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An opportunistic maintenance strategy for wind turbines

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Abstract

Maintenance strategies aim at reduction of the operation and maintenance cost of wind turbines. An opportunistic maintenance strategy offers cost advantages over the traditional preventive replacement maintenance strategy by considering cost dependency among maintenance activities. A new opportunistic maintenance strategy of wind turbines is proposed here. First, the proposed strategy includes two sets of reliability thresholds to handle subassemblies those are in operational and failed wind turbines. Using the reliability thresholds, ten maintenance modes and their service conditions are presented. Second, the Weibull distribution with an age reduction factor is introduced to describe reliability variation of subassemblies under imperfect maintenance. Third, the maintenance cost in each maintenance mode is expressed by a reliability variation-based function that is dependent on the stage of maintenance activities. Fourth, due to the randomness of failures, the expected total maintenance cost is determined with Monte Carlo simulation. The proposed approach has been validated with the data provided by a wind farm located in Northern China.

1 | INTRODUCTION

Operation and maintenance activities could make a significant cost to wind power generation, for example, 28.3% of the total cost of wind energy production in China [1]. Thus, new maintenance strategies to benefit wind energy industry are needed [2].

Wind farms generally use a traditional preventive replacement maintenance (TPRM) strategy, where components are replaced at scheduled intervals. The intervals are determined for each subassembly, however, the TPRM strategy does not address the cost dependency among the maintenance activities of components and subassemblies of a wind turbine [3, 4]. Group maintenance strategy considers the cost dependency to minimize the total maintenance cost of a wind turbine [5]. Opportunistic maintenance (OM) strategy, one of the group maintenance strategy, views preventive replacement or stochastic failure as a maintenance opportunity and selects the subassemblies requiring maintenance under this opportunity [6].

Opportunistic maintenance has received attentions in the literature. The maintenance modes contain minimum maintenance, imperfect maintenance and replacement. The minimum maintenance brings a subassembly back to work but cannot enhance its reliability, such as switching on a tripping switch, fastening bolts and so on. The imperfect maintenance is a maintenance mode that can restore the subassembly reliability to some extent but lower than a new subassembly reliability. For example, only replacing one or two components of a subassembly is equivalent to carry out imperfect maintenance on this subassembly. As only one or two components of this subassembly is replaced while the other components keep original reliability, the reliability of this subassembly restores to some extent but still lower than a new subassembly reliability. To distinguish between failed and operational wind turbines, Ding and Tian [7, 8] introduced different imperfect maintenance thresholds. Sometimes, the maintenance schedules are influenced by external weather conditions and resource constraints. The weather conditions contain seasonal factor, short-term and predictive information of wind, etc. In light of these, Su et al. [9] considered the influence of seasonal factor into the opportunistic maintenance optimization. Yang et al. [10] designed a wind-centred maintenance policy integrating multiple maintenance opportunities, which successfully integrated diverse impacts of wind conditions and resource constraints into the decision-making process. Patriksson et al. [11, 12] established a stochastic opportunistic maintenance model where short-term and predictive information was integrated to make decisions for a fleet of wind turbines [13–15]. Erguido et al. [16, 17] proposed a dynamic OM strategy involving a reliability threshold that varied according to the weather conditions. The resource constraints contain data and information requisites, maintenance group quantity, spare parts inventory status etc. In view of the resource constraints, Izquierdo et al. [18] proposed a technical framework that considers the data and information requisites, integrated a clustering-based reliability model with a dynamic opportunistic maintenance policy. Abdollahzadeh et al. [19–21] researched a multi-objective opportunistic maintenance with a limited number of maintenance groups and optimized a joint modular redundancy allocation at fixed inspection intervals. Refs. [22, 23] considered the ordering and storing management of spare parts into the opportunistic maintenance.

In addition, the accuracy and rationality of maintenance strategy can be improved by introducing some advanced models, analytic methods and optimization process. In this respect, Zhao et al. [24] utilized Weibull proportional hazards model or Weibull proportional intensity model to describe the degeneration of each component and defined condition indicators to characterize the operating state of each component. Then, when and how to maintain a component can be confirmed by comparing the value of the condition indicator with that of the maintenance threshold function. Zhou and Yin [25] proposed a dynamic opportunistic condition-based maintenance strategy for offshore wind farm by using predictive analytics. Moreover, structural dependence was considered in [26] to improve the traditional OM strategy. In [27], optimization of the maintenance intervals of subassemblies was followed by the threshold of opportunistic maintenance to minimize total maintenance cost.

The literature has concentrated on improving one aspect of the opportunistic maintenance strategy, instead of synthetically considering several factors affecting the strategy. To take full advantages of achievements of existing literature and form a complete opportunistic maintenance strategy for wind turbines, this paper proposes an integrated OM strategy for wind turbines, where two sets of reliability thresholds under different maintenance opportunities are established to distinctively treat the subassemblies in operational and failed wind turbines. All maintenance modes in the proposed OM strategy are summarized and their service conditions are confirmed based on the reliability thresholds. As some maintenance modes are related to imperfect maintenance, Weibull distribution with an age reduction factor is introduced to describe reliability variation of subassemblies under imperfect maintenance. According to these reliability variations and the diverse stages of the maintenance activities, a model is proposed to uniformly express the maintenance cost involving all maintenance modes. Monte Carlo simulation is proposed to generate the expected total maintenance cost. The paper is organized in five sections. The proposed OM strategy for wind turbines is discussed in Section 2. The Monte Carlo based simulation of the proposed OM strategy is presented in Section 3. In Section 4, a maintenance case study from a wind farm in Northern China is introduced to validate the effectiveness of the proposed OM strategy. Section 5 concludes the paper.

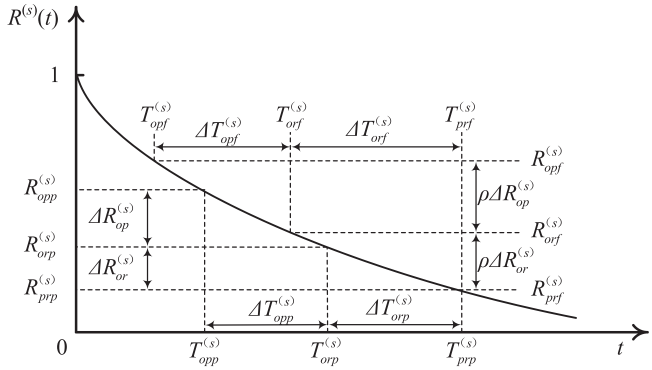

FIGURE 1 Reliability thresholds of the proposed OM strategy for different maintenance opportunities

2 | THE PROPOSED OPPORTUNISTIC MAINTENANCE STRATEGY

2.1 | Maintenance opportunities and reliability thresholds in the proposed strategy

Any failure or a preventive replacement of a subassembly could become a maintenance opportunity for other subassemblies. The maintenance mode of each subassembly is identified and multiple subassemblies are simultaneously maintained under this opportunity, which reduces the maintenance cost. The proposed OM strategy divides the reliability curve of subassembly s into four sections by the assignment of threshold $R^{(s)}_{prp}$ of preventive replacement, threshold $R^{(s)}_{orp}$ of opportunistic replacement, and threshold $R^{(s)}_{opp}$ of opportunistic imperfect maintenance, which is illustrated in Figure 1

The proposed OM strategy establishes two sets of reliability thresholds according to the different maintenance opportunities as illustrated in Figure 1 $R^{(s)}_{prp}$, $R^{(s)}_{orp}$ and $R^{(s)}_{opp}$ are the thresholds of preventive replacement, opportunistic replacement, and opportunistic imperfect maintenance under the maintenance opportunity from preventive replacement. $R^{(s)}_{prf}$, $R^{(s)}_{orf}$ and $R^{(s)}_{opf}$ are the three thresholds under the maintenance opportunity from stochastic failure. The reason of establishing two sets of thresholds is that the failure is due to a failed wind turbine, and the preventive replacement stems from an operational wind turbine. The non-failed subassemblies in a failed wind turbine are more likely to be affected by the failed subassembly. Moreover, a failure reduces performance of a wind turbine. Therefore, the

TABLE 1 Maintenance modes of the proposed OM strategy

No.	Maintenance mode	Service condition	Subassembly	Opportunity source
1	Minimum maintenance brought by failure	$R^{(s)} > R^{(s)}_{opf}$	$s = f$	Maintenance of the failed subassembly f
2	Imperfect maintenance brought by failure	$R^{(s)}_{orf} < R^{(s)} < R^{(s)}_{opf}$		
3	Replacement brought by failure	$R^{(s)}_{prf} < R^{(s)} < R^{(s)}_{orf}$		
4	Opportunistic no maintenance brought by failure	$R^{(s)} > R^{(s)}_{opf}$	$s \neq f$	
5	Opportunistic imperfect maintenance brought by failure	$R^{(s)}_{orf} < R^{(s)} < R^{(s)}_{opf}$		
6	Opportunistic replacement brought by failure	$R^{(s)}_{prf} < R^{(s)} < R^{(s)}_{orf}$		
7	Preventive replacement	$R^{(s)} < R^{(s)}_{prp}$	$s = f$	Preventive replacement of subassembly f
8	Opportunistic no maintenance brought by preventive replacement	$R^{(s)} > R^{(s)}_{opp}$	$s \neq f$	
9	Opportunistic imperfect maintenance brought by preventive replacement	$R^{(s)}_{orp} < R^{(s)} < R^{(s)}_{opp}$		
10	Opportunistic replacement under preventive replacement	$R^{(s)}_{prp} < R^{(s)} < R^{(s)}_{orp}$		

non-failed subassemblies in the failed wind turbines should be given more attention. The above reasoning implies a larger reliability threshold interval for a failure than that for a preventive replacement. The relationship between the two set of thresholds is expressed as Equation (1).

$$\begin{cases} R^{(s)}_{prf} = R^{(s)}_{prp} \\ R^{(s)}_{orp} = R^{(s)}_{prp} + \Delta R^{(s)}_{or} \\ R^{(s)}_{opp} = R^{(s)}_{orp} + \Delta R^{(s)}_{op} \\ R^{(s)}_{orf} = R^{(s)}_{prf} + \rho \cdot \Delta R^{(s)}_{or} \\ R^{(s)}_{opf} = R^{(s)}_{orf} + \rho \cdot \Delta R^{(s)}_{op} \end{cases} \tag{1}$$

where a significance coefficient $\rho \geq 1$ is introduced to reflect a concern related to the failure of a subassembly. Compared with the preventive replacement of a subassembly, the stochastic failure is more concerned by engineers. The significance coefficient p reflects this concerned degree and its value is greater than or equal to 1. If the engineers pay more attention to the failed wind turbines and considers the non-failed subassemblies more likely to be affected by the failed subassembly, the significance coefficient should be set as a larger value. In this paper, we set ρ as 1.20. The values $\Delta R^{(s)}_{or}$ and $\Delta R^{(s)}_{op}$ are the threshold intervals of an opportunistic replacement and an opportunistic imperfect maintenance under the maintenance opportunity from the preventive replacement.

2.2 | Selection of maintenance modes

The proposed OM strategy summarized ten available maintenance modes in Table 1 In one maintenance, only one maintenance mode is available for each subassembly.

Based on the reliability thresholds discussed in Section 2.1, the service conditions of each maintenance mode are provided in Table 1 If the maintenance opportunity is due to the maintenance of a failed subassembly f, the modes 1 to 6 are available for subassembly s. If the maintenance opportunity stems from the preventive replacement of a subassembly f in an operational wind turbine, the modes 7–10 are feasible for subassembly s. The modes 1–3 and 7 are for the subassembly f offering a maintenance opportunity. Under the opportunity, modes 4 to 6 and 8 to 10 are available for other subassemblies.

Modes 3, 6, 7 and 10 involve replacement. These four modes restore the subassembly reliability to the same level as a new subassembly and are suitable for subassemblies with lower reliability and shorter lifetime. Modes 2, 5 and 9 involve imperfect maintenance. The three modes restore the subassembly reliability to some extent and are suitable for subassemblies with medium reliability. As these subassemblies have medium lifetime and require maintenance to a certain degree rather than a replacement. Modes 1, 4 and 8 involve no maintenance at all or minimum maintenance. The three modes do not change the subassembly reliability and are suitable for subassemblies with high reliability. Due to a long lifetime of these subassemblies, no excessive maintenance is needed.

2.3 | The proposed opportunistic maintenance strategy

The proposed OM strategy groups subassemblies based on the two sets of reliability thresholds and the service conditions listed in Table 1 Combining with the subassembly reliability, the maintenance mode of each subassembly is labelled. The proposed OM strategy is illustrated in Figure 2 which is a theoretical example for four hypothetical subassemblies.

The graphs on the left in Figure 2 represent opportunistic maintenance from the preventive replacement and on the right from failures.

At time $T_{(1)}$, subassembly a requires a preventive replacement (mode 7) due to its reliability lower than the threshold $R^{(a)}_{prp}$.

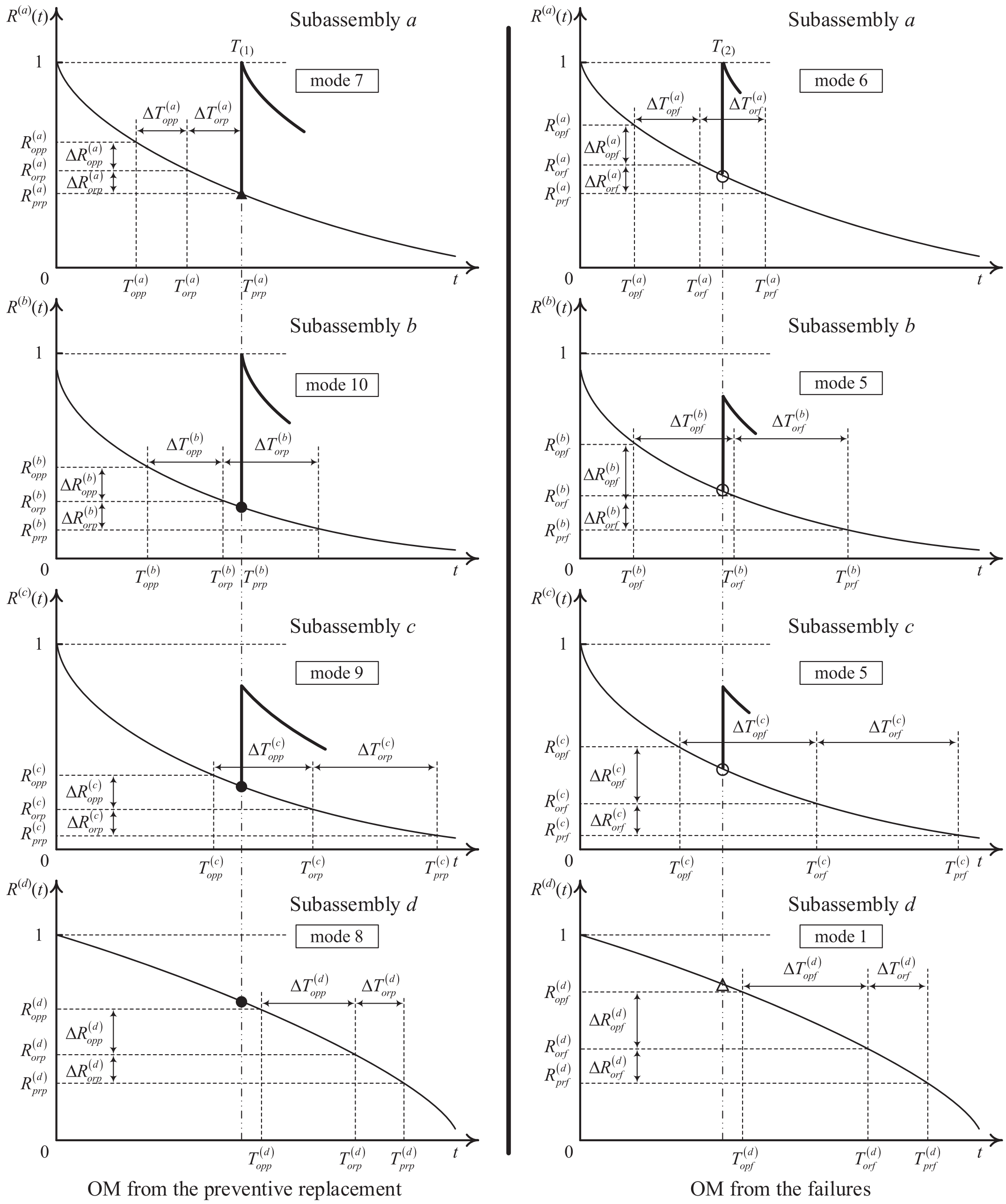

FIGURE 2 The proposed OM strategy for wind turbines

This preventive replacement generates a maintenance opportunity for subassemblies *b*, *c* and *d*. Their maintenance modes are labelled according to their reliability and the service conditions listed in Table 1 Subassembly *b* needs an opportunistic replacement (mode 10) as its reliability is higher than the threshold $R_{prp}^{(b)}$ but lower than the threshold $R_{orp}^{(b)}$. Subassembly *c* calls for an opportunistic imperfect maintenance (mode 9) due to its reliability higher than the threshold $R_{orp}^{(c)}$, but lower than the threshold $R_{opp}^{(c)}$. Subassembly *d* has no need for maintenance (mode 8) due to its reliability higher than the threshold $R_{opp}^{(d)}$.

At time $T_{(2)}$, subassembly *d* fails, and thus brings a maintenance opportunity. Under this opportunity, subassembly *a* needs the opportunistic replacement (mode 6) due to its reliability higher than the threshold $R_{prf}^{(a)}$ but lower than the threshold $R_{orf}^{(a)}$. Subassembly *b* needs the opportunistic imperfect maintenance (mode 5) due to its reliability higher than the thresholds $R_{orf}^{(b)}$ but lower than the thresholds $R_{opf}^{(b)}$. Similarly, subassembly *c* needs the opportunistic imperfect maintenance as well. For the failed subassembly *d*, the minimum maintenance (mode 1) is needed due to its reliability higher than the threshold $R_{orf}^{(d)}$.

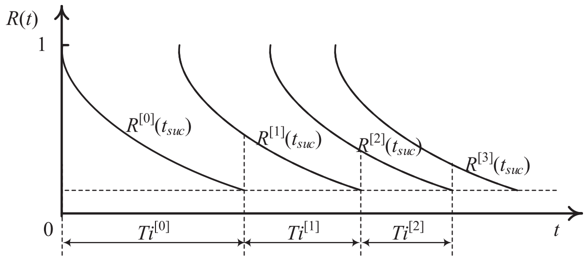

FIGURE 3 Reliability variation of the subassembly under the imperfect maintenance

2.4 | Imperfect maintenance considered reliability description of subassemblies

The reliability of a turbine subassembly is usually modelled with Weibull distribution [28]. The corresponding failure rate and reliability functions are expressed as Equations (2) and (3).

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{2}$$

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{3}$$

where, β and η are the shape parameter and the scale parameter of the Weibull distribution, respectively. These parameters can be obtained with estimation methods such as the support vector regression [29], the least square method [30], and the Bayesian parameter estimation [31].

The function in Equation (3) begins at 1 (the reliability of a new subassembly), however, the subassembly reliability cannot be fully restored after imperfect maintenance as shown in Figure 3

Figure 3 shows that the ability of restoring reliability decreases as the imperfect maintenance count increases. This variation can be depicted by the Weibull distribution with an age reduction factor. The corresponding failure rate function and reliability function are expressed in Equations (4) and (5).

$$\begin{cases} \lambda^{[0]}(t_{suc}) = \lambda(t_{suc}) = \dfrac{\beta}{\eta}\left(\dfrac{t_{suc}}{\eta}\right)^{\beta-1}, \\ \quad t_{suc} \in \left(0, Ti^{[0]}\right), \quad m = 0 \\ \lambda^{[m]}(t_{suc}) = \lambda^{[m-1]}\left(t_{suc} + a^{[m]}Ti^{[m-1]}\right), \\ \quad t_{suc} \in \left(0, Ti^{[m]}\right), \quad m = 1, 2, \ldots, M \end{cases} \tag{4}$$

$$R^{[m]}(t_{suc}) = \exp\left\{-\left(\frac{t_{suc} + \sum_{j=0}^{m} a^{[j]}Ti^{[j-1]}}{\eta}\right)^{\beta}\right\}, \times t_{suc} \in \left(0, Ti^{[m]}\right) \tag{5}$$

where, t_{suc} is the time since the last replacement or imperfect maintenance, m indicates the mth imperfect maintenance, M is the total count of imperfect maintenance cases, $\lambda^{[m]}(t_{suc})$ and $R^{[m]}(t_{suc})$ are the failure rate function and the reliability function after the mth imperfect maintenance, $Ti^{[m]}$ is the time interval between the mth and $(m+1)$th imperfect maintenance, $a^{[m]}$ is the age reduction factor after the mth imperfect maintenance. During the replacement, $M = 0$, $m = 0$, $a^{[0]} = 0$. During the imperfect maintenance, the age reduction factor can be obtained according to maintenance history of subassemblies. Usually, maintenance engineers are responsible for the determination of this factor [32–36]. Here, the age reduction factor is calculated as Equation (6).

$$a^{[m]} = \frac{m}{5m + 9} \tag{6}$$

2.5 | Reliability based maintenance cost analysis of subassemblies in wind turbines

The proposed OM strategy express the total maintenance cost C as Equation (7).

$$C = \sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{x=1}^{X} I^{[k](s)\{x\}} C^{[k](s)\{x\}} \tag{7}$$

where, K is the total maintenance count, S is the number of subassemblies, X is the number of alternative maintenance modes. $I^{[k](s)\{x\}}$ is indicator function, which is 1 if implementing maintenance mode x on subassembly s at the kth maintenance. On the remaining conditions, $I^{[k](s)\{x\}}$ equals to 0. $C^{[k](s)\{x\}}$ represents the maintenance cost of implementing maintenance mode x on subassembly s at the kth maintenance. According to the component of maintenance cost, $C^{[k](s)\{x\}}$ is uniformly computed by Equation (8), which is suitable for all subassemblies and all their maintenance modes at each maintenance.

$$C^{[k](s)\{x\}} = C_e^{[k](s)\{x\}} + C_m^{[k](s)\{x\}} + C_f^{[k](s)\{x\}} \tag{8}$$

where, $C_e^{[k](s)\{x\}}$ is the energy loss of implementing maintenance mode x on subassembly s at the kth maintenance, $C_m^{[k](s)\{x\}}$ is the direct cost, and $C_f^{[k](s)\{x\}}$ is the fixed cost from manpower and transportation. During the replacement, $C_m^{[k](s)\{x\}}$ depends only on the subassembly and equals to the subassembly price $c_m^{(s)}$. During the imperfect maintenance, $C_m^{[k](s)\{x\}}$ simultaneously depends on the subassembly and the restoring extent of its reliability. Based on the two above facts, this paper proposes a method to compute $C_m^{[k](s)\{x\}}$ under the imperfect maintenance by Equation (9).

$$C_m^{[k](s)\{x\}} = c_m^{(s)} \cdot \Delta R^{[k](s)} / \left(1 - R_{prp}^{(s)}\right) \tag{9}$$

TABLE 2 Time and cost of implementing different maintenance modes on subassembly s at the kth maintenance

Maintenance mode No. $\{x\}$	Maintenance time [h]					Maintenance cost [¥]	
	$T_w^{[k]\ (s)\{x\}}$	$T_a^{[k]\ (s)\{x\}}$	$T_c^{[k]\ (s)\{x\}}$	$T_s^{[k]\ (s)\{x\}}$	$T_m^{[k]\ (s)\{x\}}$	$C_f^{[k]\ (s)\{x\}}$	$C_m^{[k]\ (s)\{x\}}$
1	$t_w^{(s)}$	t_a	t_c	0	0	c_f	0
2	$t_w^{(s)}$	t_a	t_c	t_{s2}	$t_m^{(s)} \cdot \Delta R^{[k](s)}/(1-R_{prp}^{(s)})$	c_f	$c_m^{(s)} \cdot \Delta R^{[k](s)}/(1-R_{prp}^{(s)})$
3	$t_w^{(s)}$	t_a	t_c	t_{s3}	$t_m^{(s)}$	c_f	$c_m^{(s)}$
4	0	0	0	0	0	0	0
5	0	0	0	t_{s2}	$t_m^{(s)} \cdot \Delta R^{[k](s)}/(1-R_{prp}^{(s)})$	0	$c_m^{(s)} \cdot \Delta R^{[k](s)}/(1-R_{prp}^{(s)})$
6	0	0	0	t_{s3}	$t_m^{(s)}$	0	$c_m^{(s)}$
7	0	0	t_c	t_{s3}	$t_m^{(s)}$	c_f	$c_m^{(s)}$
8	0	0	0	0	0	0	0
9	0	0	0	t_{s2}	$t_m^{(s)} \cdot \Delta R^{[k](s)}/(1-R_{prp}^{(s)})$	0	$c_m^{(s)} \cdot \Delta R^{[k](s)}/(1-R_{prp}^{(s)})$
10	0	0	0	t_{s3}	$t_m^{(s)}$	0	$c_m^{(s)}$

where $\Delta R^{[k](s)}$ is the reliability variation of subassembly s before and after the kth maintenance.

The maintenance activities at a wind farm are categorized as waiting to a set-out activity, arriving at a wind turbine, climbing up to nacelles, hoisting up apparatus and maintaining failed subassemblies. Based on the activity stages above, Equation (10) is proposed to express the energy loss $C_e^{[k]\ (s)\{x\}}$:

$$C_e^{[k](s)\{x\}} = T^{[k](s)\{x\}} c_e = \left(T_w^{[k](s)\{x\}} + T_a^{[k](s)\{x\}} + T_c^{[k](s)\{x\}} + T_s^{[k](s)\{x\}} + T_m^{[k](s)\{x\}}\right) \cdot \tau \cdot P \cdot c_{ep} \quad (10)$$

where, $T^{[k](s)\{x\}}$ is the total downtime of implementing maintenance mode x on subassembly s at the kth maintenance, obtained by summing the time $T_w^{[k]\ (s)\{x\}}$ of waiting to set out, the time $T_a^{[k]\ (s)\{x\}}$ of arriving at wind turbines, the time $T_c^{[k]\ (s)\{x\}}$ of climbing up to nacelles, the time $T_s^{[k]\ (s)\{x\}}$ of hoisting up apparatus, and the time $T_m^{[k]\ (s)\{x\}}$ of maintaining failed subassemblies. c_e is the energy loss of the unit downtime, obtained by multiplying the wind turbine capacity coefficient τ, rated power P and electricity price c_{ep}. Actually, the energy loss depends on the wind resource, the weather condition when the maintenance happens, and other factors. To simplify the calculation of energy loss, the above dependency factors are converted into a coefficient, namely the capacity coefficient τ used in our current model.

In the proposed OM strategy, the time $T_w^{[k]\ (s)\{x\}}$, $T_a^{[k]\ (s)\{x\}}$, $T_c^{[k]\ (s)\{x\}}$ and the cost $C_f^{[k]\ (s)\{x\}}$ are undertaken by the subassembly that leads to a maintenance opportunity. Therefore, the time $T_w^{[k]\ (s)\{x\}}$, $T_a^{[k]\ (s)\{x\}}$, $T_c^{[k]\ (s)\{x\}}$ and the cost $C_f^{[k]\ (s)\{x\}}$ equal to 0 when $x = 4, 5, 6, 8, 9$ and 10, but the time $T_c^{[k]\ (s)\{x\}}$ is simplified to t_c and the cost $C_f^{[k]\ (s)\{x\}}$ is simplified to c_f when $x = 1, 2, 3$ and 7, because they only depend on maintenance mode. In addition, under the preventive replacement, wind turbines keep running before the stage of climbing up to nacelles. Therefore, the time $T_w^{[k]\ (s)\{x\}}$ and $T_a^{[k]\ (s)\{x\}}$ equal to 0 when $x = 7$. As the time $T_w^{[k]\ (s)\{x\}}$ depends on the subassembly and its maintenance mode, $T_w^{[k]\ (s)\{x\}}$ is simplified to $t_w^{(s)}$ when $x = 1, 2$ and 3. The time $T_a^{[k]\ (s)\{x\}}$ is simplified to t_a when $x = 1, 2$ and 3, because it only depends on maintenance mode.

The time $T_s^{[k]\ (s)\{x\}}$, $T_m^{[k]\ (s)\{x\}}$ and the cost $C_m^{[k]\ (s)\{x\}}$ cannot be shared according to the proposed OM strategy. The quantity of apparatus needed, the maintenance time and the direct cost vary according to the extent that the reliability is to be restored. The time $T_s^{[k]\ (s)\{x\}}$ depends on maintenance mode only, which is assigned as 0, t_{s2} and t_{s3} under no or minimum maintenance, imperfect maintenance and replacement. During the replacement, $T_m^{[k]\ (s)\{x\}}$ depends only on the type of a subassembly and equals to the time $t_m^{(s)}$ of replacing the subassembly. During the imperfect maintenance, $T_m^{[k]\ (s)\{x\}}$ simultaneously depends on the subassembly and the restoring extent of its reliability. Based on the two above factors, this paper proposes a method to calculate $T_m^{[k]\ (s)\{x\}}$ under the imperfect maintenance by Equation (11).

$$T_m^{[k](s)\{x\}} = t_m^{(s)} \cdot \Delta R^{[k](s)} / \left(1 - R_{prp}^{(s)}\right) \quad (11)$$

The time and cost of implementing each maintenance mode listed in Table 1 on subassembly s at the kth maintenance are summarized in Table 2

In Table 2 the values of $t_w^{(s)}$, t_a, t_c, t_{s2}, t_{s3} and c_f can be obtained by the statistic on the historical failure data and the maintenance cost data from wind farms.

3 | MONTE CARLO BASED SIMULATION OF THE PROPOSED OM STRATEGY

The randomness of failures makes maintenance cost C and count K be random. In this paper the Monte Carlo simulation is used to get the expected values of C and K. As the range of reliability is from 0 to 1, a random number sampled from the 0–1 uniform distribution is utilized to simulate a stochastic failure. If the random number is larger than the current reliability of a subassembly, the subassembly is considered occurring a stochastic failure, otherwise, considered operating normally. In each simulation, the total maintenance cost and the total maintenance count are recorded. By averaging the results of multiple simulations, the expectations of C and K are obtained. The Monte Carlo based simulation process of the proposed OM strategy is shown as Table 3

TABLE 3 Monte Carlo based simulation process of the proposed OM strategy

Monte Carlo based simulation process of the proposed OM strategy
Collect the historical failure data and the maintenance cost data to estimate the shape parameter $\beta^{(s)}$ and the scale parameter $\eta^{(s)}$ of each subassembly in wind turbines, where $s = 1, 2, \ldots, S$;
Conduct statistics on the time $t_w^{(s)}$ of waiting to set out, the time t_a of arriving at wind turbines, the time t_c of climbing up to nacelles, the time t_{s2} and t_{s3} of hoisting up apparatus, the time $t_m^{(s)}$ of maintaining failed subassemblies, the fixed cost c_f from manpower and transportation, and the subassembly price $c_m^{(s)}$;
Calculate the energy loss c_e of unit downtime according to the wind turbine capacity coefficient τ, the rated power P and the electricity price c_{ep};
Set the reliability threshold $R_{prp}^{(s)}$ of preventive replacement, the threshold interval $\Delta R_{or}^{(s)}$ of opportunistic replacement, the threshold interval $\Delta R_{op}^{(s)}$ of opportunistic imperfect maintenance and the significance coefficient ρ;
Calculate the reliability thresholds $R_{orp}^{(s)}$ of opportunistic replacement and $R_{opp}^{(s)}$ of opportunistic imperfect maintenance under the maintenance opportunity from the preventive replacement;
Calculate the reliability thresholds $R_{prf}^{(s)}$ of preventive replacement, $R_{orf}^{(s)}$ of opportunistic replacement and $R_{opf}^{(s)}$ of opportunistic imperfect maintenance under the maintenance opportunity from the stochastic failure;
Set the total count N of Monte Carlo simulation and initialize the current simulation count $n = 1$;
While $n < N$ **do**
Initialize the total maintenance cost $C_t^{\langle n \rangle} = 0$ at the n^{th} simulation and the cumulative operating time $T_{cum} = 0$;
Initialize the current maintenance count $k = 1$
While $T_{cum} < T$ **do**
Compute the intervals from the current time to the time with $R_{prp}^{(s)}$ for each subassembly;
Denote the minimum interval as T_{in};
Divide nodes between 1 and T_{in} in days; Initialize the current node $ti = 1$;
While $ti < T_{in}$ **do**
Sample the random numbers $U^{(s)}$ from the 0∼1 uniform distribution for each subassembly;
If $R^{(s)}(ti) > U^{(s)}$ for all subassemblies **do** $ti = ti + 1$;
Else do
Set the maintenance interval $T_{in}^{[k]} = ti$ at the k^{th} maintenance;
Compare $R^{(s)}(T_{in}^{[k]})$ with the thresholds $R_{orf}^{(s)}$ and $R_{opf}^{(s)}$ to confirm maintenance modes for each subassembly;
Break;
End If
End While
If $ti > T_{in}$ **do**
Set the maintenance interval $T_{in}^{[k]} = T_{in}$ at the k^{th} maintenance;
Compare $R^{(s)}(T_{in}^{[k]})$ with the thresholds $R_{orp}^{(s)}$ and $R_{opp}^{(s)}$ to confirm maintenance modes for each subassembly;
End If
Update the reliability $R^{(s)}(t)$ for each subassembly according to their maintenance modes, $k = k + 1$;
Compute the total maintenance cost $C^{[k]} = \sum_{s=1}^{S} C^{[k](s)}$ at the k^{th} maintenance;
Compute the cumulative operating time $T_{cum} = \sum_{i=1}^{k} T_{in}^{[i]}$;
End While
Calculate the total maintenance cost $C^{<n>} = \sum_{i=1}^{k} C^{[k]}$ and count $K^{<n>} = k$ at the n^{th} simulation, $n = n + 1$;
End While
Calculate and export the expected total maintenance cost $E(C)$ and count $E(K)$.

4 | CASE STUDY

4.1 | Data description

The data has originated from 66 wind turbines of identical type installed in Northern China. The wind turbines have the rated power of 1.5 MW and were put into operation in 2010. During the eight year operations, a large volume of failure data and maintenance cost data has been collected. In this research failure and cost data from 13 subassemblies has been used.

First, the shape parameter $\beta^{(s)}$ and the scale parameter $\eta^{(s)}$ of each subassembly are estimated by the least square method. Then the statistics on the maintenance time and cost is made. The results are listed in Table 4 Moreover, other required parameters of the proposed OM strategy for wind turbines are listed in Table 5

In Table 5 wind turbine capacity coefficient comes from the design handbook of this type of wind turbines. Electricity price refers to the grid purchase price in the area wind turbines installed. Operating life cycle is in accordance with the design service life of wind turbines, namely twenty years. The time of arriving at wind turbines t_a, the time of climbing up to nacelles t_c, the time of hoisting up apparatus under imperfect maintenance t_{s2}, and the time of hoisting up apparatus under replacement t_{s3} derive from the statistic on the time of each stage during maintenance. The fixed cost c_f is set with the consideration of the manpower and transportation, such as the worker salaries, purchase and lease of transport machines, fuel consumption etc. The threshold of preventive replacement $R_{prp}^{(s)}$, the threshold intervals of opportunistic imperfect maintenance $\Delta R_{or}^{(s)}$, and the threshold intervals of opportunistic replacement $\Delta R_{op}^{(s)}$ are preliminarily set to validate the effectiveness of the proposed OM strategy. In the future research, these threshold will be further optimized. The significance coefficient ρ is set as 1.20, which means the failed wind turbines are given more consideration.

TABLE 4 Reliability and maintenance parameters of 13 subassemblies

No. (s)	Subassembly	$\beta^{(s)}$	$\eta^{(s)}$	$t_w^{(s)}$ [h]	$t_m^{(s)}$ [h]	$c_m^{(s)}$ [¥]
1	Crowbar resistance	0.941	604.81	0.40	7.62	5071
2	UPS	1.775	1372.90	0.31	3.76	1575
3	350A insurance	1.141	741.56	0.35	10.74	333
4	Generator encoder	1.346	1150.11	0.11	7.24	1507
5	Pitch battery	1.194	1028.70	0.76	20.81	653
6	Generator brush	1.181	656.75	0.43	7.56	279
7	Anti-freezing solution	1.038	1590.02	0.91	7.24	76
8	Anemograph	1.402	838.39	0.33	9.89	2700
9	Slip ring	1.125	706.14	0.28	13.13	13676
10	Collecting ring	1.054	861.43	0.05	10.21	16500
11	Filter resistance	1.368	1226.74	0.50	8.92	349
12	Oil pump motor	1.474	1026.59	0.08	6.64	2600
13	Oil-cooling fuel filter element	1.045	1028.83	0.11	9.78	1902

4.2 | Application of the proposed OM strategy to wind turbines

Based on the process narrated in Section 3 and the parameters listed in Tables 4 and 5, 10,000 simulations have been completed. Taking once simulation as an example, the maintenance schedules of the 13 subassemblies in wind turbines are shown in Table 6 and the reliability variations of each subassembly are illustrated in Figure 4

In Table 6 the time, cost and tasks of each maintenance are provided. In once maintenance, ten maintenance modes are alternative and their number are consistent with Table 1 The reliability variation of the 13 subassemblies at the first eleven times maintenance are shown in Figure 4 which shows the two sets of reliability thresholds as well. The maintenance mode of a subassembly is determined by the relationship between its reliability at the maintenance moment and the threshold.

Taking the second maintenance as an example, Table 6 shows that it comes at the cost of ¥ 32215 and occurs in the 64th day. This maintenance is caused by the stochastic failure of subassembly 10. Since its reliability is under the threshold $R_{opf}^{(s)}$ but over the threshold $R_{orf}^{(s)}$ as shown in Figure 4 subassembly 10 needs the imperfect maintenance (mode 2), which generates a maintenance opportunity. Under the opportunity, subassemblies 2, 4, 5, 7, 8, 11 and 12 need the opportunistic no maintenance (mode 4) due to their reliability over the threshold $R_{opf}^{(s)}$, and subassemblies 1, 3, 6, 9 and 13 need the opportunistic imperfect maintenance (mode 5) due to their reliability under the threshold $R_{opf}^{(s)}$ but over the threshold $R_{orf}^{(s)}$. After this maintenance, the reliability of subassemblies 2, 4, 5, 7, 8, 11 and 12 remains unchanged, but the reliability of subassemblies 1, 3, 6, 9, 10 and 13 restores to some extent according to the regulation depicted by Equation (5).

TABLE 5 Parameters required for implementation of the proposed OM strategy

No.	Parameter	Symbol	Value
1	Wind turbine capacity coefficient	τ	0.23
2	Electricity price	c_{ep}	0.52 ¥/kWh
3	Operating life cycle	T	175200 h (20 years)
4	Time of arriving at wind turbines	t_a	0.5 h
5	Time of climbing up to nacelles	t_c	0.5 h
6	Time of hoisting up apparatus under imperfect maintenance	t_{s2}	0.5 h
7	Time of hoisting up apparatus under replacement	t_{s3}	1.0 h
8	Fixed cost	c_f	¥ 2170
9	Threshold of preventive replacement	$R_{prp}^{(s)}$	0.90 ($s = 1, 2, \ldots, S$)
10	Threshold intervals of opportunistic imperfect maintenance	$\Delta R_{or}^{(s)}$	0.01 ($s = 1, 2, \ldots, S$)
11	Threshold intervals of opportunistic replacement	$\Delta R_{op}^{(s)}$	0.04 ($s = 1, 2, \ldots, S$)
12	Significance coefficient	ρ	1.20

The 5th maintenance shows an example under the maintenance opportunity from the preventive replacement. It comes at the cost of ¥ 38731 and occurs in the 196th day. As shown in Figure 4 this maintenance opportunity is generated by the preventive replacement (mode 7) of subassembly 6, because its reliability is under the threshold $R_{prp}^{(s)}$. Under this opportunity, subassemblies 2, 4, 8, 11, 12 and 13 need the opportunistic no maintenance (mode 8) due to their reliability over the threshold $R_{opp}^{(s)}$, and subassemblies 1, 3, 5, 7 and 9 need the opportunistic imperfect maintenance (mode 9) due to their reliability under the threshold $R_{opp}^{(s)}$ but over the threshold $R_{orp}^{(s)}$. For subassembly 10, the opportunistic replacement (mode 10) is needed, because its reliability is under the threshold $R_{orp}^{(s)}$ but over the threshold $R_{prp}^{(s)}$. It should be noted that the reliability of subassemblies 6 and 10 restores as new after the 5th maintenance.

Additionally, it can be seen from Figure 4 the ability of restoring reliability of the imperfect maintenance decreases as the maintenance count increases until the next replacement. For example, the reliability restoring extent of subassembly 1 gradually decreases under the first three imperfect maintenance, until the preventive replacement in the 4$^{\text{th}}$ maintenance restores the reliability as new.

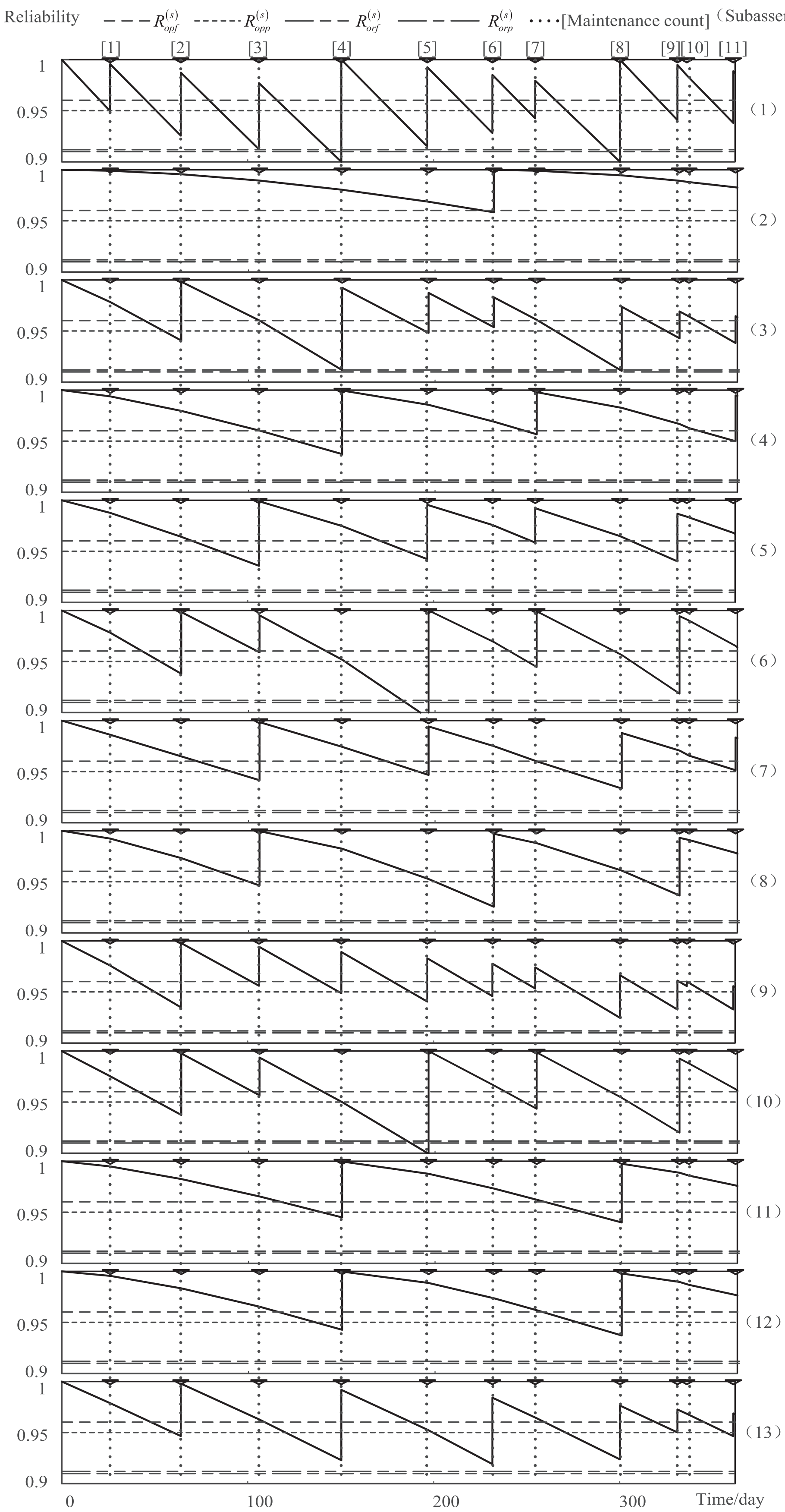

FIGURE 4 Reliability variation of 13 subassemblies using the proposed OM strategy

TABLE 6 Maintenance schedules for 13 subassemblies using the proposed OM strategy

			Task: Maintenance modes of each subassembly												
Count	**Time [day]**	**Cost [¥]**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1	26.0	5481	2	4	4	4	4	4	4	4	4	4	4	4	4
2	64.0	32215	**5**	**4**	**5**	**4**	**4**	**5**	**4**	**4**	**5**	**2**	**4**	**4**	**5**
3	106.0	26614	5	4	4	4	5	5	5	5	5	5	4	4	1
4	150.3	25227	7	8	9	9	8	8	8	8	9	8	9	9	9
5	196.5	38731	**9**	**8**	**9**	**8**	**9**	**7**	**9**	**8**	**9**	**10**	**8**	**8**	**8**
6	231.5	18904	2	5	5	4	4	4	4	5	5	4	4	4	5
7	254.5	22295	5	4	4	5	5	5	4	1	5	5	4	4	4
8	300.1	23649	7	8	9	8	8	8	9	8	9	8	9	9	9
9	331.1	31693	5	4	2	4	5	5	4	5	5	5	4	4	5
10	336.1	3179	4	4	4	4	4	4	4	4	5	4	4	4	1
11	361.1	12995	5	4	5	5	4	4	5	4	5	4	1	4	5
…	…	…	…												

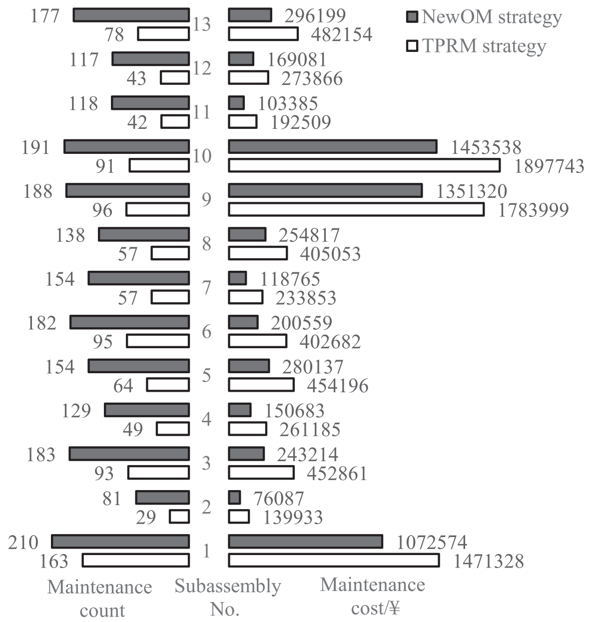

FIGURE 5 Expected maintenance count and cost of each subassembly under the two strategies

TABLE 7 Replacement intervals for each subassembly in TRPM strategy

Subassembly no.	1	2	3	4	5	6	7	8	9	10	11	12	13
Replacement intervals [day]	55	386	103	216	156	98	182	168	95	102	237	223	120

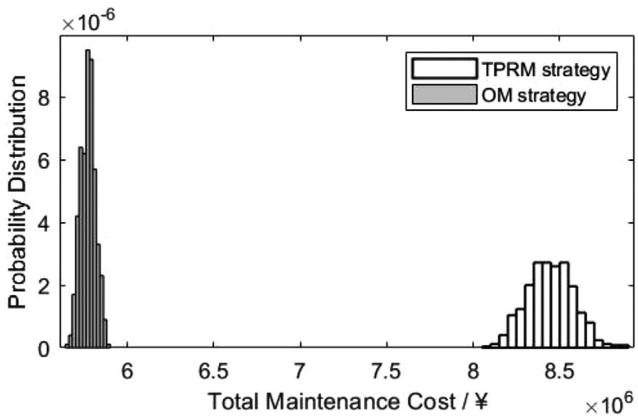

FIGURE 6 Total maintenance cost distribution for the two strategies

The maintenance schedules listed in Table 6 and the reliability variations shown in Figure 4 have stronger randomness, because the maintenance opportunity from the stochastic failures is considered in the proposed OM strategy. Compared with the strategy only considering the maintenance opportunity from the preventive replacement, the maintenance schedules under the proposed OM strategy are more flexible.

4.3 | Comparative analysis

In the simulations, the reliability thresholds of preventive replacement for each subassembly in TPRM strategy is set as listed in Table 5 which is same as the proposed OM strategy. Then, preventive replacement intervals for each subassembly can be calculated according to these thresholds and their reliability curve, which can be drawn based on the shape parameter $\beta^{(s)}$ and the scale parameter $\eta^{(s)}$ listed in Table 4 The obtained replacement intervals for each subassembly in TRPM strategy are shown in Table 7 Next, preventive replacement is carried out on each subassembly on the basis of these fixed intervals. According to the results of the 10,000 simulations, the statistics is conducted on the maintenance count and cost under the two strategies for each subassembly, and the results are illustrated in Figure 5

In Figure 5 the expected maintenance count of the proposed OM strategy is greater than TPRM strategy for each subassembly. The reason is that the subassemblies with higher reliability than the threshold $R_{prp}^{(s)}$ are maintained or replaced in advance. Nevertheless, the exchanged result is the remarkable reduction in the expectation of the maintenance cost for all subassemblies.

A histogram of total maintenance cost distribution for the two strategies is illustrated in Figure 6 Figure 6 shows that there is a remarkable difference between the total maintenance cost distribution for the two strategies, and the total maintenance cost distribution for the proposed OM strategy is much less than TPRM strategy.

Furthermore, the statistics is conducted on the total maintenance count and cost of the 13 subassemblies. Their expectations are listed in Table 8

TABLE 8 Expectations of the total maintenance count and cost under diverse strategies

Maintenance strategy	Expected total maintenance count	Expected maintenance cost [¥]			
		Energy loss	Fixed cost	Direct cost	Total
TPRM	957	2087529	2076559	4287274	8451362
Proposed OM	279	1619289	603362	3547706	5770358

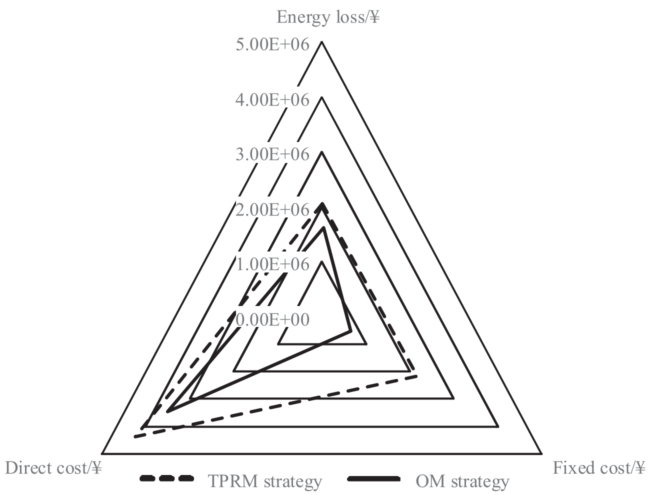

FIGURE 7 Components of the total maintenance cost under the two strategies

Table 8 shows that the proposed OM strategy reduces 70.84 percent of the expectation of the total maintenance count. From the perspective of each subassembly, the maintenance count under the proposed OM strategy is higher. However, during once maintenance of the proposed approach, several subassemblies are maintained simultaneously, which leads to the final result that the total maintenance count decreases substantially, as listed in Table 8 The total maintenance cost decreases by 31.72%, which implies that ¥ 2681004 is saved for the 13 subassemblies during their operating life cycle of 20 years. The components of the total maintenance cost are listed in Table 8 as well, which are further illustrated in Figure 7

The three vertices in Figure 7 represent the energy loss, the fixed cost, and the direct cost. The higher the cost is, the larger the triangle is. It can be obviously seen that the maximum component comes from the direct cost, no matter in TPRM strategy or the proposed OM strategy. In TPRM strategy, the fixed cost is close to the energy loss, however, the fixed cost obtains a larger extent of reductions than the energy loss and the direct cost by implementing the proposed OM strategy. This phenomenon meets the expectation of carrying out the proposed OM strategy. The strategy sufficiently utilizes the cost dependency among maintenance activities by maintaining several subassemblies simultaneously. Actually, the cost dependency mainly focuses on the fixed cost, which is caused by manpower and transportation.

The results above verify the effectiveness and superiority of the proposed OM strategy for wind turbines.

5 | CONCLUSION

A new opportunistic maintenance strategy for wind turbines was proposed, integrating advantages and overcoming shortages of existing literature, roundly considering factors affecting the opportunistic maintenance strategy, instead of focusing on one aspect. In the proposed, two sets of reliability thresholds were set to distinctively treat the subassemblies of operational and failed wind turbines. In addition, alternative maintenance modes and their service conditions were introduced. The reliability variation of subassemblies in the imperfect maintenance modes, was modelled using the Weibull distribution with an age reduction factor. To uniformly express the maintenance cost under different maintenance modes, a reliability variation-based function was introduced. A Monte Carlo approach was presented to compute the expected maintenance cost and count. Data from a wind farm located in Northern China showed that the total maintenance cost and count can be significantly reduced by implementing the proposed opportunistic maintenance strategy for wind turbines, thus validating its advantage over the traditional preventive replacement maintenance strategy.

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NOMENCLATURE

$R_{prp}^{(s)}$	Reliability threshold of preventive replacement for subassembly s in operational turbines
$R_{orp}^{(s)}$	Reliability threshold of opportunistic replacement for subassembly s in operational turbines
$R_{opp}^{(s)}$	Reliability threshold of opportunistic imperfect maintenance for subassembly s in operational turbines
$\Delta R_{or}^{(s)}$	Threshold intervals of opportunistic replacement for subassembly s in operational turbines
$C_e^{[k](s)\{x\}}$	Energy loss of maintenance mode x on subassembly s at the kth maintenance
$C_m^{[k](s)\{x\}}$	Direct cost of maintenance mode x on subassembly s at the kth maintenance
$C_f^{[k](s)\{x\}}$	Fixed cost of maintenance mode x on subassembly s at the kth maintenance
$c_m^{(s)}$	Cost of subassembly s
$R_{prf}^{(s)}$	Reliability threshold of preventive replacement for subassembly s in failed turbines
$R_{orf}^{(s)}$	Reliability threshold of opportunistic replacement for subassembly s in failed turbines
$R_{opf}^{(s)}$	Reliability threshold of opportunistic imperfect maintenance for subassembly s in failed turbines

$\Delta R_{op}^{(s)}$ Threshold intervals of opportunistic imperfect maintenance for subassembly s in operational turbines
$T_w^{[k](s)\{x\}}$ Time of waiting to set out of maintenance mode x on subassembly s at the kth maintenance
$T_a^{[k](s)\{x\}}$ Time of arriving at wind turbines of maintenance mode x on subassembly s at the kth maintenance
$T_c^{[k](s)\{x\}}$ Time of climbing up to nacelles of maintenance mode x on subassembly s at the kth maintenance
$T_s^{[k](s)\{x\}}$ Time of hoisting up apparatus of maintenance mode x on subassembly s at the kth maintenance
$T_m^{[k](s)\{x\}}$ Time of maintaining failed subassemblies of maintenance mode x on subassembly s at the kth maintenance
$t_m^{(s)}$ Time of replacing subassembly s
C Total maintenance cost
$C^{[k](s)\{x\}}$ Cost of maintenance mode x on subassembly s at the k^{th} maintenance.
c_e Cost of energy loss per unit of downtime
c_{ep} Electricity price
$I^{[k](s)\{x\}}$ Indicator function, equals to 1 if maintenance mode x is implemented on subassembly s at the kth maintenance; otherwise is 0
K Total maintenance count
k Maintenance number, $k = 1, 2, \ldots, K$
OM Opportunistic maintenance
P Rated power of wind turbines
$R^{(s)}$ Reliability of subassembly s
$R^{(s)}(t)$ Reliability of subassembly s at time t
S Number of subassemblies
s Subassembly number, $s = 1, 2, \ldots, S$
T Operational life cycle
$T^{[k](s)\{x\}}$ Total downtime of maintenance mode x on subassembly s at the kth maintenance
TPRM Traditional preventive replacement maintenance
X Total number of maintenance modes
x Maintenance mode number, $x = 1, 2, \ldots, X$
$\beta^{(s)}$ Shape parameter of life distribution of subassembly s
$\Delta R^{[k](s)}$ Reliability variation of subassembly s at the k^{th} maintenance
$\eta^{(s)}$ Scale parameter of life distribution of subassembly s
ρ Significance coefficient reflecting the concern about a stochastic failure of a subassembly
τ Wind turbine capacity coefficient

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