{ab}(t)_B}=0} h_{ab}(t)_B + \ldots\right] \times h_{ab}(t)_B\right\}. \end{aligned}$$

Let $\mathbf{h_{ab}(t)_B} = \mathbf{0}$, indicating that component a is not affected by other components, so $\kappa_a|\overrightarrow{h_{ab}(t)_B} = h_{a0}(t)$.

Let:

$$\begin{aligned} \omega_{ab}(t) &= \frac{\partial\kappa_a}{\partial h_{ab}}|\overrightarrow{h_{ab}(t)_B} = 0 + \sum_{ac}\frac{\partial^2\kappa_a}{2\partial h_{ab}h_{ac}}|\overrightarrow{h_{ab}(t)_B} = 0 h_{ac}(t)_B \\ &+ \frac{\partial^2\kappa_a}{\partial h_{ab}^2}|\overrightarrow{h_{ab}(t)_B} = 0 h_{ab}(t)_B + \ldots. \end{aligned}$$

Then:

$$h_a(t) = h_{a0}(t) + \sum_{ab}[\omega_{ab}(t)][h_{ab}(t)].$$