Comparative Study of Maintenance Strategies for Wind Turbine Systems

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ABSTRACT

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Wind power is an important source of renewable energy. Operation and maintenance (O&M) costs account for 25-30% of the wind energy generation cost. A common goal of operation and maintenance optimization for a system is to decrease downtime, improve availability, and reduce the cost as much as possible. It is even more important to offshore wind farms where accessibility is weak and maintenance workload is heavy and very costly. Therefore, there is a critical need for studying maintenance optimization of existing wind turbine systems, and investigating various strategies and optimal maintenance management models. Particularly it is significant to study a wind farm, which has multiple wind turbines and each turbine has multiple components.

In this thesis, we focus on maintenance strategies that are currently widely used in wind power industry, including corrective maintenance (i.e., failure-based maintenance), opportunity maintenance, and time-based preventive maintenance. However, these maintenance strategies have not been studied adequately in wind power industry, and more effective methods can be developed. Many studies focus on maintenance optimization of specific components or an individual wind turbine system, rather than the entire wind farm.

In this thesis, we focus on the wind farm, which involves multiple wind turbines and each wind turbine is consisted of multiple turbine components. We propose several maintenance optimization models corresponding to corrective maintenance, opportunity maintenance, and fixed-interval preventive maintenance, respectively. (1) A corrective maintenance optimization model is proposed to optimize the number of failures allowed before performing corrective maintenance, and real wind turbine data from WindStats Newsletter are used in this study; (2) Opportunity maintenance methods are developed for wind farms to perform preventive maintenance actions when a failure occurs; (3) Preventive maintenance methods are proposed considering both perfect and imperfect maintenance actions. Cost evaluation algorithms are developed for these proposed methods, and optimal maintenance strategies can be obtained via optimization.

The proposed methods are demonstrated and compared using examples. According to the comparison results, the optimized opportunity maintenance strategy is the most cost-effective way, which saves about 30% of the cost compare with corrective maintenance strategy. Moreover, perfect and imperfect preventive actions bring the same benefit according to the optimal opportunity maintenance policy.

The developed methods in this thesis can be applied to improve the current maintenance practice in wind farms, and bring immediate benefits to wind energy industry in terms of reducing cost and improving availability.

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Acronyms

CBM	Condition Based Maintenance
RCM	Reliability Centre Maintenance
MLE	Maximum Likelihood Estimation
SCADA	Supervisory Control and Data Acquisition
PHM	Proportional Hazards Model
MTTF	Mean Time to Failure

Chapter 1

1. Introduction

1.1 Background

Global warming is an increasingly crucial issue in our contemporary world. More and more industrialized countries have realized the obligation and engaged in reducing collective emissions of greenhouse gas. Accordingly the fossil fuel which is used most to generate energy has been raising concern about its finiteness and emissions. In contrast, human daily life is becoming more and more dependent on energy. Nations are challenged to find clean and renewable energy.

Wind, like solar and hydroelectric, is an important natural source that is essentially inexhaustible. Energy generated from wind is rapidly emerging as one of most clean and renewable energy sources in the world. Canada has set its wind-generated energy output target to accounting for 19% of Canada's electricity demand comparing to only 1% today, and this leads to the requirements about 22,000 wind turbines installed over 450 locations across the country (Canadian Wind Energy Association Conference, 2009).

The huge potential and significant investment increase in generation capacity comes with the highly expected responsibility to manage wind farms to ensure the lowest operation and maintenance cost. "*...net revenue from a wind farm is the revenue from sale of* *electricity less operation and maintenance (O&M) expenditure*" (Learney, 1999). To lower operation & maintenance cost as much as possible, appropriate and practical maintenance strategies need to study with big efforts for successful future developments.

Commonly used in many other industries, condition-based maintenance (CBM) is regarded by many studies as the most beneficial method due to the fact that it continuously monitors the performance of the wind turbine parts and determines the best time for a specific maintenance work. Therefore, the cost can be very much reduced without failure damage and high scheduled preventive maintenance workload, and the system reliability can be improved as well.

However, in CBM, reliable sensor providing accurate condition data will be required as any component of wind turbine system, especially under extreme environment condition and high load, in particular for offshore farms. Meanwhile, establishing the relationship between failure mode and observed data is also a big challenge. These could make operators interested more in failure-based maintenance (corrective maintenance), opportunity maintenance, and time-based maintenance (fixed interval preventive maintenance). Failure-based (corrective) maintenance is carried out only after a failure occurs. Time-based preventive maintenance is that the preventive maintenance is performed every after fixed interval of time. Opportunity Maintenance is a combined maintenance strategy, which is the preventive maintenance performed on certain running components by chance of a failure occurrence in a farm. In some cases CBM is not always cost-effective, and a study stated that scheduled inspection of the drive trains of wind turbines is more cost effective over life-cycle than CBM with almost 50% saving (Andrawus, 2008).

As discussed above, failure-based maintenance, opportunity maintenance and fixed interval maintenance deserve extensive study in case of wind projects, particularly those located at offshore wind farms where accessibility is weak and maintenance workload is heavy and very costly.

1.2 Objective

This thesis work focus on failure-based maintenance, opportunity maintenance and fixed-interval preventive maintenance, and performs comparative study of the benefits with different strategies. The main objective is to give recommendations on the use and benefit of these maintenance strategies in the wind farm applications.

1.3 Research Motivation

In wind energy industry, published researches have paid quite much attention on condition based maintenance due to the fact that the most appropriate maintenance time can be determined, and the cost can be reduced significantly, in particular for the complex working conditions associated with offshore wind farms. Discussions in CBM study area have major focuses on health condition diagnosis based on the observed data from various sensors, and signal processing techniques. However, the CBM optimization approaches are few, and there is the big challenge of limited knowledge about failure modes and their relationship with observed data. Furthermore, the component's condition data source is usually unavailable to research community.

On the other hand, failure-based and time-based maintenance have been adopted and widely used nowadays, and there's a strong motivation to make them more effective. Martinez (2010) demonstrated there is a greater need for corrective maintenance nowadays. Reasonably, in the case of extreme condition and high load associated with offshore farms, operators may be interested more in failure or opportunity maintenance taking advantage of the ease of management. Besides, as we mentioned earlier, CBM is not always cost-effective comparing other traditional maintenance strategies.

So far, failure-based maintenance, opportunity maintenance optimization, and time-based preventive maintenance haven't been studied sufficiently. Some researchers only concluded that corrective maintenance was the most costly such that the related optimization approach would be poor in this industry. Furthermore, many literatures discussed the benefits of corrective, preventive and condition monitoring maintenance in the case of individual component, but paid much less attention to a wind farm and a system with multiple components with different failure distributions. Also there are few models and methods applied to optimize a certain maintenance strategy. The other disadvantage of existing research is that preventive maintenance was commonly considered as replacement, which is the perfect action to renew a component. Practically, an imperfect preventive maintenance or minor repair action may reduce cost over the life cycle by taking advantage of fewer workload and balanced availability. Spinato et al (2008) described that the repair actions for wind turbine components can be an addition to a new part, exchange of parts, removal of a damaged part, changes or adjustment to the settings, software update, and lubrication or cleaning.

In an effort to address the issues listed above, we will propose optimization models corresponding to corrective maintenance, opportunity maintenance and time-based preventive maintenance respectively, and perfect and imperfect actions are considered in preventive maintenance task in any applicable case. Therefore, we are able to investigate the benefits of these proposed maintenance models based on comparative studies. The results can be applied to the maintenance management for any remote wind farm.

1.4 Research Contributions

In this thesis, we focus on corrective maintenance, opportunity maintenance, and time-based preventive maintenance optimization study for multiple-turbine wind farms. Supported by the thesis work results, we conclude that each maintenance strategy can be optimized, and the most economical maintenance strategy is found such that the average maintenance cost is the lowest. The contributions of this thesis are summarized as follows.

- We propose a corrective maintenance optimization model, in which a certain number of wind turbines are allowed to fail before the corrective maintenance is carried out. We also present an analytical method to accurately solve the optimization problem. The optimal number of failures is found such that the average maintenance cost per day is minimized.
- We also propose a series of opportunity maintenance optimization models. Opportunity maintenance hasn't been studied sufficiently in wind energy yet. Component's age is considered as a factor to determine the preventive maintenance is applied or not at failure instant, and consequently the optimal maintenance age is found via simulation-based approach.
- We develop preventive maintenance approaches with perfect and imperfect action considerations in the case of opportunity and time-based preventive maintenance strategies. Our results show that imperfect action is not much profitable comparing to perfect action, even though it relieves the workload.
- By these quantitative investigations, the comparative studies are conducted. These numerical studies demonstrate the effectiveness of the proposed approaches.

1.5 Thesis Layout

- **Chapter 1 –** *Introduction* This chapter introduces the background for this thesis and also establishes the objective, research motivations and contributions.

- **Chapter 2 –** *Literature Review* This chapter consists of the literatures review on the reliability analysis and maintenance in wind energy industry.
- **Chapter 3 –** *Fundamental Knowledge* In this chapter, we go through the fundamental knowledge of reliability theory, main functions of wind turbine system, major components in wind turbine system, as well as the basics of wind farm.
- **Chapter 4 –** *Wind turbines failure data analysis* In this chapter, incomplete group data published in Windstats Newsletter is analyzed to estimate failure performance for the Germany wind turbines population. The analysis result is used in one special case study.
- **Chapter 5 –** *Corrective maintenance optimization* In this chapter we apply the proposed corrective maintenance optimization model to investigate a special case where failure follows exponential distribution based on analysis in chapter 4, and present a mathematical method to accurately solve the problem.
- **Chapter 6** – *Comparative study of maintenance strategies* In this chapter, we develop maintenance optimization models for all proposed maintenance strategies, simulation-based methods are developed for these models. The quantitative study provides results at the end.
- **Chapter 7 –** *Closure* Conclusions and suggested future work are presented.

Chapter 2

2. Literature Review

In this chapter we review literatures related to reliability analysis & maintenance optimization of wind turbine systems. The reliability analysis is discussed in Section 2.1, where we present two existing effective methods for estimating reliability parameters with limited and grouped data source. In Section 2.2, we review literatures on the common maintenance strategies for wind turbine system. Meanwhile, the literatures about opportunity maintenance are discussed. Finally we give a summary and discussion in Section 2.3.

2.1 Reliability Analysis of Wind Turbine Systems

In recent decades, wind energy industry grows rapidly due to the global increasing interests in renewable power. Nowadays more and more wind turbine systems are constructed offshore due to the high energy harvest and other economic or politic reasons as well. Nevertheless, a wind power system located on sea comes with higher installation costs and more difficult maintenance condition. Furthermore, an offshore wind farm has undesirable features like higher failure rate, lower reliability and more complex working conditions. The operation & maintenance of wind turbine systems is therefore extremely challenging meanwhile the demands are higher.

Reliability Centre Maintenance (RCM) has been used broadly in many industries. It is an approach to find maintenance plans focusing on the reliability aspects. RCM is a unique approach that may considerably preserve the functions of items with appropriate maintenance plan. We should be able to analyze the reliability first, especially in case of common shortage of wind industry's operation data.

One popular data source is Windstats Newsletter, which is periodically published. The failure data consists of the number of failures of each subassembly in a fixed report interval, and the number of reported turbines. The number of reported turbines changes each interval in Windstats dataset.

Tavner et al. (2006) and Guo et al. (2009) presented their reliability analysis methods based on those grouped failure data respectively. With assumption that the time between failures are independently and identically distributed, follows exponential distribution, Tavner expressed the failure rate as the number of failures per turbine per year. The failure rate of a fixed report interval can be calculated by dividing the total number of turbine failures in this interval (the sum of reported subassemblies failures) by the number of reported turbines in the interval and by the length of the interval in a year. Therefore, the overall average failure rate over a certain study period is then given by the mean value of all intervals.

It's more common that reliability studies are based on Weibull distribution. Considering two-parameter Weibull distribution, Tavner and Guo derived the parameter formulations using Maximum Likelihood Estimation (MLE) method. Since the grouped data in Winstats provides the number of failures in each interval, thus the likelihood function is the probability of total failure events occur over study period. After the MLE process, the scale parameter α and shape parameter β can be calculated.

The Windstats data doesn't necessarily report starting from the installations of wind turbine systems. Guo (2009) also presented the reliability analysis method with three parameter Weibull distribution taking into account the parameter η. MLE and Least-squares methods to estimate parameters were applied.

Over 10 years investigated period (1994~2004) with Windstats data, Tavner et al. (2005) compared failure rate performance between German and Denmark population reported to Windstats, the Least-squares method to estimate parameters was used. The results showed the average age of German wind turbines was younger, which proved the German's failure rate has higher Infant Mortality effects, but is improving faster. They also concluded the principle contributors for the higher German wind turbines failure rate are electrical subsystems like gearbox. Later, they discussed greater impacts on failure characteristics, such as principle components, configuration, technology, weather and possible maintenance, etc. Guo (2009) and his colleagues concluded that the three-parameter Weibull function is more accurate on reliability growth of wind turbines. The reason is that the time parameter provides an extra earlier part of reliability curve that is helpful to better plan maintenance schedule. Moreover, by boldly extending the reliability curve for future 10 years, they predicted that the reliability of reported wind turbines is to be better.

Sinato and Tavner (2008) presented failure rate function for identified three important components: gearbox, generator, and converter. The data sources they used are Windstats and Landwirtschaftskammer (LWK), which is a wind power project in German. They ranked the failure rates for major components, discussed the improvement method to reliability, like more thorough test to eliminate early failures, improving design, etc.

Echavarria et al. (2008) studied the failure data from "German 250 MW Wind Program" that was promoted in 1989. They presented the components' average failure rate per wind turbine per operational year, focused on analyzing the main failures and the different design and technologies impacts on reliability through time.

To use MLE method to estimate reliability parameters, Andrawus et al. (2007) provided another likelihood function by multiplying Weibull's failure pdf and '1-cdf' with corresponding failure time and censoring occurrence data. It took advantage of the available operation data, which comes from the Supervisory Control and Data Acquisition (SCADA) system, a computer-based system provided by leading wind turbines manufacturers.

In addition to previous approaches of reliability research for wind turbine systems, some papers took comparative study on reliability performance. DOWEC project team's report (2003) compared the failure rate performance of four wind turbine populations, including the data source from Windstats, WMEP (Germany project), LWK and EPRI (California, USA). Alternatively, Johan Ribrant (2006) presented the failure rate and downtime of another four statistical sources with the total amount of 1500 wind turbines and a deeper study was conducted on the Gearbox and its CBM feasibility analysis.

Vittal and Teboul (2004), Ehsani (2005), Wen (2009) and Spahic (2009) studied the wind power production reliability. They combined wind speed and wind power generation models, and so on. The analytical method and Monte Carlo simulation method were alternatively adopted. However, these studies are not focusing on wind turbine system but the power plant. We do not intend to provide further discussion in this area since it is beyond the scope of this thesis.

Herbert et al. (2007) draw the conclusion that fewer authors have worked on reliability evaluation of wind turbine systems. Through our review, valuable information for wind turbine reliability analysis today is still little. However, reliability analysis is a mature area and can be studied effectively in the fast growing wind industry. The challenge is the reliable operational data of wind turbine system is unavailable or incomplete for most academic research. The research community should make further efforts on gathering useful data to analyze wind turbine reliability characteristics, and develop better maintenance strategies to improve reliability.

2.2 Maintenance Optimization Approaches on Wind Turbine Systems

In this section, we review the common maintenance strategies applied to wind turbine systems and wind farms, and a combined approach that has been used to other industry is discussed.

Common maintenance strategies can be categorized as failure-based, time-based and condition-based maintenance. Ribrant (2006) stated the general knowledge for these strategies in his thesis report, and provided the advantages and disadvantages of applications in wind industry. Maintenance practices on wind power system were reviewed by Alsyouf and Thalji (2008). They collected 20 papers, where 7 papers were related to operation & maintenance (O&M), the rests were classified to design & development, production & construction and retirement. Alsyouf summarized the goals and means of O&M of wind industry have more considerations on monitoring condition and predictive techniques.

2.3.1 Corrective Maintenance and Preventive Maintenance

We define preventive maintenance in this section as the maintenance without predicting health condition of component before performing the task. A preventive maintenance is to be performed at fixed intervals of time or based on the length of time actually in use for a component, so that a future failure can be prevented and makes a component more reliable.

Few papers are found on corrective or preventive maintenance applied in wind power system, which have been indeed used widely. Nevertheless, in case of continuing and larger investment on long term O&M for offshore wind farms, research should be conducted on these strategies because most owners may use them primarily by taking advantages of simplicity and ease to manage. Martínez et al. (2010) demonstrated there is greater need for corrective maintenance.

As we mentioned before, preventive maintenance is classified into time-based and age-based. Time-based preventive maintenance is that the preventive maintenance is performed every after fixed interval of time. For instance, the manufacturer undertakes maintenance every half year during first 5 years warranty. Age-based maintenance occurs when the item reaches a pre-defined age. However, age-based maintenance is not suitable for a multiple wind turbines farm due to expensive fixed cost, which is incurred whenever a preventive maintenance is performed once a component reaches a certain age.

Andrawus (2007) developed the delay-time approach to optimize time-based inspection plan. The delay-time is the time between a defect becoming apparent and functional failure actually occurring, the concept is illustrated as Figure 1. Solving this model, the data of number of observed defects over a period should be available so that the mean defect rate α and mean delay time γ can be estimated. Andrawus presented the formulation of solving optimal inspection interval based on the studies of Baker (1992 and 1997).

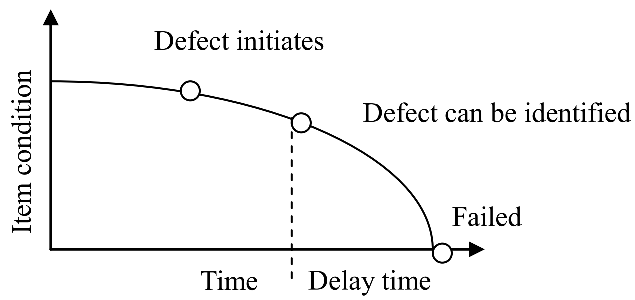


Figure 1. Potential to Functional failure process

2.3.2 Condition Based Maintenance

No surprise that there are so many studies focused on condition-based maintenance. As we mentioned previously, more and more wind power system are installed in remote sea, creating much more difficulties in maintenance. Therefore, for cost-effective operation of wind farm, the operators need to actively measure the wind turbine system's performance to prevent as much as possible the future failures and improve the system's availability. In condition-based maintenance area, the health condition diagnostic and prognostic analyses based on sensor data have drawn a lot of studies. Some focus on the overall system applications (Learney, 1999, Verbruggen 2003, Hameed and Amirat, 2007), while the others study specific important components (Wilkinson, 2007, Garcia, 2006, Besnard , 2010).

In addition to these health monitoring techniques, CBM plan could be more efficient via some optimization approaches. Lucente (2008) proposed a CBM optimization based on Proportional Hazards Model (PHM) for wind industry. PHM is the most used and cited model in other industry. It combines a baseline hazard function along with a component that takes into account the condition data, so-called covariates. PHM improves the prediction of failure with the given values of covariates and corresponding parameter. The latter indicate the degree of influence each covariate has on the hazard function. By solving an objective function for minimizing the expected average cost, the threshold hazard rate can be found. Therefore, the optimal decision is to replace the component whenever the estimated hazard exceeds optimal value. Reader can refer to Jardine [8] for more information about CBM optimization based on PHM. Lucente discussed the PHM's possible application on wind turbine components. According to her viewpoints, there is limitation due to lack of data, and also stated it remains a big challenge to identify significant covariates.

Indeed PHM or other methods for CBM haven't been discussed adequately in literatures in this industry. Instead, some researches addressed that CBM is evidently profitable by comparing with other maintenance categories in improving O&M management. Andrawus (2006) evaluated the life cycle cost under a 6-monthly scheduled maintenance policy and CBM respectively, where all related cost data for a wind farm with 26 600kw wind turbines are available. They concluded that CBM can maximize the return on investment. Nilsson et al. (2007) performed Life cycle cost analysis with different 6 strategies for a single wind turbine and a farm respectively, where CBM and corrective maintenance and preventive maintenance are all studied. The conclusion is that CBM is profitable while those maintenances are managed with different efforts.

2.3.3 Opportunity Maintenance

In practice, for a multi-component system, a combined strategy called opportunity maintenance has been proposed in many industries, and it is one of four maintenance strategies proposed in Europe Wind Energy Report (2001) for European offshore wind farms. In opportunistic maintenance, the corrective activities performed on failed components can be combined with preventive activities carried out on other components.

Opportunistic maintenance should be a considerable strategy for a wind farm because there are multiple wind turbines and a wind turbine has multiple components. Obviously the economic dependencies exist among various components and systems in the farm. When a down time opportunity has been created by the failed component, maintenance team may perform preventive maintenance for other components satisfying decision-making criterion. Consequently, substantial cost can be saved comparing with the separate maintenance. One example is that, if a component fails, preventive maintenance can be performed on another component if it reaches a certain age at the time of opportunity, and otherwise, nothing is done and the component can be left till next failure opportunity.

There are many kinds of decision-rules among this maintenance area. Laggoune (2009) proposed a decision rule for a hydrogen compressor, in which the components have different failure distributions. The maintenance decision on a component is made based on the cost comparison of performing or not performing replacements, and the conditional probability was used to calculate expected cost. Crockera (2000) used age-related rule to optimize the cost of one part of military aero-engine. They performed Monte Carlo simulation, and concluded that a potential benefit can be got from opportunistic maintenance performing on relatively cheap components. The decision rule presented by Mohamed-Salah et al. (1999) for a ball bearing system deals with the time difference between expected preventive maintenance time and failure instant. The time difference factor is considered to decide an opportunity maintenance action, and the threshold value is determined by cost evaluation. Anisul et al (2003) studied a multi-unit system by assuming the lifetime of components following Weibull distribution with the same parameters. They used a genetic algorithm technique to make an optimal decision for opportunistic replacement to maximize net benefit.

However, the opportunity maintenance application studies in wind power industry are not too much. Tian (2010) proposed an approach that a maintenance decision is made based on the failure probability during maintenance lead time. Artificial Neutral Network (ANN) technique is used to predict component's remaining life at the failure instant. Knowing that some specific turbine will fail and the power production per day over a short summer period, Besnard (2009) specified the opportunity depending on both failure chance and real wind data. They presented a cost objective function with a series of constraints, and accordingly an optimal maintenance schedule for a 5 turbines wind farm is suggested.

2.3.4 Others

In order to focus on the topic of this thesis, the weather conditions impact, design, maintenance appliance and transportation tools on maintaining wind turbines will not be considered. Several studies of these area are introduced briefly in the following paragraph.

Byon et al. (2010) developed a set of closed-form expressions for optimal maintenance policy regions with consideration of transition matrix about the deterioration states, weather conditions, production losses and repair lengthy lead times. G.Rangel (2008) presented a damage model subject to wind energy uncertainty. They conducted a total service life costs optimization function with the constraints of wind load, maximum annual failure probability and design parameters, and accordingly the optimal inspection interval is found. Rademakers et al. (2003) constructed the cost model and performed Monte Carlo simulations to examine the O&M cost for offshore wind turbines. They also took into account weather aspects, crew cost and access & hoisting equipment. The better personnel and transport allocation decision can be made to improve O&M procedure.

2.3 Summary and Discussion

Currently there are very few quantitative studies in the area of corrective maintenance optimization, which has great demands in wind power industry (Martinez et al., 2010). Most of papers focus on the preventive maintenance to avoid huge failure consequence cost when only performing corrective maintenance. However, studies discuss existing maintenance strategy but do not adequately work on how to optimize them. There should be more efforts to reduce the expected cost on this level. This motivates us to study in this thesis work.

Major interests are drawn on scheduled preventive maintenance and condition-based maintenance. Researchers discussed their benefits with various pre-defined maintenance tasks and cost data, studied the health condition prediction techniques for the components, or maintenance optimization on individual components. However, few articles discussed models and methods applied to optimize maintenance schedule with focus on a complete system that has multiple components with different failure distributions, and on a wind farm. Furthermore, the cost and condition data are usually difficult to acquire and may be viewed as proprietary (Walford, 2006).

On the other hand, preventive maintenance is commonly considered as replacement, which is perfect action that renews a component. In practice, most of equipments are repairable. An imperfect preventive maintenance or minor repair action may reduce the cost by taking advantage of fewer workloads and balanced availability. Those repair actions can be an addition of a new part, exchange of parts, removal of a damaged part, changes or adjustment to settings, software update, lubrication or cleaning (Spinato et al., 2008). To dedicate to this issue, we will develop both perfect and imperfect maintenance models to investigate O&M in this thesis.

A combined preventive maintenance strategy, opportunity maintenance, is reviewed with several different industry applications. However, few papers have been devoted to wind industry so far. These inspired us to develop an opportunity maintenance model for a wind farm, where each wind turbine system has multiple components with different failure distributions. The challenge is that it's difficult to solve this nonlinear and complex optimization problem in the analytical way, which is currently under consideration.

Taking a remote wind farm as the application platform, we will analyze the failure characteristic by using available group data published on Windstats newsletter, and extend the maintenance optimization by constructing models belongs to each maintenance category. The most suitable and practical maintenance strategy will be discussed after the comparative study of proposed optimization models.

Chapter 3

3. Fundamental Knowledge

In this chapter, first we overview the common knowledge that are closely relevant to the thesis work such as reliability definition, failure distribution and maintenance. Then we review basics of the main functions of a wind power system and its major components based on published information. Finally a wind farm will be introduced briefly.

3.1 Reliability Theory

3.1.1 Definition of Reliability

The term *Reliability* can be applied to various human activities as well as the performance of physical systems or functional objects. The objects can vary with terms 'unit', 'component', 'equipment', 'item' and 'system' as appropriate throughout this paper. To focus on functional objects, the definition of reliability is: t*he probability that an item will perform its intended function for a specified interval of time under stated conditions* (Ramadumar, 1993).

The bathtub curve is widely used in reliability engineering. Figure 2 shows the curve, it describes a particular form of the failure rate which comprises three periods:

- **Burn-in period**: it is known as early failures, and the failure rate decreases.
- **Useful life period**: the failure rate remains as constant for a certain time, and the

failure can be the result of random events.

- **Wear-out period**: the failure rate starts to increase, and it indicates an aging or wear-out effect.

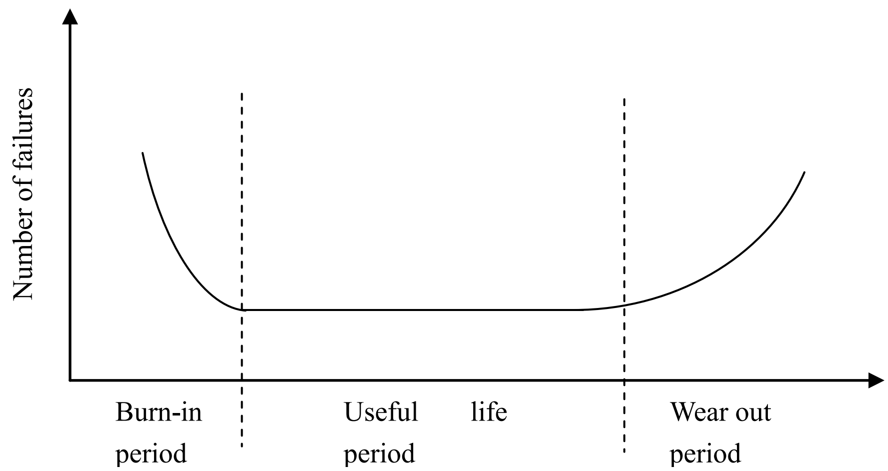


Figure 2. Bathtub Curve

As we make a maintenance decision, a common problem is to determine the most appropriate policy to adopt when item is in one of three periods (Jardine et al., 2005). In burn-in and useful life period, if the possible maintenance is only replacement, no preventive replacements should occur since such replacements will not reduce the failure risk, and the maintenance effort is being wasted. In wear-out period, preventive replacement will reduce the risk of item failure in the future.

There are many books providing detailed materials related to reliability engineering. In the following Section 3.1.2, we particularly take a brief review on the knowledge of specific probability distributions, which are under consideration in this thesis.

3.1.2 Probability Distributions

Probability distribution of an item's life time is the one of the most critical factors in reliability analysis. We also name it failure distribution while the variable is time to failure. We consider the exponential and Weibull distributions to support reliability analysis in this thesis.

Weibull Distribution

By adjusting the scale parameter α and the shape parameter β, a variety of failure rate behaviors can be modeled. The three periods in bathtub curve can be easily modeled by $\beta<1$, $\beta=1$, $\beta>1$ respectively. Thus, this distribution is very flexible, highly adaptable, and is used widely in reliability engineering.

The corresponding failure density function is:

$$f(t) = \left(\frac{1}{\alpha}\right)^{\beta} \beta t^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \tag{3-1}$$

and cdf is:

$$F(t) = 1 - e^{\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]} \tag{3-2}$$

Exponential Distribution

Consider a special case of $\beta=1$ in Weibull distribution, it reduces to the exponential distribution with a constant failure rate λ. The corresponding failure density function is:

$$f(t) = \lambda e^{-\lambda t} \tag{3-3}$$

The mean time to failure ($MTTF$) is constant, it is given by:

$$MTTF = 1/\lambda \tag{3-4}$$

The exponential distribution exhibits the useful life period where the failure rate is constant. Although the constant rate is not always realistic, it is a good approximation during the useful lifetime of the component (Ramadumar, 1993). It is most widely used to model useful life period reliability analysis, and is simple that only requires one parameter to be defined.

When we estimate the reliability function, $MTTF$, failure rate and so on, for exponential distribution, it is sufficient to just collect data on the number of observed operation time and the number of failures. The age of the component is of no interest in this context (Rausand, 2004). Therefore, it is reasonable that we approximate the failure rate of wind turbines with only a certain period observation data by assuming the wind turbines are in the useful life period.

3.2 Maintenance and Optimization

3.2.1 Introduction on Maintenance Strategy

Maintenance is categorized into failure-based, time-based, and condition-based maintenance. Some studies categorize it into two types first, corrective maintenance and preventive maintenance, then classify preventive maintenance into time-based and condition-base maintenance, see Figure 3.

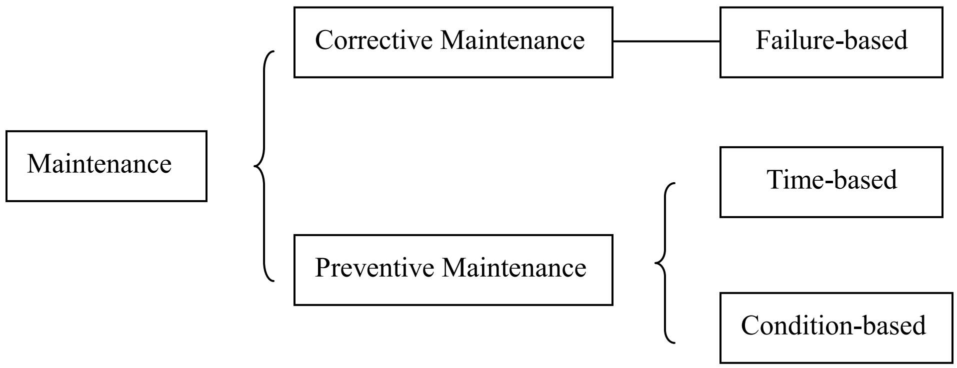


Figure 3. Maintenance classification

Failure-based (corrective) maintenance is carried out only after a failure of item occurs. It aims at return the item to functional state, either by repairing or replacing action. In this strategy, the overall cost may be very high since a failure may lead to a catastrophic damage for the system.

Time-based (scheduled) maintenance is carried out after a pre-scheduled interval no matter the failure occurs or not. This strategy can be classified into fix-interval based and age-based maintenance, according to a specified calendar time and the time that a certain age is reached respectively.

Condition-based maintenance is carried out when monitoring data signs the necessity of preventive maintenance. It will minimize the downtime and repair costs since the prediction of remaining time of components is more precise. However, CBM is not mature for wind turbine systems (Ribrant, 2006). The sensors should be reliable to present the state of component precisely. Furthermore, the knowledge of the relationship between failure mode and monitoring data is still a challenge.

Refer to Ribrant's study (2006), we summarize the advantages and disadvantages of these general maintenance strategies in the wind power industry as below:

Corrective maintenance

- Advantages

  ---- Components will be used for a maximum lifetime;

  ---- Lower investment on monitoring component.

- Disadvantages

  ---- High risk in catastrophic damage and long down time;

  ---- Spare parts and logistics allocation is complicated;

  ---- Likely long lead time for repair.

Time-based preventive maintenance

- Advantages

  ---- Easy logistics;

  ---- Shorter downtime and higher availability;

  ---- Maintenance activities can be well scheduled.

- Disadvantages

---- Components won't be used for maximum lifetime;

---- Cumulative fixed cost is higher compared to corrective maintenance due to more frequent set out.

Condition-based preventive maintenance

- Advantages

---- Components will be used the most efficiently;

---- Maintenance activities can be well scheduled;

---- Downtime is low and availability is high;

---- Easy logistics due to a failure can be predicted in time.

- Disadvantages

---- High investment and effort on reliable monitoring system;

---- Not a mature application in wind industry;

---- Difficult to identify appropriate condition threshold values.

3.2.2 Maintenance Optimization

Maintenance optimization is to determine the most cost effective maintenance strategy. It should provide the best balance between direct maintenance costs and the consequences of not performing maintenance as required. Obviously, more frequent maintenance activities result in more direct cost, thus the consequences of not performing maintenance activities decreases. In contrast, less frequent maintenance, lower cost but higher risk.

Optimization deals with the interaction between these factors and aims to determine the optimum level. This is usually obtained at the best point on the key variable, where maintenance activities will bring the lowest total cost.

Figure 4 illustrates an optimization example by determining the optimal number of failures allowed to perform corrective maintenance, for which the minimum unit cost is obtained. This example illustrates the concept of our proposed corrective maintenance optimization model.

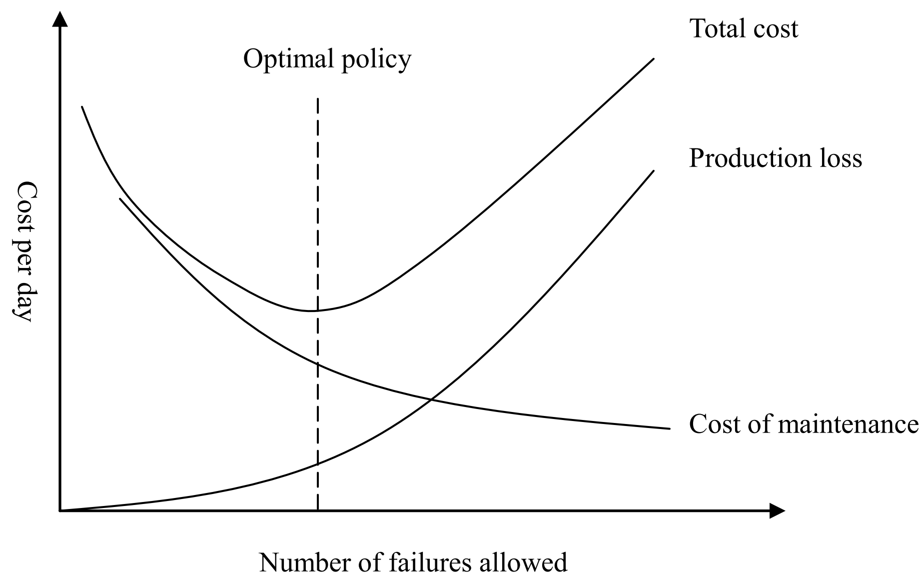


Figure 4.Optimal number of failures allowed

The objective of an optimal maintenance decision may be to minimize the total cost, or may be to maximize the availability of system, or profit and so on. In this thesis, we will focus on the cost optimization problem by determining an appropriate variable.

3.3 The basics of wind turbine system

In this section, we provide a brief introduction to the basics of wind turbine system, its components and the main failure causes of these components.

Wind turbines are stand-alone machines which are often installed and net-worked in a place referred to as a *Wind Farm* or *Wind Park*. General speaking a wind turbine system is a rotary device that extracts energy from the wind and converts to electricity.

Wind turbine system can be classified according to constructional design aspects, because it is more practicable for obvious reasons and thus more common (Hau, 2005). The most obvious characteristic is the position of the axis of rotation of the wind rotor. The oldest design of wind rotors has the feature with a vertical axis of rotation, while the rotors have their axis of rotation in a horizontal position have been built for almost all wind turbines nowadays. A schematic arrangement of a horizontal axis wind turbine is showed in Figure 5.

- **Blades**

Wind turbine blades are designed to collect energy from the wind and then transmit the rotational energy to the gearbox via the hub and main shaft. The number of blades and total area they cover affect wind turbine performance. Most wind turbines have only two or three blades on their rotors. The reason is that the space between blades should be great enough to avoid turbulence so that one blade will not encounter the disturbed, weaker air flow caused by the blade which passed before it. In an offshore environment where corrosion is a critical factor to be considered, blade material often prefers the ones that are corrosion resistant, also that have the possibility of achieving high strength and stiffness-to-weight ratio.

Blades failure causes

Cracks arising from fatigue, materials defects accumulating to critical cracks and ice build-up are known to cause failures.

- **Main Bearing**

All modern wind turbines have spherical roller bearings as main bearings. Main bearing reduces the frictional resistance between the blades, the main shaft and the gearbox while it undergoes relative motion. The main bearing is mounted in the bearing housing bolted to the main frame. Different types of wind turbines vary the quantity of bearings and bearing seats.

Main Bearings failure causes

The main bearings ensure that wind turbines withstand high loads during gusts and braking. Poor lubrication, wear, pitting, deformation of outer race and rolling elements may cause its failures however.

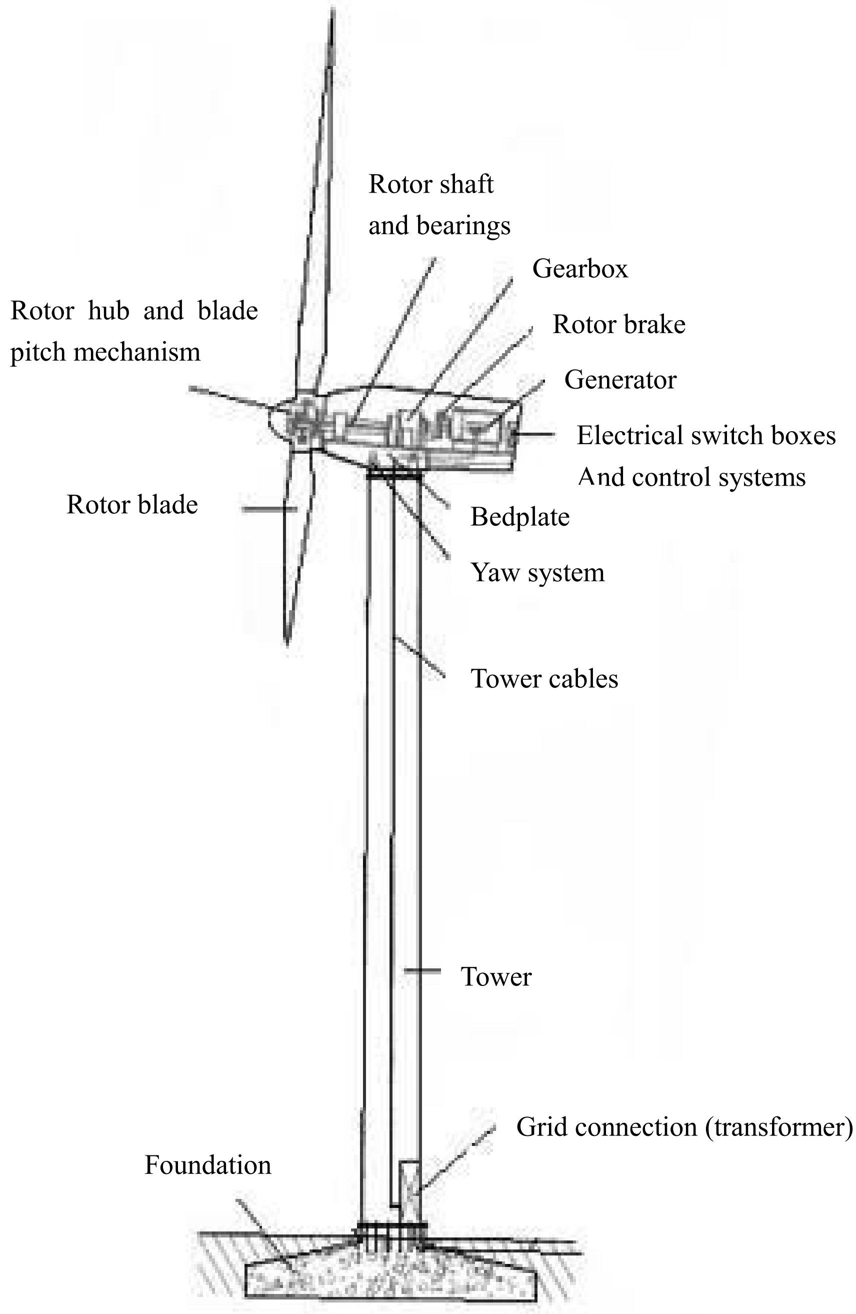


Figure 5. Components of a horizontal-axis wind turbine (Source: Hau, 2005)

- **Gearbox**

The gearbox is one of the most important and expensive main components in the wind turbine. It is placed between main shaft and generator, and the task is to increase the slow rotational speed of the rotor blades to the higher generator rotation speed. The gearbox in the wind turbine does not change speed just like a normal car gearbox. It always has the constant speed increasing ratio. Therefore, if a wind turbine has different operational speeds, it is because it has two different sized generators that each one has its own different rotation speed, or possibly, one generator has two different stator windings.

The high speed shaft from the gearbox is connected to the generator by means of a coupling. The coupling is a flexible unit made from pieces of rubber which allow some slight difference in alignment between the gearbox and the generator during normal operation.

Gearbox failure causes

Poor lubrication, bearings and gear teeth failures can cause major failures. Michele Lucente (2008) listed detailed failure modes of gearbox.

- **Generator**

The generator transforms mechanical energy into electrical energy. The blades transfer the kinetic energy from the wind into rotational energy, and then the generator supplies the energy from the wind turbine to the electrical grid.

Generator produces either alternating current (AC) or direct current (DC), and they are available in a large range of output power ratings. The generator's rating, or size, is dependent on the length of wind turbine's blades because more energy is captured by longer blades.

Generator failure causes

Bearings are the major cause of failure of generator. Thus, maintenance is mainly restricted to bearing lubrication.

- **Control and safety systems**

Control and safety systems comprise many different components. These components are combined together to insure that the wind turbine is operated with satisfaction and to prevent possible dangerous situations from arising.

Blade Pitching System fulfils two tasks. The primary task is to adjust the blade pitch angle for controlling the power and speed of the rotor. The second task is to pitch the rotor blades to the feathered position so that the rotor can be stopped aerodynamically.

Mechanical Brake is at first used as a back-up system to prevent the unacceptable high rotational speed in the drive train when the pitching system fails. Secondly it stops and holds the turbine at rest for maintenance. It's usually placed between the gearbox and generator. Mechanical brake would wear quickly if used to stop turbine from full speed.

Hydraulic System operates the mechanical braking system, the pitching system, and the yaw control system. This system ensures that the pressure is established to move pistons in hydraulic cylinders when the wind turbine starts, and also releases the pressure to the safe level when the wind turbine stops. The failure causes include contamination of hydraulic fluid, wrong oil viscosity, high hydraulic fluid temperature, faulty circuit protection devices and seal failure, etc.

Yaw system is the component responsible for the orientation of the wind turbine rotor towards the wind for maximum energy collection. Major causes of failure include bearing failures, bull gear teeth wear out, yaw brake failure and so on.

The Control System acts as replacement for the non-existent operating personnel. Its task requires an all-system data acquisition, monitoring and control system in order to maintain the turbine operating within its limit.

- **Tower**

The high tower is an essential component of the horizontal-axis turbine. Specific energy yield of the rotor increases with tower height. On the other hand transportation, erection and servicing of the components become increasingly more difficult and costly. In inland regions, large wind turbines with tower heights of 80m and more are a decisive factor for the economic use of the wind potential, while the higher towers show better returns in offshore applications. Apart from its height, the other most important design parameter is tower’s stiffness.

- **Foundation**

The foundation of a wind turbine keeps it in an upright and stable position even under extreme weather conditions. It is determined by the size of the wind turbine and by local ground conditions. Wind speed, the so-called survival wind speed is also a determining factor.

3.4 The Basics of Wind Farm

Wind farms can be located either onshore or offshore. The consideration is always based on following factors.

- **Wind resources**

The offshore wind resources are often significantly higher than onshore, even though wind resources at a specific site depend on the nature of the landscape, altitudes, shapes of hills, etc. The temperature difference between the sea surface and the air above is far smaller than the corresponding difference onshore. This means turbulence tends to be lower in offshore than onshore. Consequently, offshore wind turbines suffer less dynamic operating stress.

- **Capital cost**

Another significant difference between onshore and offshore wind energy generation is the installation cost. The foundation structures of an onshore wind farm cost about 6% of the total project cost while grid connection facilities cost about 3%. On the other hand, the foundation structures of an offshore wind farm need to ensure the turbines are connected to the seabed and are able to cope with additional factors such as loading from waves, currents and ice. Thus, the cost is about 23% of the total project cost while the cost of grid connection facilities is about 14%. These costs are significantly higher than onshore wind farm costs.

- **Technology**

The technology of the wind turbines used in onshore and offshore wind farms is very similar. The main difference is in the size and the power rating of the turbines. Onshore farms often utilize turbines with capacities of up to $2MW$ while offshore farms use multi-mega watt turbines. Offshore wind farms are usually connected to a sub-station located onshore by using submarine cables. The substation is connected to an electricity grid using over head cables in similar manner to onshore wind farms. Offshore wind farms usually require higher voltage transmission systems and technical equipment such as transformers and switch-gear. The significant wind resources offshore and the possibility to install multi-mega watt turbines are some of the major drivers of the recent shift in development of wind farms from onshore to offshore locations.

Chapter 4

4. Wind Turbines Failure Data Analysis

4.1 Data Source

In this chapter, Windstats data is analyzed to obtain information about the failure rate of wind turbines system. The data records operation details of wind turbines in many countries. Windstats Newsletter is a quarterly international publication, where the stop hours and the number of stops data of Wind turbine subassemblies are reported in table format every quarter for German turbines and every month for Danish turbines. In this study the period we use is October 2008 to July 2009, the newest failure data for German turbines.

4.2 Estimate Failure Time Distribution

German data we use starts from October 2008 to September 2009 with the reported number of turbines varying from 4767 to 5186, we consider the reported turbines as a statistics population. The wind turbine failure data is showed in Table 1, which shows the number of wind turbine component failures in each fixed interval, one quarter.

In some available wind turbine failure data, such as the Windstats, only the numbers of failures during certain period are recorded, while the component lifetimes are unknown. In this case, we can only calculate the average failure rate for reliability analysis. This is equivalent to assuming that components have constant failure rate, which means the components are in a random failure pattern during the lifecycle. To simplify the problem, we assume that any component failure will lead to a wind turbine failure, and thus the number of wind turbine failures in an interval equals to the sum of component failures. The population difference of each interval can be eliminated by calculating the average failure rate with dividing by the corresponding number of turbines in that interval. It makes sense in case of today's global renewable energy development, and also makes us to concentrate on the methods demonstrated in this Chapter.

Table 1. Windstats Turbines failure data

	Dec.08	Mar.09	Jun.09	Sep.09
No of turbines reporting	4924	5186	4767	4869
No of subassembly failures				
Entire unit	3	1	2	3
Rotor	9	9	9	12
Air brake	4	1	1	5
Mechanical brake	0	2	3	3
Pitch adjustment	16	7	7	19
Main shaft/bearing	8	5	5	3
Gearbox	37	15	12	22
Generator	15	16	17	16
Yaw System	11	14	14	9
Windvane/anemometer	7	4	3	2
Electronic controls	5	10	7	8
Electronic system	47	36	39	58
Hydraulics	25	8	6	15
Sensors	9	9	5	10
Other	9	6	3	9
Total	206	144	136	196

As we collect data from a large population, we can get an average failure rate at a given interval. The failure rate λ is the number of failures per wind turbine per year, which can be obtained by dividing the total number of failures in a specific interval by the number of population for the interval and by the length in year of the interval.

The data is recorded every quarter, then the failure rate per year of a component i with interval k is given as below:

$$\lambda_{i,k} = \frac{4n_{i,k}}{N_k} \tag{4-1}$$

where $n_{i,k}$ is the number of failures of component i in the interval k, and N_k is the total number of population in the interval k.

Similarly, the failure rate of a wind turbine system for the overall period, denoted by λ, is calculated as follows:

$$\lambda = \frac{\sum_k \sum_i n_{i,k}/N_k}{\sum_k T/4} \tag{4-2}$$

As a result, the failure rate λ_i of each component i is shown in Table 2, and we get:

$$\lambda = 0.1384$$

Figure 7 shows the failure rate of each subassembly.

With the same data source Windstats, Tavner et al.(2007) calculated the average failure rate of every year for German wind turbines population from year 1995 to 2004. They fitted them with a downward trend straight line. By boldly extending Tavner's failure rates fitting line to year 2009, we can find our result agree with it.

Table 2. Windstats turbines average failure rate

Components	Average failure rate λ over Oct.08~Sep.09
Entire unit	0.18%
Rotor	0.79%
Air brake	0.22%
Mechanical brake	0.16%
Pitch adjustment	1.00%
Main shaft/bearing	0.43%
Gearbox	1.74%
Generator	1.30%
Yaw System	0.97%
Windvane/anemometer	0.32%
Electronic controls	0.61%
Electronic system	3.66%
Hydraulics	1.10%
Sensors	0.67%
Other	0.55%
Total	13.84%

It's worth to note here, a downward trend failure rate does not indicate the German wind turbines are in early failures period. The population of wind turbines was changing, new turbines with new technologies were added continuously while older turbines were taken out of service. It makes the overall performance more reliable. This can interpret why the failure rate is going down.

The calculated average failure rate λ=0.1384 will be used to study corrective maintenance optimization in the following chapter. In case of a random failure pattern where the process follows exponential distribution, preventive replacement is not appropriate since such replacements do not lower component's failure rate.

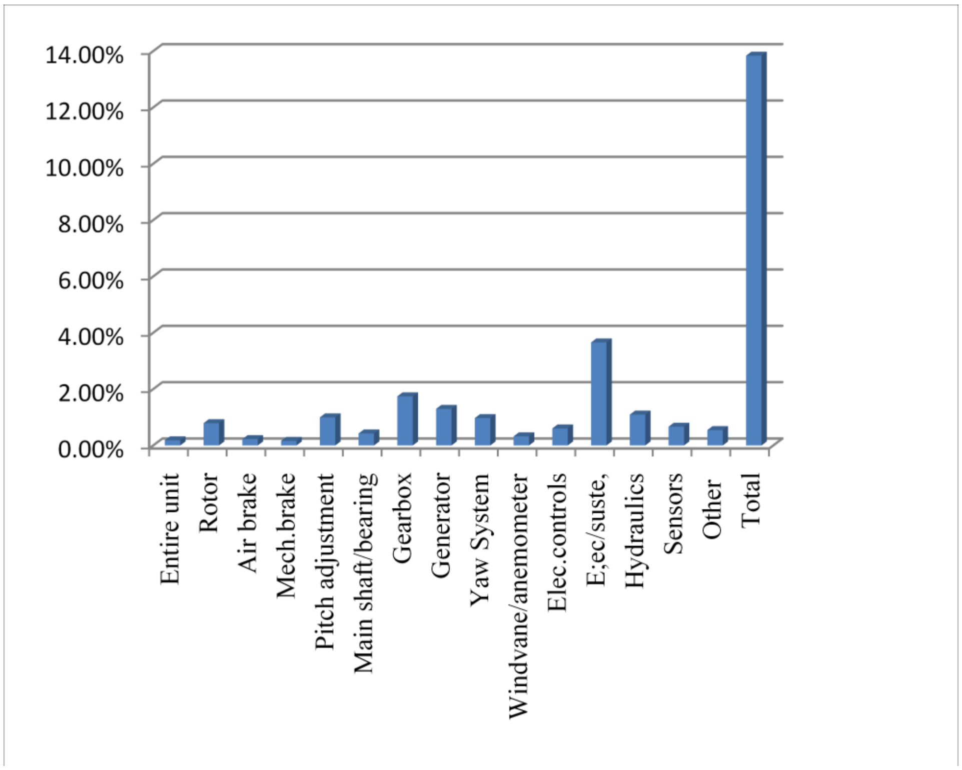


Figure 6. Failure rates for WT subassemblies in Germany (Oct.08-Jul.09)

Chapter 5

5. Corrective Maintenance Optimization

In this chapter, we discuss the corrective maintenance strategy for a remote wind farm, and construct an optimization model to make corrective maintenance more cost-effective. An approach is developed to solve the optimization problem. In application section, we use the simulation method to verify the mathematical approach.

5.1 Statement of Problem

In a remote wind farm particularly an offshore farm, a maintenance task is expensive due to the complex on-site servicing work requiring heavy transportation and lifting equipment. In addition, the wind turbine systems are exposed to wind and other undesirable weather condition which makes access difficult. Therefore, a general question regarding the maintenance is arising, whether wind turbines are often in need of maintenance (Hau, 2005)?

Thus, after manufacturers' certain warranty period, the owner may wish perform corrective maintenance only when a failure occurs. Nevertheless, a failure consequence is very large due to possible catastrophic damage caused by the failed component. Currently, studies on corrective maintenance for wind turbine systems are very few. Aiming at minimizing total operating and maintenance cost, there should be more efforts to make the study better. In this thesis, we study a corrective maintenance policy that allows multiple failures to occur before maintenance is carried out. With the comparison result, a useful recommendation in case of only performing corrective maintenance is presented.

5.2 Construction of Model

To focus on the topic study, we suppose a wind turbine system is consists of 4 key components, which are the rotor, the main bearing, the gearbox and the generator.

The model is based on the following assumptions or properties:

- The failures of components and turbine systems all follow exponential distribution.
- Any component failure will lead to turbine system failure, which means a wind turbine is a series system, and the simplified system structure is shown in Figure 8.

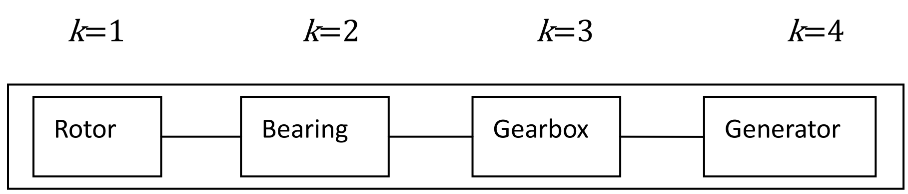


Figure 7. Series structure of a wind turbine

- Comparing to the component's long lifetime, the replacement time is negligible.
- The failure-caused replacement cost is the sum of all direct cost, which not only considers material, but labor cost, transportation cost, loading and offloading cost, access cost, etc.
- The maintenance policy is to implement corrective maintenance only, where a certain

number of wind turbines are allowed to fail before replacements are carried out. The objective is to determine the optimal number of failures allowed, denoted by n, to minimize the total expected cost per day, which consists of replacement cost and production loss that a turbine out of service.

- Some of the notations are defined as follows:

  t_n : One cycle determined by the nth failure.

  C_f : The failure replacement cost.

  P_L : The production loss per day if a turbine stops.

  C_{fix}: The fixed cost of sending a maintenance team to wind farm.

The total expected cost per unit time per turbine for one cycle t_n, denoted by $C(t_n)$, is

$$C(t_n) = \frac{Total\ expected\ cost\ per\ cycle}{Expected\ cycle\ length}$$

Expected cycle length t_n= mean time to nth failure, denoted by $MTTF_n$.

Total Expected cost per cycle

= replacement cost + fixed cost + production loss of turbines out of service

$= n \times C_f + C_{fix} + \sum_{i=1}^{n}(MTTF_n - MTTF_i) \times P_L$

The term '$MTTF_n - MTTF_i$' is the duration that a system is out of service owing to the ith failure it corresponds to. Fox example, a system fails first in the farm, then the expected failure time is the mean time to 1th failure, denoted by $MTTF_1$. If the corrective maintenance occurs at the time of nth failure, $MTTF_n$, the total stopped time of this system equals to $MTTF_n - MTTF_1$, and the total production will lose the amount of $(MTTF_n - MTTF_1) \times P_L$.

Therefore,

$$C(t_n) = \frac{n \times C_f + C_{fix} + \sum_{i=1}^{n}(MTTF_n - MTTF_i) \times P_L}{MTTF_n} \tag{5-1}$$

To solve this optimization problem, we need find $MTTF_n$ first.

5.3 Find the Cycle Length $MTTF_n$

Suppose n=3, the procedure for the cycle length computation is give as follows.

Step1. The failure probability density for a single component which follows exponential distribution can be written as below:

$$f(t) = \lambda e^{-\lambda t} \tag{5-2}$$

Thus, the probability that the 3rd failure in a group of N components occurs in [t, $t+dt$], which is denoted by $f_3(t)$, is:

$$f_3(t) = P(\text{2 failures occur before } t) \times P(\text{1 failure occurs in } [t,t+dt])$$

$$\times P(\text{N-3 failures occur after } t)$$

$$= N \times C_{N-1}^2 \times [F(t)]^2 \times f(t) \times [R(t)]^{N-3}$$

$$= NC_{N-1}^2(1-e^{-\lambda t})^2 \lambda e^{-(N-2)\lambda t} \tag{5-3}$$

where N is the number of possible choices of finding one component which fails in [$t,t+dt$]. C_{N-1}^2 is the number of possible choices of finding two components which fail before t.

Step2. The general mean time to failure can be derived by

$$MTTF = \int_0^{\infty} t f(t) dt \tag{5-4}$$

Note that the probability that the 3rd failure happens in [$0, \infty$] is unity:

$$\int_0^{\infty} f_3(t) dt = 1 \tag{5-5}$$

Substitute (5-3) into Equation (5-4), and solve the integral to get the $MTTF_3$, which is the length of cycle that every 3 failures occur.

Thus, we have

$$MTTF_3 = \frac{3N^2 - 6N + 2}{\lambda N(N-1)(N-2)} \tag{5-6}$$

This formula can also be derived easily by the sum of the mean time of the first failure for N components, the mean time of the first failure for N-1 components, and the mean time of the first failure for N-2 components (Elsen et al., 2005).

$$MTTF_3 = \frac{1}{\lambda N} + \frac{1}{\lambda(N-1)} + \frac{1}{\lambda(N-2)} \tag{5-7}$$

Now consider the general case, the expected time to the nth failure can be calculated as:

$$MTTF_n = \sum_{i=0}^{n-1} \frac{1}{\lambda(N-i)} \tag{5-8}$$

Substitute (5-8) into (5-1), we can find the total expected cost per unit time.

Based on the above analysis, $C(t_n)$ is the function of n, which can be appropriately denoted by $C(n)$, n becomes the design variable. Therefore, the objective function of proposed corrective maintenance optimization model can be briefly formulated as follows:

$$\min \; C(n) \tag{5-9}$$

where C is the total expected maintenance per unit time per turbine.

5.4 An Example

5.4.1 Data

The method is applied to a wind farm with 50 2MW turbines. Each turbine consists of four key components: rotor, main bearing, gearbox and generator.

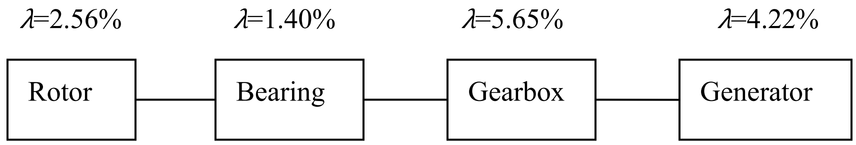
Failure distribution parameter

In Chapter 4, we calculated the average failure rate of each component. Now consider the simplified four-component system. To reasonally specify the failure rate values, we need convert their failure rate based on the component's failure contribution to the whole system, so that the failure rate of turbine system is in accordance with the result of λ=0.1384.

For example, in Chapter 4, we calculate the real failure rates of these 4 components are: rotor 0.79%, main bearing 0.43%, gearbox 1.74%, generator 1.30%. Thus, the failure rate of rotor regarding the simplified system with λ=0.1384 is given by:

$$\lambda_{Rotor} = \frac{0.79}{0.79+0.43+1.74+1.3} \times 0.1384 = 2.56\%$$

The converted failure rates of four components are:



Cost data

The best source for cost data resides with operators. The proprietary is a problem and the data are often times unavailable. We specify the cost data based on some books and literatures (Hau, 2005, Andrawus, 2008, Zhao et al., 2004, Mcmillan, 2008, Nilsson, 2007, Tian, 2010). These data are given in Table 3, including the failure replacement costs, the fixed cost of sending a maintenance crew to the wind farm and the cost of production loss.

The production loss per day is calculated by (Andrawus, 2008):

$$P_L = 24hrs \times WT_{PR} \times C_E \times Cf \tag{5-9}$$

where, WT_{PR} is wind power rating, here $WT_{PR} = 2MWh$. C_E is the cost of energy, C_E =\$50/MW (Mcmillan, 2008), Cf is capacity factor, here we suppose Cf=30%.

Based on component's failure replacement costs and their failure rates, the expected failure replacement cost C_f of wind turbine is then estimated as:

$$C_f = C_{rotor} \times \lambda_{rotor}/\lambda_{WT} + C_{Bearing} \times \lambda_{bearing}/\lambda_{WT} + C_{gearbox} \times \lambda_{gearbox}/\lambda_{WT} + C_{generator} \times \lambda_{generator}/\lambda_{WT}$$

$$= 112\times2.56/13.84+60\times1.4/13.84+152\times5.65/13.84+100\times4.22/13.84$$

$$= \$119.3k$$

Table 3. Failure replacement costs for major components

Component	Failure Replacement cost ($k)	Fixed cost to the wind farm ($k)	Production loss ($/day)
Rotor	112	50	800
Main Bearing	60		
Gearbox	152		
Generator	100		

5.4.2 Assessing Cycle Length by Simulation

Simulation is a very useful tool to solve nonlinear and complex problems. The higher number of simulations, the more accurate the result is. Although we have used the analytical method for cycle length evaluation in this chapter, the simulation method can be used to verify the result.

The flowchart of simulation process is showed in Figure 9, and detailed explanations of the procedure are given as follows.

Step1: Simulation Initialization. Specify the maximum simulation iterations *I.* As we mentioned earlier, there are 50 (m = 1,…,50) turbines considered in the wind farm, and 4 (k =1,…,4) components are considered for each turbine. The absolute time, $TA_{k,m}$, is defined as the accumulative time of every failure for that component. Obviously, at the beginning, $TA_{k,m}$ =0 for all k and m. Generate the failure times for each component in each turbine by sampling the exponential distribution for component k with parameter λ_k. The failure time of each component is represented by $TL_{k,m}$, and $TA_{k,m}= TL_{k,m}$ at the time of first failure for all components.

Step 2: Recording the time to nth failure, and updating component absolute time and failure time value. The replacement decisions can be made according to the policy, described in Section 5.2, based on the comparison of absolute times $TA_{k,m}$. Comparing the value of $TA_{k,m}$ of all the components, the nth small value implies the time of the nth failure, and the replacements are to be performed on all n components. Save this absolute time as the moment of the nth failure in the current simulation iteration, which is represented by t_i. Regenerate new failure times $TL_{k,m}$ for these replaced components, and the change in their absolute times is:

$$TA_{k,m} = t_i + TL_{k,m}.$$

The time to nth failure of the ith iteration, denoted by Δt_i, is given as:

$$\Delta t_i = t_i - t_{i-1}$$

Note that the functional components will stop working when there is failure occurring in their system. They will continue their remaining life after the replacement of the failed component. Thus, the change in their absolute times is:

$$TA_{k,m} = t_i + \textit{remaining life}$$

If the current number of iterations has not exceeded the maximum simulation iterations I, we will move to the next iteration:

$$i=i+1$$

Repeat step 2.

Step 3: Mean time to the nth failure calculation. When the maximum simulation iterations is reached, that is, $i=I$, the simulation process is completed. We have:

$$MTTF_n = \overline{\Delta t_i} = \frac{\sum_{i=1}^{I} \Delta t_i}{I}$$

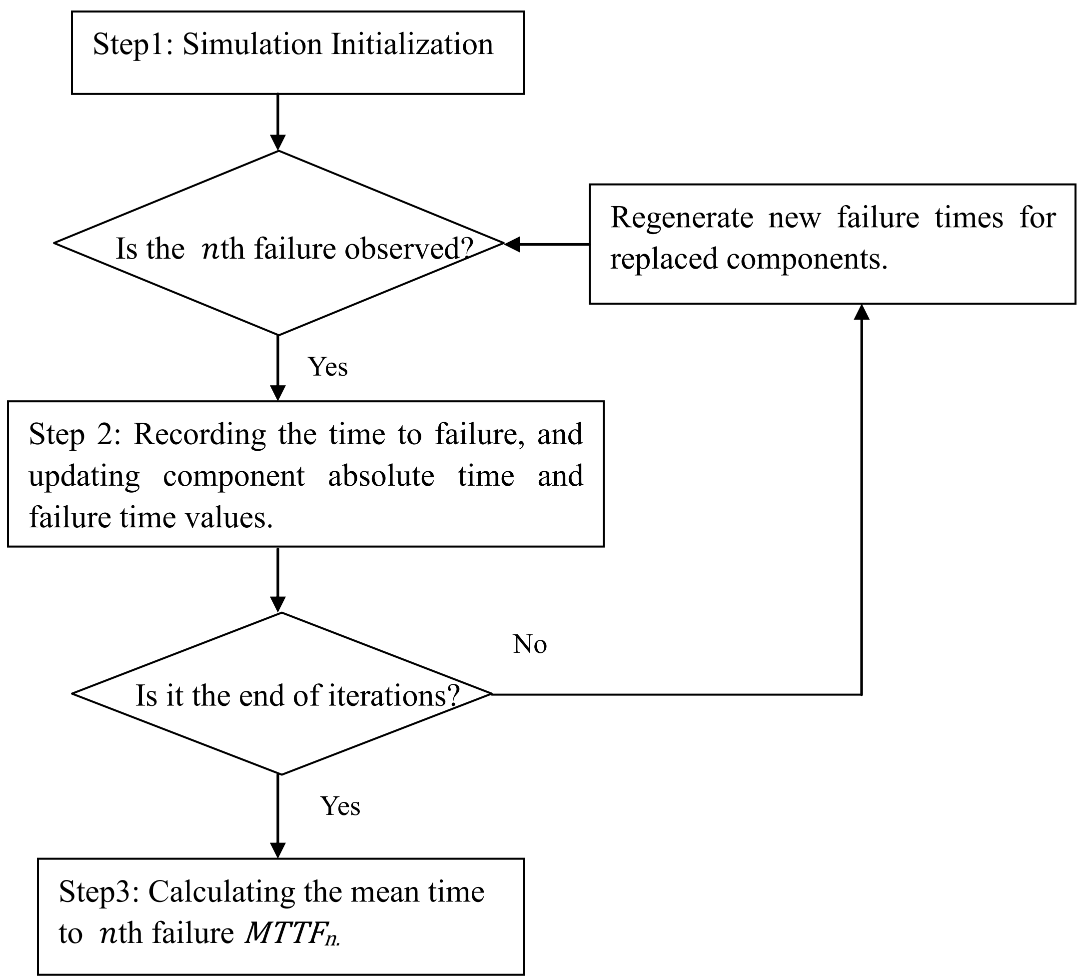


Figure 8. Flow chart of simulation process for $MTTF$ evaluation

Figure 10 shows the $MTTF_n$ obtained with simulation and the analytical method in Equation (5-8) respectively for a wind farm with 50 turbines. It can be seen that the result obtained using the simulation method and the analytical method agrees with each other

N=50 λ=13.84%

n	Simulation	Analytical
1	0.1406	0.1445
2	0.2965	0.292
3	0.4468	0.4425
4	0.5975	0.5962
5	0.7559	0.7533
6	0.9181	0.9139
7	1.0648	1.0781
8	1.2684	1.2461
9	1.4308	1.4182
10	1.5792	1.5944

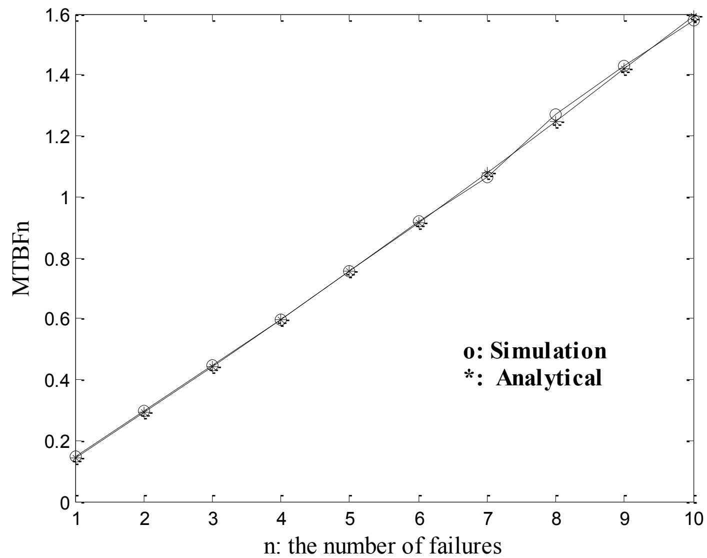


Figure 9. Simulation vs. Analytical results for $MTTF_n$

5.4.3 Cost Evaluations and Optimization Results

Using Equation (5-1) we obtained in Section 5.2, we calculate the expected costs corresponding to different number of failures allowed, then determine the optimal number of failures and cost. The result is presented in Figure 11.

We can find that the optimal failure number is 2, which corresponds to minimum total cost of $62.24/day/turbine. Even if the failure consequence is significantly large, the optimization result suggests that the owner of wind farm could get benefits by performing replacement after every 2 failures if only corrective maintenance strategy is considered.

Comparing with the cost of "replace after 1 failure", the cost savings using the proposed method is 3.5%.

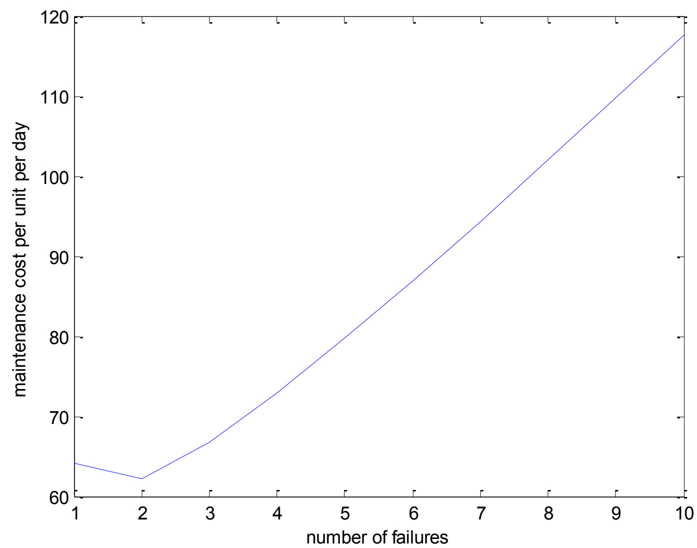


Figure 10. Cost versus the number of failures allowed (Corrective maintenance)

Chapter 6

6. Comparative Study of Maintenance Strategies

6.1 Introduction

Apart from a special case in the previous chapter that the life time of component follows exponential distribution, commonly Weibull distribution is the most appropriate one to feature failures and malfunctions of all types. It identifies the category of failure: infant mortality, random or wear out. Nowadays, it's often the case in practice that most wind turbines have increasing failure rate as most wind farms have run for 20 years or even more. Therefore, we perform the comparative study of various proposed maintenance strategies in this chapter, and assume the component's lifetime follows Weibull distribution with shape parameter $\beta>1$. Furthermore, we also compare the impacts of perfect and imperfect preventive maintenance actions on the overall expected cost, where the perfect maintenance is equivalent to preventive replacement. If the failure rate does not increase, that is, $\beta\leq1$, the preventive replacement should not occur since such replacements will not reduce the failure rate.

In this study, the total expected costs per turbine per day of different proposed maintenance strategies are compared. We also observe their benefits for 10 wind turbines and 50 wind turbines farms respectively, and the economic scale aspect of different size of wind farm is shown.

These strategies are:

1. Corrective maintenance only, where a certain number of wind turbines are allowed to fail before replacements being carried out.

2. Opportunity maintenance, where the failure replacement is executed on demand, and taking this opportunity to perform preventive maintenance at the same time for other components that satisfy certain decision-making criterion. In this thesis, the decision-making criterion is defined as component's age.

   We propose three specific policies in terms of different preventive maintenance actions:

   - 2.1 Perfect maintenance only, which is same as the preventive replacement.
   - 2.2 Imperfect maintenance only, which reduces the age of component by certain value.
   - 2.3 Two-level maintenances, where perfect and imperfect actions are applied alternatively based on different age thresholds components reach.

   Note that the costs of different level maintenance action vary.

3. Scheduled preventive maintenance. This includes schedule visits for performing preventive maintenance and corrective replacements whenever necessary.

   In this case, we propose two specific policies which preventive maintenance actions are respectively considered as:

- 3.1 Perfect maintenance only.
- 3.2 Imperfect maintenance only.

Among above strategies, design variables are specified to construct the optimization models.

Simulation algorithms are developed to evaluate the costs of different strategies. It's difficult to develop the analytical methods for some of optimization models due to complexity of the problems, e.g. opportunity maintenance optimization. Practically, most of the available reliability computational tools on the market are based on simulation technique, which is easy to implement and offers greater flexibility in modeling and analyzing complex systems (Joshi, 2007).

In Section 6.2 we propose an imperfect maintenance model. The imperfect maintenance is often the case that a maintenance task brings to the component instead of ideally returning to as-good-as new state.

An opportunity maintenance optimization model is extensively discussed in Section 6.3. In Section 6.4, we briefly describe the corrective maintenance strategy, which is same as the one we developed earlier in Chapter 5, but the lifetimes of components follow Weibull distribution. Fixed interval preventive maintenance strategy is discussed in the Section 6.5. Section 6.6 presents the examples applying different proposed maintenance strategies and compares the cost results. Finally the conclusions are given in Section 6.7.

6.2 An Imperfect Maintenance Model

In many articles related to preventive maintenance optimization for wind energy industry, preventive maintenance is often considered as replacement. However, this is not common. Scheduled maintenance of wind turbine systems generally includes verification of fluid levels and quality, inspection of structural joints and fasteners, measurement of wear items such as brake pads, bushings and seals, and functional checks of the safety and control systems (Walford, 2006). We define these inspections and repairs as imperfect actions, which do not return components to as-good-as-new status. The imperfect action takes advantage of fewer workloads and less cost. Therefore, we also propose an imperfect preventive maintenance model, that is, the age of component is reduced after maintenance.

Construction of model:

- Whenever a preventive maintenance is demanded, i.e., in opportunity maintenance or scheduled maintenance strategy, an imperfect maintenance is performed.
- The maintenance time is negligible.
- The age of component is reduced by q ($0 \leq q \leq 1$) after maintenance. For example, assume q =0.7 and a component's age before maintenance is 8 years, its new age after maintenance will be 8×0.7=5.7 years.

- The lifetime of component after maintenance will be updated as its age before maintenance with probability $\bar{q}$ and as good as new with probability q, that is:

  Expected lifetime = age before maintenance $\times\bar{q}$ + new life $\times\ q$ (6-1)

- Suppose the imperfect maintenance cost is a function of q, which represents the percentage of age reduction.

$$Cp_{Im} = q^2 Cp \qquad 0 \leq q \leq 1 \tag{6-2}$$

  where, Cp_{Im} is the imperfect maintenance cost, Cp is the preventive replacement cost. It's reasonable that the imperfect maintenance cost has an increasing nonlinear feature. The more the age of component is reduced, the faster the cost increases. No cost happens if none of age to be reduced, and the cost equals to the preventive replacement cost if 100% age is reduced as well. The other basic idea of cost function is that 50% age reduction costs one quarter of preventive replacement cost based on some industry data mentioned earlier.

This model presents well that the ultimate perfect maintenance, 100% age reduction maintenance is equivalent to the preventive replacement since the component will start a new life according to Equation (6-1) and the cost is in accordance, also.

We use this model to implement imperfect maintenance if any preventive maintenance policy demands.

6.3 Opportunity Maintenance Optimization Model

Generally, when there is not dependency between different components, a single-component maintenance model can be independently applied to each component. However, the general case of multiple components system takes account of the dependency between various components. For example, an individual component failure may damage other components, even more the system has to stop working so that the failure consequence is pretty high. Apparently the cost of simultaneous maintenance actions on various components is less than the sum of the total cost of individual maintenance. This is particularly true in the case of series system, where the failure of any component results in stopping the whole system. In addition, access to a wind turbine system shares a lot of cost, in particular for the offshore systems. Therefore, it's significant to study opportunity maintenance for wind turbine systems. This may lead to very small additional cost and great potential costs saving.

6.3.1 Construction of Model

As we mentioned earlier in Section 6.1, opportunistic maintenances are performed on the components that reach a certain age threshold, which is defined as the decision-making criterion in this thesis.

Figure 11 illustrates the policy we proposed. Suppose there is a failure occurring in the farm at present. The maintenance crew is sent to perform failure replacement, and take this opportunity to perform preventive maintenance on other qualified components. For example, component i will be performed a preventive maintenance action because its age reaches the threshold, which is p% of mean lifetime at this moment. The age of component j does not reach the threshold $p \times MTTF_j$ so that a maintenance task will not be performed and it will continue to work till next opportunity, or it may fail first in the farm.

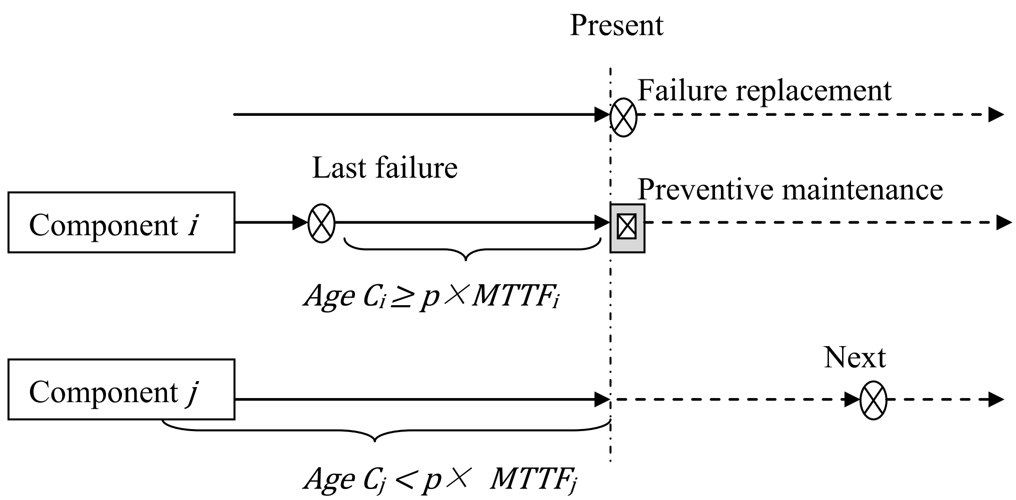


Figure 11: The proposed opportunity maintenance concept

The model is based on the following assumptions or properties:

- The failures of all components in a turbine system follow Weibull distribution, and the failure rate increases over time.
- All wind turbines in the farm are identical, and the deterioration process of each component in a wind turbine system is independent.

- Any component failure leads to turbine system failure.
- The corrective replacement time and preventive maintenance time are negligible.
- The overall maintenance policy is that, corrective replacements are performed on demand, and we take this opportunity to perform preventive maintenance on other components in the same and other turbine systems. The maintenance decision depends on the age of component at the failure instant. The detail policies are explained as follows:
  1. Perform failure replacement if a component fails.
  2. At the moment of failure, perform preventive maintenance on component k (k=1,...,K) in wind turbine m (m=1,...,M) if $age_{k,m} \geq MTTF_k \times p$, where $MTTF_k$ is the mean time to failure of component k, and p is the percentage. In terms of preventive maintenance action, we categorize to following three policies:

     Strategy 2.1, perfect maintenance only. In this policy, the component is replaced. The brief objective function is

     $$\min C_E(p) \tag{6-3}$$

     where C_E is the total expected maintenance cost per turbine per day, and p is design variable.

     Strategy 2.2, Imperfect maintenance only. In this policy, the component is not as good as new after the maintenance, but the age of component is reduced. The imperfect maintenance model we proposed in Section 6.2 is applied. The brief objective function is

$$\min C_E\ (p,q) \tag{6-4}$$

where p, q are design variables. p represents the component's age at the moment of maintenance by a percentage of its mean lifetime, and q is the percentage of age reduction after performing maintenance.

Strategy 2.3, two-level maintenance. In this policy, imperfect and perfect actions are determined by two age thresholds $MTTF \times p1$ and $MTTF \times p2$, where $p2 > p1$. The imperfect maintenance is performed when the age of component reaches $p1$ of its mean lifetime, and preventive replacement is performed when the age of the component reaches $p2$ of its mean lifetime. This implies that the older a component is, the more it tends to be replaced.

Note that in this policy, 'q', which can be described as the maintenance quality, it is a certain value other than a variable. In this model, we use the optimal result found in strategy 2.2.

The brief objective function is

$$\min C_E\ (p1,p2) \tag{6-5}$$

s.t.

$$0<p1<p2<1$$

where $p1$, $p2$ are design variables corresponding to two age level.

3. If the component will not be performed preventive maintenance, it will continue working until the next failure occurs in wind farm.

- The objective is to determine the optimal variable values to minimize the total expected maintenance cost per turbine per day.

- Some of the notations are defined as follows:

  C_f: The failure replacement cost.

  C_P: The preventive maintenance cost, different level maintenance cost varies.

  C_{Access}: The access cost from one wind turbine to another.

  C_{fix}: The fixed cost of sending a maintenance team to wind farm.

6.3.2 The Simulation Method

The simulation method is used to evaluate the expected cost of proposed strategies. We suppose there are M wind turbine systems in a wind farm, and K key components are considered for each system. Three simulations are performed to solve optimization problems respectively for these three policies. The flow chart for the solution procedure of the simulation method is presented in Figure 12, and detailed simulation procedure is explained as followings.

Step 1: Simulation Initialization. Specify the maximum simulation iterations I. Specify the number of wind turbines M and K components in a system. Specify the maximum value of design variables, $p1$, $p2$, q, which correspond to different policies. For each component k, specify the cost values including the failure replacement C_{fk}, and the preventive replacement cost C_{Pk}. The fixed cost C_{fix} and the access cost C_{Access} also need to be specified. The total cost is set to be C_T=0, and will be updated during the simulation process. The Weibull distribution parameters of each component are given, which we presented in Section 6.6.1. The absolute time, $TA_{k,m}$, is defined as the accumulative time of every failure for that component. At the beginning, generate the failure times $TL_{k,m}$ for each component in each turbine by sampling the Weibull distribution for component k with parameter α_k and β_k. Thus, the age values for all components are 0 at the beginning, that is, $Age_{k,m}=0$ for all k and m, and $TA_{k,m}=TL_{k,m}$ at the time of first failure for all components.

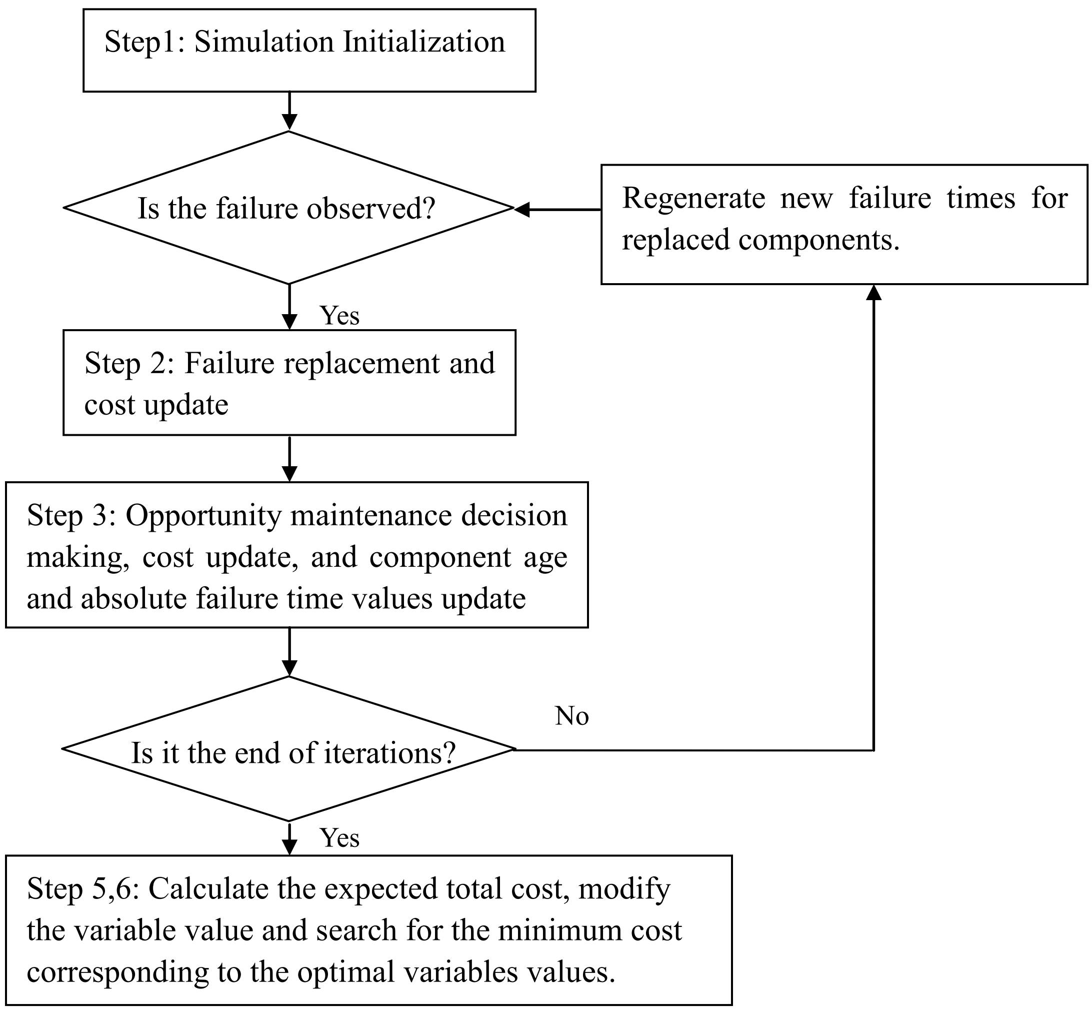


Figure 12: Flow chart of simulation process for cost evaluation (Opportunity maintenance)

Step 2: Failure replacement and cost update. Compare the values of all $TA_{k,m}$, The failure replacement of the ith iteration occurs at t_i, and $t_i = \min(TA_{k,m})$. The time to failure of the ith iteration is represented by Δt_i, and $\Delta t_i = t_i - t_{i-1}$, $t_0 = 0$. The failure replacement cost C_{fk} is incurred due to the failed component k, and meanwhile the fixed cost of sending a maintenance team to the wind farm, C_{fix}, is incurred. The total cost due to failure replacement is updated as:

$$C_T = C_T + C_{fk} + C_{fix} \tag{6-6}$$

Generate a new failure time $TL_{k,m}$ by sampling the Weibull distribution for this component with parameter α_k and β_k, and reset its age to 0. Its absolute time is moved to next failure, i.e.,

$$TA_{k,m} = t_i + TL_{k,m} \tag{6-7}$$

The age of all rest components in M turbines at current point is summed up with Δt_i, i.e.,

$$Age_{k,m} = Age_{k,m} + \Delta t_i \tag{6-8}$$

Step 3: Opportunity maintenance decision making, and updating cost, age and time values. For the rest components in all systems M, opportunity maintenance decisions can be made according to proposed strategies, described in Section 6.3.1. At the moment of failure replacement, three maintenance policies are performed respectively. The total cost due to preventive maintenances is updated as:

$$C_T = C_T + \sum_{m=1}^{M}\left(\sum_{k=1}^{K} Cp_k \times IP_{k,m} + C_{Access} \times IA_m\right) \tag{6-9}$$

where $IP_{k,m} = 1$ if a preventive maintenance is to be performed on component k in turbine

m, otherwise equals 0. IA_m =1 if any preventive maintenance is to be performed on turbine m, otherwise equals 0.

Note that Cp_k varies with different q according to Equation (6-2), where q can be considered as maintenance quality.

The changes of $TA_{k,m}$ and $Age_{k,m}$ for three different policies are different, they are explained as follows:

- Strategy 2.1, perfect maintenance only

If $Age_{k,m} \geq MTTF_m \times p$, preventive replacement is performed on component k in turbine m. Generate a new failure time $TL_{k,m}$ for this component with parameter α_k and β_k, and reset its age to 0, its absolute time will be moved to next failure, i.e.,

$$TA_{k,m} = t_i + TL_{k,m} \tag{6-9}$$

- Strategy 2.2, imperfect maintenance only

If $Age_{k,m} \geq MTTF_m \times p$, imperfect maintenance is performed on component k in turbine m. Generate a new failure time $TL_{k,m}$. Age and absolute time are updated as:

$$Age_{k,m} = Age_{km} \times (1\text{-}q) \tag{6-10}$$

$$TA_{k,m} = t_i + q \times TL_{k,m}, \tag{6-11}$$

where, $q \times TL_{k,m}$ is the remaining life of the component at this point, and it is obtained by Equation (6-1).

- Strategy 2.3, two-level maintenance

If $MTTF_m \times p2 \geq Age_{k,m} \geq MTTF_m \times p1$, imperfect maintenance is performed on the component. Generate a new failure time $TL_{k,m}$. Age and absolute time are updated as:

$$Age_{k,m} = Age_{km} \times (1\text{-}q)$$

$$TA_{k,m} = t_i + q \times TL_{k,m},$$

If $Age_{k,m} \geq MTTF_m \times p2$, preventive replacement is performed on the component. Generate a new life time $TL_{k,m}$, and reset its age to 0, its absolute time will be moved to next failure, i.e.,

$$TA_{k,m} = t_i + TL_{k,m}$$

Note that in this strategy, q is a certain value determined as the optimal result in strategy 2.2, not a variable.

Step 4: After performing maintenance decisions on all of components, the iteration moves to the next, that is, $i=i+1$. If i does not exceed the maximum simulation iteration I, repeat step 2 and step 3.

Step 5: Total expected cost calculation. When the maximum simulation iteration is reached, which is $i = I$, the simulation process for current variable value is completed. The total expected cost per wind turbine per day can be calculated as:

$$C_E = \frac{C_T}{M \times t_I} \tag{6-13}$$

If upper bound is not reached, repeat step 2, 3, 4 and 5.

Step 6: As soon as the variables go to upper bound, search the optimal value that the corresponding expected total cost per turbine per day C_E is minimal. As can be seen, once the optimal values of variables $p1$, $p2$ and q are found, the optimized maintenance strategies are determined.

The simulation algorithm for calculating the expected total cost per turbine per day can be given by:

$$C_E = \frac{\sum_{i=1}^{I}\left(C_{fix} + Cf_m + \sum_{m=1}^{M}\left(\sum_{k=1}^{K} Cp_{k,m} \times IP_{k,m} + C_{Access} \times IA_m\right)\right)}{t_I \times M} \quad (6\text{-}14)$$

where, $IP_{k,m}$ =1 if preventive maintenance is performed on the component k in turbine m, otherwise $IP_{k,m}$ =0. IA_m =1 if any maintenance is performed on the wind turbine system m, otherwise IA_m =0. t_I is the total length of I iterations.

6.4 Corrective Maintenance Optimization

In order to investigate the benefits of different strategies, we also introduce the corrective maintenance optimization model, which we illustrated in Chapter 5. The only difference is that the failure of component follows Weibull distribution with the parameter $\beta > 1$, which means the failure rate increases over time.

The simulation procedure for solving the optimization problem is same as we did in Chapter 5. We will quantitatively study the consequence via example in Section 6.6. For a wind farm having components all in wear out period, corrective replacement only would be very costly due to much higher failure risk.

6.5 Fixed Interval Preventive Maintenance Optimization

As we mentioned earlier, scheduled preventive maintenance is classified into fixed interval maintenance and age-based maintenance. In a remote wind farm the age-based maintenance is not suitable due to high fixed cost, which is incurred whenever a preventive maintenance is performed once a component reaches a certain age.

We focus on the fixed interval preventive maintenance optimization in this thesis. The policy includes scheduling visits to perform preventive maintenance, and performing corrective replacement whenever a component fails.

Consider perfect and imperfect preventive maintenance actions together, similarly, two strategies are studied respectively:

- Strategy 3.1, only performing perfect maintenance.
- Strategy3.2, only performing imperfect maintenance.

6.5.1 Construction of Model

The model is based on the following assumptions or properties:

- The failures of all components in a turbine system follow Weibull distribution, and the failure rate increases over time.
- All wind turbines in the farm are identical, and the deterioration process of each

component in a wind turbine system is independent.

- Any component failure leads to turbine system failure.
- The corrective replacement time and preventive maintenance time are negligible.
- The policy is to perform failure replacement whenever there is a failure, and preventive maintenance is performed on components at fixed intervals. The objective is to determine an optimal interval to minimize the total cost per turbine per day.
- In terms of preventive maintenance actions, we categorize to the following two policies:

  Strategy 3.1, only performing perfect maintenance. In this policy, the component is replaced.

  The brief objective function is:

$$\min C_E(\Delta) \tag{6-15}$$

where C_E is the total expected maintenance cost per turbine per day, and Δ represents the maintenance interval.

Strategy 3.2, only performing imperfect maintenance. In this policy, the component is not as good as new after performing the maintenance, but its age is reduced. The imperfect maintenance model we proposed in Section 6.2 is applied. Note that in this policy, preventive maintenance on a component will reduce the age by a certain value. However, if we run simulation processes with different age reduction values from 10% to 90% respectively, the best age reduction value will be found by comparing simulation results.

The objective function is similarly formulated as:

$$\min\ C_E(\Delta) \tag{6-16}$$

- Some of the notations are defined as follows:

  C_f: The failure replacement cost.

  C_P: The preventive maintenance cost, different level maintenance cost varies.

  C_{Access}: The access cost from one wind turbine to another.

  C_{fix}: The fixed cost of sending a maintenance team to wind farm.

6.5.2 Analytical Solution for Perfect Maintenance Policy

The analytical algorithm can be easily developed for evaluating the expect total cost of preventive replacement policy. The following equation is used to calculate cost (Jardine, 2005).

The expected total cost per turbine per day

$$C_E(\Delta) = M \times \frac{\text{Expected maintenance cost for turbine m during interval } \Delta}{\Delta} \tag{6-17}$$

where the expected maintenance cost for turbine m during interval Δ is given by

$$C_{Em}(\Delta) = \sum_{k=1}^{K} \left(Cp_k + Cf_k \times H_k(\Delta) \right) \tag{6-18}$$

where $H_k(\Delta)$ is the expected number of failures of component k during interval Δ, which can be calculated using discrete approach:

$$H(T) = \sum_{i=0}^{T-1} [1 + H(T-i-1)] \int_i^{i+1} f(t)dt, T \geq 1,\ H(0) = 0 \tag{6-19}$$

Note that i correspond to the unit time. For example, if preventive maintenance occurs every 5 weeks, then we want to find out the expected number of failures during 5 weeks, which is represented by $H(5)$. Thus $H(T)$ can be calculated from $H(1)$, then $H(2)$, $H(3)$, $H(4)$and eventually $H(5)$.

6.5.3 Simulation Procedure for the Imperfect Maintenance Policy

In case of the complexity of imperfect maintenance optimization problem, simulation method is developed to evaluate cost and search optimal variable value.

During the simulation process, the age and lifetime of a component after performing preventive maintenance are updated according to the imperfect maintenance model we proposed in Section 6.2.

The Flow chart for the solution procedure of the simulation method is presented in Figure 13, and details are explained in the following paragraphs.

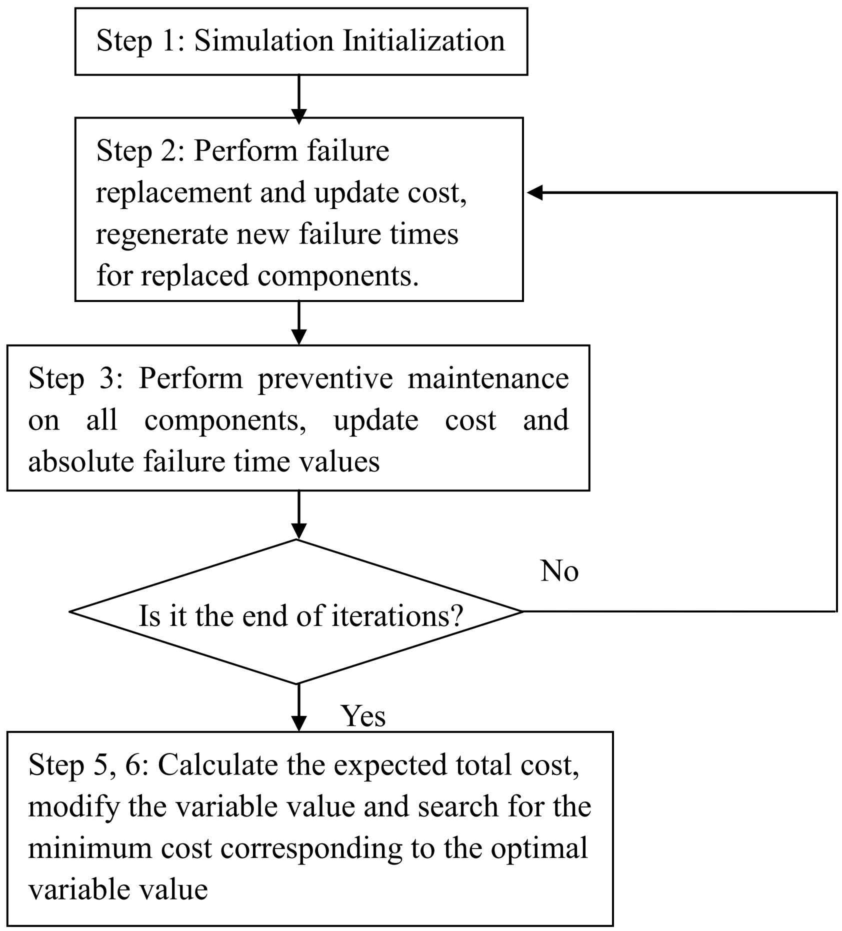


Figure 13: Flow chart of simulation process for cost evaluation
(Fixed-interval imperfect preventive Maintenance)

Step 1: Simulation Initialization. Specify the maximum simulation iterations I. Specify the number of wind turbines M and the number of components in a system K. Specify the maximum value of design variable, Δ. For each component k, specify the cost values including the failure replacement cost C_{fk}, and the preventive replacement cost C_{Pk}. The fixed cost C_{fix} and the access cost C_{Access} also need to be specified. The total cost is set to be $C_T = 0$, and will be updated during the simulation process. The Weibull distribution parameters of each component are given, which we present in Section 6.6.1. The absolute time, $TA_{k,m}$, is defined as the accumulative time of every failure for that component. At the beginning, generate the failure times for each component in each turbine $TL_{k,m}$ by sampling the Weibull distribution for component k with parameters α_k and β_k. Thus, the age values for all components are 0 at the beginning, that is, $Age_{k,m}=0$ for all k and m, and $TA_{k,m} = TL_{k,m}$ at the first failure for all components.

Step 2: Failure replacement and cost update. At each time interval, time set is denoted by t_i, and $t_i = i \times \Delta$, i is the number of current iterations.

(1) If $TA_{k,m} \leq t_i$, it complies that a component failure occurred. A failure replacement needs to be performed on the component. The change in the total cost due to failure replacement is:

$$C_T = C_T + C_{fk} + C_{fix} \tag{6-20}$$

Check all the $TA_{k,m}$, that is, repeat (1) for all components K in turbines M.

If $TA_{k,m} > t_i$, switch to Step 3.

(2) Generate new real failure times $TL_{k,m}$ by sampling the Weibull distribution for all replaced components, and $TA_{k,m}$ is updated as:

$$TA_{k,m} = TA_{k,m} + TL_{k,m} \tag{6-21}$$

Repeat (1) and (2).

Step 3: Preventive maintenance and cost update. After replacing all components failed between time interval $[t_i, t_{i-1}]$, we have $TA_{k,m} > t_i$ for all components K in turbines M.

Preventive maintenance need to be performed on all components at current time interval t_i. The total cost due to preventive maintenance is updated as:

$$C_T = C_T + \sum_{m=1}^{M} (C_{Access} + \sum_{k=1}^{K} Cp_k) \quad (6\text{-}22)$$

Generate a new failure time $TL_{k,m}$ for all components, and TA_{km} is updated as:

$$TA_{k,m} = i \times \Delta + q \times TL_{k,m} \quad (6\text{-}23)$$

where, $q \times TL_{k,m}$ is the remaining life of component k in turbine m at this point. It is obtained by Equation (6-1). Note that in this strategy, we suppose q is a certain value, and corresponding maintenance cost is determined by Equation (6-2).

Step 4: After performing all maintenance actions, time set t_i will move to the next interval, that is, $i = i + 1$. If i does not exceed maximum simulation iterations I, repeat step 2, 3 and 4.

Step 5: Total expected cost calculation. When the maximum simulation iteration is reached, that is, $i = I$, the simulation process for current variable value is completed. The total expected cost per wind turbine per day can be calculated as:

$$C_E = \frac{C_T}{M \times t_I} \quad (6\text{-}24)$$

where $t_I = I \times \Delta$.

The variable value steps on, and if upper bound is not reached, repeat step 2, 3, 4 and 5.

Step 6: As soon as the variable goes to the upper bound, search the optimal value that the corresponding expected total cost per turbine per day C_E is minimum. As can be seen, once the optimal Δ is found, the optimized maintenance strategy is determined.

The simulation algorithm to calculate total maintenance cost per turbine per day is given by:

$$C_E = \frac{\sum_{i=1}^{I}\left(C_{fix} + \sum_{m=1}^{M}\left(C_{Access} + \sum_{k=1}^{K} Cp_k\right) + \sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{\Delta}\left(Cf_k + C_{fix}\right) \times IF_{k,m}\right)}{t_I \times M} \quad (6\text{-}25)$$

where $IF_{k,m}=1$ if a failure replacement is to be performed on the component, otherwise $IF_{k,m}=0$.

6.6 Examples

6.6.1 Data

Consider 50 2MW turbines and 10 2MW turbines respectively in a wind farm at a remote site, we study four key components in each wind turbine: the rotor, the main bearing, the gearbox and the generator.

Failure distribution parameter

We assume that the failures of components all follow Weibull distribution with increasing failure rate. All wind turbines in the farm are identical and each component deteriorates independently. The failure distribution parameters are given in Figure 14 (Tian, 2010).

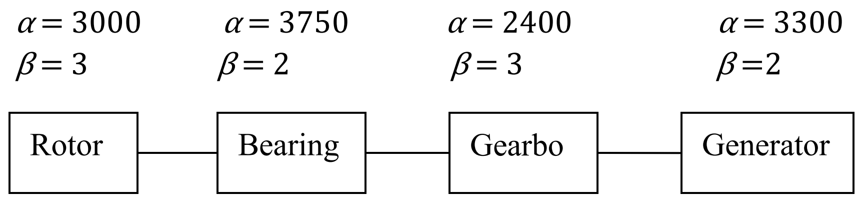


Figure 14. Components and parameters in the example

Cost data

We use the cost data presented in the corrective maintenance optimization example, the supplement cost data are given in Table 4. The imperfect maintenance cost varies according to the proposed model. They can be calculated with Equation (6-2).

Table 4. Maintenance cost data for components considered

Component	Failure Replacement ($k)	Preventive Replacement ($k)	Fixed cost to the wind farm ($k)	Access cost ($k/turbine)
Rotor	112	28	50	7
Bearing	60	15		
Gearbox	152	38		
Generator	100	25		

6.6.2 Cost Evaluations and Optimization Results

Matlab can be used to solve these optimization problems, 10000 simulation iterations are run which makes result as accurate as possible.

Strategy 1.1 Corrective maintenance

The cost versus the number of failures allowed plots are given in Figure 15. As we can see, it is more cost effective that corrective maintenance is performed after more than one failures. For the 50 turbines farm, the optimal allowed number of failures is 3, the minimum total cost per turbine per day is $196.8. This saves about 10% of the cost of replacing right after one failure. Comparing to the wind farm with 50 turbines, the benefit of the 10 turbines farm is small. However, there are still cost savings if we allow 2 failures occur.

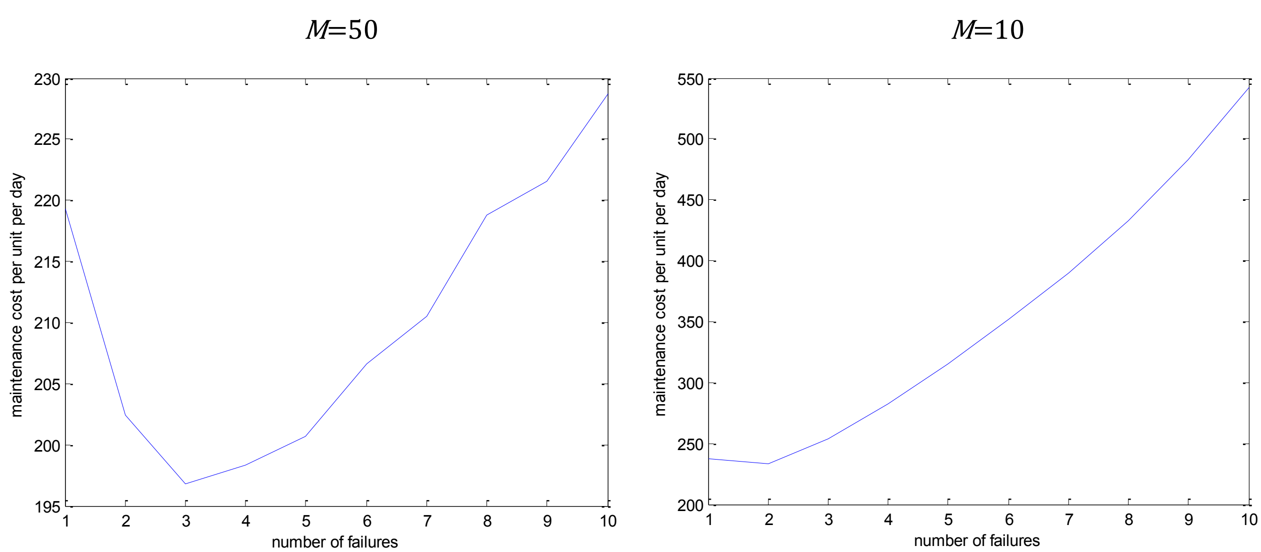


Figure 15. Cost versus the number of failures allowed (corrective maintenance)

Strategy 2.1 Opportunity maintenance with perfect action

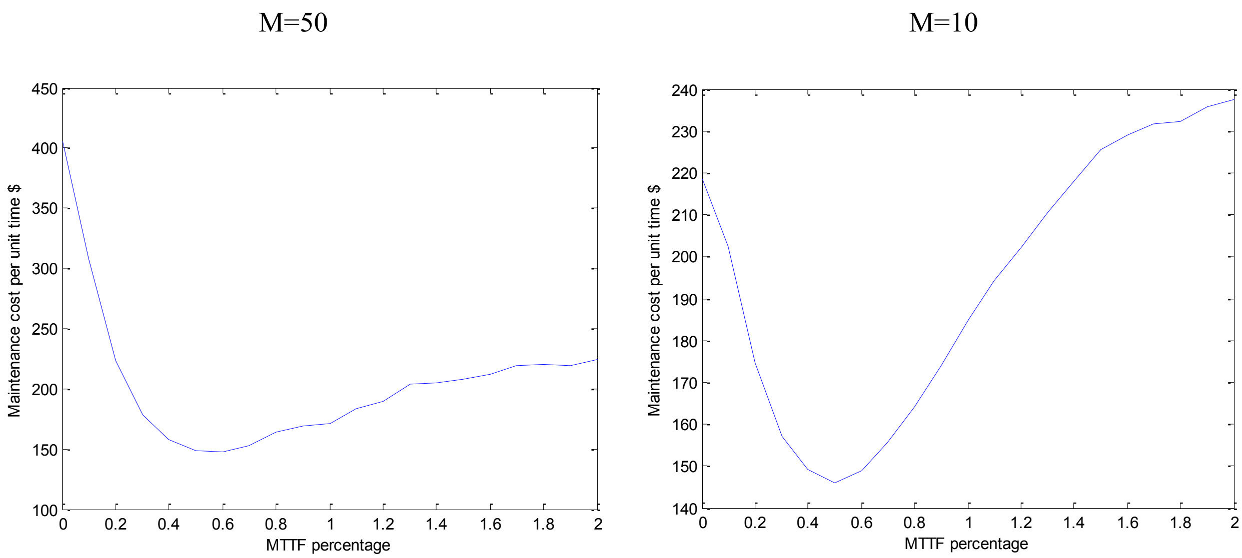


Figure 16. Cost versus preventive replacement age (opportunity maintenance)

As we can see in the figure of the farm with 50 turbines, the opportunity maintenance cost can be minimized by taking actions on the component whose age reaches 60% of its mean lifetime, and the corresponding optimal cost is \$150.4/day. Almost the same optimal cost gets from 10 turbines farm, however, the differentiation along the scope of age is quite different.

Strategy 2.2 Opportunity maintenance with imperfect action

For the wind farm with 50 turbines, the minimum total cost per turbine per day is \$149.3. The corresponding optimal maintenance plan is that, performing the imperfect maintenance action on the component whose age reaches 50% of its average lifetime, and the best maintenance action is to reduce the age of component by 90%. The optimal age and imperfect maintenance action are different for the wind farm with 10 turbines, and the minimum total cost is $146.7. This is not too much different from the 50 turbines farm.

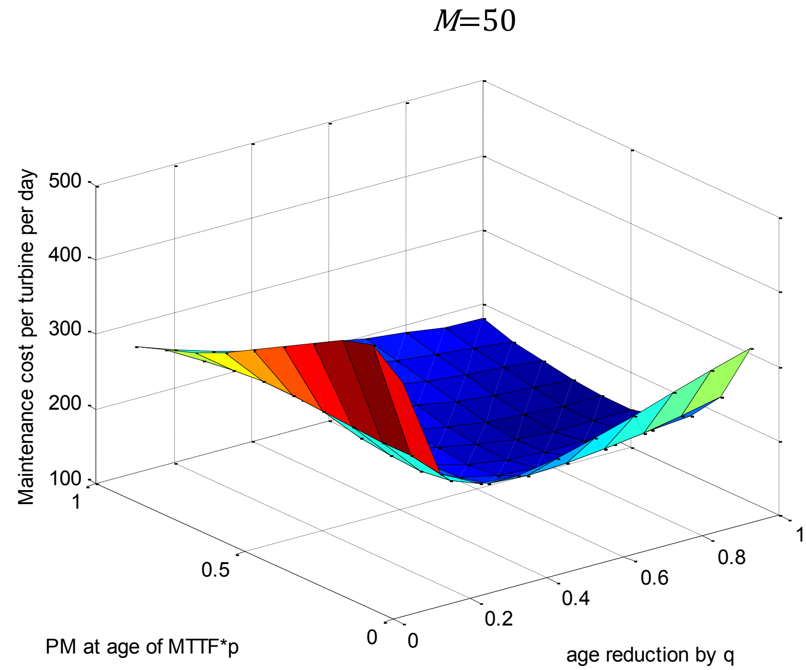


Figure 17. Cost versus maintenance age p and age reduction q (50× farm)

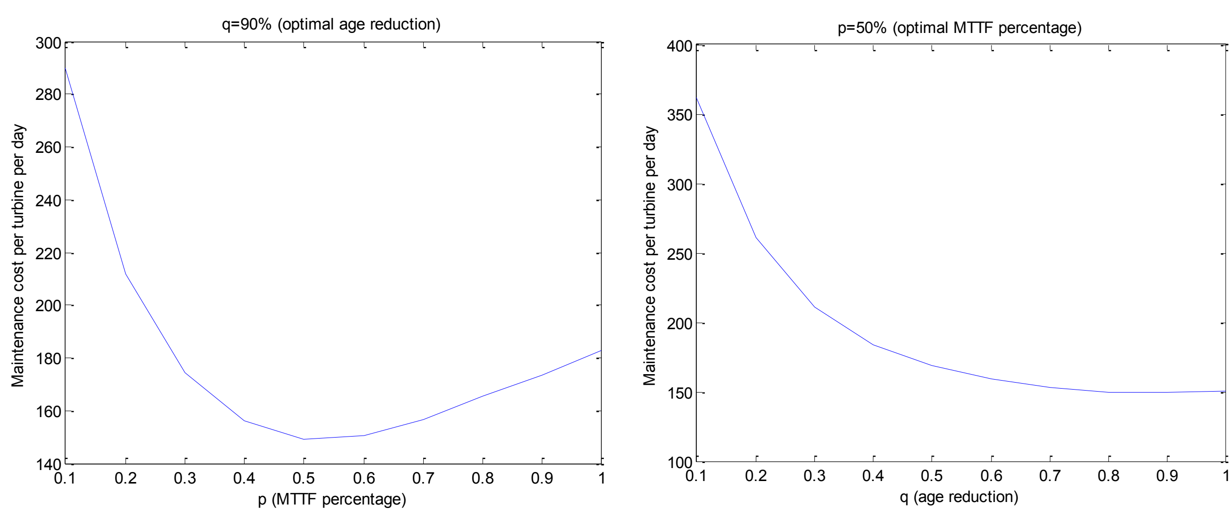


Figure 18. Cost versus p and q respectively (50× farm)

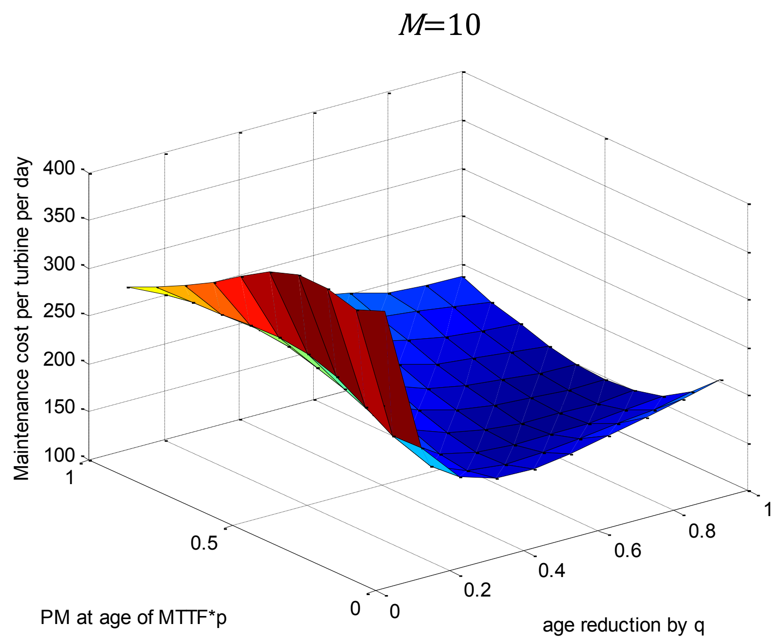


Figure 19. Cost versus maintenance age p and age reduction q (10× farm)

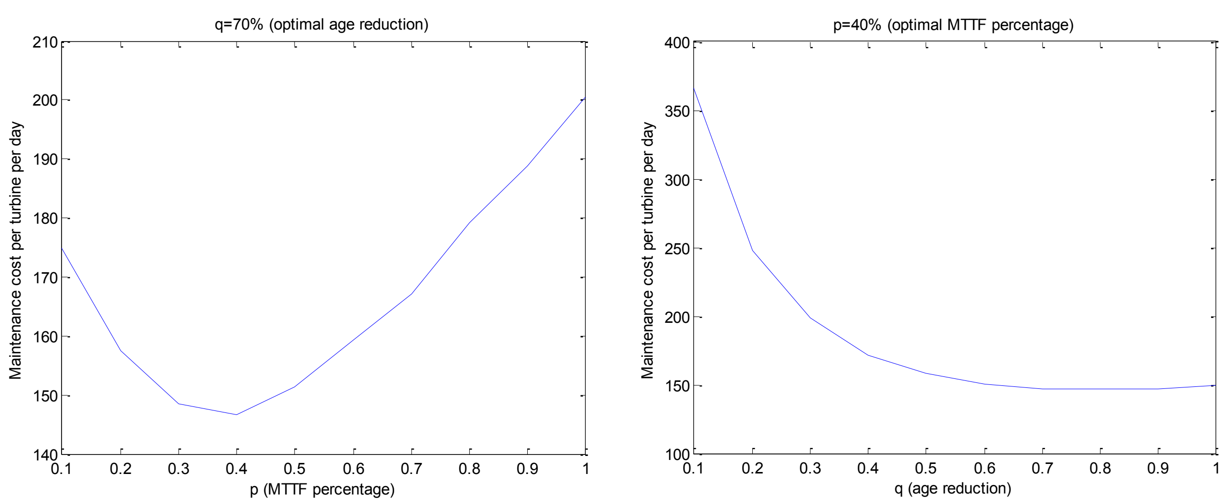


Figure 20. Cost versus p and q respectively (10× farm)

Strategy 2.3 Opportunity maintenance with two levels maintenance action

Two levels maintenance defines that the low level maintenance is imperfect and the high level is perfect, they are supposed to be performed at different age thresholds. A replacement will be considered when a component is older, while the imperfect action tends to be performed at the younger age. Based on the optimization result of strategy 2.2, the imperfect maintenance action reduces the component's age by 90% for the 50 turbines farm and 70% for the 10 turbines farm as well. These values are applied to this optimization problem.

As a result, for the 50 turbines wind farm two levels maintenance optimization model contributes the minimum cost of $147. The optimized policy is that, at the moment of a failure in the farm, imperfect preventive maintenance action is taken on the component whose age between 50% and 90% of its mean lifetime, and preventive replacement is performed on the component whose age exceeds 90% of its mean lifetime. Same optimal policy is suggested to the wind farm with 10 turbines, and the corresponding minimum cost is $145.8.

Reviewing the proposed opportunity maintenance strategies, the optimized costs are very close no matter the perfect, the imperfect or both actions are applied. This implies that there is not significant benefit existing between different optimal opportunity strategies. In addition, there is not economic scale factor existing between different sizes of wind farm.

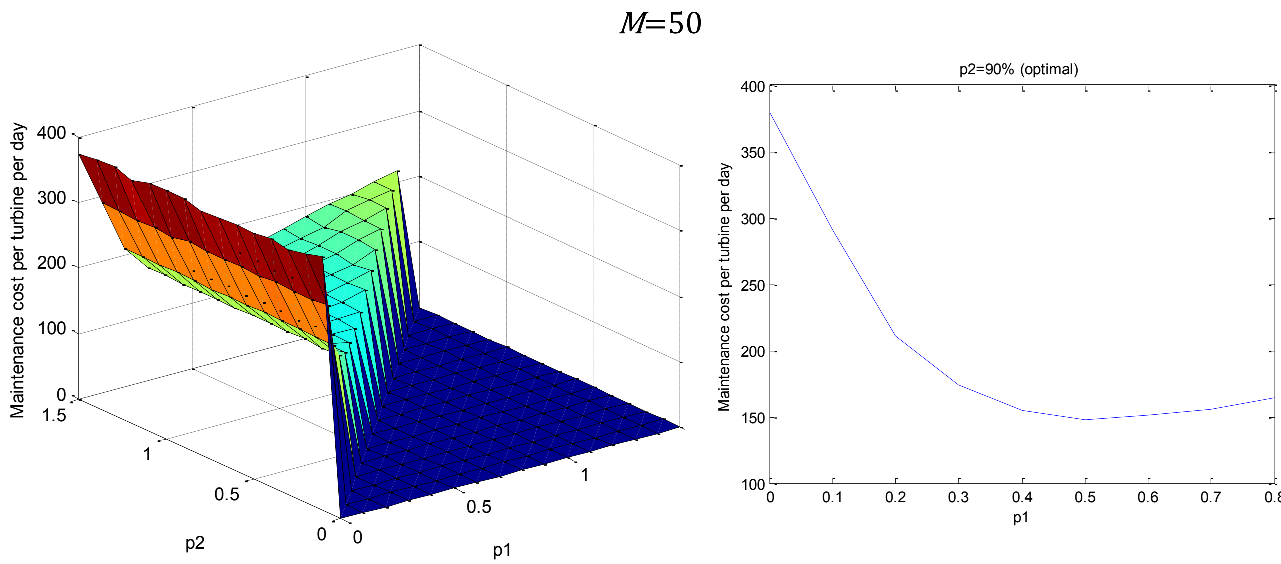


Figure 21. Cost versus two age threshold values $p1$ and $p2$ (50× farm)

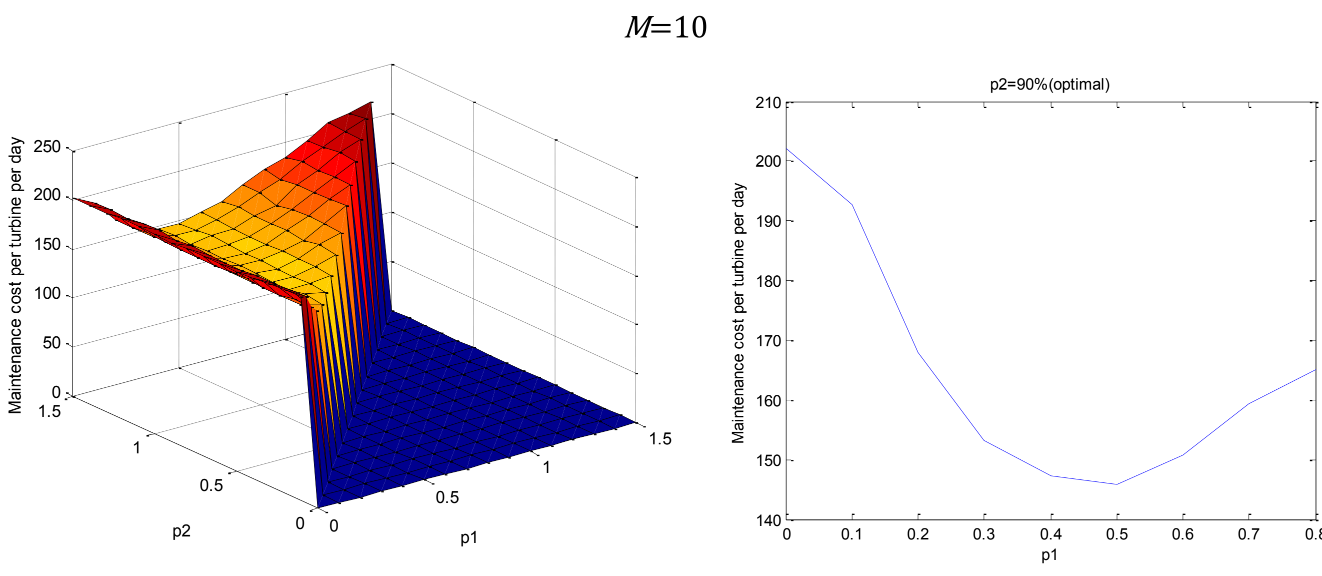
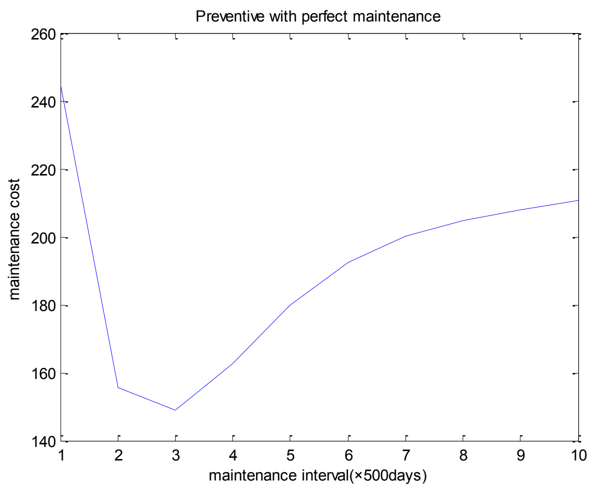


Figure 22. Cost versus two age threshold values $p1$ and $p2$ (10× farm)

Strategy 3.1 Fixed interval preventive maintenance with perfect action

M=50 M=10



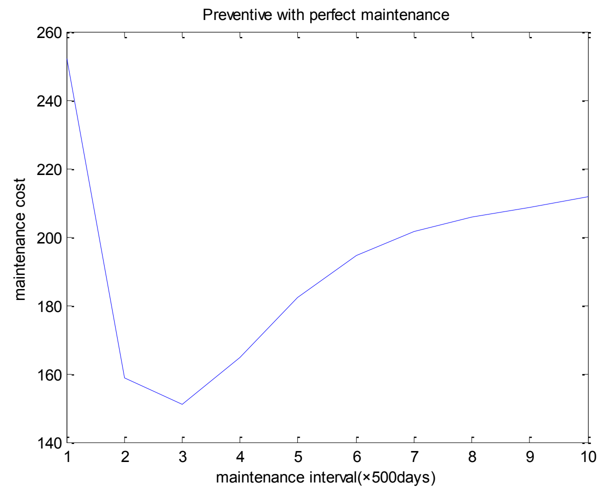


Figure 23. Cost versus interval (perfect maintenance)

The optimal total cost per turbine per day for the 50 turbines farm is \$149 and the corresponding preventive replacement interval is 1500days. For the 10 turbines farm, the optimum daily maintenance cost is \$151 when preventive replacements are planned to be performed every 1500 days too.

Strategy 3.2 Fixed interval preventive maintenance with imperfect action

We only consider one variable in this strategy, which is time interval. The imperfect maintenance action is defined as age reduction of certain value. As we mentioned earlier, simulation processes are run with different age reduction values from 10% to 90% respectively. Each simulation determines an optimal maintenance interval corresponding to a minimum cost. As a result, 80% age reduction is found to be the optimal value for both farms.

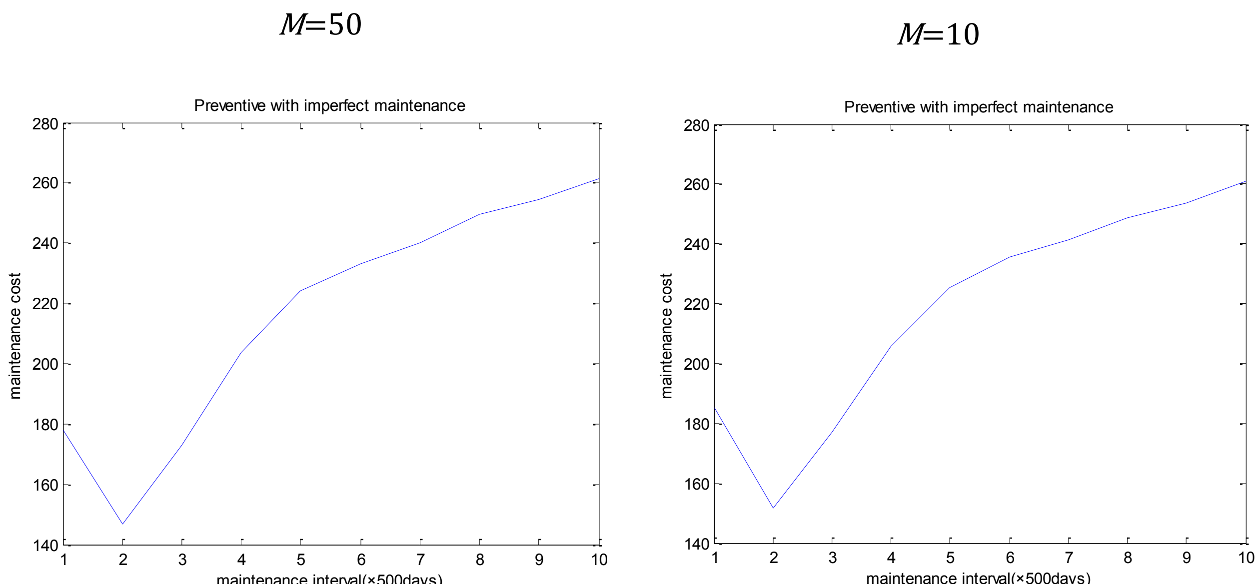


Figure 24. Cost versus interval (imperfect maintenance)

The cost versus maintenance interval with 80% age reduction plots are given in Figure 24. The optimal preventive maintenance interval is found to be 1000 days for both of 50× and 10× wind farms. The larger farm costs \$148.1/day, and the smaller farm costs \$150/day.

6.7 Conclusions

The optimal costs of proposed strategies and their cost-saving percentage comparing to corrective maintenance performed right after one failure are given in Table 5.

Table 5. Cost savings of proposed maintenance strategies

Strategy		50 × 2MW farm		10 × 2MW farm	
		Minimum cost	Saving	Minimum cost	Saving
1.Corrective maintenance allowing more than one failure		$196.8	10%	$232.9	2%
2. Opportunity Maintenance	2.1 Perfect preventive action	$150.4	31%	$147.7	38%
	2.2 Imperfect preventive action	$149.3	31.7%	$146.7	38.4%
	2.3 Two-level action	$147	32.7%	$145.8	38.7%
3. Fixed interval maintenance	3.1 perfect preventive action	$149	31.7%	$151	36.5%
	3.2 Imperfect preventive action	$148.1	32.2%	$150	36.9%

Based on comparative studies on numerical examples, the conclusions can be made as following:

- If only corrective maintenance is applied for a wind farm with 50 turbines, 3 failures can be allowed before the failure replacement. The minimum cost decreases 10% comparing to the failure replacement performed after one failure. The 10 turbines farm only saves 2% and the corresponding optimal number of failure is 2.
- Optimized opportunity maintenance and preventive replacement strategies save same cost of about 30%. It is also found that there are not significant benefits existing

between different sizes of wind farm when the optimal opportunity maintenance policy is applied.

- In case of opportunity maintenance, the imperfect maintenance action has not significant advantages. This could be explained that, the optimal variable, ‘q’, so called the maintenance quality, is found to be much close to 100% in our model.

Chapter 7

7. Closure

7.1 Conclusions

Maintenance optimization creates outstanding benefits for many industries. However, it is relatively new for wind power industry, which has been growing very fast in recent years due to the highly increasing requirements on clean and renewable energy in human life.

In this thesis, we focus on maintenance strategies that are currently widely used in wind power industry, including corrective maintenance (i.e., failure-based maintenance), opportunity maintenance, and time-based preventive maintenance. However, these maintenance strategies have not been studied adequately in wind power industry, and more effective methods can be developed. Many studies focus on maintenance optimization of specific components or an individual wind turbine system, rather than the entire wind farm.

In this thesis, we focus on the wind farm, which involves multiple wind turbines and each wind turbine is consisted of multiple turbine components. We propose several maintenance optimization models corresponding to corrective maintenance, opportunity maintenance, and fixed-interval preventive maintenance, respectively. (1) A corrective maintenance optimization model is proposed to optimize the number of failures allowed before performing corrective maintenance, and real wind turbine data from WindStat Newsletter are used in this study; (2) Opportunity maintenance methods are developed for wind farms to perform preventive maintenance actions when a failure occurs; (3) Preventive maintenance are proposed considering both perfect and imperfect maintenance actions. Cost evaluation algorithms are developed for these proposed methods, and optimal maintenance strategies can be obtained via optimization.

The proposed methods are demonstrated and compared using examples. According to the comparison results, the optimized opportunity maintenance strategy is the most cost-effective way, which saves about 30% of the cost compare with corrective maintenance strategy. Moreover, perfect and imperfect preventive actions bring the same benefit according to the optimal opportunity maintenance policy.

The developed methods in this thesis can be applied to improve the current maintenance practice in wind farms, and bring immediate benefits to wind energy industry in terms of reducing cost and improving availability.

7.2 Future work

Our first future work is to find analytical methods, which are more efficient for maintenance cost evaluation in the opportunity maintenance optimization problems.

There suppose to be various imperfect maintenance models that can be studied. Different imperfect actions have different effects on reliability after a component is being maintained, which consequently affect the maintenance cost.

We can also extend the optimization study by considering additional variables and optimizing these variables.

Finally, the real wind turbine operating data are important to reliability analysis, so that practical maintenance actions can be better planed. Sharable data and standard reporting scheme among organizations are needed.

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