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# Condition Based Maintenance Optimization for Multi-State Wind Power Generation Systems under Periodic Inspection

*As the wind power system moves toward more efficient operation, one of the main challenges for managers is to determine a cost effective maintenance strategy. Most maintenance optimization studies for wind power generation systems deal with wind turbine components separately. However, there are economic dependencies among wind turbines and their components. In addition, most current researches assume that the components in a wind turbine only have two states, while condition monitoring techniques can often provide more detailed health information of components. This study aims to construct an optimal condition based maintenance model for a multi-state wind farm under the condition that individual components or subsystems can be monitored in periodic inspection. The results are demonstrated using a numerical example.*

***Keywords:*** *Multi-state; Wind farm; Economic dependence, Periodic inspection, Condition based maintenance, Three-phase simulation.*

## 1. INTRODUCTION

Wind farms (WF) have been used around the world both onshore and offshore as a cleaner way of generating electricity. WFs are multi-component systems and they are often located in remote areas or off-shore sites. There are economic dependencies among wind turbines (WT) and their components. Opportunistic maintenance policies can be an effective maintenance approach in a WF [1, 2].

Most opportunistic maintenance studies of WFs was focused on corrective deployment of maintenance groups. That is, maintenance teams are deployed to the WF only when a failure occurs. Almgren et. al. [3] considered an optimization model for determining optimal opportunistic replacement of component. Patriksson et. al. [4, 5] extended the model in Ref. [3] by considering a stochastic programming approach. Ding and Tian [6] dealt with the study of an opportunistic maintenance policy based on the component's age threshold values. Ding and Tian [7] further extended the model to accommodate different age thresholds between functional turbines and failed turbines. Tian et. al [8] developed a condition based maintenance method, based on two failure probability threshold values and the condition monitoring data.

Many of the reported work on maintenance optimization of WF assume that the system is composed of a number of components which have only two working states. However, WF structure is made up of a number of WTs which are composed of several multi-state components. In addition, the above-mentioned works assumed that components are monitored continuously. However, continuous monitoring of a WT is not always practicable. For such systems, data are usually collected intermittently and analyzed by experienced condition monitoring engineers [9]. Therefore, inspection intervals should be optimized when the inspection cost is not negligible. To address the above issues, in this paper a new opportunistic maintenance optimization approach for a WF considering the economic dependence among WT is introduced. It is assumed that each WT may be inspected at discrete time intervals. The optimization approach is to minimize the expected maintenance cost with respect to availability constraint. To model the behaviour of different entities of the system and to evaluate main performance measures, a three-phase discrete event simulation is introduced.

This paper is organized as follows: in section 2 features of the problem are presented. Section 3 defines the proposed performance evaluation method. The mathematical model is described in section 4. An example is also shown in section 5, while concluding remarks are presented in section 6.

## 2. PROBLEM DESCRIPTION

Suppose that there are $k$ types of WTs in a WF, and also, $M_i$ WT of type $i$ ($i=1,2,..,k$) have been installed in a WF. We assume that each turbine type has $N$ critical component connected in series. The components in a WT are assumed to deteriorate over time, and the degradation processes follow a multi-state model. The number of the health state of the $j$th ($j=1,2,...,N$) component of each WT can be represented by a finite set of discrete states $\psi_j = \{1,2,\ldots,m_j\}$. State 1 is the initial health state of the component, and states $2,...,(m_j-1)$ reflect its deteriorating conditions. The degradation process is represented by the transition from one state to another state. Each state $d$ ($d=1,2,...,m_j$) is characterized

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by a level of efficiency denoted by $g_{j,d}$, ranging from the best efficiency rate $g_{j,1}=1$ to the last acceptable one $g_{j,m_j-1}$ ($g_{j,1} \geq g_{j,2} \geq \cdots \geq g_{j,m_j-1}$). The efficiency rate of the failed state is zero (i.e., $g_{j,m_j}=0$). The efficiency rate of the component ($G_j(t)$) at any time $t \geq 0$ is a random variable that takes its value from the set $G_j=\{g_{j,1}, g_{j,2}, \ldots, g_{j,m_j}\}$. Indeed, the WT is also multi-state. Therefore, the production rate of a WT ($G(t)$) is a function of the efficiency level of its components and WT nominal production rate ($PR$) which can be calculated based on the following structure function:

$$G(t) = PR * arc \min_{j \in \{1,2,\ldots,j\}} \left(G_j(t)\right) \tag{1}$$

The production rate of entire WF system ($W(t)$) at any time $t \geq 0$ equals to the sum of the production rate of all its working WT. Given a required demand $W^0$, the WF availability is defined as $Pr(W(t)>W^0)$. The availability of the system is a function of load demand ($W^0$), structure of WF and maintenance strategy. Assuming the operation period $T$, the availability can be written as fallow:

$$A = \Pr\left(W(t) > W^0\right) = 1 - \frac{TTOL}{T} \tag{2}$$

Where $TTOL$ is the total time that the total capacity of the system is lower than required demand.

It is assumed that the deteriorating conditions of a component in a WT can only be detected when the WT is under inspection. However, if a component deteriorates to the failure state, its failure can be detected at any time. In the case of a failure, it is assumed that the component must be replaced with a new one. Imperfect preventive repair could be implemented according to the inspection results. It is assumed that a repair action can restore the component state from state s to the any of its previous degraded state r ($s > r$). There is a fix cost in sending maintenance facilities to the WF and also there is an access cost to each WT. It is further assumed that parallel maintenance of different component of a WT is not allowed. In addition, there is a limit on the number of repair facility or teams that can work simultaneously in the system. The time it takes to prepare a maintenance facility and the duration of maintenance activities are also considered in the model.

Three kind of maintenance thresholds ($TH_j^{PM}$, $TH_j^{OM}$ and $TH_j^{IM}$) are considered. These thresholds are related to the components health state. Indeed, repair facilities are sent to the WF when a failure is occurred in the system or the inspection indicates that for at least one of the components the state of that component is more than preventive maintenance threshold ($TH_j^{PM}$). After sending a maintenance team to the WF, if there is a failed component corrective replacement is performed on all the failed components. Preventive repair which restore the component to the pervious state $TH_j^{IM}$ is performed on all the component whose state are above the opportunistic maintenance threshold $TH_j^{OM}$. The WF is inspected every $\Delta T = \rho * \Delta INS$ unit of time ($\rho = 1,2,\ldots,N_{INS}$). $\Delta INS$ is the minimum time between two consecutive inspections and $N_{INS}$ corresponds to the maximum inspection interval. Therefore, the proposed maintenance strategy can be described by a vector $\theta = [\theta_1, \theta_2, \ldots, \theta_N, \Delta T]$, where the sub-vectors $\theta_j = \left[TH_j^{PM}, TH_j^{OM}, TH_j^{IM}\right]$ denotes the maintenance strategy of $j$ th component type. The thresholds in $\theta_j$ have the following relationships:

$$m_j \geq TH_j^{PM} \geq TH_j^{OM} \geq TH_j^{IM} \geq 1 \tag{3}$$

This multi-threshold strategy includes several typical maintenance strategy structures. For example, when $m_j = TH_j^{PM} = TH_j^{OM}$, the $j$ th component in each WT would not be maintained before the component fails. When the set-up cost of the maintenance facilities is not significant, an opportunistic maintenance would not be implemented and $TH_j^{PM} = TH_j^{OM}$. For the situation where the inspection cost of the system is low, inspections would be conducted every other time unit and $\Delta T = \Delta INS$. Consequently, the objective is to define the optimal maintenance policy and inspection intervals, so that the WF life cycle cost and the WF availability are optimized.

## 3. PERFORMANCE EVALUATION

Three classes of entities including subsystem components, maintenance teams and inspection are considered for the studied system. The proposed simulation models the operations in which these entities engaged as a sequence of seven significant events in time. Table 1 addresses these seven events.

**Table 1. List of seven important event in the proposed discrete event simulation**

| Event | Name | description |
|---|---|---|
| $B_1$ | End-of-health state | a component degraded to the next healthy state |
| $B_2$ | End-of-repair | a component maintenance is complete |
| $B_3$ | End-of-dispatch | a maintenance team arrive at wind farm and it is ready for the maintenance. |
| $B_4$ | End-of-inspection | the time between two consecutive inspections ends. Causing the whole system to be inspected. |
| $C_1$ | Begin-repair | Maintenance activity of a component begins. |
| $C_2$ | Begin-delay-dispatch | A maintenance facility is sent to the system. |
| $C_3$ | Begin-running | A subsystem restarts the production. |

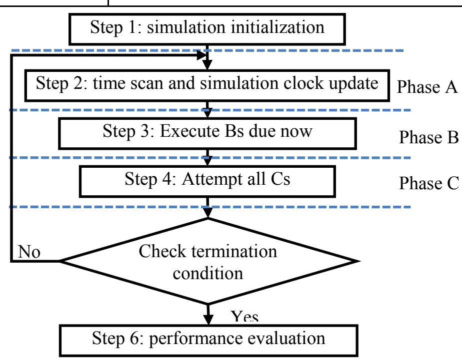


**Figure 1. Simulation process for performance criteria evaluation**

**Table 2. Wind farm simulation information table**

| Entity | Name | Time Cell | Availability | Next Activity | Component | | | | Subsystem | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CHS | OCC | SU | CST | OSS | G |
| 1 | Component 1 of WT 1 | 450 | false | B1 | 1 | W | 0 | 450 | W | 600 |
| 2 | Component 2 of WT 1 | 530 | false | B1 | 1 | W | 0 | 530 | | |
| 3 | Component 3 of WT 1 | 420 | false | B1 | 1 | W | 0 | 420 | | |
| 4 | Component 1 of WT 2 | 760 | false | B1 | 1 | W | 0 | 760 | W | 600 |
| 5 | Component 2 of WT 2 | 230 | false | B1 | 1 | W | 0 | 230 | | |
| 6 | Component 3 of WT 2 | 410 | false | B1 | 1 | W | 0 | 410 | | |
| Entity | Name | Time Cell | Availability | Next Activity | OGS | List of maintenance activity | | | | |
| 7 | Maintenance team 1 | -- | true | -- | Idle | -- | | | | |
| Entity | Name | Time Cell | Availability | Next Activity | | | | | | |
| 9 | Inspection team | 270 | false | B4 | | | | | | |
| Status variable: *clock*=0; *LOM*=0; *TTOL*=0; *TCM*=0; DueNowlist=[] | | | | | | | | | | |

Figure 1 shows the flow chart of the simulation procedure. In this procedure the behaviour of entities is individually tracked in a repeated cycle of three phases, known as A, B and C. The simulation process is explained in detail as follows:

Step 1: initialize the simulation. Specify all the parameters used in simulation process, which includes maximum simulation time $T_{\max}$, the system configuration $M=\{M_1,M_2,\ldots,M_k\}$ and maintenance strategy vector $\theta=[\theta_1,\theta_2,\ldots,\theta_N,\Delta T]$. Specify all related costs, which include maintenance activity costs $CPM_{s,r}^{i,j}$, inspection cost $C_{INS}$, fix cost of sending maintenance facility $C_{fix}$, and the access cost to a WT $C_{Access}$. The sojourn time, the preparation time of a maintenance team and the repair activity duration distributions are given. Specify the efficiency rate $G_j=\{g_1,g_2,\ldots,g_{m_j}\}$ of each component, the WT nominal rate $PR_i$ and the whole system required demand $W^0$. The simulation clock (*clock*), loss of load moment (*LOM*), total time of loss (*TTOL*), and the total maintenance cost (*TCM*) at the beginning are set to be 0, and will be update during simulation process

The simulated data of each entity is recorded in a simulation table. The sample table for a WF included two WTs. This table denotes each WT included three critical components and there exists only one maintenance team. In Table 2, time cell indicates the expected time to do the activity provided by next activity column. For example, for the first row it is expected that after 450 in an assumed measure, $B_1$ will be done. In the case that false is addressed by the availability column, it means that the activity recorded in the next activity is allowed to do.

It is assumed that at the beginning of the simulation all components are in the initial health state. Therefore, *CHS* which denotes the health state of a component set to be 1. *OCS* provides the overall four condition of a component (working, fail, under repair and standby). The remaining sojourn time of a component in an individual health state is shown by *CST*. A WT has four states based on its components overall state as working, fail, under repair and standby, which are shown by *OSS*. *G* is the production rate of a WT. The four states of a maintenance group as idle, dispatch, ready and repair are recorded by *GS* in the seventh row and the list and sequence of maintenance activity of a maintenance team is shown in the last column. The last row shows the simulated data of the inspection team.

Step 2: Time scan and simulation clock update (phase A). In this phase, the executive examines its simulation table to see when the next event is due and it moves the clock to that point. Using the simulation table described above, the executive searches for any entity record with the minimum time cell and which has an availability field set to False. The clock is now held constant until the next A phase. Because there may be several Bs due at this new clock time, the executive must also make a note of which of the non-available entities have this new clock time as their time cell. These form the DueNow list. For an example, in Table 2, the next event is due at time 230. Thus the *clock* value is now 230. The only entity due to engage in a B at this stage is entity 5, the second component of WT 2. Thus the DueNow list contains only entity 5.

**Procedure 1. End of health state ($B_1$)**

1) Update the total system production and the total time of system loss of load:

$$TSP = TSP + \sum_{n=1}^{N} G_n * (clock - SPUM) \tag{4}$$

$$SPUM = clock \tag{5}$$

**If** the production rate of the entire system (W(clock)) is lower than required demand ($W^0$) **then**:

$$TTOL = TTOL + clock - LOM \tag{6}$$

**End if**

2) Increment the component health state by 1.

**If** the component reaches the unacceptable state ( $m_j$ ) **Then**

Update the component and the related subsystem state to "Fail" and call for a corrective replacement.

**For** other component of the subsystem **do**

Update the component overall state to "Standby".

Update the component availability to "True".

Update the component remaining life as:

$$CST = Time\,cell - clock \tag{7}$$

**End for**

**Else**

Update the component availability to "True".

A new sojourn time (CST) is sampled based on failure distribution of the component.

Update the time cell as follow:

$$Time\,cell = clock + CST \tag{8}$$

**End if**

3) Update production rate of the subsystem.

**If** the production rate of the entire system (W(clock)) is lower than required demand ($W^0$) **then**

$$LOM = clock \tag{9}$$

**End if**

Step 3: Execute Bs due now (phase B). The executive systematically searches through the DueNow list and examines the record for each entity that is on that list. For each such entity, in turn, the executive does the following: (1) Removes the entity from the DueNow list, (2) Puts its availability field to True, (3) Executes the B that is shown in the next activity field.

$B_1$ represents the degradation of a component to its next health state. If the component reaches the unacceptable state ($m_j$), this must be treated as a failure. The pseudo-code of $B_1$ is reported in Procedure 1.

End of maintenance activities are approached by $B_2$. In this event, the component is released to "Standby" state. The maintenance team may move to "Ready" if there is another activity that should be done, otherwise it moves to the "Idle" state.

**Procedure 2. End of repair ($B_2$)**

1) Update the component and subsystem state:
   Update the component heath state based on the maintenance activity has been done.
   A new sojourn time (CST) is sampled based on failure distribution of the component.
   Update the component overall state to "standby".
   **If** all the subsystem components are in standby state **then**
      Update the subsystem state to "standby".
   **End if**
2) Update the total cost of maintenance activity as:

$$TCM = TCM + CPM_{s,r}^{i,j} \quad (10)$$

3) Update maintenance team state:
   Remove the component from the list of maintenance activity.
   Update the maintenance team availability to "true".
   **If** list of the maintenance activity is empty **and** the system maintenance list (SLM) is empty **then**
      Update the maintenance team state to "Idle".
   **Else**
      Update the maintenance team state to "Ready".
   **End if**

$B_3$ represents the changes that occur in the state of different entities of the system in the instance of a maintenance team arrival.

**Procedure 3. End of dispatch ($B_3$)**

1) Update the maintenance team availability to "true"
2) Update the maintenance team state to "Ready".

$B_4$ is an event in which the time between two consecutive inspections ends. Causing the whole system to be inspected and to schedule End-of-inspection after some known time.

**Procedure 4. End of inspection ($B_4$)**

1) Update the total cost of maintenance as:

$$TCM = TCM + C_{INS} \quad (11)$$

2) Update the inspection team state:
   Update the inspection team availability to "False".
   Update the time cell as:

$$Time\,cell = clock + \Delta T \quad (12)$$

3) inspect entire system components:
   **For** all the components **do**
      **If** component health state is greater than $TH_j^{PM}$ **then**
         Call for a maintenance team.
      **End if**
   **End for**

Step 4: Attempt all Cs (phase C). In this phase, the executive merely causes the Cs to be attempted one after the other. It does this by looking at each C in turn to see if the conditions in its test-head can be satisfied. If they can then the actions are executed. In the studied system, there are three Cs. Begin-Repair ($C_1$) requires a component waiting for repair and a maintenance team to be "Ready". Begin-Dispatch ($C_2$) requires a call for maintenance and a maintenance team to be "Idle". If all the components of a subsystem are in "standby" state, begin running ($C_3$) can be execute. Begin running has the highest priority and begin dispatch has the lowest priority. Procedure 5 to 7 address the pseudo-codes of three Cs described in Table 1.

**Procedure 5. Begin running ($C_1$)**

Test-head:
**If** there is a subsystem in "standby" state **then**

Actions:
1) Update the total system production and the total time of system loss of load base on Eq. (4) to (6).
2) Update the subsystem state as:
   **For** all the subsystem components **do**
      Update the component availability to "false".
      Update the component overall state to "working"
      Update the component next activity to $B_1$.
      Update the component time cell as:

$$Time\,cell = clock + CST \quad (13)$$

   **End for**
3) Update production rate of the subsystem
   Update the loss of load moment based on Eq.(9).

**End if**

**Procedure 6. Begin repair ($C_2$)**

Test-head:
**If** there is a component waiting for repair **then**
   **For** all the maintenance team in "Ready" state **do**

Actions:
1) Select and update the component
   **If** List of maintenance activity is empty **then**
      Put the first subsystem of system maintenance list to list of maintenance team.
      Remove the subsystem form system maintenance list.
   **End if**
   **If** the subsystem in list of maintenance team is "working" **then**
      Update the total system production and the total time of system loss of load base on Eq. (4) to (6).
      **For** all the subsystem components **do**
         Update the component availability to "false".
         Update the component overall state to "standby"
         Update the component remaining life based on Eq. (7).
      **End for**
      Update the subsystem and the related component state to "under repair".
      Update production rate of the subsystem.
      Update loss of load moment based on Eq. (9).
      Update the total cost of maintenance as:

$$TCM = TCM + C_{Access} \quad (14)$$

   **End if**
2) Update the maintenance team state
   Update the maintenance team availability to "false".
   Update the maintenance team overall state to "repair".
   Update the maintenance team next activity to $B_1$.
   A new repair duration ( $PM_{s,r}^{i,j}$ ) is sampled based on maintenance activity duration distribution.
   Update the maintenance team time cell as:

$$TCM = TCM + PM_{s,r}^{i,j} \quad (15)$$

   **End for**
**End if**

Step 5: check termination condition. In this paper, we consider the maximum simulated time ($T_{max}$) as a termination condition of the simulation. If the simulation clock does not exceed maximum simulated time ($T_{max}$), repeat step 2, 3 and 4.

Step 6: Performance evaluation. The WF availability and the total expected life cycle costs of the system can be calculated as:

$$A\left(\theta, M, W^0\right) = 1 - \frac{TTOL}{clock} \quad (16)$$

$$TC(\theta, M) = \frac{TCM}{clock} \tag{17}$$

**Procedure 7. Begin dispatch ($C_3$)**

| | |
|---|---|
| Test-head | **If** there is at least one maintenance team in "Idle" **and** there is a call for maintenance **then** |
| Actions | 1) Update the system maintenance list<br>For all the system modules do<br>Update the system maintenance list based of proposed maintenance strategy.<br>End for<br>2) dispatch maintenance teams<br>Update the maintenance team availability to "false".<br>Update the maintenance team overall state to "dispatch".<br>Update the maintenance team next activity to $B_2$.<br>A new dispatch duration (LT) is sampled based on preparation time of maintenance teams distribution.<br>Update the maintenance team time cell as:<br>$Time\,cell = Time\,cell + LT$ (18)<br>Update the total cost of maintenance teams as:<br>$TCM = TCM + C_{fix}$ (19) |
| | **End if** |

## 4. THE MODEL FORMULATION

The general mathematical formulation of the proposed problem will take the following form:

$$Minimize\, TC(\theta, M) \tag{20}$$

$$Maximize\, A(\theta, M, W^0) \tag{21}$$

$$S.T.$$

$$m_j \geq TH_j^{PM} \geq TH_j^{OM} \geq TH_j^{IM} \geq 1 \qquad \forall j = 1,2,\ldots,N, \tag{22}$$

$TC(\theta, M)$, In (20), is the total expected costs of design and maintenance activities.

The second objective requires that the availability of the system should be maximized based on required demand. The logical relationship of the each WT maintenance strategy is represents in (22).

## 5. A NUMERICAL EXAMPLE

The optimization problem described in this paper is a constrained non-linear integer programming model with a limited number of solution points. However, depending on the bounds given for decision variables, complete enumeration may take a huge amount of time. That is why any kind of meta- heuristic, such as Genetic algorithm, can be used to find the optimal solution in a shorter time period.

In this paper, Genetic algorithm which is a widely used meta-heuristic approach for solving large optimization problems is employed due to its flexibility in representing design variables in a discrete form and its good global optimization capability.

### 5.1. Optimization results

Consider a WF consists of 4 types of 600 (KW) WTs, produced by three different manufacturers, at a remote site. We study 4 key components in each WT: the rotor, the main bearing, the gearbox and the generator. In addition, we assume that there are 3, 2, 2 and 4 WTs from the type 1, 2, 3 and 4 in this WF, respectively.

The number of the health state of rotor, main bearing, gearbox and generator are respectively equal to 6, 8, 6, and 5.

Table 3 shows the efficiency level of these four components. In this case it is assumed that the required demand is equal to 6 megawatt (MW). It is also assumed that the sojourn time of a component in each state follows a Weibull distribution. The details are shown on Table 4.

**Table 3. Efficiency level for major components**

| Component | Health state | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Rotor | 1 | 0.95 | 0.85 | 0.65 | 0.50 | 0 | -- | -- |
| Main Bearing | 1 | 0.95 | 0.90 | 0.85 | 0.70 | 0.60 | 0.45 | 0 |
| Gearbox | 1 | 0.95 | 0.90 | 0.65 | 0.35 | 0 | -- | -- |
| Generator | 1 | 0.85 | 0.70 | 0.65 | 0 | -- | -- | -- |

**Table 4. Sojourn time distribution parameters for rotor**

| Turbine Type | Scale Parameter □ (days) | | | | | Shape Parameter □ |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | |
| Type 1 | 155 | 120 | 105 | 90 | 50 | 3 |
| Type 2 | 135 | 110 | 110 | 85 | 65 | 2 |
| Type 3 | 120 | 95 | 80 | 75 | 45 | 3 |
| Type 4 | 130 | 120 | 95 | 80 | 65 | 2 |

**Table 5. Sojourn time distribution parameters for gearbox**

| Turbine Type | Scale Parameter □ (days) | | | | | Shape Parameter □ |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | |
| Type 1 | 135 | 100 | 85 | 70 | 30 | 3 |
| Type 2 | 115 | 90 | 90 | 65 | 45 | 2 |
| Type 3 | 105 | 80 | 65 | 65 | 35 | 3 |
| Type 4 | 110 | 100 | 75 | 60 | 50 | 2 |

**Table 6. Sojourn time distribution parameters for bearing**

| Turbine Type | Scale Parameter □ (days) | | | | | | | Shape Parameter □ |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| Type 1 | 130 | 110 | 95 | 90 | 90 | 65 | 40 | 3 |
| Type 2 | 125 | 110 | 100 | 95 | 85 | 70 | 35 | 2 |
| Type 3 | 110 | 95 | 90 | 80 | 75 | 75 | 50 | 3 |
| Type 4 | 115 | 105 | 95 | 75 | 80 | 70 | 55 | 2 |

**Table 7. Sojourn time distribution parameters for generator**

| Turbine Type | Scale Parameter □ (days) | | | | Shape Parameter □ |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | |
| Type 1 | 135 | 105 | 85 | 55 | 3 |
| Type 2 | 120 | 95 | 75 | 65 | 2 |
| Type 3 | 110 | 100 | 95 | 70 | 3 |
| Type 4 | 130 | 105 | 85 | 60 | 2 |

Table 8 to 11 involved costs corresponding to maintenance efforts. In these tables the costs are in 1000 dollars. The access cost of a wind turbine and the fixed cost of dispatching maintenance facilities are 7000$ and 50000$, respectively.

**Table 8. Maintenance costs for rotor**

| | Turbine type 1 | | | | | | Turbine type 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | 1 | 2 | 3 | 4 | 5 |
| 1 | 10 | | | | | 1 | 10 | | | | |
| 2 | 15 | 10 | | | | 2 | 15 | 10 | | | |
| 3 | 40 | 15 | 10 | | | 3 | 35 | 15 | 10 | | |
| 4 | 45 | 30 | 15 | 10 | | 4 | 75 | 50 | 20 | 10 | |
| 5 | 100 | 80 | 40 | 15 | 10 | 5 | 95 | 70 | 55 | 30 | 10 |
| 6 | 112 | 100 | 60 | 30 | 15 | 6 | 105 | 95 | 75 | 55 | 30 |
| | Turbine type 3 | | | | | | Turbine type 4 | | | | |
| | 1 | 2 | 3 | 4 | 5 | | 1 | 2 | 3 | 4 | 5 |
| 1 | 10 | | | | | 1 | 10 | | | | |
| 2 | 15 | 10 | | | | 2 | 25 | 10 | | | |
| 3 | 30 | 15 | 10 | | | 3 | 40 | 20 | 10 | | |
| 4 | 40 | 30 | 25 | 10 | | 4 | 55 | 50 | 25 | 10 | |
| 5 | 80 | 75 | 55 | 30 | 10 | 5 | 65 | 60 | 35 | 20 | 10 |
| 6 | 98 | 80 | 60 | 40 | 25 | 6 | 80 | 65 | 45 | 30 | 20 |

**Table 9. Maintenance costs for main bearing**

| | Turbine type 1 | | | | | | | | Turbine type 2 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | 5 | | | | | | | 1 | 5 | | | | | | |
| 2 | 10 | 5 | | | | | | 2 | 10 | 5 | | | | | |
| 3 | 15 | 10 | 5 | | | | | 3 | 20 | 15 | 5 | | | | |
| 4 | 35 | 25 | 15 | 5 | | | | 4 | 30 | 25 | 15 | 5 | | | |
| 5 | 40 | 35 | 30 | 20 | 5 | | | 5 | 45 | 35 | 25 | 10 | 5 | | |
| 6 | 55 | 50 | 45 | 35 | 15 | 5 | | 6 | 50 | 40 | 35 | 20 | 15 | 5 | |
| 7 | 60 | 55 | 50 | 40 | 25 | 15 | 5 | 7 | 55 | 45 | 40 | 30 | 20 | 15 | 5 |
| 8 | 70 | 65 | 60 | 50 | 35 | 15 | 10 | 8 | 60 | 60 | 55 | 50 | 30 | 25 | 10 |
| | Turbine type 3 | | | | | | | | Turbine type 4 | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | 5 | | | | | | | 1 | 5 | | | | | | |
| 2 | 15 | 5 | | | | | | 2 | 10 | 5 | | | | | |
| 3 | 20 | 15 | 5 | | | | | 3 | 25 | 15 | 5 | | | | |
| 4 | 25 | 20 | 15 | 5 | | | | 4 | 30 | 25 | 20 | 5 | | | |
| 5 | 30 | 25 | 15 | 10 | 5 | | | 5 | 35 | 20 | 20 | 10 | 5 | | |
| 6 | 40 | 35 | 20 | 15 | 10 | 5 | | 6 | 35 | 25 | 20 | 15 | 10 | 5 | |
| 7 | 45 | 40 | 30 | 25 | 20 | 10 | 5 | 7 | 40 | 30 | 25 | 20 | 15 | 10 | 5 |
| 8 | 50 | 45 | 40 | 35 | 25 | 15 | 10 | 8 | 45 | 40 | 35 | 30 | 25 | 15 | 10 |

**Table 10. Maintenance costs for gearbox**

| | Turbine type 1 | | | | | | Turbine type 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | 1 | 2 | 3 | 4 | 5 |
| 1 | 25 | | | | | 1 | 25 | | | | |
| 2 | 75 | 25 | | | | 2 | 70 | 25 | | | |
| 3 | 100 | 85 | 30 | | | 3 | 95 | 65 | 30 | | |
| 4 | 120 | 110 | 80 | 35 | | 4 | 120 | 100 | 75 | 35 | |
| 5 | 135 | 120 | 105 | 45 | 20 | 5 | 135 | 105 | 85 | 65 | 25 |
| 6 | 150 | 140 | 135 | 110 | 95 | 6 | 140 | 125 | 100 | 85 | 75 |
| | Turbine type 3 | | | | | | Turbine type 4 | | | | |
| | 1 | 2 | 3 | 4 | 5 | | 1 | 2 | 3 | 4 | 5 |
| 1 | 25 | | | | | 1 | 25 | | | | |
| 2 | 55 | 25 | | | | 2 | 45 | 25 | | | |
| 3 | 80 | 65 | 30 | | | 3 | 60 | 40 | 30 | | |
| 4 | 90 | 85 | 55 | 35 | | 4 | 75 | 55 | 45 | 35 | |
| 5 | 105 | 95 | 75 | 60 | 35 | 5 | 85 | 70 | 65 | 55 | 35 |
| 6 | 120 | 100 | 85 | 55 | 40 | 6 | 90 | 85 | 70 | 60 | 45 |

**Table 11. Maintenance costs for generator**

| | Turbine type 1 | | | | | Turbine type 2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | | 1 | 2 | 3 | 4 |
| 1 | 25 | | | | 1 | 20 | | | |
| 2 | 50 | 25 | | | 2 | 45 | 25 | | |
| 3 | 80 | 60 | 30 | | 3 | 65 | 45 | 25 | |
| 4 | 90 | 80 | 55 | 35 | 4 | 80 | 70 | 50 | 30 |
| 5 | 100 | 85 | 65 | 40 | 5 | 95 | 80 | 65 | 35 |
| | Turbine type 3 | | | | | Turbine type 4 | | | |
| | 1 | 2 | 3 | 4 | | 1 | 2 | 3 | 4 |
| 1 | 20 | | | | 1 | 15 | | | |
| 2 | 40 | 25 | | | 2 | 30 | 20 | | |
| 3 | 65 | 40 | 25 | | 3 | 45 | 35 | 25 | |
| 4 | 80 | 70 | 50 | 30 | 4 | 65 | 50 | 45 | 25 |
| 5 | 90 | 80 | 60 | 35 | 5 | 80 | 70 | 55 | 30 |

It is also assumed that a Lognormal distribution i.e. ($LT \approx N(25{,}3)$) properly is capable to describe the required time to prepare a maintenance team. The maintenance activity duration fallows lognormal distribution.

Table 12 to 15 are shown the mean parameter of maintenance activity duration for each main component and the variance of the maintenance activity duration are assumed to be 0.10.

**Table 12. Mean parameter of maintenance duration for rotor**

| | Turbine type 1 | | | | | | Turbine type 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | 1 | 2 | 3 | 4 | 5 |
| 1 | 1 | | | | | 1 | 1 | | | | |
| 2 | 1 | 1 | | | | 2 | 1 | 1 | | | |
| 3 | 2 | 2 | 1 | | | 3 | 1.8 | 1.5 | 1 | | |
| 4 | 3 | 2.8 | 1.5 | 1 | | 4 | 3 | 2.5 | 2.5 | 1.8 | |
| 5 | 3.5 | 3 | 3 | 1.5 | 1 | 5 | 3 | 3 | 2.5 | 2 | 1.5 |
| 6 | 3.5 | 3 | 3 | 2 | 1.5 | 6 | 3.5 | 2.8 | 2.5 | 2 | 2 |
| | Turbine type 3 | | | | | | Turbine type 4 | | | | |
| | 1 | 2 | 3 | 4 | 5 | | 1 | 2 | 3 | 4 | 5 |
| 1 | 1 | | | | | 1 | 0.5 | | | | |
| 2 | 1.2 | 1 | | | | 2 | 1 | 0.5 | | | |
| 3 | 1.5 | 1.3 | 1 | | | 3 | 1.3 | 1 | 0.75 | | |
| 4 | 2 | 1.8 | 1.5 | 1 | | 4 | 2 | 1.8 | 1.2 | 1 | |
| 5 | 2 | 2 | 1.7 | 1.5 | 1.5 | 5 | 2.5 | 2 | 2 | 1.5 | 1.2 |
| 6 | 2.5 | 2.5 | 2.3 | 2 | 1.5 | 6 | 2.5 | 2.3 | 2 | 1.8 | 1.5 |

**Table 13. Mean parameter of maintenance duration for main bearing**

| | Turbine type 1 | | | | | | | | Turbine type 2 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | 0.7 | | | | | | | 1 | 0.5 | | | | | | |
| 2 | 1 | 0.7 | | | | | | 2 | 1 | 0.5 | | | | | |
| 3 | 2 | 1.8 | 1 | | | | | 3 | 1.8 | 1 | 0.75 | | | | |
| 4 | 2.8 | 2.5 | 1.7 | 1.5 | | | | 4 | 2 | 1.5 | 1.3 | 1 | | | |
| 5 | 3 | 3 | 2.5 | 2 | 1 | | | 5 | 2.5 | 2 | 1.8 | 1.2 | 1 | | |
| 6 | 3.5 | 3.5 | 3 | 2.5 | 2 | 1.5 | | 6 | 2.5 | 2.2 | 1.5 | 1.5 | 1 | 0.5 | |
| 7 | 3.8 | 3.5 | 3.2 | 3 | 2.8 | 1.8 | 1 | 7 | 3 | 2.5 | 2.5 | 1.8 | 1.2 | 1 | 0.75 |
| 8 | 4 | 4 | 3.5 | 3.2 | 2.5 | 2 | 1.5 | 8 | 3 | 2.7 | 2.5 | 2 | 1.8 | 1.5 | 1 |
| | Turbine type 3 | | | | | | | | Turbine type 4 | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | 0.5 | | | | | | | 1 | 0.3 | | | | | | |
| 2 | 1 | 0.5 | | | | | | 2 | 0.7 | 0.3 | | | | | |
| 3 | 1.8 | 1 | 0.7 | | | | | 3 | 1.2 | 0.7 | 0.5 | | | | |
| 4 | 1.8 | 1.5 | 1.3 | 0.75 | | | | 4 | 1.2 | 1 | 0.9 | 0.5 | | | |
| 5 | 2 | 2 | 1.5 | 1.2 | 1 | | | 5 | 1.4 | 1.4 | 1 | 0.8 | 0.7 | | |
| 6 | 2.5 | 2.2 | 1.5 | 1.5 | 1 | 0.5 | | 6 | 1.7 | 1.5 | 1 | 1 | 0.7 | 0.3 | |
| 7 | 2.7 | 2.5 | 2.5 | 1.5 | 1.2 | 1 | 0.75 | 7 | 1.8 | 1.7 | 1.7 | 1 | 0.8 | 0.7 | 0.5 |
| 8 | 3 | 2.6 | 2.2 | 2 | 1.8 | 1.5 | 1 | 8 | 2.1 | 1.8 | 1.5 | 1.4 | 1.2 | 1 | 0.7 |

**Table 14. Mean parameter of maintenance duration for gearbox**

| | Turbine type 1 | | | | | | Turbine type 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | 1 | 2 | 3 | 4 | 5 |
| 1 | 0.75 | | | | | 1 | 0.5 | | | | |
| 2 | 1 | 0.75 | | | | 2 | 1 | 0.5 | | | |
| 3 | 2 | 1.8 | 1.5 | | | 3 | 2 | 1.5 | 1 | | |
| 4 | 2.5 | 2.3 | 2 | 1.5 | | 4 | 2.5 | 2.2 | 2 | 1.5 | |
| 5 | 3 | 2.5 | 2.5 | 2.2 | 1 | 5 | 2.8 | 2.5 | 2.3 | 2 | 2 |
| 6 | 3 | 2.8 | 2.5 | 2 | 1.8 | 6 | 3 | 2.5 | 2.5 | 2.3 | 1.8 |
| | Turbine type 3 | | | | | | Turbine type 4 | | | | |
| | 1 | 2 | 3 | 4 | 5 | | 1 | 2 | 3 | 4 | 5 |
| 1 | 0.5 | | | | | 1 | 0.5 | | | | |
| 2 | 1 | 0.5 | | | | 2 | 0.75 | 0.5 | | | |
| 3 | 1.8 | 1.5 | 1 | | | 3 | 1.2 | 1 | 0.75 | | |
| 4 | 2 | 1.8 | 1.5 | 1 | | 4 | 1.8 | 1.2 | 0.75 | 0.5 | |
| 5 | 2.5 | 2.3 | 2 | 1.8 | 1.5 | 5 | 2 | 1.8 | 1.5 | 1 | 0.75 |
| 6 | 2.8 | 2.5 | 2.5 | 2.1 | 1.8 | 6 | 2.5 | 2.5 | 2.1 | 1.5 | 1 |

The inspection cost is assumed to be 10000 \$ and 30 days is the minimum time between two consecutive inspections (e,g. $\Delta INS = 30$). It is also assumed that the maximum inspection interval is equals to 360 days (e.g. $N_{INS} = 12$ ).

**Table 15. Mean parameter of maintenance duration for generator**

| | Turbine type 1 | | | | | Turbine type 2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | | 1 | 2 | 3 | 4 |
| 1 | 0.5 | | | | 1 | 035 | | | |
| 2 | 1 | 0.5 | | | 2 | 0.75 | 0.5 | | |
| 3 | 2 | 1.8 | 0.75 | | 3 | 1.8 | 1.5 | 0.75 | |
| 4 | 2.2 | 2 | 1.8 | 1 | 4 | 2 | 1.9 | 0.75 | 0.5 |
| 5 | 2.5 | 2.2 | 1.5 | 1 | 5 | 2.3 | 2 | 1 | 0.75 |
| | Turbine type 3 | | | | | Turbine type 4 | | | |
| | 1 | 2 | 3 | 4 | | 1 | 2 | 3 | 4 |
| 1 | 0.35 | | | | 1 | 0.5 | | | |
| 2 | 0.7 | 0.35 | | | 2 | 0.75 | 0.5 | | |
| 3 | 1.5 | 1 | 0.5 | | 3 | 1.5 | 1.3 | 1 | |
| 4 | 2 | 1.3 | 1 | 0.75 | 4 | 1.5 | 1.2 | 1 | 0.75 |
| 5 | 2 | 1.5 | 1.2 | 1 | 5 | 1.8 | 1.5 | 1.2 | 1 |

Figure 2 to 5 show the set of non-dominated solutions based on different number of maintenance groups. In these figures, the vertical axis represents the expected availability and the horizontal axis represents the average maintenance costs per day.

The set of Pareto solutions using one, two, three and four maintenance teams are concurrently shown in Figure 6 and the general information of these solutions are listed in Table 16. As it is expected, with an increase in the number of maintenance teams, the expected cost of maintenance activities and the expected availability are increased and hence the sets of Pareto solutions moves up and right ward.

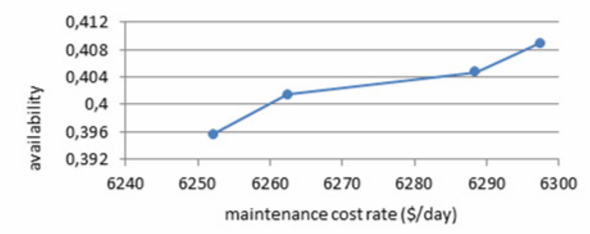


**Figure 2. Non-dominated solutions obtained based on hiring one maintenance group**

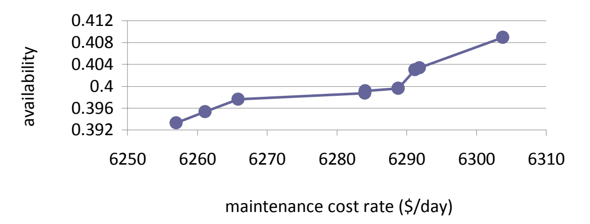


**Figure 3. Non-dominated solutions obtained based on hiring two maintenance groups**

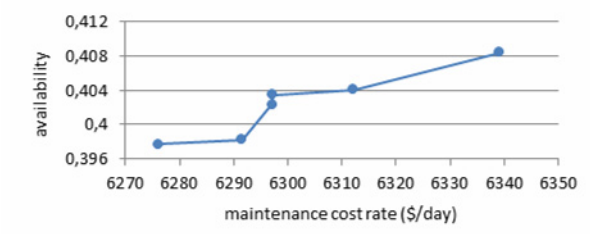


**Figure 4. Non-dominated solutions obtained based on hiring three maintenance groups**

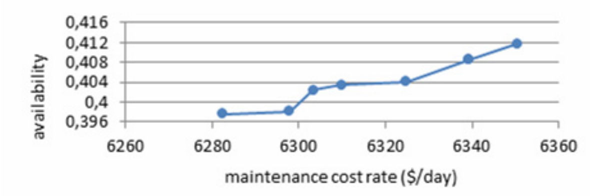


**Figure 5. Non-dominated solutions obtained based on hiring four maintenance groups**

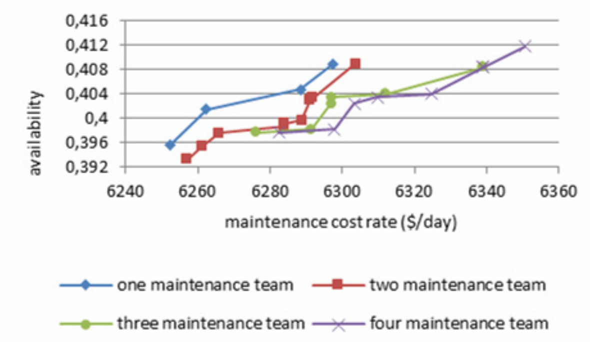


**Figure 6. Non-dominated solutions obtained based on hiring different number of maintenance groups**

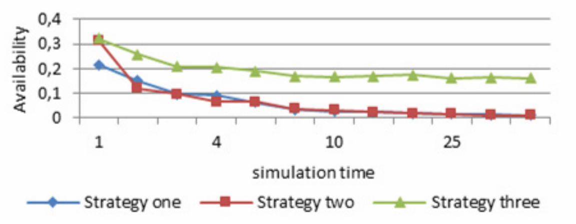


**Figure 7. The system expected availability with different simulation time**

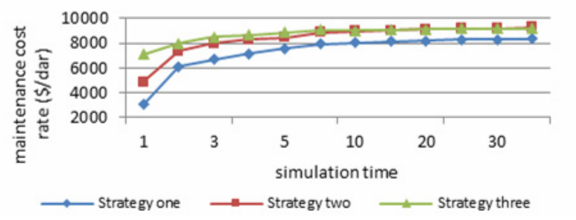


**Figure 8. The system expected maintenance cost with different simulation time**

**Table 16. Non-dominated solutions information based on different number of maintenance teams**

| Sol. | $A$ | $TC$ | Maintenance strategy | | | | | NO. teams |
|---|---|---|---|---|---|---|---|---|
| | | | $\theta_1$ | $\theta_2$ | $\theta_3$ | $\theta_4$ | $\Delta T$ | |
| 1 | 0.396 | 6252.18 | [1,1,1] | [2,1,1] | [3,1,1] | [1,1,1] | 150 | 1 |
| 2 | 0.401 | 6262.41 | [3,1,1] | [1,1,1] | [2,1,1] | [3,1,1] | 150 | 1 |
| 3 | 0.405 | 6288.50 | [1,1,1] | [7,1,1] | [1,1,1] | [1,1,1] | 150 | 1 |
| 4 | 0.409 | 6297.48 | [2,1,1] | [1,1,1] | [2,1,1] | [1,1,1] | 150 | 1 |
| 5 | 0.393 | 6256.97 | [4,1,1] | [2,1,1] | [6,1,1] | [2,1,1] | 120 | 2 |
| 6 | 0.395 | 6261.11 | [6,1,1] | [2,1,1] | [2,1,1] | [2,1,1] | 150 | 2 |
| 7 | 0.398 | 6265.87 | [5,1,1] | [2,1,1] | [1,1,1] | [1,1,1] | 150 | 2 |
| 8 | 0.399 | 6284.04 | [4,1,1] | [2,1,1] | [1,1,1] | [5,1,1] | 120 | 2 |
| 9 | 0.399 | 6284.07 | [1,1,1] | [5,1,1] | [4,1,1] | [2,1,1] | 150 | 2 |
| 10 | 0.400 | 6288.80 | [3,1,1] | [5,1,1] | [1,1,1] | [5,1,1] | 180 | 2 |
| 11 | 0.403 | 6291.18 | [1,1,1] | [7,1,1] | [2,1,1] | [2,1,1] | 150 | 2 |
| 12 | 0.403 | 6291.82 | [6,1,1] | [3,1,1] | [2,1,1] | [1,1,1] | 150 | 2 |
| 13 | 0.409 | 6303.78 | [1,1,1] | [7,1,1] | [1,1,1] | [4,1,1] | 150 | 2 |
| 14 | 0.398 | 6276.13 | [6,1,1] | [5,1,1] | [1,1,1] | [5,1,1] | 150 | 3 |
| 15 | 0.398 | 6291.54 | [3,1,1] | [1,1,1] | [3,1,1] | [2,1,1] | 150 | 3 |
| 16 | 0.402 | 6297.03 | [5,1,1] | [2,1,1] | [2,1,1] | [3,1,1] | 150 | 3 |
| 17 | 0.403 | 6297.22 | [5,1,1] | [4,1,1] | [5,1,1] | [1,1,1] | 180 | 3 |
| 18 | 0.404 | 6312.14 | [3,1,1] | [7,1,1] | [5,1,1] | [4,1,1] | 180 | 3 |
| 19 | 0.408 | 6339.12 | [1,1,1] | [5,1,1] | [6,1,1] | [4,1,1] | 150 | 3 |
| 20 | 0.398 | 6282.40 | [1,1,1] | [3,1,1] | [3,1,1] | [2,1,1] | 150 | 4 |
| 21 | 0.398 | 6297.83 | [2,1,1] | [8,1,1] | [2,1,1] | [5,1,1] | 150 | 4 |
| 22 | 0.402 | 6303.32 | [3,1,1] | [5,1,1] | [2,1,1] | [3,1,1] | 120 | 4 |
| 23 | 0.403 | 6309.82 | [2,1,1] | [4,1,1] | [2,1,1] | [4,1,1] | 120 | 4 |
| 24 | 0.404 | 6324.77 | [2,1,1] | [5,1,1] | [2,1,1] | [2,1,1] | 150 | 4 |
| 25 | 0.408 | 6339.12 | [3,1,1] | [1,1,1] | [2,1,1] | [5,1,1] | 150 | 4 |
| 26 | 0.408 | 6339.12 | [1,1,1] | [4,1,1] | [2,1,1] | [4,1,1] | 120 | 4 |
| 27 | 0.412 | 6350.58 | [1,1,1] | [4,1,1] | [2,1,1] | [2,1,1] | 150 | 4 |

### 5.2. Sensitivity analysis and simulation validation

This subsection discusses the influence of the different assumption and parameters of simulation model over the WF system performance. Three maintenance strategies are considered, as follows:

- Strategy 1: only corrective replacement is performed ($\theta = \{[6,6,1],[8,8,1],[6,6,1],[5,5,1],[5,5,1],4\}$).
- Strategy 2: teams are sent when a failure occurs ($\theta = \{[6,4,1],[8,5,1],[6,4,1],[5,3,1],2\}$).
- Strategy 3: where teams are preventively sent to the WF ($\theta = \{[3,2,1],[4,3,1],[3,2,1],[3,2,1],1\}$).

The sub-vectors in these three strategies denote the maintenance strategy of *j*th component type.

Figure 7 and Figure 8 show the estimated wind farm performance according to different simulation time $T_{\max} = \{1,2,3,4,5,8,10,12,18,20,25,30,35,40\}$. For each value of $T_{max}$, the simulation is executed 100 times. It is illustrated that as the simulation time increases, the system performance under three considered maintenance strategy gradually stabilizes to a certain value.

In order to control the amount and speed of calculation, the maximum simulation time is set as $T_{max}$=30 (year). Local sensitivity analysis of the parameters under three considered maintenance strategy is carried out.

Number of maintenance team: It is expected that with increasing the number of maintenance teams, the capability of simultaneous performing of maintenance activities will increase. This will reduce the delays in performing the maintenance activities and thus increases the availability and maintenance efforts. Figure 9 and 10 show this situation.

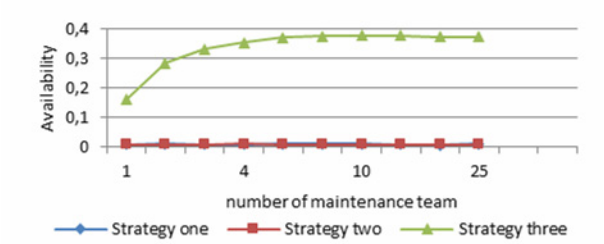


**Figure 9. Expected availability with different number of maintenance team**

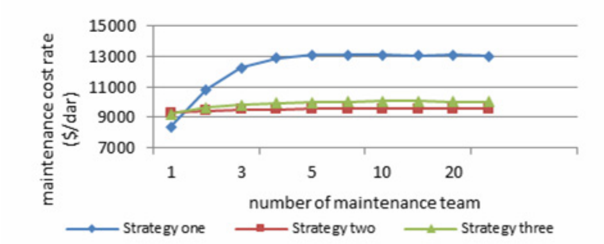


**Figure 10. Expected maintenance cost rate with different number of maintenance team**

(1) System inspection cost: It is expected that with increasing the inspection cost, the WF maintenance cost rate increases. The sensitivity analysis verifies the situation (Figure 12). However, the system availability does not change obviously (Figure 11).

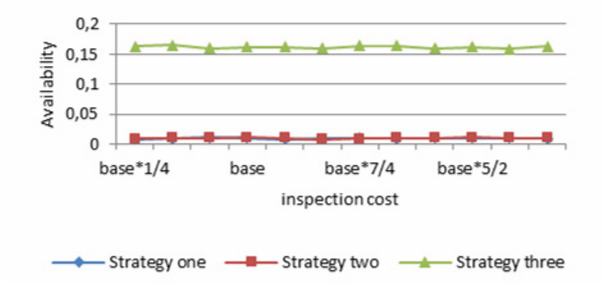


**Figure 11. Availability with different inspection cost**

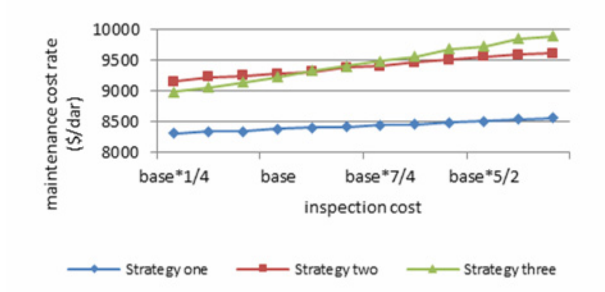


**Figure 12. Expected maintenance cost rate with different inspection cost**

(2) The scale parameter of failure distribution: as the scale parameter of failure distribution of components increase, it is expected that the WF availability increase and the maintenance cost rate decrease. Figure 13 and Figure 14, graphically show the situation.

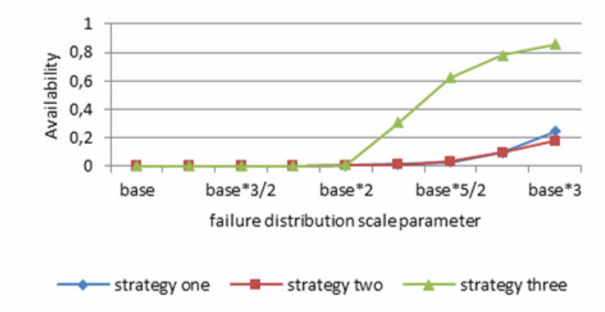


**Figure 13. Expected availability with different failure distribution scale parameter**


**Figure 14. Expected maintenance cost rate with failure distribution scale parameter**

## 6. CONCLUSION

A maintenance optimization approach was developed in this paper for a wind farm system with multi state components. Both opportunistic maintenance and inspection intervals were considered in the model. Different constraints related to the maintenance activities and limited number of maintenance teams is considered. Three phase discrete event simulation method is developed to evaluate life cycle costs and availability of the system. A numerical example is provided to illustrate the proposed approach. Pareto optimal solutions are driven. Sensitivity analysis is conducted to discuss the influence of the different assumption and parameters of simulation model over the wind farm performance.

We believe that due to the simplicity of the proposed maintenance strategy real application of this method, both technically and economically, would be feasible and affordable. Further research will continue to study the stochastic dependence considering imperfect inspection efforts and a closer analysis of the demand randomness and the cost of unsupplied demand.

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## ОПТИМИЗАЦИЈА ОДРЖАВАЊА НА БАЗИ УСЛОВЉЕНИХ СТАЊА ВЕТРОЕЛЕКТРАНА СА ВИШЕ СТАЊА ПОД УСЛОВИМА ПЕРИОДИЧНИХ ИНСПЕКЦИЈА


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Са развојем система ветроелектрана, у правцу што ефикаснијег функционисања менаџери су суочени са изазовом дефинисања што економичније стратегије одржавања. Највећи број студија посвећен оптимизацији одржавања система ветроелектрана бави се појединачним компонентама ветро-турбина. Међутим, постоји економска међузависност ветро-турбина и њихових компонената. Поред тога, највећи број актуелних истраживања полази од претпоставке да компоненте ветро-турбине имају само два стања, док технике надзора условлности стања често могу да пруже детаљније податке о стању “здравља” компонената. Циљ ове студије јесте да се изгради оптимални модел одржавања на бази условљених стања за примену код ветро парка са више стања у условима у којима се појединачне компоненте или подсистеми могу пратити периодичним инспекцијама. Резултати су приказани на нумеричком примеру.